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Report for Webb Henderson

Review of nbn's network selection
methodology and the efficiency
and prudency of the design of its
FTTN, FTTB and HFC networks

April 2016

Public version
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Annexes

Acknowledgement

I have read, understood and complied with the contents of the 'Practice Note CM 7: Expert Witnesses in proceedings in the Federal Court of Australia' supplied to me by Webb Henderson. I agree to comply with the terms of the Practice Note.

Amrish Kacker for Analysys Mason Ltd

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Date: 1 April 2016

1 Executive summary

NBN Co Limited (nbn) was established in April 2009 to design, build and operate a national broadband network to deliver high-bandwidth broadband and telephony services across Australia. nbn is a wholly owned Commonwealth company that has been prescribed as a government business enterprise (GBE). The company has two 'shareholder ministers' – the Minister for Communications and the Minister for Finance.

Initially, nbn's remit was to design, build and operate a wholesale-only, super-fast broadband network that was to provide downlink bandwidths of up to 100Mbit/s to 93% of premises in Australia using fibre to the premises (FTTP), and bandwidths of up to 12Mbit/s to the remaining 7% of Australian premises using fixed wireless access (FWA) and satellite networks.

However, following a strategic review published on 12 December 2013, the Australian Government has decided that nbn's roll-out should now transition from a three-technology network (FTTP + FWA + satellite) to an optimised multi-technology mix (MTM) approach, with the addition of fibre-to-the-node (FTTN), fibre-to-the-building (FTTB) and hybrid-fibre-coaxial (HFC) networks.

Assets that are required to support nbn's MTM strategy are being acquired from two well-established fixed operators, Telstra and Optus. These assets include elements of the following networks:

- Telstra's copper access network
- Telstra's HFC network
- Optus's HFC network.

nbn has concluded negotiations with Telstra and Optus to acquire the relevant network assets. Key elements of the transaction to acquire the Optus HFC network have received final authorisation by the ACCC.

Consistent with the Government's policy in relation to the national broadband network, nbn intends to lodge a variation to its current Special Access Undertaking (SAU) for assessment by the ACCC. The current SAU, as accepted by the ACCC on 13 December 2013, is based on an FTTP, FWA and satellite access strategy and the variation includes updates to account for the shift to the MTM strategy.

As part of the application for the SAU variation process, Webb Henderson, on behalf of nbn, engaged Analysys Mason to undertake an independent review of the prudency and efficiency of the following matters:

- nbn's methodology and processes for determining which type of network it will deploy in particular geographical areas
- nbn's initial design of its FTTN, FTTB and HFC networks.

In undertaking this review, Webb Henderson requested Analysys Mason to:

(1) Review the prudency and efficiency of nbn's methodology and processes for determining which MTM network type is to be deployed in particular geographical areas. The analysis should take account of the requirements of the Statement of Expectations (SoE), in particular, the Australian Government's intention that nbn will determine which network technologies are utilised on an area-by-area basis, so as to minimise peak funding, optimise economic returns and enhance the company's viability. This part of the report focuses on network selection at the geo-type level and need not consider network choices on a more granular level (e.g. at the street level, or post code level).

(2) Review whether, and the extent to which, nbn's initial design for its FTTN, FTTB and HFC networks reflects a prudent and efficient network design. This part of the report should focus on nbn's design choices in respect of each MTM network type. It does not consider how nbn determines the extent or size of each MTM network (e.g. how many 'modules' of each MTM network are to be deployed and why). The analysis should take account of the requirements of the SoE, in particular the Australian Government's intention that:

– nbn should be a wholesale-only access network, available on equivalent terms to all access seekers, that operates at the lowest practical levels in the network stack
– the design of a MTM mix should be guided by the Australian Government's policy objectives of providing download data rates (and proportional upload rates) of at least 25Mbit/s to all premises and at least 50Mbit/s to 90% of fixed line premises as soon as possible
– nbn should integrate existing HFC networks into the roll-out where this is feasible and economically beneficial, and provide for wholesale-only, open-access operation of these networks

(3) Review whether, and to what extent, nbn's initial network design of each MTM network:

– provides a sufficient basis for the implementation of nbn's initial wholesale product set and current planned product set

– has a sufficient upgrade path to meet anticipated demand for bandwidth, functionality, flexibility and reliability up to 30 June 2040, based on currently available technology roadmaps for each MTM technology and available forecasts for each MTM technology beyond the period of available technology roadmaps, to the extent such forecasts are available.[1] The analysis should have regard to the possibility that nbn may eventually upgrade the relevant MTM network to another technology type, as further described in Section 4.3.2 of the NBN Co Strategic Review report dated 12 December 2013.[2]

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[1]   Analysys Mason is not required to consider speculative or disruptive technologies that may potentially be available in the future as part of its analysis up to 30 June 2040.

[2]   http://www.nbnco.com.au/content/dam/nbnco/documents/NBN-Co-Strategic-Review-Report.pdf

Furthermore, Webb Henderson has stipulated the following:

- Policy decisions (or the merits of such decisions) made by the Australian Government that have an impact upon the design of the network (i.e. as set out in the SoE) should not be assessed. Instead, the review should focus on the key choices or decisions that have been made by nbn within the overall parameters that have been established by the Australian Government at a policy level through its SoE.

- As the MTM model involves the re-use and upgrading of networks that are already constructed, the report should only consider design choices in a way that has regard to the fact that:

  – some elements of the overall design are pre-determined, or not capable of being readily changed (e.g. the location of exchange buildings and distribution points) by virtue of the legacy network
  – there may be constraints in the manner in which nbn may utilise the MTM network in the future (e.g. nbn will need to continue to support the provision of Foxtel's pay-TV services over the Telstra HFC network).

- The review of the prudency and efficiency of nbn's initial design of its FTTN, FTTB and HFC networks should:

  – not re-open matters that were considered in the previous review of the prudency or efficiency of the original network design for FTTP, FWA and satellite, given that these matters relate to a separate and now concluded statutory process

  – only focus on the prudency or efficiency of the initial design of nbn's FTTN, FTTB and HFC networks. It should not consider other network designs that are currently being reviewed or trialled by nbn, such as FTTdp (e.g. reversed powered FTTdp using G.fast) or other technologies that are not yet commercially deployed in Australia. Discussion of these future network designs should be provided for background purposes and in the context of analysis on whether the MTM networks being initially constructed by nbn have a sufficient upgrade path in accordance with question (3) above.

In addition, Webb Henderson has requested that, in preparing our report, we have regard to the following additional matters in respect of each type of MTM network:

- In relation to FTTN/FTTB networks, the application of any short-term constraints that nbn must take into account in making design decisions in connection with nbn's utilisation of the FTTN/FTTB network, including the requirement for legacy copper services to co-exist with FTTN/FTTB networks during the co-existence period and the associated implications for service speeds and nbn's implementation of its initial wholesale product set and planned product set.

- In relation to FTTB networks, the technical limitations of vectored VDSL2 technology and the policy requirement that industry arrangements nevertheless be implemented to manage

interference and co-existence between competing superfast broadband providers that use vectored technology to serve a particular premises, including the associated implications for service speeds and nbn's implementation of its initial and planned wholesale product set.

- In relation to HFC networks, the application of any short-term constraints that nbn must take into account in making design decisions in connection with nbn's utilisation of assets from the Telstra and Optus HFC networks, including:

  – the fact that each HFC network is currently dimensioned to support a significantly lower penetration rate than is expected to be the case for nbn's usage of those networks
  – the spectrum limitations that currently exist in respect of those networks, including the continued requirement to use the Telstra HFC network to support the supply of Foxtel's pay-TV services and any consequential impediments associated with the upgrade of these HFC networks to DOCSIS 3.0 or 3.1.

Our framework for analysis in relation to the matters covered by this report is set out in Section 2 of this report.

Our assessment of nbn's network design is based on the information provided by nbn up to January 2016 and we note that some aspects of nbn's FTTN, FTTB and HFC network designs are expected to evolve and undergo further refinement as nbn moves forward with implementing its transaction with Telstra and Optus and also undertakes more detailed design work and planning activities to support the roll-out of those networks. Our assessment seeks to identify those areas where the network design continues to evolve or undergo refinement (e.g. network dimensioning rules) and also seeks to identify the way in which nbn is seeking to address that matter in the future, if currently known with sufficient certainty.

In preparing our responses to the questions put to us, we considered multiple sources of information that capture or explain the key decisions that have been made to date in respect of the design of nbn's FTTN, FTTB and HFC networks. These have included:

- NBN Co Strategic Review report, 12 December 2013[3]
- SoE, Australian Government, 8 April, 2014
- Final decision by the ACCC to authorise the Optus transaction, 28 August 2015[4]
- nbn's wholesale broadband agreement, including drafts for industry consultation
- nbn internal design documents.

This report does not examine the merits of the specifications given by the Australian Government to nbn at a policy level that have an impact on the design of the network. Rather, this report examines the key choices or decisions that have been made by nbn in the design of its network within the overall parameters that have been established by the Australian Government at a policy level through its SoE.

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[3]   http://www.nbnco.com.au/content/dam/nbnco/documents/NBN-Co-Strategic-Review-Report.pdf

[4]   https://www.accc.gov.au/media-release/accc-approves-revised-nbn-deal-with-optus

1.1 Analysys Mason's view on the efficiency and prudency of nbn's network selection

Analysys Mason believes that the methodology and processes used by nbn for determining which type of MTM network it will deploy in a particular geographical area is prudent and efficient.

Analysys Mason's assessment of nbn's network selection methodology

nbn has adopted a two-step approach for the selection of the optimum technology across the network, which comprises the strategic modelling process and the strategic overlay process:

• **Strategic modelling process**: the optimum technology for each area is determined based on a linear programme model (the 'MTM Optimiser'), which is based on a series of parameters that have been developed in line with SoE principles to derive the optimal network type to be used for that area. We are satisfied with the methodology used for the strategic modelling process to determine the optimum network type to be deployed in a given area.

• **Strategic overlay process**: once the optimum technology has been determined by the MTM Optimiser, nbn then applies a strategic overlay process to review the outcome of the MTM Optimiser to address practical issues. nbn's methodology is based on a series of business rules that consider a range of relevant factors, including the minimisation of peak funding, the maximisation of cash flows and a long term NPV consideration.

We believe the strategic overlay process to be prudent and efficient as it is critical to consider the different operational and financial constraints in the different areas to ensure an efficient deployment of the network.

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1.2 Analysys Mason's view on the efficiency and prudency of nbn's FTTN/B network

Analysys Mason considers that nbn's design of its FTTN/FTTB network reflects an efficient and prudent network design, notwithstanding the fact that certain components of the design and industry initiatives to support the competitive deployment of these networks are still in a state of development.

Service and technology decisions

- Implementing the network based on VDSL2 (using spectrum profile 17a) is both prudent and efficient as this is a mature technology that has been deployed by many incumbent operators around the world to provide broadband services and has also been selected for commercial use in Australia, as reflected in the recent work by the VDSL2 and Vectoring Working Committee (WC58[6]) of the Communication Alliance.

- nbn offers three classes of services, each with different priorities for different applications:

  – TC-4-based services represent low-priority traffic and are used for non-time-sensitive applications such as web browsing.

  – TC-1-based services represent high-priority traffic and are used for time-sensitive applications such as voice services.

  – TC-2-based services represent high-priority traffic and are used for symmetrical business applications.

- nbn offers the speed tiers for its FTTB and FTTN service, as illustrated in Figure 1.1 below:

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[6]   WC58 is responsible for the industry codes and standards that ensure harmonious deployment of xDSL technology on copper access cables in Australia.

Figure 1.1: nbn Ethernet bitstream services (NEBS) for FTTB and FTTN technologies [Source: nbn product description, NBN Co Ethernet Bitstream Service, Dec 2015]

Downstream access bandwidth (TC-4)	Upstream access bandwidth (TC-4)	Technology
12	1	FTTB and FTTN
25	5	FTTB and FTTN
25	5–10[7]	FTTB and FTTN
25–50[7]	5–20[7]	FTTB and FTTN
25–100[7]	5–40[7]	FTTB and FTTN

- Based on plant records provided by Telstra and on nbn's modelling of the copper access network (CAN) based on the samples available to date, nbn should be able to meet the Australian Government's target download data rates of 25Mbit/s to 100% of premises and 50Mbit/s to 90% of premises (and proportionate upload rates) in areas served by FTTN/FTTB technology, after the co-existence period.[8]

- However, it should be noted that:

    – Due to constraints inherent to FTTB and FTTN, for higher speed tiers (25–50 or 25–100Mbit/s for the downlink and 5–20Mbit/s or 5–40Mbit/s for the uplink), the design objective for peak bandwidth provided will fall within the specified range (i.e. services may not be able to attain the maximum bandwidth value specified for the range, depending on local condition of the CAN and copper loop length). We believe that the strategy associated with higher speed tiers is prudent and reasonably accounts for uncertainties regarding the actual physical characteristics of the existing CAN.

    – During the co-existence period, the lower end of the peak information rate range for the TC-4-based service may be lowered; although the lowered range for a NEBS service on the FTTB network will still start at 25Mbit/s download bandwidth and 5Mbit/s upload bandwidth (with the exception of the 12/1 Mbit/s AVC TC-4 service), on the FTTN network the lowered range will start at 12Mbit/s download bandwidth and 1Mbit/s upload bandwidth. This means that, in certain areas served by FTTN technology, nbn may only be able to meet the Australian Government objectives (in terms of minimum speed requirements) after the co-existence period has ended. This is because, during the co-existence period, the power back-off feature has to be used by nbn to mitigate the interference impact on copper pairs that are being used by Telstra within the same cable

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7   nbn will supply services on its FTTB and FTTN networks using ranged bandwidth profiles. The range specifies the maximum PIR which may be achieved for the relevant bandwidth profile, with the PIR falling anywhere in the range for the relevant bandwidth profile (i.e. they are not minimum/maximum PIR ranges). During the co-existence period, the peak information rate (and the lower end of any PIR range) for each AVC TC-4 bandwidth profile will be 25/5 Mbit/s in areas served by FTTB (with the exception of the 12/1 Mbit/s AVC TC-4 service) and 12/1 Mbit/s in areas served by FTTN.

8   'Co-existence period' is the period during which nbn is required to adjust the normal operations of the FTTB and FTTN networks by way of a Downstream Power Back-off, to accommodate the simultaneous supply of nbn NEBS services and Telstra exchange-fed services using copper pairs within the same copper binder.

binder used by nbn. This will result in a lower bandwidth for nbn services during that period. We believe this strategy to be in line with best international practice as it will mitigate the performance degradation caused by nbn to Telstra's existing services.

• nbn's choice of Ethernet as the Layer 2 protocol is both efficient and prudent, as this aligns with global standards, uses a proven technology, minimises technology risk and the risk of stranded assets, and will facilitate competitive vendor pricing.

Architecture-related decisions

► *End-to-end architecture*

• The end-to-end architecture is both prudent and efficient as it relies on a standard design similar to other FTTN/FTTB networks around the world, and maximises the re-use of Telstra's CAN as much as possible, thereby minimising capital investment.

► *Spectrum allocation and use of vectoring*

• The use of 17MHz spectrum by nbn is prudent because profile 17a is being used by many operators worldwide to provide VDSL2 services. The Communications Alliance has also developed a framework for the use of this profile in Australia.

• nbn is working with the Communications Alliance's WC58 to address the interference issues which may arise in xDSL systems when several operators use copper pairs within the same cable binder to provide services to their end-users. This process is on-going at the time of writing this report but it is expected to provide for spectrum separation to avoid interference. This approach seeks to avoid interference through the allocation of separate spectrum bands to the xDSL system of each operator that is seeking to serve MDUs using copper pairs that are contained within the same cable binder.

• nbn's current default position is to enable vectoring for all FTTB and FTTN architectures. nbn will be able to turn vectoring off in areas where interference with other operators causes an issue regarding the service performance:

  – For the FTTN architecture, it will allow each street cabinet to serve a larger footprint, thereby reducing the number of cabinets and compact DSLAMs needed. However, for the special case when nbn customers in an MDU are served from an nbn street cabinet and nbn has to use copper pairs within the same cable binder being used by another operator also serving the building, nbn's strategy for addressing interference issues will be dependent on the outcome of the Communications Alliance process referred to above. If vectoring has to be turned off due to interference issues, there may be a case where a new FTTN micro-node may have to be installed closer to end-users to ensure the SoE objectives are met in terms of service speeds.

- – For the FTTB architecture, nbn has decided to also use vectoring when copper pairs within a cable binder are to be used by nbn and another operator located in the MDU building on the basis that there are service stability benefits for nbn's services with this approach, with nbn having the flexibility to turn vectoring off if it causes performance degradation to the other operator's services.

- It is a prudent decision to use power back-off in cabinet locations to mitigate interference caused to the ADSL2+ signal on Telstra's broadband lines during the co-existence period. Power back-off is a mature feature in VDSL2 DSLAMs and has been used by many operators worldwide to mitigate this particular issue. In addition, the Communications Alliance has developed a framework for the use of this solution and believes that the degradation in bandwidth caused to nbn services will be modest (e.g. approximately 10%).

► *Network dimensioning*

- nbn has developed and refined a detailed dimensioning methodology since the launch of the FTTP network, and can now benefit from actual data from that network to benchmark its dimensioning calculations for the FTTN/FTTB network.

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- Overall, nbn's dimensioning process takes appropriately into account all classes of traffic. The dimensioning process will also undergo further refinement subsequent to the launch of FTTN/FTTB services when actual usage will be measured and fed back into the dimensioning process.

► *Network resilience and availability*

- nbn's design target for average end-to-end service availability of 99.9% (across all access networks) is prudent, and is in line with other operators internationally. The overall approach to assuring availability through the network design is in line with the approach we have seen from other large-scale operators.

- nbn has undertaken calculations of end-to-end service availability for the FTTN/FTTB network to the best of its ability based on the information currently available. Based on these calculations, end-to-end availability will be lower than the design target (across all access networks), depending on the infrastructure and type of DSLAM used. These figures reflect an average across the FTTN/FTTB access network as a whole and it is conceivable that end-to-end service availability will be higher in some areas and lower in other areas.

- The largest contributor of downtime in the access network is typically the DSLAM. nbn's decision to implement four-hour battery backup in every DSLAM is prudent as it will improve DSLAM availability. In our experience, operators usually equip DSLAMs with 2–6 hours of battery backup, depending on the reliability of local mains power.

- nbn's calculations in relation to availability of the CAN, which is also a major contribution to downtime in the access network, are based on Telstra's figures, but these relate to the average availability of the customer access network at a national level whereas the performance of particular lines will vary for different locations.

- Based on current estimates, although the estimated end-to-end availability of services falls short of the average national design target of 99.9%, when considering the mix of technology used, the expected average availability across all networks is 99.875%, just 0.025% short of the target. We believe this to be reasonable in the circumstances. In particular, we note that the availability of services provided over the HFC network may change as it is currently based on a theoretical estimate and the real availability of services provided over the HFC network may be different. The addition of the cable modem availability on the end-to-end service availability may lower the overall end-to-end services availability of the complete technology mix network.

► *Options for future capacity upgrades*

- Although nbn does not currently have a detailed roadmap for upgrading the FTTN/FTTB network, the options it is considering appear to be prudent, being in line with other operators internationally. The following options for upgrading its network would be available to nbn in the future:

  – exploiting the evolving xDSL standards, and potentially using G.fast technology
  – using the 30a frequency profile for VDSL2, which extends the spectrum available from 17MHz to 30MHz
  – extending the distribution fibre network to reduce the copper loop length (e.g. by deploying FTTdp architecture)
  – using other technologies coexisting and overlapping in the MTM network
  – upgrading to FTTP.

- The options available to nbn are also likely to achieve efficient outcomes as it is based on an incremental upgrade of the existing network rather than deploying new infrastructure, thereby maximising the use of, and the investment return on, existing assets.

- We have not identified any concerns regarding the way that the FTTN/FTTB network is designed which would prevent efficient and prudent upgrades being made to increase network capacity to address future demand.

- nbn's ability to undertake upgrades will be dependent to some extent on the outcome of the current Communications Alliance process that seeks to deal with interference issues caused by the co-existence of different xDSL systems. Resolving these issues at the industry level will be important as interference may become a greater issue when FTTN/FTTB networks are

upgraded to new xDSL technologies (e.g. G.fast provided over FTTdp) that will increasingly rely on vectoring to deliver their full potential in terms of bandwidth and return on investment.

Infrastructure-related decisions

► *Customer premises*

- nbn's decision to terminate the wholesale service at the wall plate is prudent, and in line with other operators internationally. Retail service providers (RSPs) typically like the option to provide their own CPE in a single device to end-users, as this enables them to differentiate themselves and allows a single CPE to be installed on the customer premises. The decision not to provide a CPE as part of the wholesale service will also remove significant costs from the wholesale solution.

- nbn has published CPE specifications to ensure they are compatible with the rest of the wholesale service being offered. RSPs and end-users will need to comply with these specifications to ensure that they can receive specified levels of support. nbn has also established a process that permits RSPs to register CPE against the published specification, which in turn will allow nbn to commit to fully supporting the use of registered CPEs on its network. This is an efficient approach on the whole, and balances the need to have specifications in the market for compatible CPEs with a degree of service flexibility for RSPs. In addition, as part of the registration programme, nbn may also wish to consider initiating a testing programme to validate which CPEs can be supported by its network to provide the required functionalities.

- FTTN/FTTB is the only access network type for which nbn does not provide any CPE to end-users, meaning that the service provisioning process is different from other network types. nbn has designed a specific service provisioning process for its FTTN/FTTB network to account for this.

- Re-using lead-ins from Telstra whenever possible is prudent and efficient, as it will accelerate the provisioning process and will be cost-effective.

► *Copper access network*

- nbn will maximise the re-use of the existing Telstra CAN. This is prudent because the CAN is already deployed, so nbn will avoid costs associated with civil engineering. It is also efficient because it will expedite the roll-out of the network.

- nbn has correctly identified the main types of remedial work on the CAN that are likely to be needed to ensure the required performance of VDSL-based services. Its two-stage rehabilitation strategy is efficient in that it will ensure that no undue investment is made to deliver the minimum service bandwidth required. In addition, the principles guiding the augmentation of the CAN are sound and will lead to efficient use of funds.

- However, there is currently insufficient data available on the condition of the CAN to be able to evaluate how much remedial and augmentation work will be required. Depending on the local condition of the CAN, if the extent of remedial and augmentation work is significantly different from what has been allowed for, then this may potentially raise cost issues from both a capex and opex perspective. However, as the network roll-out proceeds, further real data regarding the condition of the CAN will become available which may enable nbn to change its strategy to reduce its costs.

► *Street cabinets, pillars and MDU basements*

- nbn's decision to maximise the re-use of Telstra's pillars and implement separate street cabinets for the FTTN network is both prudent and efficient. This approach is in line with the approach taken by other operators internationally.

► *Distribution fibre network*

- The architecture of the distribution fibre network, which links exchanges to FTTN/FTTB nodes, is prudent and efficient. In terms of resiliency, the design ensures that a single fibre break would not affect more than 4000 end-users. Incumbent operators around the world take different approaches to this issue, typically ranging between 5000 and 40 000 end-users[11] across a range of markets. Therefore nbn's approach to resiliency is prudent compared with other international operators.

- In terms of scalability and ease of upgrade, the provisioning of a 12-fibre cable to connect the FTTN/FTTB nodes to the fibre access nodes (FAN[12]) is prudent. It means there are ten spare fibres at each FTTN/FTTB node, which facilitates a number of upgrade options for nbn. These can be used either for point-to-point fibre connections or for upgrading the FTTN network to a GPON FTTP network, or for additional capacity on the DSLAM.

► *Fibre access node*

- nbn's use of co-location space within Telstra's FANs is both prudent and efficient. The FANs are already operational facilities and therefore are fit for purpose in terms of hosting passive and active equipment. They also provide natural locations for the installation of aggregation nodes where all infrastructure can converge, thereby enabling a rapid network deployment.

- We understand that nbn's arrangements with Telstra provide for long-term access to FAN sites, minimising the risk associated with the potential closure of FANs where nbn operates.

- Aggregation of traffic as soon as practically possible within a network when there is sufficient traffic is good practice as it saves capacity in the network further downstream. We therefore believe that aggregating the traffic from all FTTN/FTTB nodes connected to a FAN into an access aggregation switch in the nbn network is efficient.

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[11]   Based on incumbent operators in developed Western European and Asia-Pacific markets.

[12]   This is equivalent to a telecommunications exchange.

► *Transit network*

- The architecture of the transit network was reviewed as part of our previous report[13] and we understand that no material changes in terms of architecture and design has been made for the implementation of the MTM strategy. Therefore, we have not re-assessed the transit network architecture from a prudency and efficiency perspective.

► *Aggregation nodes and POIs*

- nbn's approach to the aggregation nodes and POIs is prudent and efficient as it is agnostic regarding the type of access networks being used in a particular area, and therefore results in a unified architecture and consistent interconnection points for RSPs.

1.3 Analysys Mason's view on the efficiency and prudency of nbn's HFC network

Analysys Mason considers that nbn's design of its HFC network reflects an efficient and prudent network design on the whole, although there are potential issues that nbn recognises and is addressing.

Services and technology decisions

- HFC networks using DOCSIS 3.0 technology are being used widely throughout the world to provide downlink services equal to or in excess of the speed that nbn will offer to meet the SoE requirements and as part of its standard wholesale product set. Overall, DOCSIS 3.0 based HFC networks provide a prudent and efficient way to roll out services that meet the requirements of nbn supported services.

- The acquisition and use of the assets from the Telstra and Optus HFC networks where it is efficient for nbn to do so, is the quickest and most cost-effective route to providing services in areas where HFC networks have already been deployed. This allows nbn to offer services as soon as possible. It is therefore a prudent and efficient path to take.

- At commercial launch, nbn intends to offer two classes of services, each with different priorities for different applications, as follows:

  – TC-4-based services represent low-priority traffic and are used for non-time-sensitive applications such as web browsing
  – TC-1-based services represent high-priority traffic and are used for time-sensitive applications such as voice services.

- After the coexistence period, once Telstra and Optus cease to provide their own broadband services using their respective HFC networks, nbn also intends to offer TC-2- based services (i.e. high-priority traffic and are used for symmetrical business applications).

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13   *Review of the efficiency and prudency of NBN Co's fibre and wireless network design*, Analysys Mason, Sept 2012.

- nbn offers the following speed tiers on its HFC service, as illustrated in Figure 1.2:

Figure 1.2: NEBS for HFC technologies [Source: nbn, Dec 2015]

Downstream access bandwidth (TC-4)	Upstream access bandwidth (TC-4)	Technology
12	1	HFC
25	5	HFC
25	10	HFC
50	20	HFC
100	40	HFC

- Cable operators tend to offer services with a downlink-to-uplink speed ratio of 10:1, whereas nbn has services where the ratio is as low as 2.5:1. The standard ratio is due to the strongly asymmetrical nature of DOCSIS 3.0 and the greater susceptibility of the uplink signal to interference. In particular, we note that nbn has included a 100/40Mbit/s speed tier for HFC services to be consistent with the existing FTTP product set. To meet the maximum 40Mbit/s uplink bandwidth speed, there will be a need for nbn to undertake network upgrades, such as node splits. However, this situation will be alleviated with the implementation of the appropriate elements of DOCSIS 3.1 by nbn in the second half of 2017 which will reduce the requirement for node splits.

Architecture-related decisions

► *End-to-end architecture*

- nbn is being prudent and efficient by maximising the re-use of the existing assets that comprise the Telstra and Optus HFC networks, particularly in the access network (i.e. from the RF combiner site to end-user cable modems). The two cable networks are fundamentally of standard design compared to other HFC networks around the world. nbn is also planning to initially re-use existing Telstra and Optus fibre to connect its optic nodes to the RF multiplexers. This is an efficient approach as it will expedite the roll-out of HFC network services. In the future, nbn expects to deploy its own distribution fibre network for backhaul from the RF combiner site, rather than mirroring the existing networks back to head-end sites. This is also prudent, as it will be more cost-effective and provide nbn with more flexibility for future upgrades.

- It may be arguable that it is more capex-efficient if end-users continue to be served by Telstra/Optus cable modems and CMTSs, rather than being served by new nbn devices. However, this approach would introduce significant technical design and operational complexity as nbn would have to support a wider range of cable modems with different levels of functionality. This would result in the overall process not being prudent and efficient.

► *Spectrum allocation*

- nbn's approach to the use of spectrum is prudent, making use of available spectrum both during and after the co-existence period.[14] On the Telstra HFC network (and possibly[15] the Optus HFC network), nbn will have the option to further expand the use of DOCSIS 3.0 to 32 channels in the downlink, or to introduce DOCSIS 3.1. Future downlink plans will depend on the spectrum used for the Foxtel pay-TV service being made available,[16] and whether nbn decides to expand the spectrum to DOCSIS 3.0 limits (862MHz) or in line with DOCSIS 3.1 specified values – though network upgrades will be required to accommodate this approach. nbn has recently decided that it will implement DOCSIS 3.1 in the second half of 2017,[17] significantly alleviating capacity growth issues.

► *Network dimensioning*

- Careful traffic forecast management and an active approach to network re-configuration will be an important part of nbn's approach to managing the HFC network. nbn understands these issues and is taking a prudent approach. It intends to address network upgrades as required, utilising a combination of network performance data and traffic modelling. This approach is similar to that used by cable operators throughout the world and provides a prudent and efficient approach to providing additional traffic capacity.

- The delayed release of Optus downlink spectrum and the limitations on upstream spectrum could cause problems during the co-existence period, but this will be mitigated by not launching TC-2 services until after the end of that period and is unlikely to become a major concern.

- The RF segment configuration after the co-existence period is likely to be able to support service demands up to around 2020 in terms of headline bandwidth and peak average bandwidth, if uptake is in line with nbn forecasts. nbn's decision to implement DOCSIS 3.1 in the second half of 2017[18] will ensure that, by 2020, there will not be any bottleneck regarding headline bandwidth. nbn has also stated it may want to launch premium business services with higher headline speeds up to 1Gbit/s, while maintaining a downlink-to-uplink ratio of 2.5:1. It may be possible to accommodate such services in a limited way, particularly if business usage is mainly during the daytime, when HFC nodes are typically subject to less load from residential users. However, the higher uplink speeds proposed (200Mbit/s+) will entail an expansion of uplink spectrum in line with DOCSIS 3.1 specifications.

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[14]   The co-existence period corresponds to the period during which the HFC network will be shared between Telstra and nbn and between Optus and nbn so that each operator can offer services to their respective customers.

[15]   At the time of writing this report, the Optus HFC spectrum plan was not available, precluding us from concluding firmly on this fact

[16]   Foxtel's pay-TV service will also be offered beyond the co-existence period on the Telstra network.

[17]   http://www.nbnco.com.au/blog/the-nbn-project/nbn-wraps-up-HFC-pilot-steam-ahead-to-launch.html

[18]   http://www.nbnco.com.au/blog/the-nbn-project/nbn-wraps-up-HFC-pilot-steam-ahead-to-launch.html

- From the perspective of peak average bandwidth per user, our forecasts suggest that network upgrades such as node splitting, greater channel bonding and the introduction of DOCSIS 3.1 features are likely to be required from around 2020, particularly in high-traffic areas. nbn has recently decided that it will introduce DOCSIS 3.1 in the second half on 2017.[19]

► *Network resilience and availability*

- nbn has undertaken HFC network availability modelling to the best of its ability given the level of information available. Currently, nbn has only been able to estimate these values on a theoretical basis as actual measured values from Telstra and Optus are not yet available. Further information about the availability of the HFC networks from Telstra and Optus will provide the basis for nbn to further develop and refine its availability modelling and to compare its modelling against real-world data. In addition, nbn has not yet been able to include the availability of the cable modem, which is the element that typically has the highest impact on service availability. Also, it should be noted that the availability calculations assume the more resilient 'diverse chassis redundancy mode' option, whereas most service providers take the less resilient 'single chassis redundancy mode' option. The use of the 'diverse chassis redundancy mode' option will have a slight positive impact on the availability values compared to the version used by most service providers.

- The RF combiner represents the highest-impact single point of failure in the HFC network, affecting around 4000 end-users. Incumbent operators around the world take different approaches to this issue, typically ranging between 5000 and 40 000 end-users[20] across a range of markets. Therefore nbn's approach to resiliency is in line with the approach used by other operators internationally.

- Overall, nbn's approach to availability in its network design is in line with what we would expect and is a prudent approach. As the calculations currently stand, nbn is very close to meeting its overall average availability target across all networks, and it is being prudent and efficient in its approach to ensuring network availability targets are adhered to as closely as possible.

► *Future capacity upgrade options*

- nbn has a number of upgrade options for ensuring that the HFC network can continue to meet service requirements as demand for bandwidth increases in the future. In particular, it needs to ensure that demand for upstream bandwidth can be met. This risk will be addressed by the adoption of DOCSIS 3.1 standards, which provide the ability to offer downlink services in excess of 1Gbit/s.

- nbn does not have detailed plans for the upgrade of its HFC network in the longer term as it is concentrating on its shorter-term challenges such as network integration and reducing HFC

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[19]   http://www.nbnco.com.au/blog/the-nbn-project/nbn-wraps-up-HFC-pilot-steam-ahead-to-launch.html

[20]   Based on incumbent operators in developed Western European and Asia-Pacific markets.

node sizes. However, recently, nbn have decided that it will upgrade to DOCSIS 3.1 in the second half of 2017 to keep up with rising demand.[21]

Infrastructure-related design decisions

► *Customer premises*

• nbn is taking a prudent and efficient approach to the deployment of customer lead-ins by using existing lead-ins where possible. This will save both time and cost compared to using new connections. Telstra and Optus use industry-standard cables and components, and nbn plans to continue to use the same approach for new network connections. This is a prudent and efficient decision.

• nbn has currently decided to limit the cable modem to support the provision of downstream services by a single RSP, rather than multiple RSPs (as is the case for the FTTP service). This approach is in line with international approaches to providing HFC services.

► *Coaxial network*

• nbn intends to use the existing Telstra and Optus coaxial networks to provide its service, and this is a prudent and efficient approach for roll-out as it uses the existing spectrum plans and makes extensive use of existing infrastructure. The designs of the two coaxial networks differ, but are both within the bounds of standard design practice.

• nbn plans the use of a DOCSIS 3.1-compatible wider spectrum plan and fewer RF amplifiers in the coaxial section of the network for HFC new built network. This highlights the limitations of the existing plant architecture for offering higher-capacity services in the medium to long term (e.g. in terms of the spectrum bandwidth supported). nbn will need to address these issues by network upgrades and re-configuration. A combination of network reconfigurations (e.g. node splitting) and DOCSIS 3.1 deployment should provide a high degree of future-proofing.

► *Optic node*

• nbn is taking a prudent and efficient approach to optic node use by re-using the existing nodes from Optus and Telstra, which are industry-standard deployments. Where nbn undertakes optic node upgrades to newer equipment as per its current plans, this should enable nbn to undertake subsequent upgrade activities, such as node splitting and spectrum changes, without changing the optic node equipment. This will help to provide cost-efficient upgrades relative to a situation where nbn is re-using existing nodes from Optus and Telstra. For new optic nodes, nbn will deploy nodes that can facilitate capacity upgrades via re-configuration activities, such as changing the mid-split and expanding the spectrum band. These are possible without additional physical equipment upgrades, and thus can be conducted in a prudent and efficient manner.

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[21] http://www.nbnco.com.au/blog/the-nbn-project/nbn-wraps-up-HFC-pilot-steam-ahead-to-launch.html

► *Distribution fibre network*

- In the distribution fibre network, which connects the RF combiner and optic nodes, nbn will utilise existing Telstra and Optus fibre. This approach is prudent and efficient as it will enable service to be established quickly and cost-effectively as no additional investment will be required. However, in some cases, the paths of the fibre do not follow the preferred nbn architecture. nbn is likely to deploy its own fibre if more capacity is required in the future as this is likely to be more cost-effective than utilising dark fibre from other providers. We consider this a prudent and efficient approach.

- When additional fibre is required, nbn intends to follow the Telstra approach of using a point-to-point architecture rather than the more resilient ring approach used by Optus. This will provide the most efficient approach, but nbn does need to consider network resiliency targets, and would need to revisit this if there were any future changes to the network resilience strategy as the result of more data on the Telstra and Optus HFC networks becoming available.

► *Fibre aggregation node*

- nbn's intention to use existing RF combiner and RF transmission equipment at the FAN is both prudent and efficient as their specifications are compatible with the spectrum requirements of nbn's network roll-out plans. nbn's choice of RF combiner and transmission equipment for its network expansion will need to be compatible with its overall spectrum strategy, including matching the spectrum capability with its planned new amplifiers (up to 1GHz).

► *Aggregation node and PoI*

- At the aggregation node, nbn is using equipment from a leading CMTS vendor and is working closely with it to ensure its likely roadmap requirements are being addressed, while ensuring its roll-out targets can be met. We consider this approach to be prudent.

- As far as the Ethernet aggregation network and PoI are concerned, nbn is aiming to be as consistent as possible with the approaches of other access networks while also addressing some specific issues that arise in the context of HFC networks overlapping existing nbn boundaries. This is an efficient and prudent solution to maintaining consistency with existing deployments and meeting requirements for PoI alignment.

2 Introduction

2.1 Background

NBN Co Limited (nbn) was established in April 2009 to design, build and operate a national broadband network to deliver high-bandwidth broadband and telephony services across Australia. nbn is a wholly owned Commonwealth company that has been prescribed as a government business enterprise (GBE). The company has two 'shareholder ministers' – the Minister for Communications, and the Minister for Finance.

Initially, nbn's remit was to design, build and operate a wholesale-only, super-fast broadband network to provide downlink bandwidths of up to 100Mbit/s to 93% of premises in Australia using fibre to the premises (FTTP), and bandwidths of up to 12Mbit/s to the remaining 7% of Australian premises using fixed wireless access (FWA) and satellite networks.

However, following a strategic review published on 12 December 2013, the Australian Government has agreed that nbn's roll-out should now transition from a three-technology network (FTTP + FWA + satellite) to an optimised multi-technology mix (MTM) approach, with the addition of fibre-to-the-node (FTTN), fibre-to-the-building (FTTB) and hybrid-fibre-coaxial (HFC) networks.

Assets that are required to support nbn's MTM strategy are being acquired from two well-established fixed operators, Telstra and Optus. These assets include elements of the following networks:

- Telstra's copper access network
- Telstra's HFC network
- Optus's HFC network.

nbn has concluded negotiations with Telstra and Optus to acquire the relevant network assets. Key elements of the transaction to acquire the Optus HFC network have received final authorisation by the ACCC.

Consistent with the Government's policy in relation to the national broadband network, nbn intends to lodge a variation to its current Special Access Undertaking (SAU) for assessment by the ACCC. The current SAU, as accepted by the ACCC on 13 December 2013, is based on an FTTP, FWA and satellite access strategy and the variation includes updates to account for the shift to the MTM strategy.

As part of the application for the SAU variation process, Webb Henderson, on behalf of nbn, engaged Analysys Mason to undertake an independent review of the prudency and efficiency of the following matters:

- nbn's methodology and processes for determining which type of network it will deploy in particular geographical areas
- nbn's initial design of its FTTN, FTTB and HFC networks.

2.2 Statement of Expectations

The Australian Government issued a Statement of Expectations (SoE) on 8 April 2014 that captures nbn's new objectives. The new SoE from the Australian Government supersedes the previous SoE published on 17 December 2010.

The key objectives with regard to delivering the network in the new SoE are as follows:

1. nbn will determine which technology is utilised on an area-by-area basis so as to minimise peak funding, optimise economic returns and enhance the Company's viability.

2. The design of an MTM NBN will be guided by the Australian Government's policy objectives of providing downlink bandwidth of at least 25Mbit/s to all premises in Australia and at least 50Mbit/s to 90% of fixed-line premises (and proportionate upload bandwidths) as soon as possible.

3. nbn will ensure that any network upgrade paths are made available as required.

4. nbn will prioritise areas identified as poorly served by the Broadband Availability and Quality report published by the Department of Communication in February 2014 (including any subsequent refinements arising from additional data) to the extent commercially and operationally feasible.

5. nbn will ensure that the business rules it establishes to determine which technology is to be utilised in each locality is transparent to the community and is periodically updated to reflect technological and commercial developments.[22]

6. As proposed by the Strategy Review, nbn will integrate existing HFC networks into the roll-out where this is technically feasible and economically beneficial and provide for a wholesale-only, open-access operation of these.

7. nbn will trial fibre-to-the-*x* (FTTx) network architectures to inform nbn's planning and implementation decisions.

8. nbn will take proportionate responsibility for the quality, consistency and continuity of service experienced by retail service providers (RSPs) and their end-users.

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[22]   http://www.nbnco.com.au/content/dam/nbnco2/documents/nbn-multi-technology-deployment-principles.pdf

9. The Australian Government expects nbn will contribute leadership and resources to the industry-wide challenge of migrating services to nbn.

10. nbn's board and management will monitor the capabilities required to implement an MTM NBN, and ensure alignment between these and nbn's personnel.

In addition, to achieve the above objectives, the SoE provides nbn with the flexibility and discretion in operational, technology and network design decisions, within the constraints of a public equity capital limit of AUD29.5 billion.

In the rest of this report, we use the SoE as a reference to assess the prudency and efficiency of nbn's HFC, FTTN and FTTB network architecture in light of the transition to an MTM model. However, we note that we have not been asked to assess whether the objectives stated in the SoE are prudent and efficient but rather to assess whether nbn's planned implementation to address the SoE is prudent and efficient.

2.3 Scope of our review and factors to be addressed

As part of the variation of the SAU, nbn will need to satisfy the ACCC and access seekers that the costs associated with the initial design of the MTM networks, which will be rolled into nbn's cost base and which will be recoverable through the cost recovery mechanism in the SAU, are prudent and efficient.

In this context, we have been asked to address the following specific questions by Webb Henderson:

(1) Review the prudency and efficiency of nbn's methodology and processes for determining which MTM network type is to be deployed in particular geographical areas. The analysis should account of the requirements of the SoE, in particular, the Australian Government's intention that nbn will determine which network technologies are utilised on an area-by-area basis, so as to minimise peak funding, optimise economic returns and enhance the company's viability. This part of the report should focus on network selection at the geo-type level and need not consider network choices on a more granular level (e.g. at the street level, or post code level).

(2) Review whether, and the extent to which, nbn's initial design for its FTTN, FTTB and HFC networks reflects a prudent and efficient network design. This part of the report should focus on nbn's design choices in respect of each MTM network type. It need not consider how nbn determines the extent or size of each MTM network (e.g. how many 'modules' of each MTM network are to be deployed and why). The analysis should take account of the requirements of the SoE, in particular the Australian Government's intention that:

  – nbn be a wholesale-only access network, available on equivalent terms to all access seekers, that operates at the lowest practical levels in the network stack

– the design of an MTM will be guided by the Australian Government's policy objectives of providing download data rates (and proportional upload rates) of at least 25Mbit/s to all premises and at least 50Mbit/s to 90% of fixed line premises as soon as possible

– nbn will integrate existing HFC networks into the roll-out where this is feasible and economically beneficial, and provide for wholesale-only, open access operation of these networks.

(3) The review of nbn's initial design for its FTTN, FTTB and HFC networks described in Item 2 should consider whether, and the extent to which, nbn's initial network design of each MTM network:

– provides a sufficient basis for the implementation of nbn's initial wholesale product set and current planned product set

– has a sufficient upgrade path to meet anticipated demand for bandwidth, functionality, flexibility and reliability up to 30 June 2040, based on currently available technology roadmaps for each MTM technology and available forecasts for each MTM technology beyond the period of available technology roadmaps, to the extent such forecasts are available.[23] In undertaking this analysis, please have regard to the possibility that nbn may eventually upgrade the relevant MTM network to another technology type, as further described in Section 4.3.2 of the NBN Co Strategic Review report dated 12 December 2013.[24]

Specific factors to be considered

Webb Henderson has requested that in undertaking this assessment, the following should be considered:

• the prudency and efficiency of nbn's network selection methodology and process
• the prudency and efficiency of nbn's initial design of its FTTN, FTTB and HFC networks.

Furthermore, Webb Henderson has requested that in undertaking our assessment, we consider the following factors:

• Policy decisions (or the merits of such decisions) made by the Australian Government that impact upon the design of the network (i.e. as set out in the SoE) should not be assessed. Instead, the review should focus on the key choices or decisions that have been made by nbn within the overall parameters that have been established by the Australian Government at a policy level through its SoE.

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[23]   Analysys Mason is not required to consider speculative or disruptive technologies that may potentially be available in the future as part of its analysis up to 30 June 2040.

[24]   http://www.nbnco.com.au/content/dam/nbnco/documents/NBN-Co-Strategic-Review-Report.pdf

- As the MTM model involves the re-use and upgrading of networks that are already constructed, the report should only consider design choices in a way that has regard to the fact that:

  – Some elements of the overall design are pre-determined, or not capable of being readily changed (e.g. the location of exchange buildings and distribution points (DPs) by virtue of the legacy nature of the network being upgraded).

  – There may be constraints to the manner in which nbn may utilise the MTM network in the future (e.g. nbn will need to continue to support the provision of Foxtel pay-TV services over the Telstra HFC network).

- the review of the prudency and efficiency of nbn's initial design of its FTTN, FTTB and HFC networks should:

  – not re-open matters that were considered in the previous review of the prudency or efficiency of the original network design for FTTP, FWA and satellite, given that these matters relate to a separate and now concluded statutory process;

  – only focus on the prudency or efficiency of the initial design of nbn's FTTN, FTTB and HFC networks. It should not consider other network designs that are currently being reviewed or trialled by nbn, such as FTTdp (e.g. reversed powered FTTdp using G.fast)) or other networks that are not yet commercially deployed in Australia. Discussion of these future network designs should be provided for background purposes and in the context of analysis on whether the MTM networks being initially constructed by nbn have a sufficient upgrade path in accordance with question (3) above.

Additional factors to be considered in relation to each type of MTM network

In addition, Webb Henderson has requested that, in preparing our report, we have regard to the following additional matters in respect of each type of MTM network:

- In relation to FTTN/FTTB networks, the application of any short-term constraints that nbn must take into account in making design decisions in connection with nbn's utilisation of the FTTN/FTTB network, including the requirement for legacy copper services from Telstra to co-exist with FTTN/FTTB networks during the co-existence period and the associated implications for service speeds and nbn's implementation of its initial wholesale product set and current planned product set.

- In relation to FTTB networks, the technical limitations of vectored VDSL2 technology and the policy requirement that industry arrangements nevertheless be implemented to manage interference and co-existence between competing superfast broadband providers that use vectored technology to serve a particular premises, including the associated implications for service speeds and nbn's implementation of its initial and planned wholesale product set.

- In relation to HFC networks, the application of any short-term constraints that nbn must take into account in making design decisions in connection with nbn's utilisation of the assets that comprise the Telstra and Optus HFC networks, including:

  – the fact that each HFC network is currently dimensioned to support a significantly lower penetration rate than what is expected to be the case for nbn's usage of those networks
  – the spectrum limitations that currently exist in respect of those networks, including the continued requirement to use the Telstra HFC network to support the supply of Foxtel pay-TV services and any consequential impediments associated with the upgrade of these HFC networks to DOCSIS 3.0 or 3.1.

Matters excluded from the scope of our report

The review only focuses on the FTTN, FTTB and HFC networks that form part of the initial roll-out by nbn. It does not include a re-assessment of our previous review of the efficiency of the original network design for FTTP, FWA and satellite, given that these matters relate to a separate and now concluded statutory process.

Our report also does not evaluate the prudency or efficiency of other network designs, such as those network designs that are currently being reviewed or trialled by nbn, such as reversed powered FTTdp.

The discussion of these network architectures and design are primarily for background purposes (e.g. on discussions of the future evolution of MTM networks) or in the context of the review of whether the MTM networks being initially constructed by nbn have a sufficient upgrade path.

We also note that while some of these network architecture and design are currently being reviewed or trialled by nbn, no final decision has been taken by nbn on these options.

2.4 Our approach to determining the prudency and efficiency of nbn's network selection methodology

Through its SoE, the Australian Government has mandated nbn to design and deploy an optimised MTM network and has provided for nbn to determine which network types are utilised on an area-by-area basis, so as to minimise peak funding, optimise economic returns and enhance the company's viability.

In addition, the SoE requires nbn to ensure that the business rules it establishes to determine which technology is used in each locality are transparent to the community, and periodically updated to reflect technological and commercial developments.[25]

As nbn will now have responsibility for determining which network type it is to deploy in particular geographical areas, it is necessary to consider whether nbn's methodology and processes

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[25]   http://www.nbnco.com.au/content/dam/nbnco2/documents/nbn-multi-technology-deployment-principles.pdf

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for determining which network type is to be deployed in a particular geographical area are prudent and efficient.

We have had regard to the above stated requirements in the SoE as the basis for our prudency and efficiency analysis of nbn's network selection methodology and processes. In doing so, we have focused our prudency and efficiency review on network selection at the geo-type level.

In particular, we have considered whether the decisions that are made by nbn as a consequence of the application of its network selection methodology and processes would result in (or be likely to result in) outcomes that are consistent with the outcomes that we would expect from a prudent and efficient telecoms operator subject to the same requirements and constraints as those applicable to nbn under the SoE.

2.5 Our approach to determining the prudency and efficiency of nbn's network design

Analysys Mason considers that the key decisions that influence the efficiency and prudency of a network design include:

- technology choices, which mainly relate to the access network technology being used to supply services
- architectural choices, which mainly relate to the topology of the network
- infrastructure choices, which relate to the physical implementation of different sections and nodes of the network.

It is on these specific areas of nbn's design of its FTTN, FTTB and HFC networks that we have focused our analysis, bearing in mind that some design decisions of existing networks that are to be integrated into nbn have already been made by third parties, namely Telstra and Optus.

In performing this analysis, we have considered whether nbn's design decisions are consistent with current international best practice for the deployment of FTTN/FTTB and HFC networks in other developed markets.

In undertaking this analysis and forming the conclusions, we have used the following framework for analysis:

- In reviewing the 'prudency' of network design decisions made by nbn, we have considered whether those decisions have been made with care and thought for the future based on various factors, such as scalability, resilience and flexibility of the relevant element of the network design.

- In reviewing the 'efficiency' of network design decisions made by nbn, we have considered whether those decisions are likely to achieve the best result with minimum wasted effort or expense taking into account local circumstances.

Therefore, in developing this report, we have referred to the concepts of prudency and efficiency separately, using the plain English meaning attributed above. Due to the subject matter or nature of some of the decisions associated with developing a network design, we note that it is not always necessary or, indeed, practically possible to evaluate all design decisions simultaneously from both a prudency and efficiency perspective. In practice, this has meant that the analysis of some design decisions has, depending on the subject matter, focused on the prudency or efficiency of the particular choice, but not both. Accordingly, where an assessment in this report only refers to the efficiency or the prudency of the relevant design decision, but not to both, this should be taken to mean that Analysys Mason has only evaluated that particular decision by reference to the relevant specified factor.

As part of our prudency analysis, we have sought to analyse whether, and the extent to which, nbn's design decisions include a sufficient upgrade path to meet anticipated demand requirements of access seekers for bandwidth, functionality, flexibility and reliability until 30 June 2040, based on currently available technology roadmaps for each MTM technology and available forecasts for each MTM technology beyond the period of available technology roadmaps, to the extent such forecasts are available. The purpose behind this analytical approach is to ensure that the analysis of nbn's key technology decisions is not static or 'frozen at a point in time', but that consideration is also given to the extent to which key technology decisions made by nbn today allow nbn to readily upgrade its network over time to meet the evolving demand from access seekers and end-users (e.g. for additional bandwidth). This reflects, in our view, a key element of considering the prudency of nbn's design decisions, as described above.

Then, for each technology implemented, our analysis has sought to consider, from an efficiency and prudency perspective, many of the key individual design choices that have been made by nbn.

It is the combination of these individual design choices and decisions that together determine whether the nbn FTTN, FTTB and HFC networks, as a whole, are efficient and prudent from a design perspective. Therefore, while we have made individual assessments of the efficiency and prudency of individual design choices and decisions, the overall conclusion on the question of whether, and the extent to which, nbn's design for FTTN, FTTB and HFC networks reflects an efficient and prudent network design, is based on Analysys Mason taking a view on nbn's design of each network in its totality.

2.6 Documents reviewed in the preparation of this report

In undertaking our assessment of the efficiency and prudency of nbn's design of its MTM network, we considered multiple sources of information that were provided by Webb Henderson. This included the SoE, ACCC documents and nbn documents which capture or explain the key decisions that have been made to date in respect of the design of nbn's MTM network.

2.7 Structure of this report

The remainder of this report is laid out as follows:

- **Section 3** presents a technical overview of FTTN and FTTB networks; it is designed as a reference point for all FTTN/FTTB architectures discussed in the rest of the report.

- **Section 4** provides a technical overview of HFC network technology that is suitable for the provision of broadband services; it is designed as a reference point for all HFC architecture discussed in the rest of the report.

- **Section 5** presents our analysis and conclusions in respect of whether, and the extent to which, the methodology and processes used by nbn to determine the optimum network type in different geographical areas result in an efficient and prudent network mix.

- **Section 6** presents our analysis and conclusions in respect of whether, and the extent to which, nbn's design for its FTTN and FTTB networks reflects an efficient and prudent network design.

- **Section 7** presents our analysis and conclusions in respect of whether, and the extent to which, nbn's design for its HFC network reflects an efficient and prudent network design.

In addition, a number of annexes are included which contain the following supporting documentation:

- **Annex A** describes the expertise and experience of the principal authors of this report.

- **Annex B** includes declarations from Analysys Mason as per the requirements of *Practice Note CM 7: Expert Witnesses in proceedings in the Federal Court of Australia* (4 June 2013) supplied by Webb Henderson.

- **Annex C** provides a description of network selection for areas with buildings with multiple dwellings.

- **Annex D** includes a description of nbn's main FTTN architectures considered for the design of the MTM network.

3 Technical overview of FTTN and FTTB networks

This section presents a technical overview of FTTN and FTTB technologies, and is designed as a reference point for the rest of this report. It is structured as follows:

- Section 3.1 provides an overview of FTTN and FTTB.

- Section 3.2 describes the technology available for FTTN and FTTB in terms of their standards, architecture options and key network elements.

- Section 3.3 provides an overview of the key worldwide deployments of FTTN and FTTB technologies.

- Section 3.4 includes a technology roadmap for the next 25 years for both FTTN and FTTB technologies, to show the expected evolution of bandwidth and reach for each technology.

- Section 3.5 presents a simple demand model scenario, which evolves over time, to assess whether FTTN and FTTB technology roadmaps will be able to meet the expected demand in the future.

- Section 3.6 provides insight into key operational issues associated with technology upgrades for both FTTN and FTTB networks.

3.1 Overview of FTTN/FTTB architecture

In this section we first describe the characteristics and the evolution of the broadband technology known as digital subscriber line (DSL). We then describe legacy copper access networks (CANs), defining all key elements of the network which serves as a reference for the rest of this report.

DSL technology

Incumbent operators designed and built their copper access networks to deliver legacy 'plain old telephony services' (POTS). With the increasing demand for higher-bandwidth data services, a broadband technology –asymmetrical digital subscriber line (ADSL) – was developed and used by operators over their legacy copper access infrastructure to provide end-users with downlink bandwidth of 'up to' 512Mbit/s. The reason that broadband services are marketed as 'up to' a certain bandwidth is because, with DSL technologies, the actual bandwidth experienced at customer premises is dependent on the length (and quality) of the copper loop between the active equipment providing the broadband signal in the operator's network and the customer premises.

To address increasing broadband bandwidth demand, various DSL standards (referred to collectively as xDSL) have significantly evolved over time providing ever-increasing downlink

and uplink bandwidth capability. xDSL standards are described in detail in Section 3.2 of this report and include:

- ADSL family
  - ADSL1
  - ADSL 2
  - ADSL 2+.

- VDSL family
  - VDSL 1
  - VDSL 2.

The dependence between bandwidth performance and copper loop distance for the above xDSL technology is illustrated in Figure 3.1.

Figure 3.1: illustration of downlink broadband bandwidth as a function of the copper loop length for different xDSL technologies [Source: Analysys Mason, 2015]
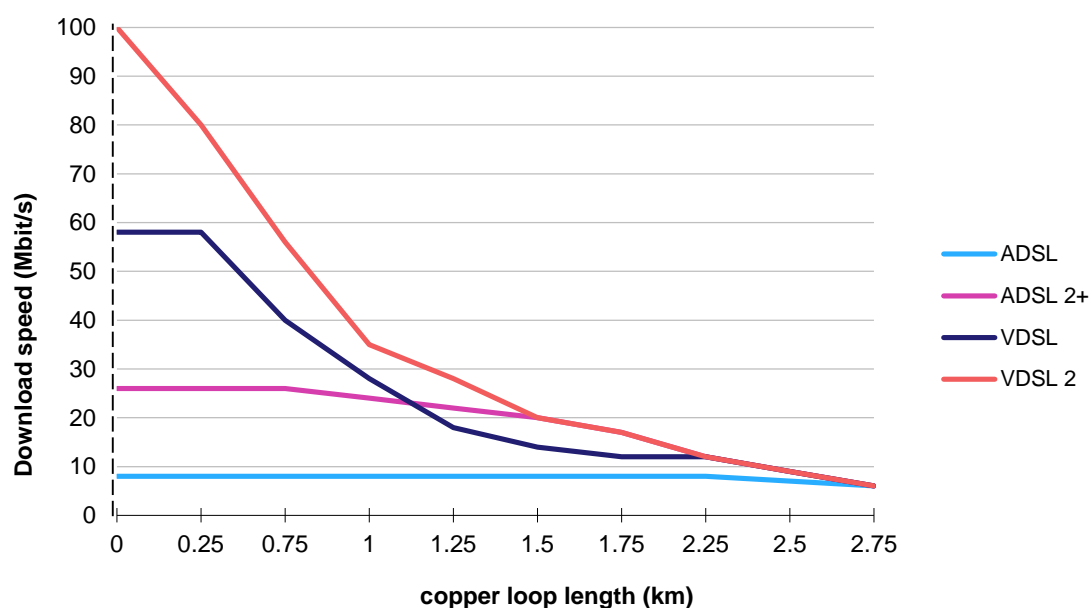
Two important observations can be made from Figure 3.1:

- the bandwidth decreases with the copper loop length for all xDSL technologies
- improvement in bandwidth provided by latest VDSL technology is for relatively short copper loops (up to about 1.5km in the above figure).

Therefore, advances in xDSL technology tend to benefit premises that are connected with shorter loop lengths.

Legacy copper network architecture

A typical legacy broadband network, using the legacy copper network is illustrated in Figure 3.2.

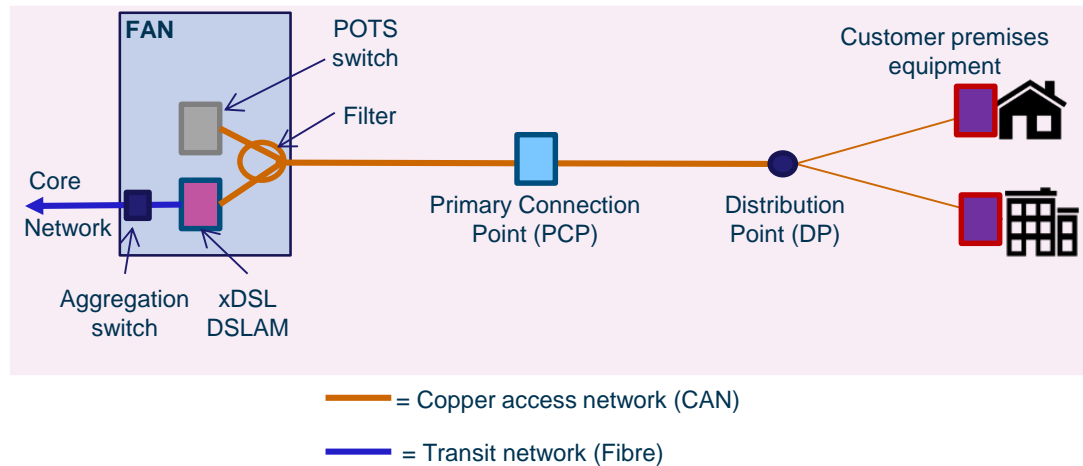*Figure 3.2: Legacy broadband access network architecture [Source: Analysys Mason, 2015]*

In Figure 3.2, the key network nodes in a legacy broadband network architecture include the following:

- fibre access node (FAN)
- copper access network (CAN)
- primary connection point (PCP)
- DP
- customer premises equipment (CPE).

We describe the (legacy) equipment contained in each of these network nodes below.

► *FAN*

A FAN, which is most likely to be an existing telephone exchange building, hosts key active and passive network components including:

- **Main distribution frame (MDF):** a passive connection panel in the FAN between copper lines connecting customer premises to the FAN and core network equipment.

- **Filters** to separate PSTN telephony connections from broadband connections.

- **POTS switch:** the legacy switch used for telephony services.

- **DSL access multiplexer (DSLAM):** the equipment used to provide the broadband connection using the copper telephone lines. The first deployments of xDSL technology used variants of ADSL technology providing bandwidths up to 24Mbit/s.

- **Ethernet aggregation switch (EAS)** which aggregates all broadband connections from different DSLAMs and routes the traffic between the core and access networks.

► *CAN and PCP*

The PCP provides a flexible passive copper connection point usually hosted in a cabinet or pillar physically located between the FAN enclosure and customer premises and serves between 50 and 500 customer premises. In Australia, a typical PCP is implemented using a pillar. Typically, each exchange has a number of PCPs hosted from it, all connected via the legacy CAN. The copper network between the FAN and the PCP is usually referred to as the exchange side (or E-side) and the copper network between the PCP and customer premises is usually referred to as the distribution side (or D-side). The PCP connects E-side and D-side by using copper jumpers (connectors) in a connection panel (mini-MDF).

► *DP*

The DP is another passive connection point in the network which connects the copper network to customer premises. It usually takes the form of a small box and can be located either on a pole (overhead infrastructure) or in a foot-hole (underground infrastructure). The DP usually connects between five and 20 customer premises to the copper network. The network segment between the DP and customer premises is usually referred to as the last drop.

► *Customer premises*

The last drop is usually terminated at the customer premises using a wall plate which is commonly known as the master telephone socket. A DSL filter is installed in the telephone socket to separate PSTN telephony (baseband) signals from broadband signals. The CPE is connected to the DSL filter. It usually takes the form of a DSL modem/router with Ethernet and/or Wi-Fi connections to connect to customers' terminals, for example laptop PCs and tablets to provide access to the Internet. It should be noted that the CPE must be compatible with the DSL technology used by the DSLAM located in the FAN site.

Based on observations made in this section, operators have had to shorten their copper local loops to be able to take full advantage of new standards and to provide ever-increasing broadband bandwidth to their end-users. In the following sections, we describe the typical architectures which can be deployed to reduce the copper loop length, namely:

- FTTN
- FTTB
- FTTdp.

3.1.2 FTTN architecture overview

Figure 3.1 clearly shows that more recent xDSL standards (e.g. VDSL 2) provide a significant increase in downlink and uplink bandwidth for shorter copper loops (i.e. loops up to 1.5km) compared to more mature standards (e.g. ADSL 2+). However, VDSL 2 performance gain compared with other DSL technologies significantly decreases for copper loops longer than 1.5km providing a similar absolute performance to earlier DSL technologies.

The shortening of copper loops can be achieved by the deployment of an FTTN architecture. FTTN involves rolling out fibre from the FAN to the PCP location where usually a street cabinet hosting the DSLAM will be deployed. Typically, an additional cabinet hosting the DSLAM is located close to the PCP cabinet to enable copper line connections between the DSLAM and the PCP (see Option 1 in Figure 3.3). Alternatively, if there are constraints on physical space at the PCP location, or planning permission restrictions, a new integrated cabinet hosting both the PCP and the DSLAM can be deployed at the original PCP location (see Option 2 in Figure 3.3). Finally, if no new cabinets can be installed at the PCP location due to physical space or planning permission restrictions, the DSLAM cabinet could also be hosted in a totally new location between the PCP and customer premises, above an existing manhole which has suitable joints for copper interconnection (see Option 3 in Figure 3.3).

Figure 3.3: FTTN architecture options [Source: Analysys Mason, 2015]
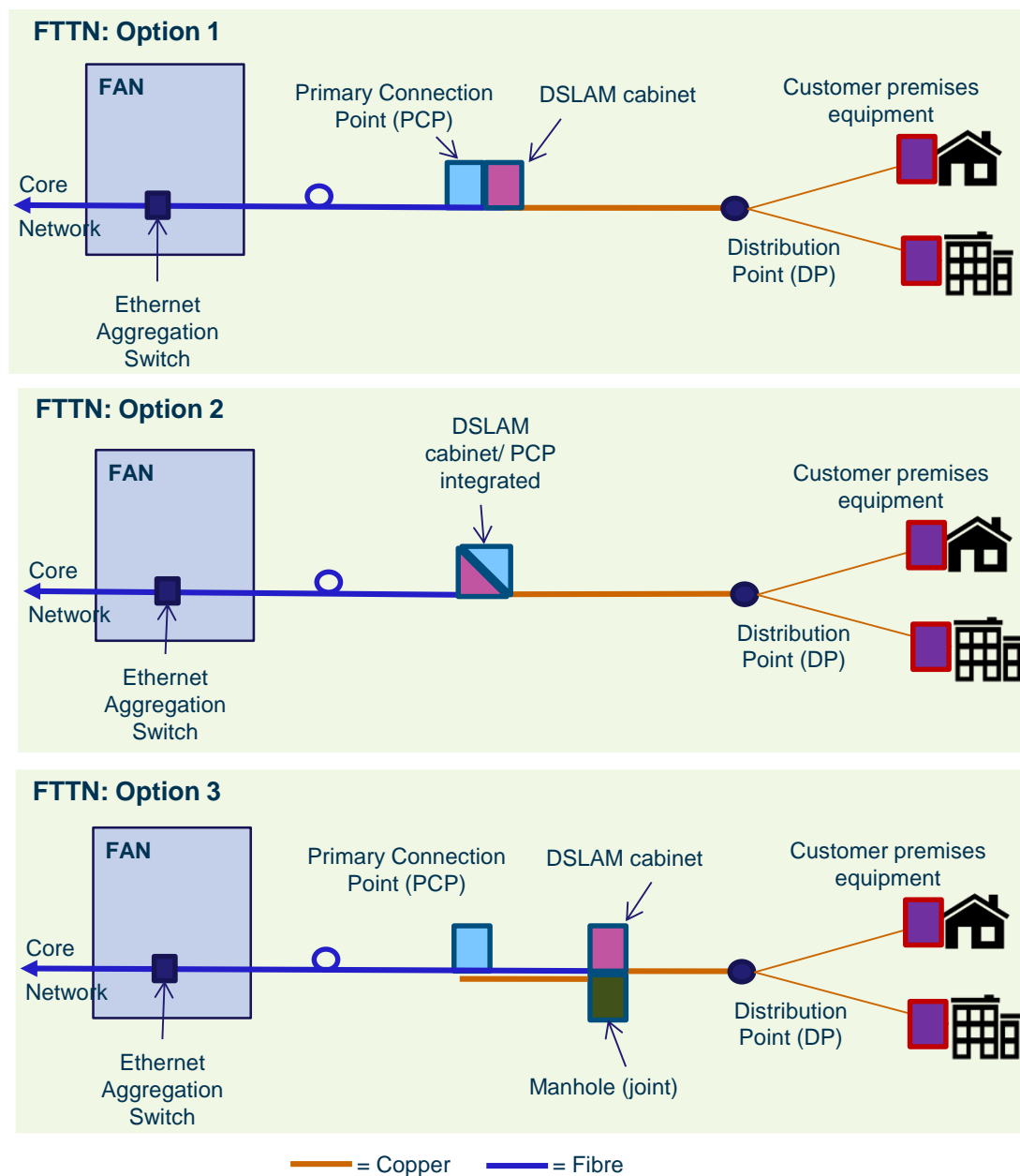
Where possible to minimise civil engineering costs, fibre is deployed using the same duct infrastructure as the legacy copper cables between the exchange and the DSLAM cabinet.

The longer the copper loop length, the lower the bandwidth that can be achieved at the customer premises, so the positioning of the DSLAM cabinet is a key design factor. This is a compromise between the broadband bandwidth that can be achieved and the number of customer premises that can be served from a single cabinet. In general, the closer to the FAN the cabinet is, the more customer premises it can serve and consequently the more cost-effective as fewer cabinets can be deployed to serve the customer premises in a defined area. However, as illustrated in Figure 3.1, the further away the cabinet is from the customer premises, the lower the broadband bandwidth due to the increasing copper loop length. Therefore, when designing their FTTN networks,

operators have to carefully consider the location of street cabinets as they need to optimise the balance between cost and performance (bandwidth) by taking account of:

- existing locations for interconnecting with the copper network
- the economies of scale associated with the number of customer premises served from a single cabinet
- the distance from the customer premises to ensure the broadband speeds advertised by the operator can be delivered.

3.1.3 FTTB architecture overview

An FTTB network architecture is used to provide broadband services to a building that accommodates many customer premises, often referred to as a multi-dwelling unit (MDU). Whilst a key design and performance factor of an FTTN network is the position of the DSLAM cabinet (usually close to the PCP), an FTTB network reduces the copper loop further by placing the DSLAM either in a small cabinet just outside the MDU (see Option 1 in Figure 3.4) or in the basement of the MDU (see Option 2 in Figure 3.4).

Figure 3.4: FTTB architecture options [Source: Analysys Mason, 2015]
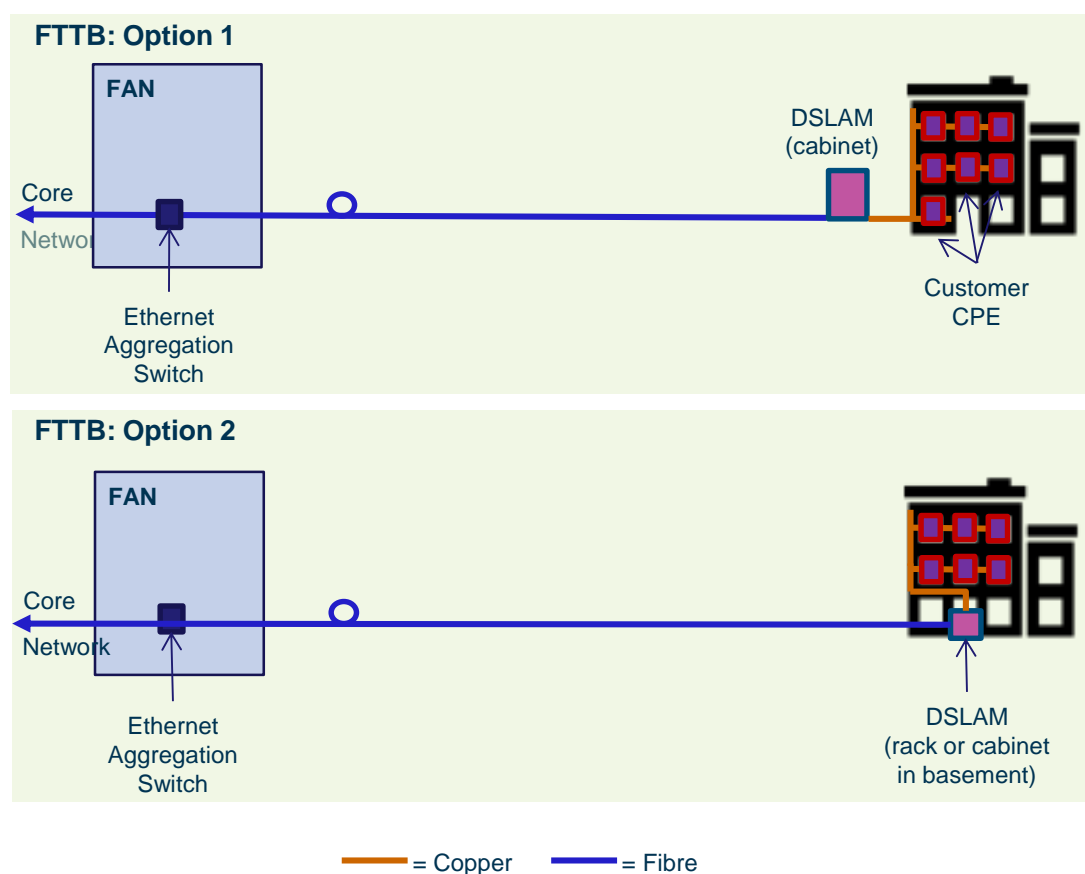
Today, VDSL2 is the technology typically used in an FTTB architecture to deliver broadband services.

We describe FTTB architecture Options 1 and 2 in more detail below.

FTTB Option 1

In Option 1, a small street cabinet (hosting the DSLAM) is deployed just outside the MDU to serve all premises within the building, and connected to the FAN using fibre. Assuming that the building's internal copper wiring is suitable, it can be used to connect each customer premises to the DSLAM cabinet. Re-using the building's internal wiring reduces the disruption within the building, which is beneficial to both building owners and premises tenants/owners, and network operators as it minimises costs. However, when the internal copper wiring is not suitable, new internal wiring has to be deployed. Not only is this costly and disruptive but it also requires prior agreement of the building owner, which in some cases can be difficult to obtain. Therefore, the suitability of a building's internal wiring represents a financial and technical risk for operators when deploying an FTTB solution. Note that in some far-sighted developed countries the governments/local authorities have changed building regulations so that all new MDUs must be built so that they can accommodate high-performance broadband connections internally to maximise broadband availability and take-up. However, there may still be issues related to delivering high-performance broadband connections within older existing MDUs.

In Option 1, the external DSLAM cabinet may provide broadband services to several MDUs, depending on the proximity of the MDUs to be served and depending on the number of premises within each MDU. For example, if four MDUs are within 250m of each other and if each MDU contains 10 premises, then the optimum solution for the operator may be to pursue Option 1 using a 48-port DSLAM compact cabinet.

FTTB Option 2

In Option 2, the DSLAM is deployed in the basement of an MDU and can take the form of a standard rack hosting DSLAM equipment or a standalone compact DSLAM unit. Deploying the DSLAM in a rack is scalable as DSLAM cards can be added to match the number of premises to be served.

Option 2 tends to be deployed in large MDUs (e.g. 40 or more customer premises) to take advantage of scale economies since the entire DSLAM can be dedicated to that building. However, it is not always possible for operators to have convenient access to the basement of an MDU as it requires prior permission from the building's owner. In cases where the operator cannot get access to the MDU's basement, it will deploy a cabinet just outside the MDU, as explained for Option 1.

3.1.4 FTTdp architecture overview

The FTTdp architecture consists of deploying fibre to a small DSLAM located at the DP, known as a distribution point unit (DPU). Typically, the FTTdp DPU takes the form of a small box located at the top of a pole for last drops delivered overhead (see Option 1 in Figure 3.5). Alternatively, for premises served by underground infrastructure, the DPU can be hosted in a

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sealed box in the last foot-hole of the network connecting the copper last drop to the customer premises (see Option 2 in Figure 3.5).

Figure 3.5: FTTdp architecture options [Source: Analysys Mason, 2015]
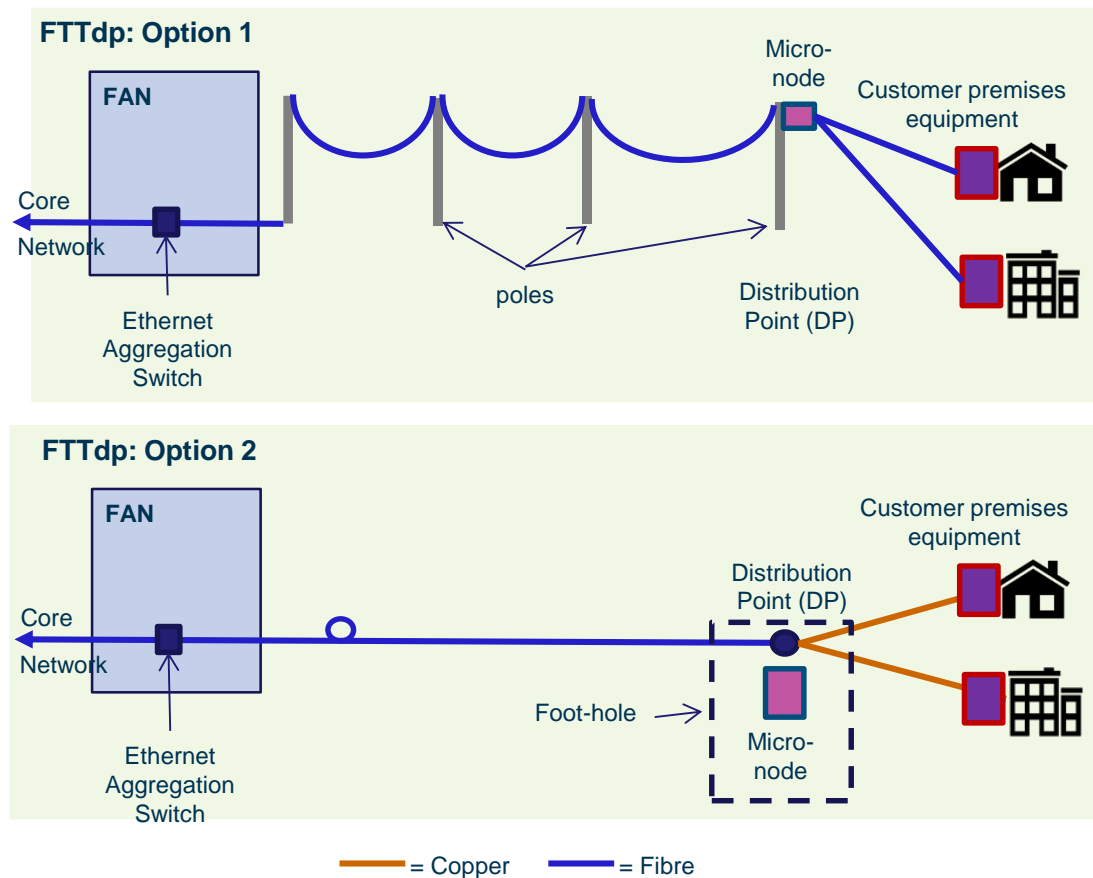
FTTdp is still considered to be less mature than other architectures but a number of trials are being carried out by major operators around the world to evaluate its performance (see case studies in Section 3.3). nbn itself is also currently undertaking a trial of G.fast technology.[26]

The performance of FTTdp infrastructure has been enhanced by the development of the G.fast standard (see Section 3.2.4) which enables broadband bandwidth[27] in excess of 600Mbit/s to be achieved over short copper loop lengths (i.e. less than 250m).

FTTdp remains less mature than other architectures. The Communication Alliance has not yet developed a framework for the use of this architecture in Australia.

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[26]   http://www.nbnco.com.au/blog/the-nbn-project/nbn-takes-first-steps-towards-g-fast-launch.html

[27]   Combined uplink and downlink bandwidth.

3.2 Factors affecting DSL performance and technology standards

To assess whether the implementation of the FTTN and FTTB networks is prudent and efficient, it is important to first understand the main factors affecting the performance of xDSL networks. Therefore, Section 3.2.1 provides an overview of the key factors affecting the performance of DSL systems. Also, in Sections 3.2.2, 3.2.3 and 3.2.4, we briefly describe ADSL, VDSL and G.fast standards respectively to better understand the capability of each technology. Finally, we discuss how some of the acceleration technologies can mitigate some of the physical factors affecting the performance of DSL systems.

3.2.1 Factors affecting the performance of DSL systems

Below, we consider a number of factors that can affect xDSL performance, the most influential of which are attenuation, bridged taps, loading coils and crosstalk, as well as moisture ingress into the relevant cables. Other factors include return loss, longitudinal balance, noise, split pairs and gauge changes. The factors we address in this report are:

- attenuation with respect to length of copper loops
- signal-to-noise ratio (SNR)
- maximum achievable bandwidth with respect to copper loop length
- copper loop wire gauges
- bridged taps
- party lines and pair gain systems
- loading coils
- effects of near-end cross-talk (NEXT) and far-end cross-talk (FEXT)
- other physical factors such as installation practices, deterioration of components over time and the sometimes practised deployment of aluminium instead of copper loops.

Attenuation with respect to length of copper loops

The reduction of the broadband signal (or loss of power, of the electrical broadband signal) as it propagates along the copper loop is known as attenuation and is measured in decibels. The longer the loop, the greater the attenuation and the weaker the signal.

The attenuation per unit length is mainly dependent on three variables, namely the thickness (or gauge) of the copper wire used to make the loop, the insulation material surrounding the conductors and the frequency of the transmitted signal. Thicker wires offer less attenuation than thinner wires; polyethylene insulation causes less attenuation than paper; whilst a wire of a given diameter will present a higher attenuation as the frequency of the signal propagating through it increases.

SNR

The SNR (the size of the broadband signal divided by the size of the noise signal) is a measure of signal strength relative to background noise taken at the receiver. The SNR is a key metric and describes the characteristics of the copper loop, including its quality and length. The SNR effectively defines the maximum rate at which information can be transmitted across the copper loop and therefore defines the downlink and uplink bandwidth of broadband services.

Maximum achievable bandwidth with respect to copper loop length

The bandwidth is a function of the SNR. As the length of the loop increases, the broadband signal will experience more attenuation and the strength of the signal arriving at the receiver will decrease, thereby lowering the SNR. Therefore, the maximum bandwidth for any xDSL system will be achieved over the shortest loops, i.e. when the distance between the DSLAM and CPE is shortest, as illustrated in Figure 3.1.

Wire gauges

The gauge or thickness of the copper wire comprising a twisted pair copper loop affects the amount of attenuation, the thicker the wire the smaller the attenuation (all other things being equal). Usually, the thinnest wire that can achieve the target level of attenuation is used, as this keeps raw material costs to a minimum, and cables occupy less duct space in the ground. Using less duct space in turn reduces the cost of civil works, which is the major driver of total network deployment costs. However, to maintain target levels of attenuation operators typically use thicker wire on longer loops.

Bridged taps

A bridged tap is an unused pair of wires which is connected to a loop at some point along its length. The final end of the unused pair is typically un-terminated, resulting in an open electrical circuit. The configuration is shown in Figure 3.6.
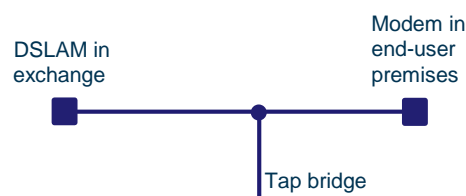
Figure 3.6: Bridged tap
[Source: Analysys Mason, 2015]

A bridged tap occurs in the access network either intentionally, where it is provided in anticipation of service demand at a new location, or unintentionally as a result of service to an end-user being discontinued and the copper pair being reassigned to a different end-user at a different location. bridged taps cause signal reflections. The signal reflections mix with the original signal, creating constructive and destructive interference effects, and confuse the CPE i.e. DSL modems. The

length of the bridged tap determines which frequencies are the subject of attenuation, and newer DSL technologies are affected by bridged taps as short as two metres (VDSL2) or less than one metre (G.fast). Bridged taps may occur in either the network or at the end-user premises, and are understood to be present in the majority of end-user premises in Australia. To help maximise xDSL performance, bridged taps should be removed.

Party lines and pair gain systems

Historically, as the number of analogue telephone subscribers increased, operators around the world found it difficult to expand the local loop infrastructure fast enough to keep up with demand. Operators in many countries resorted to providing so-called 'party lines', where a single copper loop was used to provide service to more than one subscriber, therefore making them unsuitable for xDSL-based broadband services. Party lines created a variety of technical issues for operators, as well as privacy issues for subscribers. Most operators began to remove party lines as demand for telephony services plateaued, and only a very small number remains in existence today. However, to enable selective ringing on party lines, many operators installed bridged taps from one wire to a local earth in each property. It is possible that a larger proportion of these bridged taps are still connected to what were once party lines, even if the other end of the tap connection is no longer earthed. This arrangement results in electrical characteristics of the copper loop that degrade the performance of xDSL services.

Some subscribers were also connected over analogue or digital pair gain systems designed to provide two or more analogue POTS services on a single copper pair using time-division or frequency-division multiplexing. Such pair gain systems are generally incompatible with xDSL services and need to be removed from the network for correct operation of xDSL services.

Loading coils

Loading coils are devices that are installed at regular points along a copper loop to reduce attenuation at the top end of the POTS band (baseband up to 4kHz) to improve the quality of the POTS service. Loading coils are only employed in long loops, typically on loops that are greater than 5.5km. Although the performance of POTS systems has improved with the use of loading coils, they increase attenuation at the higher xDSL frequencies, thereby preventing successful operation of xDSL systems. For the xDSL services to perform adequately, loading coils must be removed.

NEXT

In the context of local loop cables comprising many twisted pair copper loops, crosstalk describes the interference effect between broadband signals in adjacent twisted pairs, normally located within the same cable binder. The impact of crosstalk increases with cable length and with signal frequency. The standard terminology is that the 'disturbing pairs' cause crosstalk in the 'victim pair'.

NEXT is the interference caused between transmitters and receivers located at the same end of a cable. NEXT usually limits xDSL performance if co-located transmitters and receivers use the same frequency band. NEXT can have an especially high negative impact on longer loops, where

the signal arriving at the receiver is relatively weak. This weak signal at the victim receiver is therefore relatively significantly affected by crosstalk caused by an adjacent disturbing transmitter. To some extent crosstalk between loops using different frequency bands can be addressed using 'spectrum management'.

FEXT

If the crosstalk is detected by receivers on the victim pair at the opposite end of the cable from the transmitters, the interference is called FEXT. FEXT is attenuated as the loop length increases, simply because the crosstalk from the disturbing transmitter has to travel further to reach the victim receiver. For pairs with a gauge (thickness) of 26 AWG (American Wire Gauge) and a length in excess of 3km, FEXT is generally attenuated to beneath the background noise level, and is therefore negligible. FEXT is therefore a significant impairment only on shorter loops, and can significantly affect the performance of FTTN and FTTB networks.

The effect of FEXT on the downlink 'rate-reach' performance of a copper pair not only decreases with line length, but also with the number of adjacent disturbing pairs. If all of the lines in a cable binder are managed together, a technique called vectoring can be employed to every pair and can virtually eliminate the negative effects of FEXT (see Section 3.2.5 for more details on vectoring). However, if each line is managed separately (i.e. by different operators), it is much more difficult to implement vectoring to mitigate the impact of FEXT.

Other physical factors

► *Deterioration of components*

A deterioration in the condition of the components may also have a significant impact on the xDSL performance of the copper loop. For example, if the conductivity of one of the wires changes, perhaps through corrosion at some connections, the optimum electrical characteristics of the copper pairs can be detrimentally affected. Corrosion can occur slowly through continuous exposure to air and moisture, or be caused by direct water ingress (e.g. due to flooding). Direct water ingress may significantly affect the performance of cables even when corrosion is not present in the cable.

► *Installation practices*

The quality of copper loops can also be affected by the installation and maintenance practices employed by operators, which can have an impact on the xDSL performance delivered over the copper loops. For example, if cables are crushed, stretched or flattened during or after installation, the electrical characteristics of the cable can be degraded. Elevated NEXT can occur at the modems if cables are terminated poorly (for example, by fitting low-quality connectors or employing poor termination practice).

► *Aluminium twisted pairs*

In some areas of Europe (e.g. the new town of Milton Keynes in the UK, which was mostly built during the 1970s) but also in Australia, the access loop was constructed with aluminium rather than copper pairs due to the very high price of copper prevailing at the time of construction. Notably, aluminium has a higher attenuation per metre than copper therefore, for a given loop length, the SNR of an aluminium loop will be lower than that for a copper loop. Issues can also occur at any aluminium-copper connection due to the different expansion properties of the two metals and the electro-chemical effects between them. The prevalence of aluminium cables in Australia is very low, amounting to a low single-digit percentage.

3.2.2 ADSL standards

A number of standards that describe different versions of ADSL have been developed over time, namely ADSL1, ADSL2 and ADSL2+. These are summarised in the following subsections.

ADSL1

The first ADSL recommendation from ITU-T (G.992.1), generally denoted as ADSL1, was completed in 1999. ADSL was originally intended for delivering video on demand at a maximum bitrate of 8Mbit/s downlink and 640kbit/s uplink. The standard contains two[28] different operational modes:

- Annex A: ADSL over the POTS network, in which the frequencies between 0 and 4kHz are used to deliver POTS services, and the frequencies between 25kHz and 1104kHz are used for the uplink and downlink frequencies of the broadband signal. A guard band between 4kHz and 25kHz is used to isolate the voice signal from the broadband signals.

- Annex B: ADSL over the integrated service digital network (ISDN), in which the frequencies between 0kHz and 120kHz are reserved for ISDN services, and the frequencies between 120kHz and 1104kHz are used for the uplink and downlink frequencies of the broadband signal. A guard band is used to isolate the ISDN signal from the broadband signals. This mode is not deployed in Australia.

The frequency plans for the above operational modes are illustrated in Figure 3.7.

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[28] There is also an *Annex C*, which defines ADSL over POTS for operation in a TCM-ISDN environment, i.e. where ISDN uses time compression multiplexing (TCM) to separate uplink and downlink signals. However, this system only exists in Japan and is therefore not relevant to this project.

Figure 3.7: Frequency plans for ADSL1 [Source: Adapted from ITU Recommendation G.992.1]
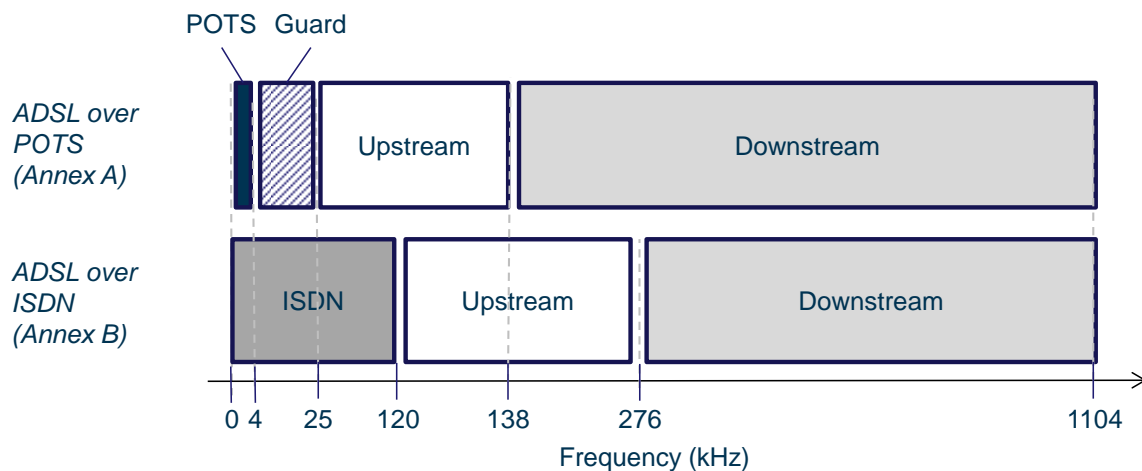
Each annex in the standard also describes different power spectral density (PSD) masks (not shown). The PSD masks define maximum permissible electrical power levels across the various frequency sub-channels to minimise crosstalk and interference in the system deployment. Of course, the PSD masks also reflect the frequency plans described in Figure 3.7 above.

ADSL2

The second-generation ADSL standard (ADSL2, ITU-T G.992.3) was issued in July 2002. The standard contains the original operational modes of ADSL1, namely:

- Annex A: ADSL over the POTS network.

- Annex B: ADSL over ISDN.

Although the spectrum allocations for these modes are similar to those for ADSL1, the delivered bandwidths are higher due to various enhancements (such as the mandatory use of a new modulation method called trellis coding).

Also, a number of new operational modes were introduced in ADSL2 to meet a more diverse range of requirements from the service provider, such as:

- Annex J: 'All-digital' mode, in which the full spectrum (i.e. from 0kHz through to 1104kHz) can be used wholly for the broadband signal. This mode is not deployed in Australia.

- Annex L: ADSL over POTS extended reach, where both the downlink and uplink masks are truncated, but the total transmitter power is kept constant. This narrower-bandwidth mode results in greatly improved performance over long loops (since lower-frequency signals experience less attenuation). This allowed ADSL services to work at distances of up to 7km from the exchange.

- Annex M: ADSL over POTS extended uplink, where the uplink bandwidth is increased, at the expense of downlink bandwidth. This makes it possible to have a higher uplink bandwidth (up to 3.5Mbit/s in the case of short loops).

The frequency plans for some of the operational modes described above are illustrated in Figure 3.8.

Figure 3.8: Frequency plans for ADSL2 [Source: Adapted from ITU Recommendation G.992.3]
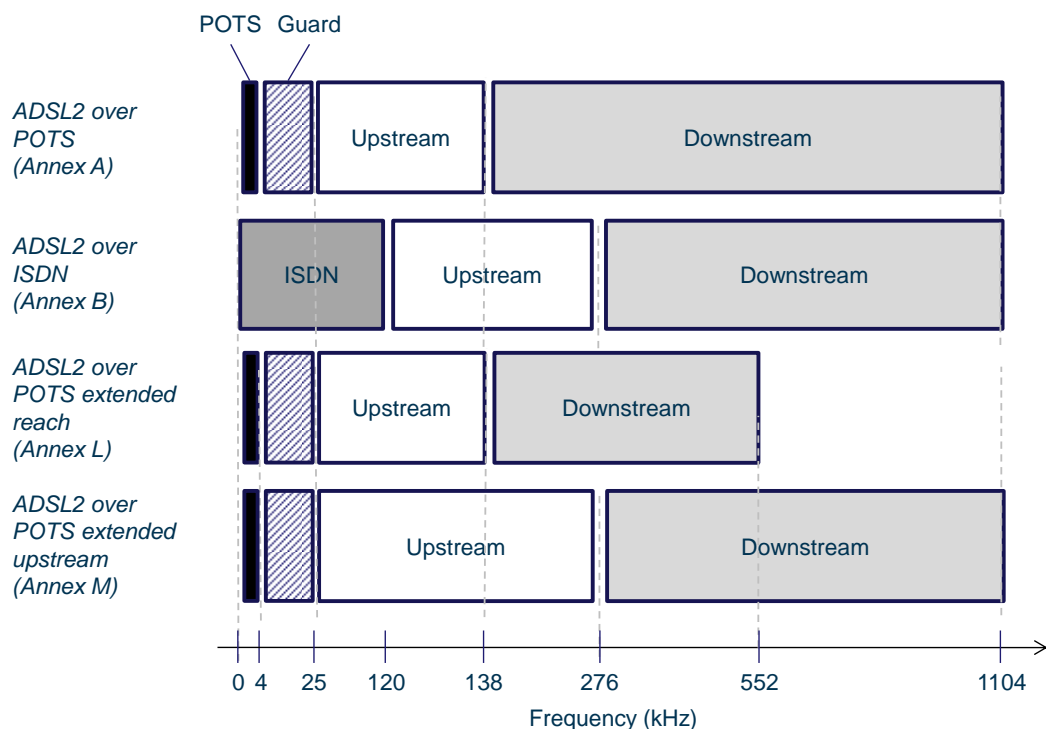
ADSL2+

The ADSL2+ standard (ITU-T G.992.5), issued in 2003, doubled the spectrum allocated to downlink data. Although the higher frequencies were attenuated over long loops (and so it was not possible to deliver higher bandwidths over long loops), improved bandwidth could be delivered over short- and medium-length loops.[29] The annexes that define the various operational modes in the ADSL2 G.992.3 standard are all present in the ADSL2+ G.992.5 standard, with the exception of *Annex L: extended reach ADSL2*, which is not applicable and is excluded. The G.992.5 standard is classed as an additional standard to G.992.3, such that ADSL2+ systems are capable of ADSL2 operation.

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[29] This standard effectively filled the gap between ADSL1 and the later standard VDSL, which delivered very high rates over short loops.

The frequency plans for the key operational modes of ADSL2+ are illustrated in Figure 3.9, showing the extension to the downlink spectrum:

Figure 3.9: Frequency plans for ADSL2+ (not to scale) [Source: Adapted from ITU Recommendation G.992.5]
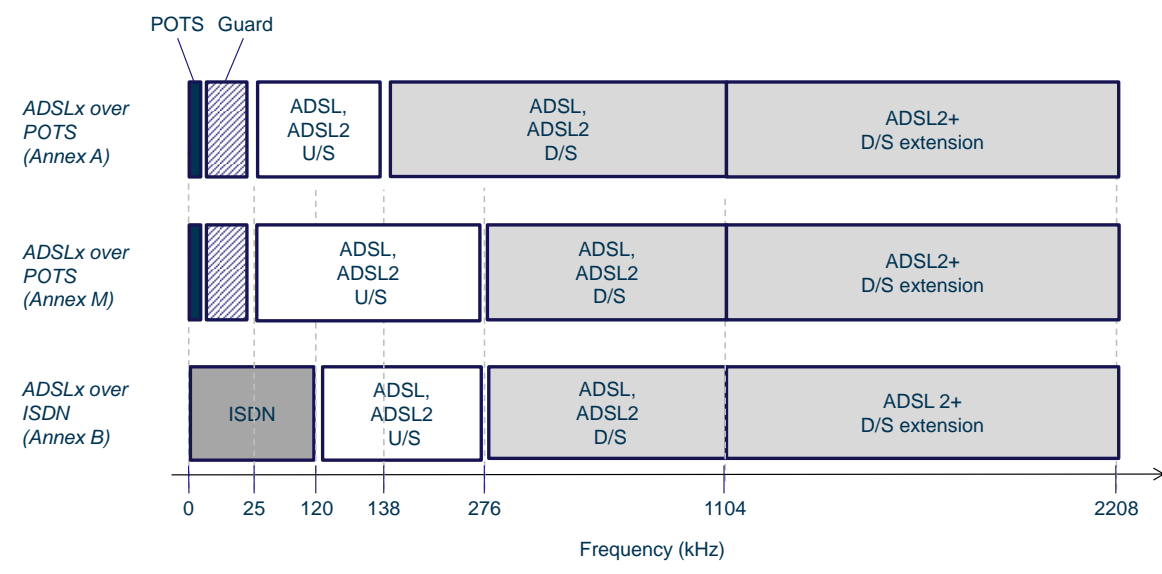
3.2.3 VDSL standards

VDSL systems were developed to deliver higher bandwidth than ADSL systems, by using more spectrum in the copper cable. Since higher-frequency signals are more attenuated than low-frequency signals, VDSL is typically used over shorter loops than the loops used in ADSL systems. VDSL can also provide either symmetric or asymmetric bandwidths, although most services in Europe are asymmetric. Second-generation systems (VDSL2; ITU-T G.993.2) typically use frequencies of up to 17MHz to provide bandwidths exceeding 100Mbit/s downstream and 40Mbit/s upstream, or frequencies up to 30MHz to simultaneously provide bandwidths exceeding 100Mbit/s in both the uplink and downlink directions.

VDSL1

First-generation VDSL1 standards were published in 2001. They define the use of the frequency band from 25kHz to 12MHz, and support (over a single pair) downlink rates of up to 52Mbit/s and uplink rates of up to 16Mbit/s. The key factors in the standard are:

- The selection of frequency division duplexing (FDD) as the preferred duplexing method instead of time division duplexing (TDD). FDD reduces the effect of crosstalk compared to TDD systems and therefore increases bandwidth capability. DMT modulation is the preferred modulation scheme for VDSL1 (as it was for ADSL systems). An explanation of modulation technologies is provided in Annex A.

- The introduction of a novel band-plan approach that used alternating uplink and downlink spectra. Annex A of the VDSL standard defines North American requirements, whilst

Annex B defines European requirements. Note that the frequency band used for VDSL1 was later extended from 12MHz to 30MHz.

Despite the apparently performance-favourable deployment conditions presented by relatively short copper loops, VDSL still needs to accommodate a number of special issues, as follows.

- Radio interference of VDSL systems with other wireless systems. The larger range of frequencies used by VDSL1 overlaps with those licensed to other users. This is addressed by creating frequency 'notches' (filters) where the transmitted power level in the VDSL system across the frequencies that third-party systems use is reduced.

- In the downlink direction, cabinet-based modems can inject excessive levels of FEXT into lines from exchange-based modems. This typically occurs between cabinet-based VDSL and exchange-based ADSL2/2+ systems. The cabinet-based VDSL modems interfere with signals on the longer ADSL exchange loop at a point where the signal in that loop is already relatively weak. Therefore, in cabinet-based VDSL systems, the PSD is reduced across the ADSL frequency band.

- In the uplink direction, transmitters on short cabinet loops operating at full power can create excessive levels of FEXT into long cabinet loops. This is referred to as the 'near-far' problem and typically occurs between VDSL systems. The short loops interfere with signals on longer loops at a point where the signal in that loop is already relatively weak. Since cabinet loops are much shorter than exchange loops (as used in ADSL2/2+ systems) and because FEXT is not fully attenuated in loops up to around 1.5km, the level of uplink FEXT at the receiver (located in the cabinet) can be high. This problem is addressed by reducing the transmit powers on short cabinet loops, referred to as 'uplink power back-off' (UPBO).[30]

- Elevated levels of FEXT interference because of the high frequencies used. This can be overcome very effectively using a process called vectoring (which is explained in Section 3.2.5).

VDSL2

The VDSL2 standard (G.993.2), published in 2006, was developed to meet the requirements of many diverse deployment scenarios. For example, the short-reach, potentially high-bandwidth conditions presented by MDUs (in an FTTB architecture) are very different from those presented by cabinets that feed residential households via longer cabinet loops (in FTTN architecture), where in addition to bandwidth, reach is also an important consideration.

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[30] Downstream power back-off is not generally required, as the transmitters are co-located (either in the exchange or cabinet), such that the FEXT that couples into the long line has to travel further than in the uplink case, and is therefore attenuated; any problems in the downlink direction can be managed using PSD shaping.

Such reach-rate trade-off requirements were met not by specifying a single compromise solution, but by introducing a set of so-called 'profiles' that matched specific deployment conditions. The profiles are defined in terms of the following parameters:

- sub-carrier spacing
- transmit power in uplink and downlink directions
- minimum bidirectional net bandwidth capability
- index of the highest data-bearing sub-carrier supported in uplink and downlink direction
- inter-leave and de inter-leave delay
- whether support for ADSL uplink band US0 is required or not.

Eight profiles (labelled 8a, 8b, 8c, 8d, 12a, 12b, 17a and 30a) were consequently specified. For example, Profile 30a is designed for situations where distances are very short, making it practical to use spectrum up to 30MHz. The vast majority of VDSL2 deployments internationally use the 17a profile and this is also the case for most, if not all, current deployments in Australia. The PSDs defined in VDSL2 are similar to those defined in VDSL1. However, there is one main difference, concerning the way PSDs are amended to reduce interference between cabinet- and exchange-based xDSL systems. In VDSL1, separate PSDs were defined for cabinet- and exchange-based systems, whilst in VDSL2 the PSD can be changed via a set of parameters, whereas the transmit powers vary with frequency range employed by the system, as shown in Figure 3.10.
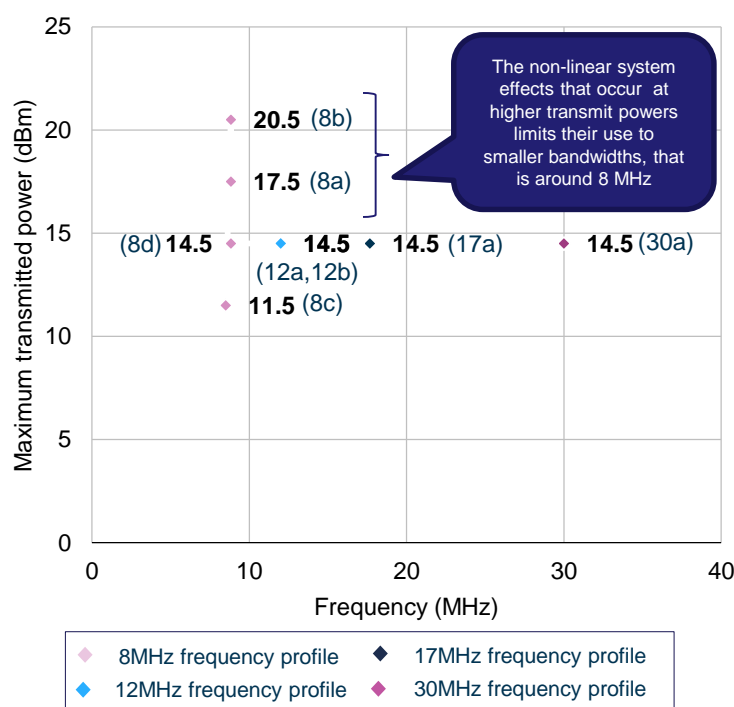
Figure 3.10: VDSL2 transmit power versus frequency [Source: Adapted from ITU Recommendation G.993.2]

For 8MHz frequency ranges (shown as pink scatter points on Figure 3.10), there are a range of transmit powers specified. For other frequency ranges, the transmit power is specified at 14.5dBm. Note that VDSL2 can use as a first uplink band the same frequencies as used by ADSL2/2+ (denoted US0 in the VDSL standard). This low-frequency band extends the reach of VDSL2

compared with VDSL1. However, for copper loop lengths (reach) in excess of 1.5km, ADSL2 remains the most appropriate xDSL solution.

The frequency plans for VDSL2 Annex B (which details Europe-specific requirements) are shown in Figure 3.11.

Figure 3.11: Frequency plans for VDSL2 Annex B (European requirements) [Source: Adapted from ITU Recommendation G.993.2]
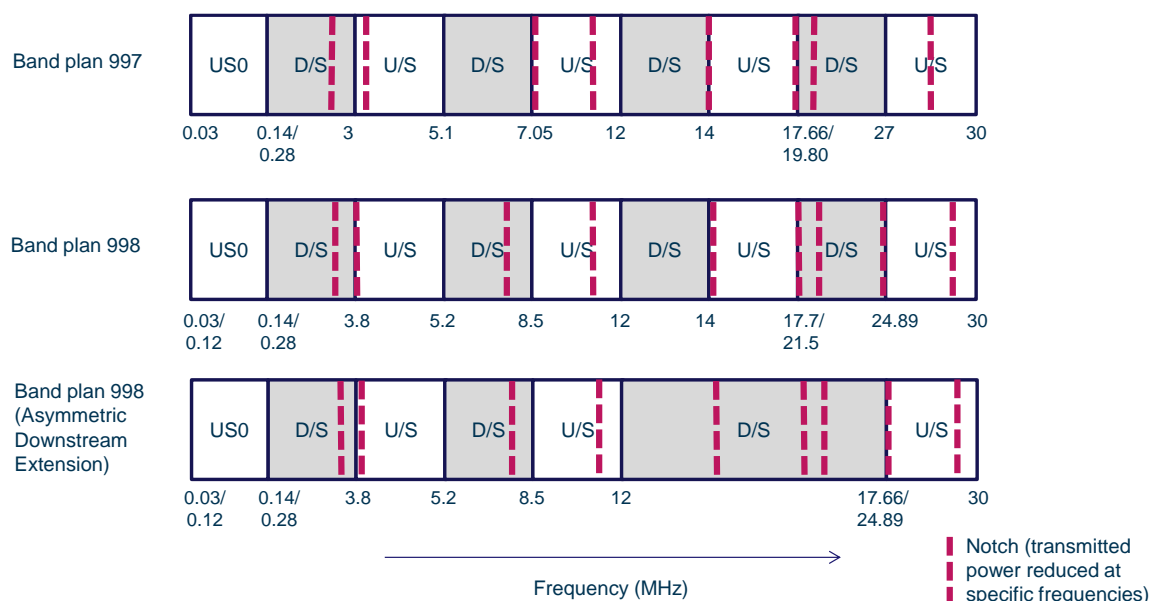
Note the use of 'notches' to mitigate interference of the VDSL2 system with external radio systems, such as ham radio.

3.2.4 G.fast standards

The G.fast[31] standards (G.9700 and G.9701) were published in 2014, and were developed to provide a very high broadband bandwidth over a very short copper loop length (typically less than 250m). Therefore, G.fast technology is typically associated with FTTdp architecture (see Section 3.1.4) or FTTB architectures, where the copper loops are relatively short.

It should be noted that while nbn is currently trialling G.fast technology, no decision has yet been taken by nbn on whether or not to implement G.fast technology.[32] Accordingly, this report does not consider the use of G.fast as a technology option within the MTM, nor prudency or efficiency of any network design that implements the G.fast standard.

The G.fast standard was designed to be optionally compatible with VDSL standards by operating at higher frequencies than VDSL2, i.e. the starting frequency for G.fast can be 2.2, 8.5, 17.6 or

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[31]   "fast" is a recursive acronym for 'fast access to subscriber terminals'.

[32]   http://www.nbnco.com.au/blog/nbn-takes-first-steps-towards-g-fast-launch.html

30MHz. Initially, G.fast was designed to operate over a 106MHz spectrum band. However, the next iteration of the standard will double the operating frequency band to 212MHz.

To cancel FEXT, vectoring is mandatory when using G.fast. This means that it is challenging to use G.fast when multiple operators use copper pairs within the same cable binder to provide services to their end-users (see more detail on vectoring in Section 3.2.5). There are currently no standards under development that would enable multiple G.fast operators to share the same cables.

G.fast uses TDD technology, which means that the full spectrum can be used by the uplink or by the downlink at different moments in time. Therefore, G.fast bandwidth is usually specified as an aggregate between the uplink and downlink bandwidth. The initial aggregated uplink and downlink bandwidth targets defined by the standard are provided in Figure 3.12.

Figure 3.12: G.fast target bandwidth [Source: Analysys Mason, 2015]

Copper loop length (m)	Target aggregate bandwidth (Mbit/s)
<100	500–1000
100	500
200	200
250	150

3.2.5 DSL acceleration technologies

A variety of other so-called 'DSL acceleration' technologies can be used to improve the rate-reach performance of copper loops. These include vectored DSL, bonded DSL and phantom-mode DSL, which are outlined in the following sub-sections.

Vectoring

Vectoring is a noise-cancellation technology that can be used to virtually eliminate FEXT at receivers. In VDSL deployments, FEXT has a relatively large impact on system performance. The impact of FEXT becomes stronger as higher signal frequencies are used, and as the loop lengths become shorter. The level of FEXT experienced by a single copper pair also depends on the number of copper pairs within the relevant cable binder that are also being used by other operators to deliver broadband services.

Vectoring uses advanced signal processing located in the DSLAM. One future deployment option is to deploy vectored mini-DSLAMs at the DP (i.e. to form a DPU very close to the end-user). The specific techniques that are used in vectoring are described in the ITU standard G.993.5 (also referred to as 'G.Vector'), which was published in 2010.

Although vectoring can virtually eliminate FEXT noise within a vectored group (specifically referred to as self-FEXT), and therefore improve broadband performance for end-users, it cannot be used in a cable in which copper pairs are used by multiple operators to provide broadband

services to their end-user, as all lines in the cable need to be monitored simultaneously (i.e. all lines need to belong to the same vectored group).

Bonding

Bonding logically combines the capacity of two discrete copper loop pairs, and can be used to increase the range of an xDSL system for a given bandwidth for a given loop length. However, the use of additional copper pairs is difficult in many markets due to a lack of spare pairs in existing networks and the additional operational complexity that such an approach introduces.

Phantom mode

Phantom-mode xDSL works with a bonded pair to increase its bandwidth by around another 50%. It works by converting one ground wire into a signal wire (in a single twisted pair, one wire is used as the ground wire and one for the signal; since a connection requires only one ground wire, the ground wire in the second twisted pair can be converted to a signal wire). In the case where a single pair with VDSL2 vectoring can carry 100Mbit/s, adding a second pair and using phantom mode increases the theoretical maximum rate to 300Mbit/s. But again, phantom mode requires two copper pairs which is not practical in many markets, including the Australian market. We understand that bonding and/or phantom mode technologies will not be used by nbn and therefore are not discussed in the rest of this document.

3.3 Worldwide deployments

In this section, we present five case studies of FTTN/FTTB networks deployed by the following operators:

- Openreach (UK)
- Belgacom (Belgium)
- Deutsche Telekom (Germany)
- TIM (Italy)
- AT&T (USA).

These case studies are sample references of international broadband network design good practice to allow a comparative assessment of the efficiency and prudency of nbn's FTTN/FTTB network. Each operator has its own individual commercial and market objectives to meet and faces specific network deployment and operational challenges due to its historical evolution as well as different geographical and regulatory challenges. However, these case studies serve to demonstrate the different technical approaches operators have adopted to deliver high-speed national broadband services.

3.3.1 Openreach

BT's functionally separated wholesale access arm Openreach started deploying fibre-based access networks (collectively known as superfast broadband) in 2009, and retail services using Openreach's wholesale broadband access services were launched in January 2010. Openreach offers superfast (>24Mbit/s) virtual unbundled access services to retail service providers (including BT's downstream businesses) on an open equal access (Equivalence of Inputs) basis. Openreach's initial announcements indicated an architecture mix consisting mainly of FTTN, exploiting its legacy copper access PSTN, with some FTTP, although it never publicly committed to a specific proportion for FTTP. Like other incumbent fixed network operators, BT faced increased competition from higher-capacity cable broadband services, namely from Virgin Media, and needed a suitable access network to enable its downstream service providers to be able to offer IPTV services. The first two commercially funded phases of deployment took superfast broadband coverage to 66% of customer premises in England, Scotland and Wales by the end of 2014, and were concentrated in urban/suburban locations where there was a clear commercial business case due to the lowest cost per premises passed (CPPP). Alongside this commercial roll-out, funding from the UK government, devolved UK administrations, local authorities and the European Union enabled Openreach (the winning bidder in almost every broadband public sector intervention case) to extend its total coverage to over 22 million premises (about 75% of the total) by the end of March 2015. The remaining premises not covered are mainly rural, though they also include a significant number of city-centre properties that have exchange-only lines that are technically difficult (e.g. ADSL2+ and VDSL interference issues) and costly to upgrade. To date, Openreach has rolled out FTTP to pass only an estimated 200 000 premises, many of these in publicly funded areas. FTTP is, however, available as an on-demand build-and-lease wholesale service in many FTTN served areas.

Openreach establishes new powered cabinets, tied to existing PCP cabinets. There are 85 000 legacy cabinets in the Openreach network, and hence on average each covers around 325 premises, though the number of lines they serve is typically lower. Cabinets are equipped with DSLAMs which can accommodate *n* cards of 48 ports each. These are installed in relation to demand, and there have been instances of orders being accepted before sufficient port capacity is installed in the new cabinet. The sole technology used in connection with FTTN to date is VDSL2. In April 2012, Openreach upgraded from the VDSL2 8a to the VDSL2 17a variant allowing maximum downlink speed to rise from 38Mbit/s to 76Mbit/s. Openreach is conducting field trials of VDSL2 vectoring, which is the technology used by nbn to achieve downlink speeds up to 100Mbit/s, but has not indicated whether it will deploy this technology commercially.

In early 2015, BT indicated that it has an ambition to make 500Mbit/s services, based on G.fast technology, available to the majority of premises in the UK by 2025. Openreach has no separate FTTN products to address MDUs. Unlike many other FTTN/FTTN deployments, Openreach FTTN is an overlay data-only network: migration to FTTN-based services is based on demand, with voice services remaining based on the legacy PSTN copper infrastructure and TDM exchange switches. BT has indicated it will decommission PSTN by 2025, but has not indicated whether it expects this to be achieved using voice over broadband or by switching to cabinet-based MSANs.

3.3.2 Belgacom

Belgacom, the incumbent PSTN operator in Belgium, started deploying FTTN as far back as 2004. Cable TV networks cover nearly all of Belgium and, as a result, Belgacom had suffered significant loss of market share in fixed services to cable operators, especially in Flanders and Brussels, and needed a robust platform for its own TV services. FTTN also helped Belgacom pre-empt the threat, seen in neighbouring countries, from local loop unbundlers, which subsequently failed to capture more than a small share (<5%) of Belgian broadband. A further major consideration for Belgacom was that the specific architecture it chose enables it to close exchanges, rationalise its property portfolio and decommission PSTN voice services. Belgium is densely and (compared with many European countries) evenly populated. FTTN networks passed 90% of premises nationally by September 2014, having reached 75% in 2010.

Belgacom deploys new cabinets using remote optical nodes (RONs) that mainly sit alongside existing PCP cabinets. Similar to Openreach in the UK, Belgacom has no separate FTTN wholesale products to address MDUs. RONs are equipped with access gateways that convert analogue voice signals to IP. ISDN services are migrated to broadband IP. Unlike most FTTN deployments, migration is not based on demand. Belgacom migrates all its retail Internet customers to RON-based VDSL and all of its voice traffic to RON-based IP. Belgacom initially deployed VDSL1 at RONs, but changed over to VDSL2 starting in 2008. In line with its aim to phase out exchange-based wholesale services, it introduced ADSL2+ at the RON in 2013. This is offered on a wholesale basis and via its own discount brand Scarlet. Belgacom started using dynamic line management techniques with VDSL2 in 2012, and started selective deployment of VDSL2 vectoring in 2014. Initial use of vectoring was only in RONs that served short sub-loops. Having a competitive IPTV service is strategically critical for Belgacom: unlike BT, it was unable to use hybrid DTT/IPTV platforms, and had to build its own multicast network that reaches all RONs. Hence it has prioritised investment in network enhancements that improve the stability and robustness of the network. Belgacom is now committed to FTTP/GPON for greenfield sites, but its future strategy for brownfield is likely to involve G.fast. Given the short length of sub-loops, this will probably be mainly cabinet-based, but Belgacom has indicated that single copper pair nodes are a potential solution for accelerating the rate of connections for what would otherwise be FTTP.

3.3.3 Deutsche Telekom

Deutsche Telekom (Telekom), the incumbent PSTN operator in Germany, started deploying FTTN/VDSL in 2006. As with many other incumbents, it needed to be able to respond swiftly to the growing threat of cable operators to telcos, and FTTN enabled it to do so much faster than FTTP. Initially Telekom sold VDSL only as part of a triple-play package that included TV. In a first phase of roll-out, Telekom passed 10.5 million premises with FTTN, or about 23% of the total in Germany. In this phase, 33 000 active cabinets were built. Take-up was not strong and this level of coverage remained the same for about five years until December 2012, when Telekom announced a new target of 65% coverage by 2016 (a further 74 000 cabinets). A further target of 80% is subject to government funding. The active cabinet is typically adjacent to the legacy

passive cabinet, forming a single modular block. Legacy cabinets, of which there are 330 000 in Germany, typically serve only 100–150 lines, and as a consequence, have shorter loops on average than those of e.g. Openreach or AT&T. Migration of customers to VDSL is demand-led, but VDSL customers are automatically migrated to voice over broadband, and bitstream VDSL is available only as a data-only ('naked') connection. Through a combination of demand for voice over broadband, and the deployment of MSANs, Telekom aims to switch off the legacy PSTN in Germany in 2018.

Telekom uses VDSL2 17a technology. It started rolling out vectoring in the second phase of roll-out and added vectoring retrospectively to the installed first phase. Retail services based on vectoring were launched in July 2014, and maximum retail speeds doubled from 50Mbit/s to 100Mbit/s. The short average sub-loop length, and the additional fact that Telekom's network does not have suitable DPs, shapes the options Telekom has for future CAN design. Moreover, Telekom has the scale to influence vendors' roadmaps for copper-based broadband equipment. Further network upgrades, which it labels 'SuperVectoring' and which it expects to deliver up to 250Mbit/s downstream, will involve integrating VDSL2 17a with some higher-speed standard, VDSL2 30a or G.fast, or possibly a non-standards-based 35MHz version of VDSL. Telekom also has a small footprint of FTTP networks (passing about 250 000 apartments), which came about as the result of demand aggregation exercises in selected cities. It has not indicated that it will expand FTTP in Germany.

3.3.4 TIM

FTTN deployment by TIM (the incumbent PSTN operator in Italy) started in earnest in 2012, and TIM's retail arm started to sell FTTN-based services in 2013. The company had in 2008 initiated a plan, named NGN2, which was intended to pass 2 million premises by the end of 2010 using a mix of FTTP, FTTB/VDSL and FTTN. It rolled out some FTTP, mainly in Milan, and at the end of 2014 TIM's FTTP infrastructure passed 560 000 premises. The FTTB element involved basement-located mini-DSLAMs with a maximum capacity of 48 ports (but serving an average of 14 properties) and a mix of VDSL2 17a and 30a. The initial plan was not fully realised and evolved slowly into a revised plan with a less ambitious technology mix, but offering broader coverage. Under the revised plan, TIM was to achieve 35% FTTN coverage by the end of 2015. At the end of 2014, FTTN coverage stood at 29%. The areas covered were mainly dense urban areas. TIM's targets for coverage have been revised upwards twice, and the most recent plan for FTTN coverage was 75% of premises nationally by 2017. The pressures for operators to deploy next-generation access of any kind in Italy are less intense than in most other developed markets because there are no cable TV networks, and fixed broadband and pay-TV penetration rates are low. The main infrastructure-based competition outside Milan (where several operators have used Metroweb's metro fibre for FTTP), comes from Fastweb, which is using sub-loop unbundling of TIM's copper infrastructure to deliver its own FTTN services.

TIM installs new powered cabinets next to the legacy PCPs, of which there are 145 000 in Italy. The operator had deployed 40 000 new cabinets by March 2015, which works out as an average of

about 210 premises per cabinet. VDSL2 17a is used in FTTN deployments. TIM has short sub-loops (the average is about 300m), suitable for vectoring, but the operator has so far only initiated a field-trial of vectoring in a single city, Vicenza. The presence of sub-loop unbundlers – unusual in other countries – poses a problem for TIM because a vectoring system will function only if it controls all the copper pairs at the cabinet: one operator would have to cede control of the system to its competitor if vectoring were to be used. In July 2015, TIM started to communicate major new plans for additional FTTP outside Milan. In conjunction with Infratel, a commercial arm of the government, it has started to implement a plan to deploy FTTP to 10 million premises by 2018.

3.3.5 AT&T

Deployment of AT&T's U-verse triple-play (telephony, Internet and IPTV) network started in 2005, and services were launched in the first cities in 2006. The network was until recently entirely FTTN in brownfield areas, exploiting the legacy CAN of its regional Bell operating company (RBOC), though it rolled out some FTTP in greenfield areas. It also started to commercialise some exchange-based ADSL2+ as 'U-verse', even though these DSLAMs do not support the IPTV service. By the end of 2012, U-verse FTTN passed about 24.5 million premises, and the company aimed to increase this to 33 million by the end of 2015. This represents about 58% of AT&T's wireline footprint, although an ongoing process of disposals make this ratio a variable figure. AT&T's original decision to roll out FTTN contrasted with that of its most obvious peer, Verizon, which opted to roll out FTTP/GPON, although the rationale for both operators was to compete more effectively against cable operators. Of the mid-sized incumbent local exchange company (ILECs) in the USA, only Cincinnati Bell opted primarily for FTTP, while the others opted mostly for FTTN. Verizon is now much shrunk and confined to a number of densely populated North-Eastern states, so it is possible that Verizon always intended to have a smaller but higher-value wireline footprint than that of AT&T. AT&T's decisions as to where to deploy FTTN first were based as much on predicted demand for high-end TV services as on cost.

AT&T installs a single powered cabinet – which it calls a video-ready access device (VRAD) – up to 100m from most (but not all) existing PCPs. VRADs support VDSL2 17a (having upgraded from VDSL2 8a at the end of 2014) and ADSL2+, and customers on former exchange-based ADSL are migrated to the VRAD. Only VDSL2 is used for the full U-verse retail triple-play. AT&T has long sub-loop lengths and to increase the reach of TV services, AT&T was an early adopter of VDSL2 pair-bonding. This extended the maximum sub-loop length from 1000m to 1600m, and increased the addressable market for the U-verse services. VRADS have 384 xDSL ports, but pair bonding means that many customers use more than one port. At the end of 2014, AT&T had about 100 000 VRADs in service, making an average of around 300 premises passed per VRAD. AT&T intends to decommission its legacy PSTN by 2020. U-verse and IP-fed ADSL2+ customers are automatically migrated to native voice over IP (VoIP).

AT&T has a separate programme for FTTB, but this addresses multi-tenant business buildings only. While customers in the building can order xDSL, AT&T also introduces, on the basis of demand, fibre cabling and an Ethernet multiplexer. FTTB passes approximately 800 000

businesses, or half the multi-tenant business buildings in AT&T's service area. Over the past two years the availability of FTTP from new operators has increased significantly in the USA. Most notable among these is Google, which has rolled out FTTP in a small number of cities and has proposed expansion to far more. AT&T has therefore started to roll out FTTP/GPON, known as U-Verse with AT&T GigaPower, in former FTTN areas. FTTP was available in locations in 11 cities at July 2015. As with Google, targets and aims for expansion to multiple cities are subject to a great deal of uncertainty.

3.4 FTTN/FTTB technology roadmap

Figure 3.13 provides a roadmap of xDSL technologies with indicative bandwidth for different copper loop lengths.

Figure 3.13: DSL technology roadmap for different copper loop lengths [Source: Analysys Mason, 2015]
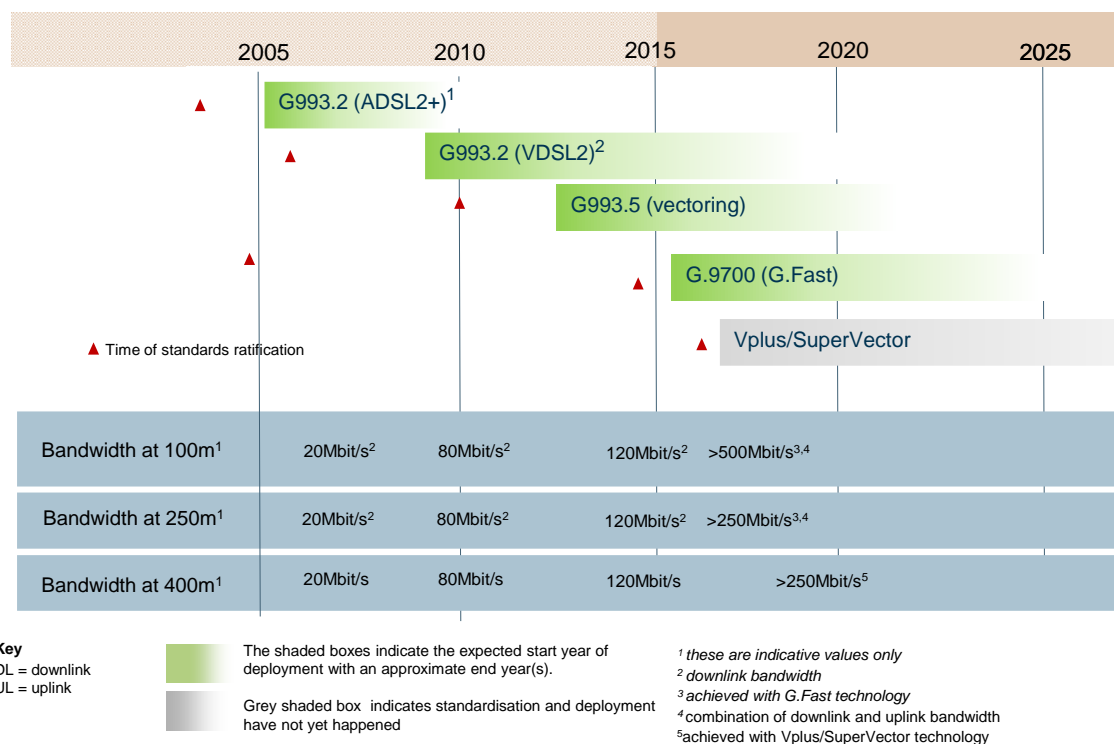
The roadmap shows current technologies that have already been widely implemented by operators, namely ADSL2+, VDSL2 and vectoring, as well as important future technologies, such as G.fast and Vplus/SuperVector, which are further discussed below. The above roadmap is not necessarily representative of the deployment timelines in Australia as it is meant to be generic for worldwide operators.

3.4.1 G.fast

As discussed in Section 3.3 and 3.4, most FTTN/FTTB deployments currently use VDSL2, which is now considered to be a mature technology as it has been in commercially use since 2008. In addition, many operators have now enabled vectoring within their DSLAMs to further improve the performance of broadband services provided to their end-users (e.g. Belgacom, DT, and AT&T).

As discussed in Section 3.2.4, G.fast is the latest addition to the xDSL technology family and is currently ready to be deployed commercially on a wide scale, with a number of trials currently under way internationally. It is designed to achieve very high bandwidths but only over short copper loops (i.e. less than 250m). G.fast is therefore more suitable for FTTB architectures (e.g. providing broadband services to many closely located premises in one or several MDUs, or for FTTN architectures with short copper loops to SDUs). However, we understand that in Australia, only 50% of copper loops (loops from the PCP to customer premises) will be less than 250m after the FTTN architecture is implemented by nbn.[33] In theory, it would therefore be possible to use G.fast for 50% of the copper loops to cost-effectively increase the performance of the FTTN network in the future when required. However, this assumption relies on the commercial availability of large G.fast systems (i.e. greater than 200 lines) which are not available at the time of writing this report (only up to 24-line systems are available). For the remaining 50%, a different technical solution will have to be provided if the performance is to be increased.

In a recent report published by Analysys Mason entitled "*FTTdp: the opportunities for deployment*", we highlight that there is a technology constraint to improve the performance of broadband services for existing FTTN architectures with loop lengths greater than 250 metres. The solution currently available to increase performance on longer loops would be to effectively shorten the loop by extending the fibre and establishing a new FTTN node closer to the premises. However, this will likely be a costly exercise due to the civil engineering that would be required to extend the fibre and establish a new FTTN cabinet.

3.4.2 Vplus/SuperVector

To address the performance constraint for loop lengths between 250–650m, Alcatel Lucent and Huawei have proposed variants of VDSL, branded as Vplus and SuperVector, respectively. Both technologies aim to improve performance, compared to VDSL2, from existing cabinet locations for short-to-medium copper loop lengths (i.e. with loop lengths up to 650m).

In Figure 3.14 and Figure 3.15, we compare the downlink and uplink bandwidths for different technologies. It should be noted that since Vplus/SuperVector and G.fast are technologies based on TDD, the aggregate downlink and uplink bandwidth is usually specified. Therefore, to allow a like-for-like comparison with VDSL technologies, we have assumed that for the Vplus/SuperVector and G.fast technologies the downlink bandwidth represents 80% of the total bandwidth and the uplink bandwidth 20% of the total bandwidth.

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[33]   And 90% of copper loops will be less than 650m.

Figure 3.14: Comparison of downlink bandwidths between technologies [Source: Adapted from Alcatel Lucent, 2015]
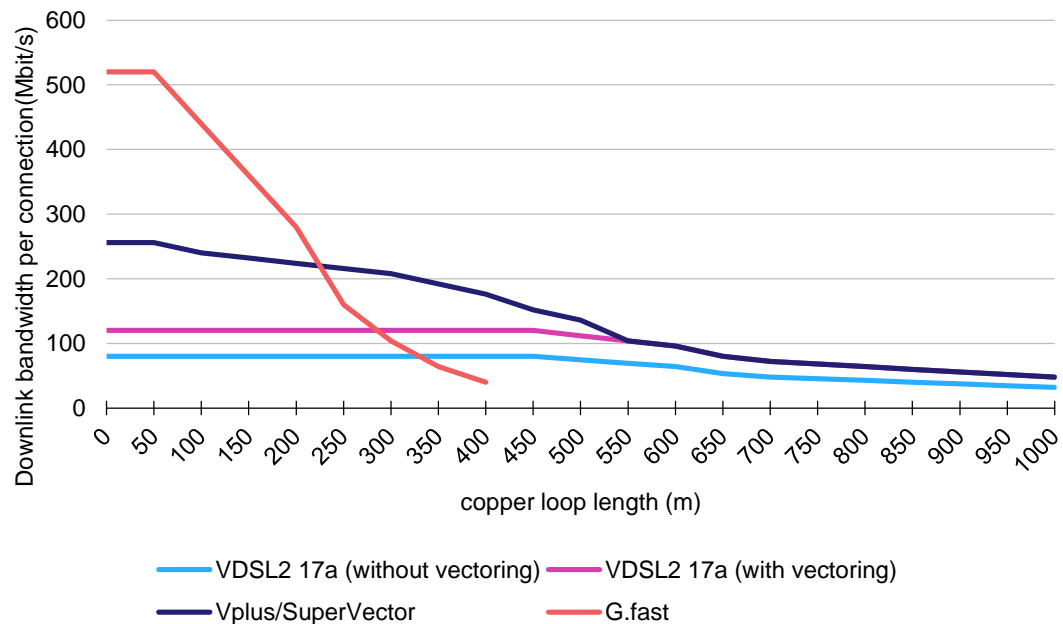
Figure 3.15: Comparison of uplink bandwidths between technologies [Source: Analysys Mason, 2015]
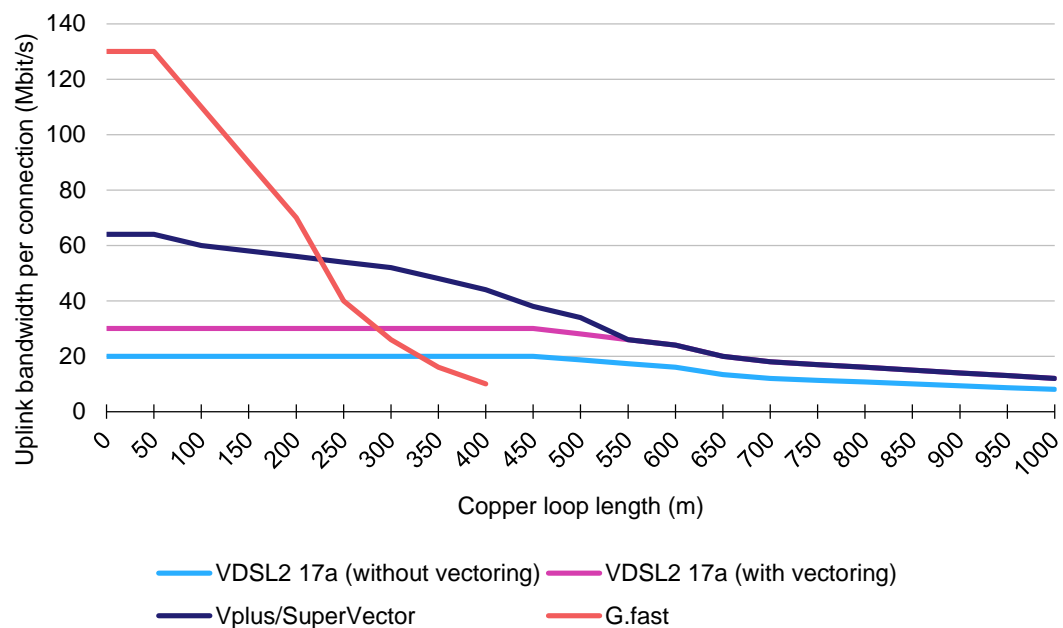
As illustrated in Figure 3.14 and Figure 3.15, Vplus/SuperVector technology is, in terms of broadband performance, an intermediate upgrade option between VDSL and G.fast for short loops. It can be seen in Figure 3.14 that when upgrading from VDSL2 with vectoring to Vplus/SuperVector for a loop length of 100 metres, the downlink performance is doubled from 120Mbit/s to 240Mbit/s. Using G.fast for the same 100 metre loop length increases performance

further to 450Mbits/s. Also, compared with VDSL performance, Vplus/SuperVector promises to improve broadband performance for loop lengths up to 650 metres. Most importantly, for existing loop lengths of between 250 metres and 650 metres where other currently available technologies, including G.fast, cannot improve broadband performance, Vplus/SuperVector technology allows operators to upgrade their current FTTN VDSL architectures without costly civil works to shorten copper loop lengths.

In the long term, operators will have to incrementally shorten the copper loop length to provide ever-increasing bandwidth, which may ultimately result in an FTTdp or FTTP architecture.[34]

In addition, SuperVector/VPlus is designed to be compatible with established VDSL vectoring deployments using 17MHz of spectrum.

It is expected that a single standard will be produced and that the standardisation process will be completed in 2016. The standard will be the combination of ideas from both vendors.

3.4.3 Advanced vectoring

Another key advancement in the xDSL roadmap would be the provisioning of a feature aimed at mitigating crosstalk from multiple-party DSL systems (separate operator systems which use copper loops in the same cable binder). Such a feature would allow separate xDSL systems that use copper pairs that co-exist within the same cable binder to benefit from vectoring and therefore better addressing the various infrastructure-sharing initiatives stipulated by a number of governments and industry bodies worldwide. However, the most recent ITU meeting has determined to focus on a range of enhancements that do not include vectoring between systems.

AT&T is interested in the standardisation of multi-operator vectoring (MOV) technology and recently submitted a white paper to SG Q4/15 discussing the standardisation process and the associated technical challenges. It is anticipated that the study group will not be able to complete a standard before 2019 – assuming it decides to standardise this technology at all. Since there is usually one or two years between the publication of a standard and its implementation by the industry, we do not anticipate there will be any standardised MOV systems available before 2020–2021.

3.5 Ability of FTTN/FTTB technology to meet evolving bandwidth demand

In this section, we determine the extent to which FTTN/FTTB architectures and associated technologies will be able to meet present and future bandwidth demand. To achieve this, we first review the key market drivers for bandwidth demand. We then provide an estimation of the likely evolution of bandwidth demand in Australia till 2030, based on our forecast for the top 1% of end-users in developed markets (i.e. we use our forecast for developed markets as a proxy for Australia). Then, based on the likely future roadmap of FTTN/FTTB technology, we conclude as to whether or not FTTN/FTTB architectures and associated technologies will be able to meet that demand.

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[34]   See *Review of the efficiency and prudency of NBN Co's fibre, wireless and satellite network design*, Analysys Mason, 2010 for discussion of FTTP architecture and technology options.

3.5.1 Market drivers for bandwidth demand

Between 2013 and 2014, Australian fixed Internet traffic grew at an annual rate of 35%.[35] This traffic growth is mainly being driven by video-based services as they become more and more dominant in terms of bandwidth consumption than other less bandwidth-intensive services such as web browsing and email. This is also true to some extent for social networking services such as Facebook and Twitter, but these services are now also making greater use of video in their applications. The increased use of 'cloud'-based storage services is also driving traffic growth as the use of hosted applications and storage services grows.

In line with other developed markets, the combination of greater availability of NGA services and increased use of on-demand, video-over-broadband services are likely to be key factors in driving future demand for bandwidth in Australia.

Importance of video in driving bandwidth demand

Many new services, platforms and devices support on-demand, TV-based viewing of TV content and films via broadband connections. These often paid-for services are the main new drivers of traffic, and they are supplanting, in terms of traffic, the longer-established free video-hosting services such as YouTube. These new services have different business models compared with longer-established services and their fit with local and regional circumstances, as well as the popularity of the content in individual markets, will define their impact on traffic. The main categories are:

- Subscription video on demand (SVoD) OTT services (e.g. Quickflix, Presto, Stan and Netflix). Netflix has only recently been launched in Australia. In some markets, it now accounts for 20–35% of total traffic. This trend is being followed worldwide by proprietary SVoD OTT services including US-based HBO and NOW TV (Sky) in the UK

- Catch-up, free-to-air (FTA) platforms and services such as ABC iView in Australia and BBC iPlayer in the UK. The impact on traffic of these platforms and of the services they support primarily depends on the share of TV viewing that their broadcast counterparts enjoy.

Increased use of online video on connected TV sets – whether through a managed IPTV service, a simple broadband-based multicast or (as is increasingly the case) OTT Internet TV – helps to drive up demand for NGA and these trends help to enable two steps that will further increase traffic:

- More simultaneous use of multiple screens in the home, which are likely to be a combination of small screens (e.g. tablets, PC and smart phone) and large screens (e.g. TV).

- The use of streamed UHDTV (4K TV), which in practice requires an access bandwidth in the NGA range.

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[35]   *Fixed network data traffic worldwide: forecasts and analysis 2015–2020,* Analysys Mason, May 2015.

It is difficult to come to a clear view of video share of traffic because of the variety of format types available (including non-real-time downloads). However, Analysys Mason is of the view that it will become an even more dominant part of the fixed broadband traffic and we consider it could rise in developed markets from around 60% of total traffic in 2015 to over 80% by 2020.[36]

4K video is likely to become a key driver of video traffic in the future

4K has the potential to account for large amounts of traffic (see Figure 3.16 for a bandwidth per technology comparison) and is likely to become mainstream before the end of the decade considering:

- Netflix already offers 4K OTT video content.

- Broadcast 4K channels are already operational in Japan and South Korea.

- French operator Free announced in March 2015 that its latest Freebox (an integrated home router/set-top box) was 4K-ready.

- UK operator BT announced the launch of a 4K sports channel in August 2015.

In addition, it is likely that before long most screens of 40 inches or more will be 4K-ready by default, irrespective of the appeal or availability of 4K content. Moreover, 4K is set to become the first video format to be primarily online rather than a broadcast or physical medium.

Bandwidth and data volume requirements of video services

A key component in determining the bandwidth requirement of a video stream is not only its definition (e.g. standard definition (SD) versus high definition (HD)) but also the efficiency of the codec used for compressing the stream into digital format for transmission to the end-user. The current most advanced compression standard implemented is high-efficiency video coding (HEVC), which is expected to be a key feature of 4K streams. This is important for both linear and on-demand content. The bandwidth required for resolutions using MPEG 4 AVC (H.264) and HEVC lies within a wide range because of variations in picture quality within each resolution. Even more efficient codecs are available, but it is difficult to establish new approaches to compression in the content industry. The ranges of bandwidth requirements are shown in Figure 3.16.

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[36]   *Fixed network data traffic worldwide: forecasts and analysis 2015–2020* Analysys Mason, May 2015.

Figure 3.16: Bandwidth consumed by pixel resolution and type of MPEG-4 compression [Source: Analysys Mason, 2015]
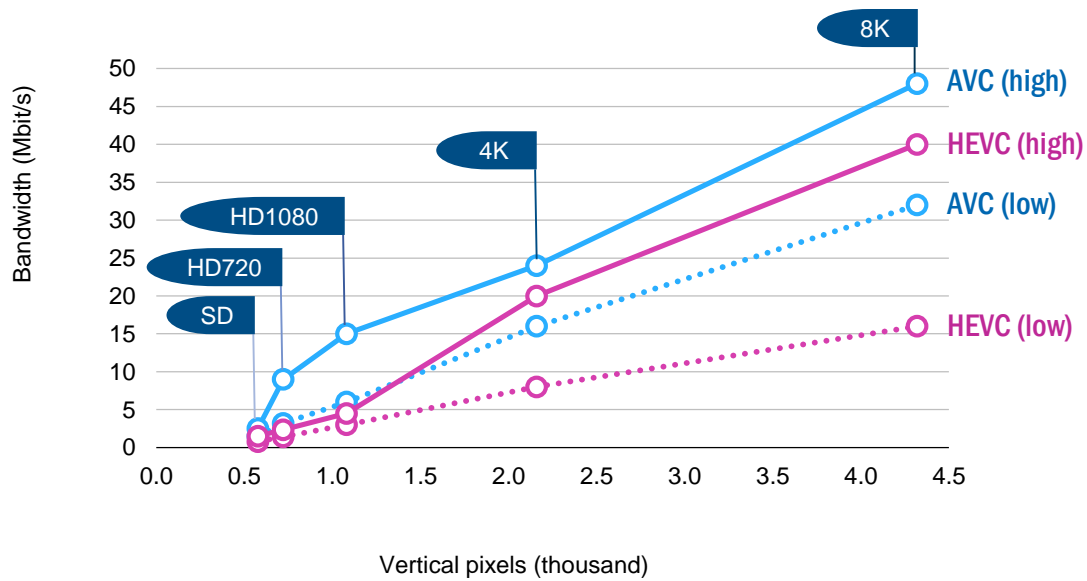
The data volume needed for the delivery of content is heavily influenced by the format and frame rate of the stream delivery as shown in Figure 3.17.

Figure 3.17: Data volume per 60-minute video by pixel resolution and frame rate [Source: Analysys Mason, 2015]
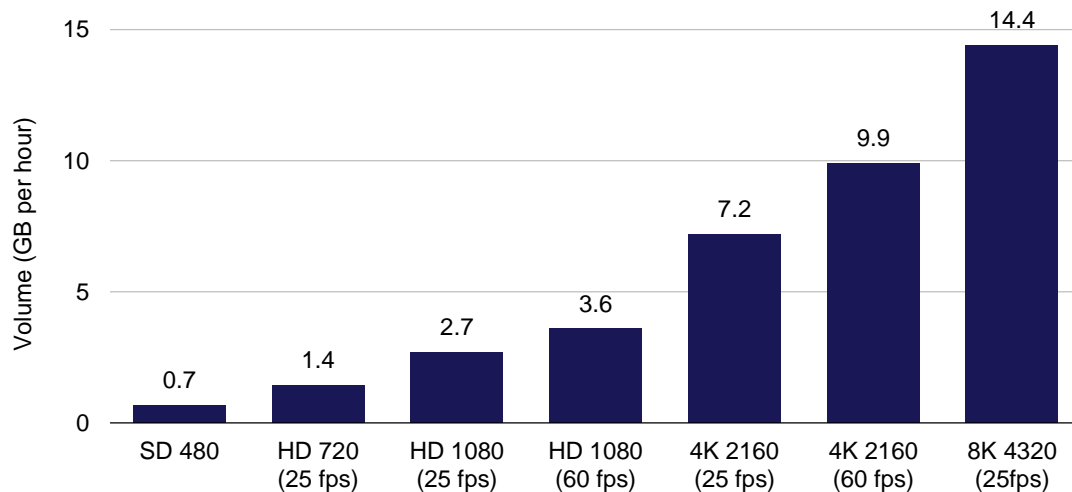
HD video streams typically refresh at 25 frames per second (fps), but 60fps is a future option. For most types of content, 60fps will not be perceptibly better than the standard 25fps. Indeed, SVoD providers like Netflix do not currently see a commercial case for content with such a high frame-rate. However, gamers and sport viewers may benefit from higher rates, so it may be used for

some 4K-based services as they become available and help drive demand for higher bandwidth and volumes.

Development of uplink traffic demand

Trends in uplink traffic are less clear than those in downlink traffic because uplink traffic encompasses a variety of applications, some of which are of decreasing importance, while some are of increasing importance.

Peer-to-peer (P2P) traffic was the greatest driver of uplink traffic, but its importance has diminished as end-user bandwidth has increased, intellectual property legislation has tightened, and simple, low-cost access to legal streaming sites has grown. For example, changes in legislation saw uplink share of end-user traffic in Japan diminish from 42% in 2008 to 24% in 2014. However, in some countries, such as Hong Kong and Romania, the use of P2P services remains a key driver of high uplink usage.

Data from Ofcom in the UK from June 2014 showed that not only did FTTN connections generate much more uplink traffic per connection than ADSL (which is to be expected), but that they also generated a less asymmetrical mix of traffic, which is unexpected. The step change from non-NGA uplink bandwidth (usually below 1Mbit/s) to NGA (usually at least 10Mbit/s) makes a massive difference in usability for home-working and distribution of user-generated content and is likely to be driving this. However, after this NGA step change, we do not expect a long-term growth trend in the uplink's share of traffic, with its proportion likely to remain stable or decline as downlink video traffic grows.

3.5.2 Estimation of bandwidth demand

In this section, we assume that the bandwidth requirements from end-users drives the supply of broadband services in terms of headline bandwidth. In reality, the supply of broadband services is also driven by competition between operators and headline bandwidth is increasingly perceived as a differentiator. We analyse the competition driver for bandwidth in Section 3.5.3 of this report.

We provide an estimation of downlink bandwidth and of uplink bandwidth likely to be required at present and in the future by Australian end-users in the next sub-sections.

Downlink bandwidth demand

Based on the observations made in the previous section, Analysys Mason's Research division published a report in 2014 entitled "*Fixed network data traffic worldwide: forecasts and analysis 2014–2019*", where the bandwidth requirements for the top 1% of households in developed markets (i.e. heavy users) were estimated for the 2014–2020 period. We use the bandwidth requirements for the top 1% of households in developed markets as a proxy for predicting the bandwidth requirements of the top 1% Australian households. The bandwidth requirement forecast includes the following categories of traffic:

- bandwidth required to download Internet content and for cloud applications (download, cloud)
- bandwidth required for small screens including PC, tablets and smartphones
- bandwidth required for large screens (TV)
- bandwidth required for voice applications (audio)
- other bandwidth required for connected objects (other M2M).

The bandwidth requirement forecast assumes the following in terms of simultaneous use of different devices and different applications in a single home:

Figure 3.18: Use case for top 1% of households, by screen and application, 2012–2020 [Source: Analysys Mason, 2014]

	2015	2016	2017	2018	2019	2020
Download format	HD (25)	True HD	True HD	True HD	UHD	UHD
PC, tablets, handsets	HD (720) (×2.85)	HD (720) (×3)	HD (720) (×3.125)	HD (1080) (×3.25)	HD (1080) (×3.375)	HD (1080) (×3.5)
Large screen TV	HD (25) + True HD (25)	True HD (60) + True HD (25)	True HD (60) + True HD (25)	UHD (25) + True HD (25)	UHD (25) + True HD (25)	UHD (25) + True HD (25)
Audio	SD	SD	SD	SD	HD	HD
Other (M2M)	minor	minor	minor	minor	minor	minor

In the above table:

- HD (25) refers to high-definition TV with 25fps
- HD (720) refers to high-definition TV with 720 pixels
- HD (1080) refers to high-definition TV with 1080 pixels
- True HD refers to high-definition TV with 1920 by 1080 pixels
- UHD (25) refers to 4K high-definition TV with 3840x2160 pixels.

Based on the bandwidth for each of the above TV applications provided in Figure 3.17 and the assumptions provided in Figure 3.18, the total traffic for the top 1% of households was calculated for the 2015–20 period and the results are shown in Figure 3.19.

Figure 3.19: Evolution of downlink bandwidth requirements by connection between 2015 and 2030 [Source: Analysys Mason, 2015]
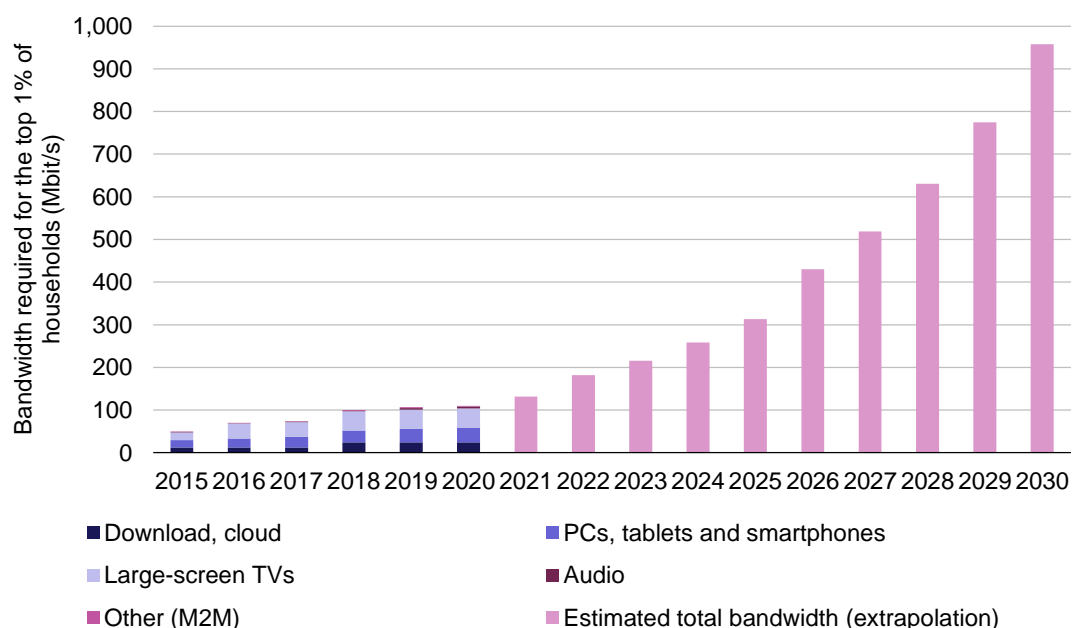
It is quite challenging to predict what application will use what bandwidth after 2020. However, based on the bandwidth requirements trends observed in the above figure for 2015 to 2020, we were able to extrapolate the results to provide an indicative bandwidth forecast till 2030. The extrapolation assumes that the observed trend for 2015–20 will continue till 2030. It should be noted that the extended forecast corresponds to a doubling in bandwidth demand every three years, which is consistent with the annual traffic increase of 35% observed in Australia between Q1 2013 and Q1 2014. It should be noted that the above forecast is for the top 1% of households, and therefore represents an aggressive profile (i.e. if the technology can meet the demand bandwidth requirements for the top 1% of households, it will be able to more than meet the demand from the average household).

Uplink bandwidth demand

Trends in uplink traffic are less clear than those in downlink traffic because uplink traffic encompasses a variety of applications, some of which are of decreasing importance, and some of which are of increasing importance. However, in the Analysys Mason report entitled "*Fixed Network Data Traffic Worldwide: Forecasts And Analysis 2015–2020*", the total worldwide average Internet traffic was forecast for both uplink and downlink and is illustrated in Figure 3.20.

Figure 3.20: Mean average Internet traffic per connection by type, and uplink's share of traffic, worldwide
[Source: Analysys Mason, 2015]
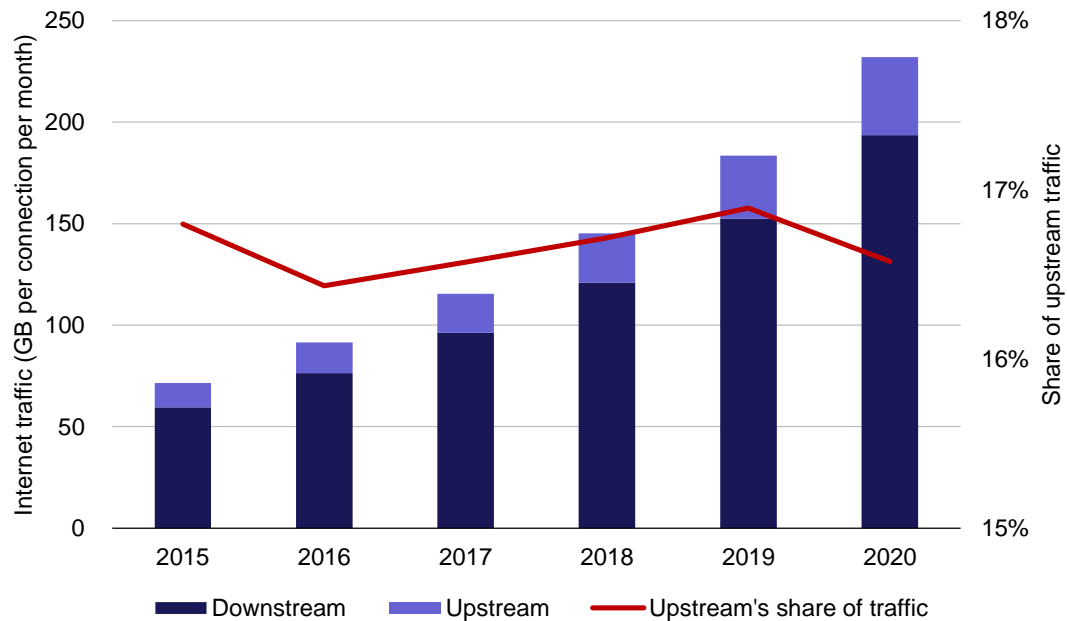
We use the mean average monthly Internet traffic volume per connection as a proxy to estimate the uplink bandwidth. In the above graph, it can be seen that, overall the estimate of the share of uplink traffic of total Internet traffic is forecast to be quite flat in the next five years. As mentioned in the Analysys Mason report "*Fixed network data traffic worldwide: forecasts and analysis 2014–2019*", the apparent flattening of the uplink share worldwide is the result of an increasing proportion of broadband connections in countries where we expect a relatively high level of uplink traffic, but the trend in individual countries will tend to be downwards.

Considering the downlink bandwidth requirements provided in Figure 3.19 and assuming that the uplink bandwidth represents a 17% share of the total bandwidth, it is possible to forecast the uplink bandwidth demand, as illustrated in Figure 3.21.

Figure 3.21: Evolution of uplink bandwidth requirement [Source: Analysys Mason, 2015]
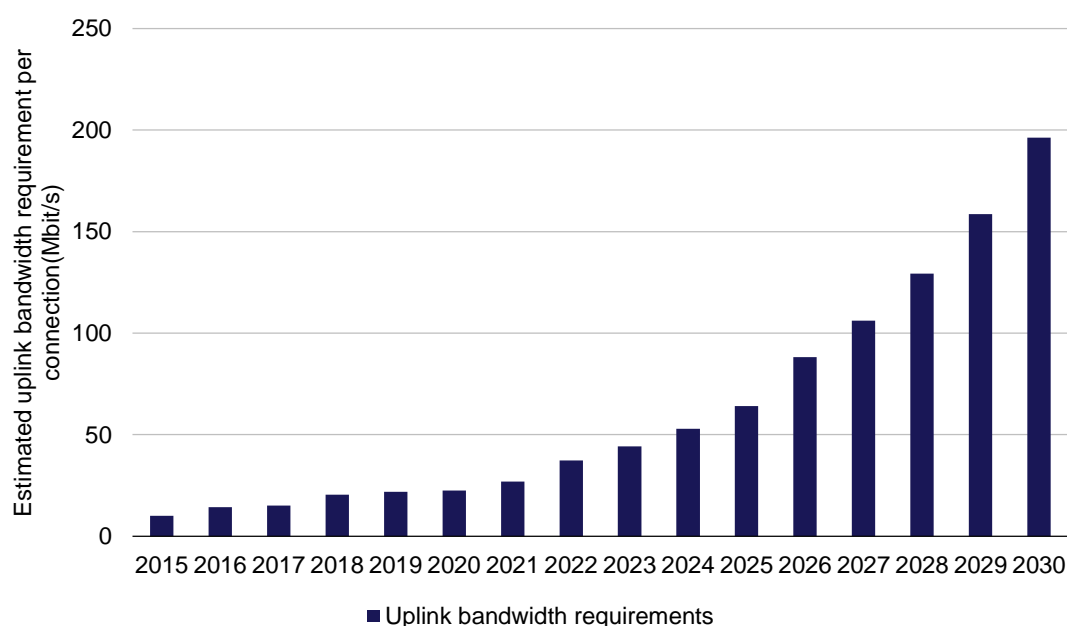
Based on the above figure, it can be seen that the required bandwidth for uplink for the top 1% of Australian households may evolve from 10Mbit/s in 2015 to approximately 200Mbit/s by 2030. Again, it should be noted that the estimated evolution of uplink bandwidth is based on the top 1% of households and is therefore aggressive.

3.5.3 International competition considerations

In addition to calculating likely end-user bandwidth requirements, another factor to be considered is the potential demand from end-users, RSPs and possible future Australian Government requirements to be able to offer bandwidth comparable to other developed countries. This may bring forward the need to offer higher bandwidth services from the time indicated by household need.

For FTTN deployment, in the UK, BT has indicated that it intends to make 500Mbit/s services available to 'most of the UK' within the next decade[37] by deploying fibre deeper into the network (i.e. FTTdp) using mini-DSLAM equipment based on the G.fast specification.

The trend for higher downlink bandwidth has developed more quickly in HFC markets. We show in Section 4.3 that many cable operators in developed countries are already offering headline downlink bandwidth in excess of 200Mbit/s. In addition, supporters of the DOCSIS 3.1 specification are promoting it as the upgrade path to enable the delivery of 1Gbit/s services, particularly in markets such as parts of the USA where cable networks have significant

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[37]   http://www.btplc.com/news/#/pressreleases/results-for-the-fourth-quarter-and-year-to-31-march-2015-1156845.

competition from FTTP operators. In addition, in areas with FTTP networks, 1Gbit/s services are likely to become a standard product offering.

3.5.4 Ability for FTTN/FTTB technology to meet market demand

In this section, we assess the ability of different xDSL technologies to meet the future bandwidth demand for both uplink and downlink, by considering the bandwidth forecast estimated in Section 3.5.2[38] and the bandwidth which can be typically delivered by different technologies over different distances derived in Section 3.4.2.

Downlink bandwidth assessment

As explained in Sections 3.1 and 3.2, the performance associated with any xDSL technology is heavily dependent upon:

- the copper loop length (i.e. the longer the copper loop, the lower the bandwidth)
- frequency range used in the copper
- the effects of interference and crosstalk caused by other systems.

The comparison of demand and bandwidth delivered by different xDSL technologies is illustrated in Figure 3.22 for the downlink.

Figure 3.22: Estimated downlink bandwidth demand vs. estimated downlink bandwidth provided by different technologies [Source: Analysys Mason, 2015]

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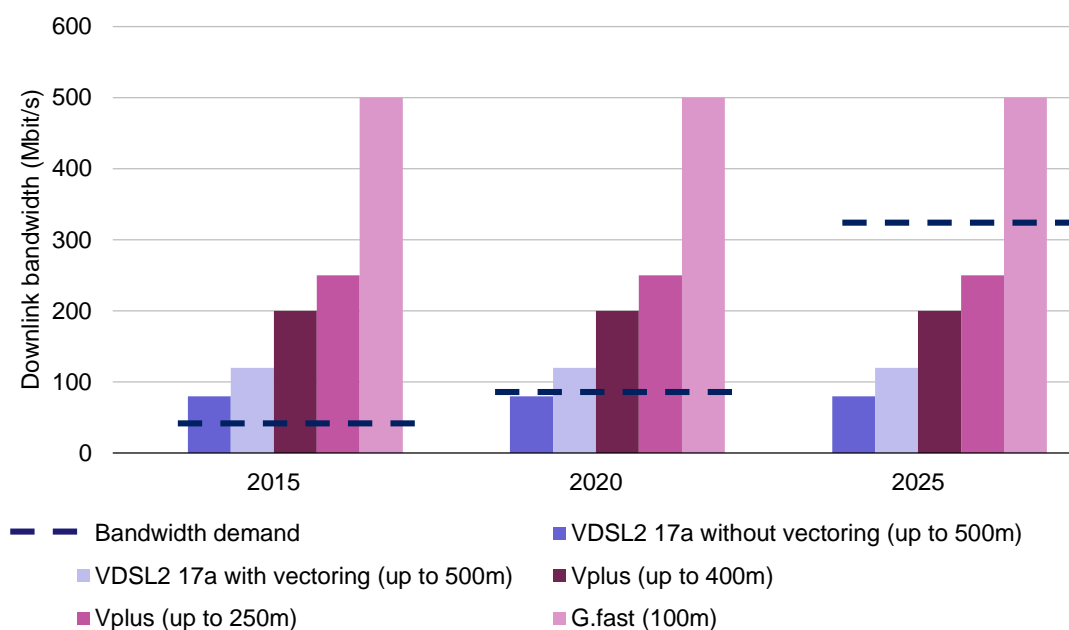
38   For clarity, we do not assess the ability of the NBN network to meet the bandwidth requirement, which requires to take into account the specific distribution of the NBN sub loop length.

First, it should be noted that the bandwidth delivered by different xDSL technologies does not only depend upon the copper loop length but is also dependent on many other factors, as illustrated in Section 3.2. Therefore the downlink bandwidth we provide for different technologies in Figure 3.22 is for illustration purposes only and is aimed at providing orders of magnitude to determine if a particular technology is suitable for different bandwidth requirements.

In Figure 3.22, it can be seen that, for lines up to 500m, VDSL2 without vectoring can meet today's requirements but will not be able to meet future bandwidth requirements. However, VDSL2 with vectoring technology should meet the bandwidth requirements up until 2020, for lines up to 500m. Finally, it can be seen that, if there is no new disruptive technology by 2025, only G.fast will be able to meet the downlink bandwidth requirement for short lines (i.e. lines of less than 250m).

Uplink bandwidth assessment

To be able to assess whether the uplink bandwidth provided by different technologies will be able to meet the uplink bandwidth demand from end-users, we compare the uplink bandwidth offered by each technology for different copper loop lengths estimated in Section 3.4.2 with the likely uplink bandwidth demand provided in Section 3.5.2. The comparison is illustrated below in Figure 3.23.

Figure 3.23: Estimated uplink bandwidth demand vs. estimated uplink bandwidth provided by different technologies [Source: Analysys Mason, 2015]

First, the uplink bandwidth delivered by different xDSL technologies does not only depend upon the copper loop length but is also dependent on many other factors. Therefore, the uplink bandwidth we provide for different technologies in Figure 3.23 is for illustration purposes only

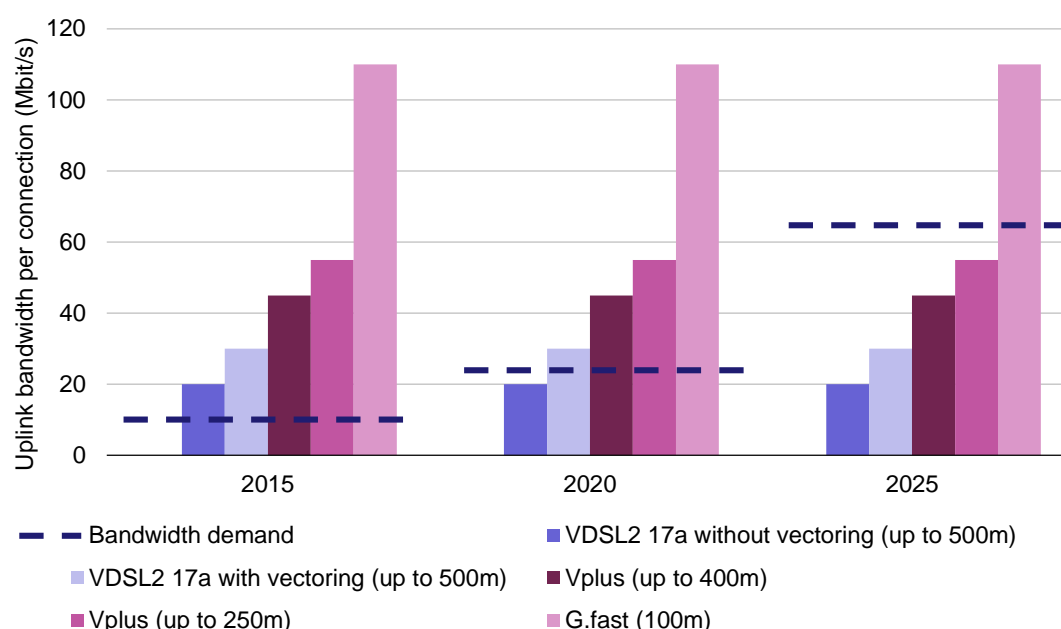and is aimed at providing orders of magnitude to determine if a particular technology is suitable for different bandwidth requirements.

The comparison of uplink bandwidths for different xDSL technologies with the likely bandwidth demand leads to the same conclusion as the analysis for the downlink bandwidth performed in the previous section: for lines up to 500m, VDSL2 (profile 17a) without vectoring can meet today's uplink bandwidth demand but will not be able to meet future bandwidth requirements. However, VDSL2 (profile 17a) with vectoring technology should meet the bandwidth requirements up until 2020, for lines up to 500m. Finally, it can be seen that, assuming there is no new disruptive technology by 2025, only G.fast will be able to meet the uplink bandwidth demand for short lines (i.e. lines less than 250m).

3.6 Operational considerations for technology upgrades

FTTN operators have a number of options for upgrading their networks to increase the broadband service bandwidth available to end-users. One option is to upgrade xDSL equipment (e.g. DSLAM) according to the roadmap described in Section 3.4 without having to make any major change in the architecture or physical composition of the network. However, such upgrades are not always feasible due to the fundamental limitations of xDSL technology whose performance heavily depends on the copper loop length. Therefore, another upgrade option is to extend the fibre network closer to the customer premises, which results in a shortening of the copper loop length and consequently, in an improvement of the bandwidth that can be delivered to the customer premises. In this analysis, we consider three main upgrade options:

- activate vectoring feature on existing VDSL2 DSLAMs
- upgrade DSL technology and maximise the use of existing copper loops
- extend the fibre closer to the end-user to reduce the copper loop length.

We discuss each of these options below.

3.6.1 Activation of vectoring

Activating vectoring virtually eliminates FEXT, providing significant gain in terms of bandwidth to all lines. A report[39] commissioned by the Body of European Regulators for Electronic Communication (BEREC) states that the bandwidth gain associated with vectoring can be up to 100%. The latest VDSL2 DSLAMs have in-built vectoring capabilities which can be turned on or off, depending on the requirement and feasibility of vectoring implementation (see *limitation of vectoring implementation* below for more detail). Also, it should be noted that all end-user premises must be equipped with vectoring-enabled CPE, which usually involves a swap out of all end-user CPEs.

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[39]   *Case Studies on Regulatory Decisions regarding Vectoring in the European Union*, BEREC, September 2014.

Activation of vectoring is considered to be a cost-effective upgrade by operators as it does not involve any changes in infrastructure; that is vectoring can be deployed using the existing FTTN infrastructure and in particular does not require any fibre extension.

However, if the vectoring system does not compensate for the interference of **all** VDSL2 lines in a cable (binder), the vectoring gain can be reduced significantly. This situation can occur if multiple operators want to use copper pairs within the same cable binder with their own separate DSLAMs for providing VDSL2-based broadband services to their respective end-users. To avoid this issue, the vectoring system has to control all VDSL2 lines of a cable. This means it is not usually possible that more than one operator can use vectoring on VDSL2 lines in the same cable, unless an industry solution is implemented to deal with situations where more than one operator is using sub-loops within the same cable binder. Some equipment vendors are also currently looking for solutions to resolve this issue.

Also, VDSL2 vectoring cannot cancel interference from adjacent ADSL lines. ADSL DSLAMs are usually installed in the exchange and their copper loops can physically transit VDSL2 cabinets and sub-loops to reach customer premises. However, the ADSL downlink signal will be attenuated between the exchange and the VDSL cabinet and will therefore be small compared with the VDSL downlink signal which is sourced at the cabinet. The stronger VDSL2 signal could interfere with the weaker ADSL signal. However, ADSL can continue to be used from the exchange if the VDSL2 DSLAM at the cabinet uses downlink power back off, which (as explained in Section 3.2.3) involves reducing the power supplied by the VDSL lines at the cabinet in the ADSL2+ spectrum band to minimise ADSL interference. However, in this case, VDSL2 can be used with vectoring at the cabinet to gain performance with the ADSL systems at the exchange only slightly reducing the achievable vectoring gain. This situation can occur if a single operator deploys ADSL2+ and VDSL2 in the same cable or if one operator deploys ADSL2+ from the exchange and if another operator deploys VDSL2 from the street cabinet, using individual copper loops in the same copper cable.

3.6.2 Upgrade of DSL technology

As mentioned in Section 3.4, some technologies (e.g. Vplus and SuperVector) are emerging which will allow the capability of existing FTTN networks to be further upgraded in terms of bandwidth, without having to deploy any additional fibre. Upgrading FTTN to VPlus/SuperVector technology will consist of replacing some cards in existing street cabinets and replacing end-user CPE. This upgrade will be particularly well suited to medium-length sub-loops[40] and will prevent operators from incurring the high costs associated with extending the fibre network closer to the end-user.

Since Vplus/SuperVector technologies are designed to be compatible with established VDSL vectoring deployment using 17MHz, the co-existence of VDSL2 and VPlus/SuperVector lines in the same copper cable should not cause any issues in terms of interference.

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[40]   Vplus and SuperVector are not designed to improve the bandwidth on copper lines longer than 500m as illustrated in Figure 3.14.

3.6.3 Extension of the fibre closer to the end-user

As illustrated in Figure 3.22, we expect that VPlus/SuperVector technologies may not have the capability to meet broadband market demand after 2025. Unless a new disruptive technology is put forward by equipment vendors, operators will eventually have to extend the fibre closer to the end-user (i.e. FTTdp) to provide suitable bandwidth, using xDSL technologies[41] specifically designed to provide high bandwidth over very short copper loops (i.e. 200m and less). Since the vast majority of the cost associated with fibre deployment is related to civil engineering works (i.e. trenching or aerial deployment), operators will try to maximise the re-use of the existing network infrastructure (i.e. ducts and poles).

An FTTdp architecture will consist of installing DPUs[42] at the DP locations, which will either be on top of existing poles (for aerial deployments) or in foot-holes (for underground deployment). Key considerations for this upgrade include:

- space on existing infrastructure for locating DPUs
- space in ducts and poles for fibre cable
- loading of poles.

For aerial deployment, space on existing poles for locating a DPU is usually not an issue (i.e. the DPU does not apply any radial force on the pole). However, the deployment of additional fibre cable on poles has to consider the loading capability of existing poles. If existing poles cannot support additional cables, they may have to be strengthened or replaced depending on their condition, which can add significant capex to the upgrade process.

For underground deployment, the DPU has to be located in a foot-hole, a small chamber in the ground typically located in a publicly accessible (with permissions) area e.g. footpath or roadside verge. If there is not enough available space in the existing foot-hole, civil engineering work may have to be carried out to augment the foot-hole dimension. This can be capex-intensive, depending on the number of foot-holes which have to be increased in size. Also, when deploying a new fibre cable in a duct, the fibre and copper cable have to co-exist for a period to prevent major service outage (i.e. end-users connected to the copper cable do not want to be disconnected before the fibre connection is established). Therefore, if the operator is to minimise capex, ducts have to have sufficient available space for additional fibre cable. If enough space is not available in the existing ducts, new ducts may have to be installed which involves trenching. Again, the civil works associated with trenching add significant costs to the upgrade.

3.7 Conclusions

FTTN and FTTB networks are used by leading operators around the world to provide broadband services. Currently, the most widespread technology for delivery of broadband services is VDSL2,

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[41]   Such as G.fast.

[42]   i.e. mini DSLAM using G.fast technology with up to 24 ports.

which is now considered to be a mature technology. FTTN/FTTB operators have a number of options for upgrading their networks to support future bandwidth demand:

- introduction of vectoring
- upgrade of DSL technology e.g. from VDSL2+ to G.fast
- extension of the fibre network closer to end-users.

However, these options may be significantly affected by any requirements to support infrastructure sharing[43] (i.e. sharing of copper cables between operators).

Vectoring, used on VDSL2 subscriber access lines, significantly increases the achievable bandwidth on copper lines and has recently been rolled out by a number of operators around the world. The advantage of vectoring is that it does not require any costly civil works (i.e. no extension of the fibre network required). It is implemented by activating the vectoring feature in a VDSL2 DSLAM located in the cabinet and providing vectoring-capable CPE to customer premises. However, to achieve the full advantages of vectoring, an operator must be able to control all lines in the copper cable, which cannot be achieved when several operators use the same copper cable to deliver broadband services to their respective end-users.

The upgrade of existing DSL technology equipment is usually the approach preferred by FTTN operators as it does not involve any civil works and is therefore relatively cost-effective. However, there is currently a lack of technology upgrades for loops longer than 250 metres. Emerging technologies such as VPlus and SuperVector will provide operators with the ability to upgrade their medium-length (250–500m) copper loop to further extend the life of their existing copper networks. Such technologies are currently being designed to be compatible with VDSL2 but will require replacing equipment at in the cabinet (DSLAMs) and at the customer premises.

We have demonstrated that the performance associated with different xDSL technologies is highly dependent on the copper loop length. As such, we believe it is possible that (in the absence of a disruptive technology altering the current roadmap for xDSL technologies) the lengths of copper loops will need to be reduced in 2025–30 to be able to keep up with anticipated levels of end-user demand in Australia, and with international market trends. This will be achieved by deploying fibre increasingly close to customer premises towards an FTTdp architecture and by using xDSL technologies that are specifically designed for very short copper loops (e.g. G.fast). However, as the deployment of G.fast uses vectoring as a default technology, the issues identified in this report with respect to vectoring will also need to be managed in the context of G.fast deployments. Also, we would like to re-iterate that while nbn is currently trialling G.fast technology, nbn has not taken any decisions to deploy G.fast technology as part of its technology roadmap.[44]

Ultimately, the extension of the fibre access network will result in an FTTP network, where fibre is deployed all the way to the customer premises.

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[43] Unless technology developments can resolve this issue.

[44] Accordingly, this report does not consider the prudency or efficiency of G.fast technology.

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The upgrade path chosen by a particular operator will depend on a combination of:

- current passive and active network characteristics, in particular, the length and condition of existing copper loops
- requirements by governments/national regulatory authorities to support infrastructure sharing
- end-user demand for increased peak and sustained bandwidth
- retailers' response to market competitive pressures
- availability of funds and appetite for long-term capital investment.

Upgrades are not likely to be uniformly applied across networks as the operators will have to consider the distribution of copper loops in their network to formulate the optimum techno-economic upgrade strategy (i.e. balancing performance and cost).

Overall, we believe that FTTN/FTTB networks have a technically feasible, incremental upgrade path to keep up with market demand for bandwidth, but maximum performance may be compromised by infrastructure-sharing requirements, unless a technology (e.g. advanced vectoring system) aimed at mitigating interference between different systems is developed in the near future.

4 Technical overview of HFC networks

This section presents a technical overview of hybrid fibre coaxial (HFC) technology, and is designed as a reference point for the rest of this report. It is structured as follows:

- Section 4.1 provides an overview of the HFC network architecture.

- Section 4.2 describes HFC in terms of the DOCSIS broadband service specifications and examines the possible architectures and key network elements.

- Section 4.3 provides an overview of worldwide HFC network deployments focusing on the version of the DOCSIS specifications relevant to nbn.

- Section 4.4 shows the technology roadmap for HFC networks based on the DOCSIS 3.1 specification showing the expected evolution of bandwidth with this specification.

- Section 4.5 presents the bandwidth capability of current and future HFC technology to help assess whether this network type will be able to meet the expected demand in the future.

- Section 4.6 provides insight into key operational issues associated with technology upgrades for HFC networks.

Supplementary reference material can be found in the Analysys Mason report for Ofcom entitled *Future capability of cable networks for superfast broadband*.[45]

4.1 Overview of HFC architecture

A telecommunications network is referred to as a hybrid fibre coaxial (HFC) network if it contains both fibre-optic and coaxial cable 'plant' in its access network. The term 'plant' refers to all cabling used to connect access and core network elements. The key elements of the network are shown in Figure 4.1.

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[45] *Future capability of cable networks for superfast broadband,* April 2014. Available at:
http://stakeholders.ofcom.org.uk/binaries/research/technology-research/2014/cable-sfbb.pdf

Figure 4.1: Network overview of HFC plant and network [Source: Analysys Mason, 2015]
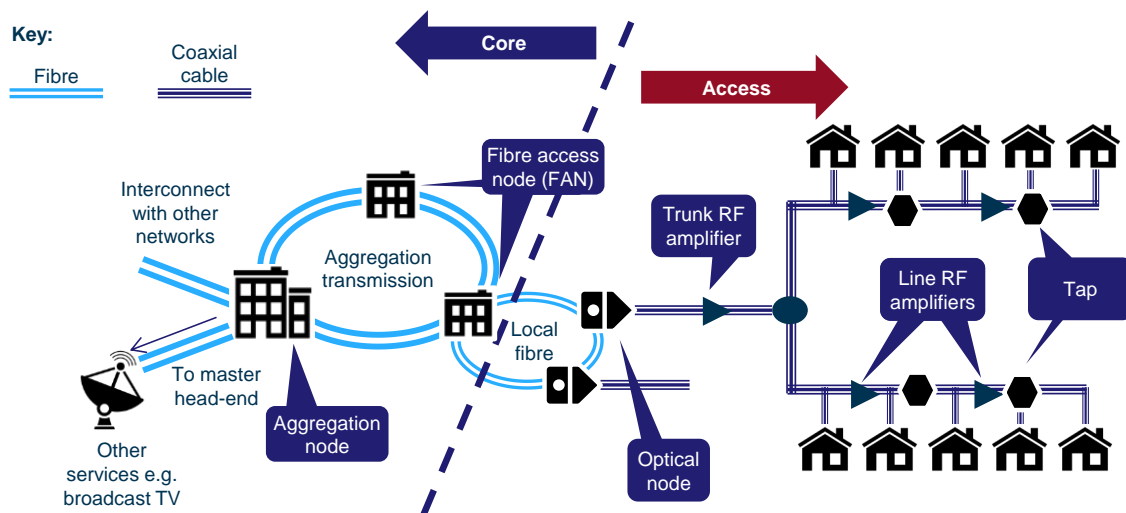
Generally, HFC networks can be split into access and core networks. The access network is the distributed part of the HFC network, used to connect customer premises to services provided by the core network. The access network typically covers large geographical areas and comprises a fibre-based feeder network and a coaxial cable distribution network. The core network is the central part of the HFC network used to aggregate and manage cable TV, video on demand (VoD), broadband and telephony services. It includes fibre backbone rings,[46] the master head-end and local head-ends (or aggregation nodes).

4.1.1 Core network

Fibre access and aggregation nodes

Each optical node is connected to a local head-end or hub. In NBN terms, this is the FAN. The optical node connects to the FAN over a fibre feeder. The fibre feeder typically uses amplitude modulation to transmit the radio frequencies over the optical fibre and its characteristics are designed for the delivery of the required bandwidth. However, fibre feeder signal losses can also contribute to limiting the encoding level supported by a particular link and so reduce the bandwidth supported.

The FAN will typically include the RF combiner which combines the multitude of broadcast (e.g. TV services) and narrowcast signals (e.g. broadband and VoD services) into a single stream. As the narrowcast streams are unique for each optical node, there needs to be one combiner per optical node. The FAN may also contain a cable edge quadrature amplitude modulation (EQAM), cable modem termination system (CMTS) and supporting elements. In nbn's case, the CMTS may only be located at certain FANs that are also combined with an aggregation node. This combined arrangement is illustrated in Figure 4.2.

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[46] This can be further broken down into a core ring and a metro ring.

Figure 4.2: Key elements of a combined FAN and aggregation node [Source: Analysys Mason, 2015]
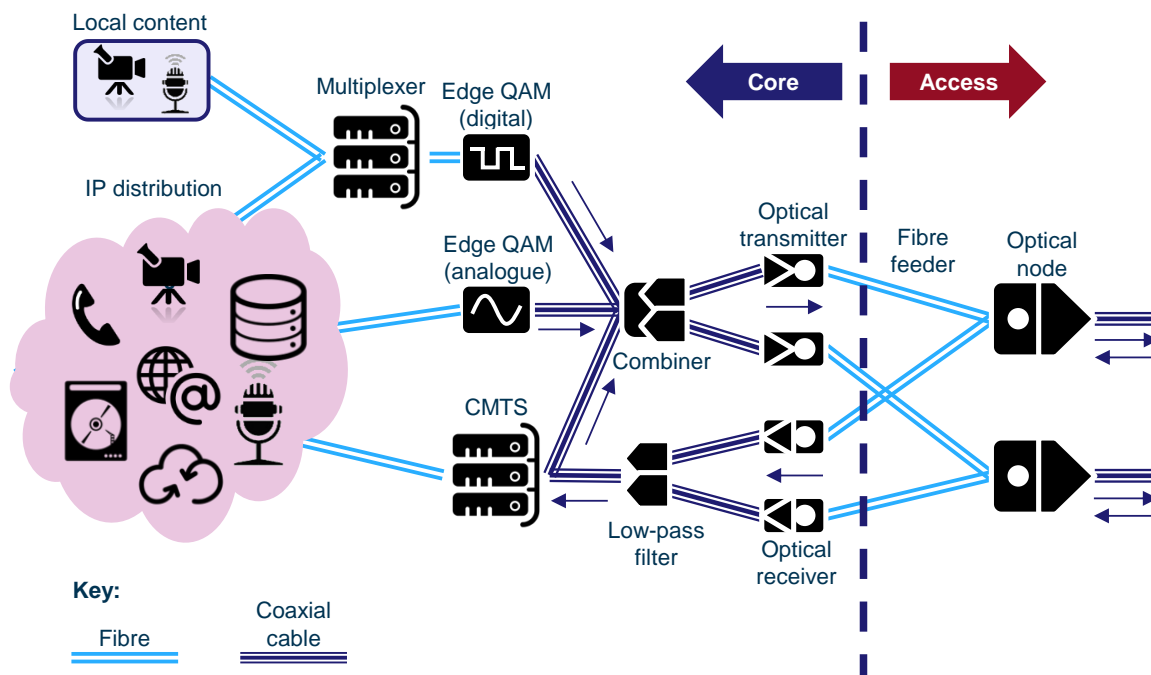
The CMTS is used to provide data services (including Internet connectivity and VoIP) using DOCSIS over a cable network and is a key element of the nbn solution. Various types of CMTS exist, including integrated (I-CMTS), modular (M-CMTS) or distributed (D-CMTS):

- *I-CMTS* includes all the components necessary for DOCSIS data transmission, including built-in QAM functionality; that is, an I-CMTS is able to directly modulate RF channels.

- *M-CMTS* has functionality split into various 'sub-modules' (such as DOCSIS media access control, DOCSIS timing servers, EQAM modulators, etc.), which are often situated in different locations and connected by Ethernet. This is the type that nbn proposes to use.

- *D-CMTS* is a small-scale, low-power CMTS suitable for serving <500 subscribers. It is generally deployed extremely close to the end-users, such as in outdoor cabinets, on pole mountings, or in the basement of large MDUs. A D-CMTS can be an extension of the N+0 architecture (as discussed in Section 4.6.3).

The CMTS can also be used to perform various traffic management/data scheduling tasks, including prioritisation of certain subscriber plans or quality of service (QoS) provision for specific applications (i.e. VoIP or IPTV).

The FAN will also include the optical transmitter and receivers which convert light signals to electrical (RF) signals, and vice versa. This kind of system can either be deployed within the same 'box', known as a transceiver (as in the case of the optical node), or it can be attached to ports of larger equipment such as the CMTS. An optical receiver may also include low-pass RF filters to

ensure that only the relevant uplink signal frequencies (5–65MHz) are transmitted to the CMTS for processing.

Traditionally, each cable network modulator was designed for a specific service (i.e. digital TV or VoD), which is to be encoded onto a specified spectrum channel. However, modern networks typically provide additional flexibility for channel service allocation, which has led to the development of more flexible modulators, known as EQAMs. EQAMs are capable of modulating both VoD and broadcast services, with the latest versions ('universal EQAMs') also able to modulate IP-related services (including data and voice) through voice over IP (VoIP), all within a single box.

The FAN may also include a DVB-C multiplexer which encodes and combines multiple digital TV/radio channels into a single transmission, but this, together with the EQAM is part of TV distribution, which is outside the requirements of the nbn broadband service.

Master head-end

In a cable network, FANs and aggregation nodes will typically connect back to a master head-end which provides connectivity and control of the cable network services. A typical arrangement is shown in Figure 4.3.

Figure 4.3: Key elements of master head-end [Source: Analysys Mason, 2015]
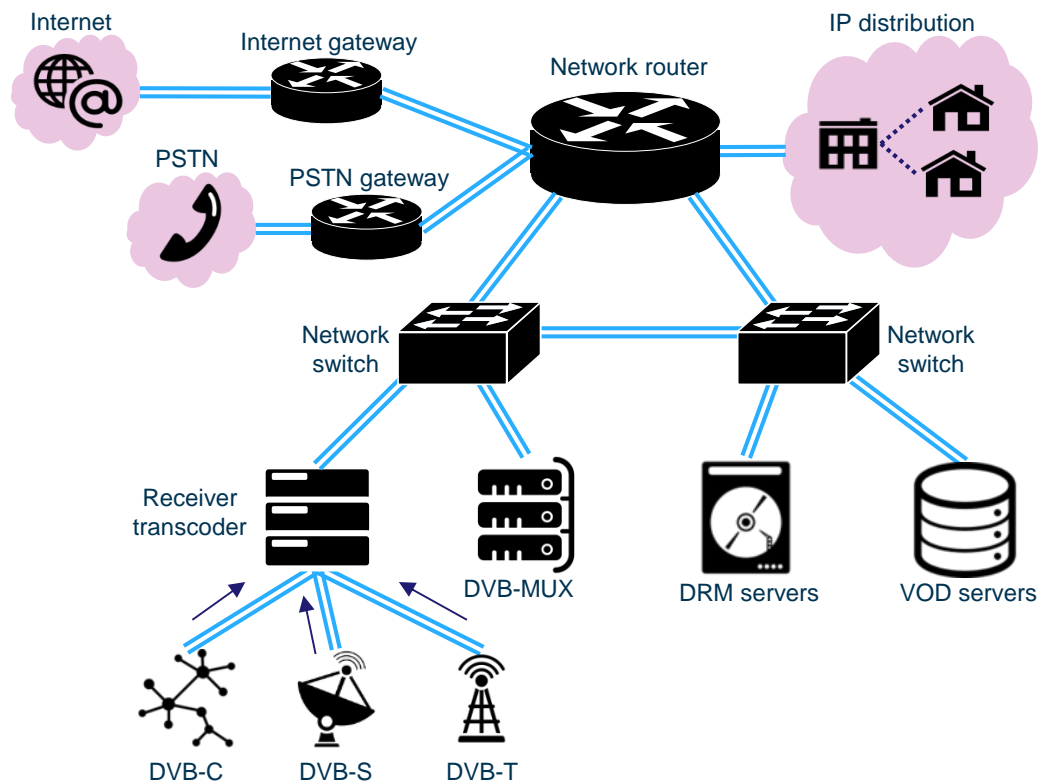
The master head-end typically provides access to the Internet, via interconnect or local caching servers, and may also include voice PSTN control systems and interconnect. The head-end also provides access to broadcast TV service play-out systems (for terrestrial, satellite and cable delivered services) and VoD servers. The master head-end may also have digital rights management servers that are used to track and manage the rights of content stored on the cable network.

However, it should be noted that the master head-end is not directly applicable to the nbn environment as nbn is focused on providing broadband wholesale access services. As such, nbn effectively only provides aggregation services from the CMTS in the aggregation node to the points of interconnect (PoI) with the RSPs as shown in Figure 4.4. In the diagram, the EAS aggregates the traffic from the different CMTSs in the network and the Ethernet fan-out switch (EFS) provides the interface to the RSPs. A cable modem is the end-user interface device on the customer premises.

Figure 4.4: nbn's interconnect arrangement with RSPs[47] [Source: Analysys Mason, 2015]
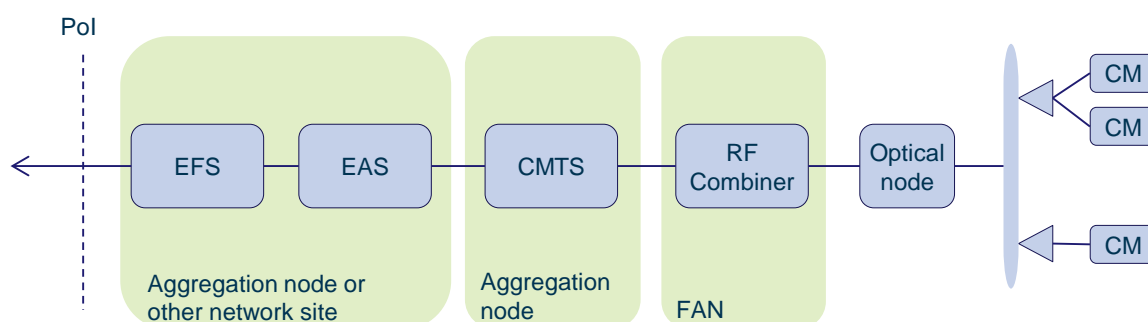
4.1.2 Access network

The key components of the access network, as shown in Figure 4.1, are the optical node, line or trunk amplifiers and coaxial cable taps.

An optical node acts as a converter between the coaxial and fibre sections of the access network. Each optical node is connected to a FAN fibre connecting the access network to the core network. This connection may be a single direct link or resilient dual links where a second fibre pair is provided for redundancy. A single coaxial cable leaves the optical node towards the customer premises.

An RF signal carries traffic (video, data or voice) on the coaxial cable between the optical node and the customer premises. A line, or trunk, amplifier located in sections of the coaxial cable is a bi-directional active component that amplifies the RF signal to overcome coaxial cable signal attenuation and passive 'tapping' losses. These amplifiers can be powered either by external power supplies, or via a specific power supply carried along the trunk cable. A coaxial cable tap splits out one (or more) smaller drop cables from a main coaxial cable for connection to the customer

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47   Please note that, in addition, the Foxtel TV signal is injected into the network, but this is not shown on this diagram.

premises, ensuring a minimal drop in signal level on the main cable so that it can be used for additional downstream premises. Cable taps have one input connection and multiple output connections, one of which is normally a continuation of the main cable. The drop cables connect to a network interface unit (NIU) located at the customer premises which is the termination point of the cable operator's network, and isolates the cable network from a subscriber's home network. The NIU is also used to separate the various service channels (data/TV) and direct them to the relevant CPE. Alternatively, the coaxial cable may connect directly to a coaxial wall plate (commonly referred to as the cable socket) and a separate device is used to separate the services.

A cable modem is a specific type of CPE that is used to provide bi-directional broadband services to customer premises over the cable network using the DOCSIS set of protocols. The cable modem acts as a gateway between the home local area network (LAN) connecting to internal equipment (such as a computer) via an Ethernet connection and a CMTS via the operator's cable network. Most modern cable data systems use more complicated cable 'hubs' instead of cable modems, which frequently incorporate Internet firewalls, Wi-Fi connections, landline phone ports and multiple Ethernet ports.

Other CPE may also be used for other services such as a set-top box (STB) for digital television or VoD services.

4.2 HFC standards and architecture options

This section examines the DOCSIS protocol specifications that are used to deliver broadband services on HFC networks and also reviews the different architecture options that are available to HFC network designers including configuration options for the CMTS, which is central to the delivery of high-quality broadband services over the HFC network.

4.2.1 DOCSIS and EuroDOCSIS

Specification development

The first DOCSIS specification (DOCSIS 1.0) was finalised by CableLabs in March 1997. Two years later, Cisco Systems received 'qualification' from CableLabs for its first CMTS, and Toshiba and Thomson Consumer Electronics received 'certification' for the first DOCSIS-compliant cable modems.

Alongside the development of DOCSIS in the USA, a slightly adjusted European version was developed, called EuroDOCSIS.[48] The EuroDOCSIS standard has been adopted by Australian HFC network operators including Telstra and Optus. This modified specification allowed for differences in standard TV broadcast channel width between the USA and Europe. In Europe, 8MHz (and 7MHz) width channels were used for compatibility with PAL (and SECAM

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[48]   European cable operators originally intended to have their own European standard, EuroModem, but finally settled on the modified EuroDOCSIS standard instead.

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respectively) analogue TV specifications. This was in contrast to the narrower 6MHz DOCSIS channels used in North America, to conform to the NTSC TV standard.

The EuroDOCSIS specification is included as an Annex within each of the main DOCSIS Physical Layer Specification (PHY) documents. While certification/qualification testing of the US standard is undertaken by CableLabs, EuroDOCSIS products are tested by Excentis (based in Belgium) on behalf of Cable Europe,[49] although there is a strong degree of co-operation between the European and US cable associations.

Following the development of (Euro)DOCSIS 1.0, several versions of the standard have been released, each designed to be 'backwards compatible' with previous versions:

- DOCSIS 1.1 was released in April 1999, adding enhanced QoS and security capabilities to the DOCSIS 1.0 specification.

- In 2001, DOCSIS 2.0 was released, providing enhanced uplink transmission bandwidth through the use of more advanced modulation techniques. With DOCSIS 2.0, each 8MHz EuroDOCSIS channel was able to transmit at a bandwidth of around 38Mbit/s using a 64 quadrature amplitude modulation (64-QAM) scheme, rising to 51Mbit/s using 256-QAM.[50]

- DOCSIS 3.0,[51] the most current commercially available standard, was released in August 2006. This standard increased both uplink and downlink bandwidth by allowing channel bonding, as well as including support for IPv6. DOCSIS 3.0 (or EuroDOCSIS 3.0) is the standard used by the majority of cable systems today. Given a standard bonded group of eight channels, EuroDOCSIS 3.0 allows transfers of up to 400Mbit/s at 256-QAM.

- In October 2013, the newest standard, DOCSIS 3.1,[52] was finalised, adding orthogonal frequency division multiplexing (OFDM) and improved error correction characteristics, along with multiple other improvements. Commercial deployment of DOCSIS 3.1 is likely to begin in 2016. EuroDOCSIS 3.1 maintains support for legacy EuroDOCSIS 3.0 QAM modulation and still allows support of the 8MHz channelisation in the frequency plan, although there are no new features that need to be specifically defined for EuroDOCSIS in the 3.1 specification. The capabilities of DOCSIS 3.1 are discussed in more detail in Section 4.4.

It should be noted that although there is a rigorous process in place for certification/qualification of equipment with DOCSIS and EuroDOCSIS standards, the equipment deployed by individual operators is frequently customised to their own individual specifications. Divergence from the

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[49]   Cable Europe is a not-for-profit professional membership organisation, whose members include operators and national cable associations within the European Union.

[50]   Quadrature amplitude modulation (QAM) is a modulation scheme used to transport digital information over an analogue network. QAM works by varying the amplitude of a sine and cosine carrier at the same frequency to different degrees, allowing the encoding of a various number of 'bits'; for example, 64-QAM can be encoded through the use of 5bits.

[51]   http://www.cablelabs.com/specs/

[52]   Ibid.

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DOCSIS specifications is largely driven by the business and operational requirements of individual cable operators. It is also believed to be partly due to the complexity of the specifications, as well as the fact that large-scale cable networks only rarely have geographical overlap with other cable networks. However, even though systems may not fully comply with DOCSIS standards, this does not often reduce their effectiveness when deployed in the field.

Spectrum usage

DOCSIS data services operate as narrowcast services, across a defined number of RF channels. The total number of RF channels allocated to data and the modulation scheme used define the total broadband bandwidth that is available. This fixed bandwidth is shared among a group of subscribers who are all connected to a single optical node. If the network becomes congested by, for example, many simultaneous active users, the average sustained bandwidth per active user is reduced. Therefore, one of the key aspects of a modern HFC network implementation is the total amount of RF spectrum used, and the proportion of this spectrum i.e. number of RF channels, which is allocated to each of the services that is offered including analogue and digital TV and VoD services as well as broadband data services.

The RF spectrum plan for all services is split into an uplink band operating at low frequencies and a (significantly wider) downlink band operating at higher frequencies, as shown in Figure 4.5. Different ranges are specified for DOCSIS and EuroDOCSIS, with the Australian operators following the European approach.

Figure 4.5: Band plan range for European cable systems [Source: Analysys Mason, 2015][53]
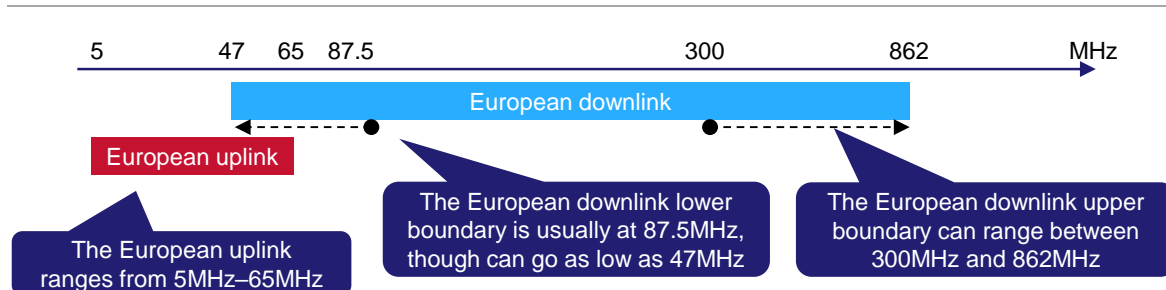
Given the typical customisation of various systems, the specific frequency plan used by individual operators may vary from one system (geographical region) to another, with the DOCSIS specifications stating that "the upper edge is implementation dependent but is typically in the range of 300 to 862MHz". Modern European systems typically operate with an uplink band of 5–65MHz, and a downlink band of 87.5–862MHz. The Telstra and Optus networks both operate in this uplink band range, but only up to 750MHz in the downlink direction.

However, DOCSIS 3.0 data services operate over smaller frequency bands within this total range, as shown for EuroDOCSIS in Figure 4.6. Under EuroDOCSIS 3.0, the total frequency range is

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[53]   It should be noted that an upper uplink boundary of only 30MHz is extremely rare, with all DOCSIS 3.0 modems required to support at least up to 42MHz.

split into 8MHz 'single carrier QAM' (SC-QAM) channels, where these can be grouped as discussed in Section 4.5.2.

Figure 4.6: Typical spectrum usage plan under EuroDOCSIS 3.0 [Source: Analysys Mason, 2015][54,55]
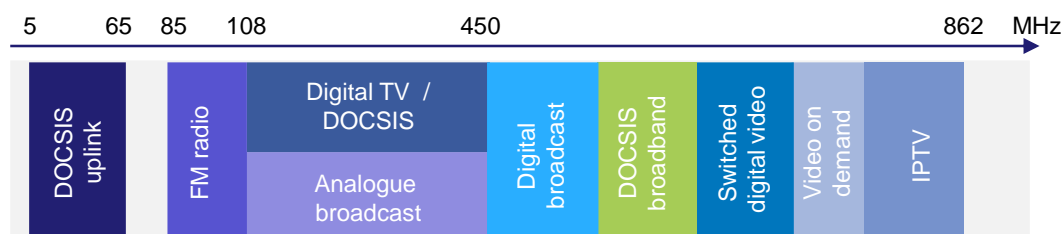
Analogue broadcast is a particularly inefficient use of spectrum as one 8MHz channel is required for each TV channel. In comparison, several digital TV channels can be delivered using one 8MHz RF channel depending on the definition and encoding and modulation schemes used. However, many countries (though not Australia) still retain analogue services. This can be either due to obligations on the operator to continue providing these services or because there is a need to provide services to legacy analogue end-user devices that remain in the network.

IPTV and VoD spectrum can be used to deliver similar on-demand content, but whereas IPTV services are delivered within IP packets, VoD content is delivered directly using DVB-C or DVB-C2 encoding (in the same way as digital broadcast channels).

In practice, the total spectrum band is shared among multiple services, with data services generally receiving between eight and 24 channels in today's networks. As such, the allocation of spectrum is key to ensuring optimum performance for subscribers for all services including broadband services. While it is theoretically possible for services to be allocated spectrum in proportion to the level of demand from end-users, there is finite spectrum to be shared among all services.

4.2.2 Access architecture options

There are two main topologies for cable access network architectures – 'tree and branch' (for example as found in the UK) and 'star' (for example as found in the Netherlands), though some networks use a mixture of the two topologies. Telstra and Optus have adopted a tree-and-branch topology.

The choice of architecture is often dictated by the underlying network geography and the distribution of housing within the region (i.e. whether households are evenly spread or clustered in particular areas). This leads to particular network architectures often having similar characteristics, as detailed in Figure 4.7.

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[54]   In practice, uplink spectrum below 20MHz can suffer from significant signal noise, so is often avoided.

[55]   This can be in the range of 300MHz to 862MHz, with modern data systems tending to use higher boundaries.

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Figure 4.7: Example parameters for different cable network architectures [Source: Analysys Mason 2015, ReDeSign, 2008]

	Tree and branch	Hybrid	Star
% of networks in Europe	50%	30%	20%
Branches per optical node	2–4	2–3	3–6
Cascade length (no. of amplifiers)	4–15	4–6	2–3
Households passed per optical node	250–1500	500–2000	500–700

Tree-and-branch topology

With a tree-and-branch topology, as shown in Figure 4.8, the feeder cable is an effective way of covering large distances of evenly spaced houses (as found along suburban roads), with amplifiers required at various distances. This topology also generally requires less trenching and/or aerial network deployment to deploy than a star topology, thus reducing plant deployment costs.

The tree-and-branch topology can be more difficult to implement node splitting to increase network capacity (see Section 4.6.1) or replace coaxial with fibre, as there are fewer logical points of (roughly even) division. In addition, subscribers at either end of a branch may experience highly differential signal powers, so signal strength issues may be more common.
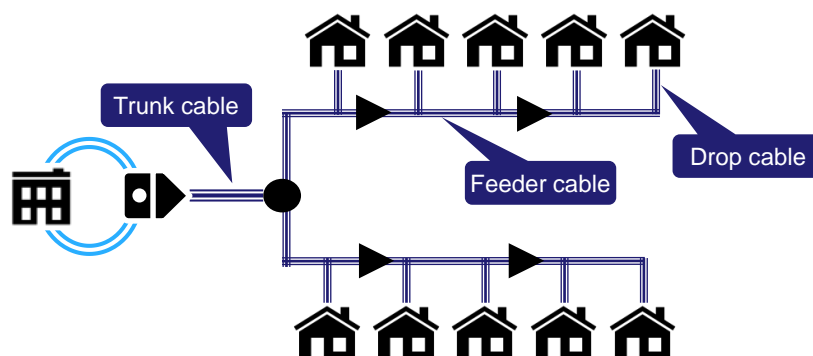
Figure 4.8: Tree-and-branch network topology [Source: Analysys Mason, 2015]

Star topology

With a star topology, as shown in Figure 4.9, the feeder cable is more effective at covering non-homogenous clustered household layouts, as found in either more rural or extremely dense urban geographies. This topology requires fewer amplifiers within a single cascade than found under the tree-and-branch topology, thus improving the maximum potential distance between an optical node and the households it serves. This is because RF amplifiers introduce noise in the signal and to maintain the SNR above the signal detection level, the number of amplifiers has to be limited, which itself limits the length of the coaxial segment which can be used for transmitting the signal.

As this topology has multiple natural splits, it is significantly easier to implement node splitting.
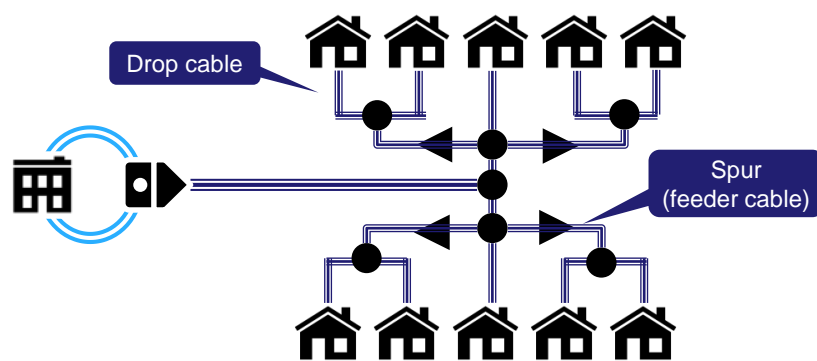
Figure 4.9: Star network topology [Source: Analysys Mason, 2015]

4.2.3 CMTS configuration options

A cable operator has different options for sharing the spectrum allocated to broadband services across its network, depending on how it configures its CMTS. Typical scenarios that are deployed include:

- sharing spectrum across a 'service group' comprising end-users connected to a number of fibre nodes (typically up to eight)
- sharing spectrum across subscribers connected to a single fibre node
- logically splitting each fibre node into sub-groups. This depends on the architecture deployed and is more suited to star network configurations (as described in Section 4.2.2).

The choice of approach will depend on the headline bandwidth and sustainable bandwidth that the cable operator wants to be able to offer end-users, balanced against customer penetration in different parts of the network. If customer penetration levels are high then spectrum is likely to be shared on a fibre node basis, but if penetration levels are low then larger 'service groups' will be used. This reduces the investment that needs to be made in broadband channel cards at the CMTS, as the number of cards required depends on the number of distinct channels that are configured. nbn has indicated that its initial policy will be to have one service group per fibre node.

4.3 Worldwide deployments

HFC networks are widely deployed and many markets are leading the way in terms of coverage and bandwidth offered. Figure 4.10 provides some details of the fastest products offered by HFC operators in selected countries. It can be seen that the headline downlink bandwidth is in excess of 100Mbit/s in all cases, with the uplink bandwidth offered typically being around 10% of the downlink bandwidth. The data allowances offered are typically unlimited, although a level of traffic management may be applied in some cases.

Most HFC operators also offer business grade services using their DOCSIS based network with the service speeds invariably being different to those offered for residential services (both faster and slower than residential services), which is likely due to varying stages of development in the business segment in each country.

Figure 4.10: Comparison of high bandwidth tier 'superfast' broadband products offered by cable operators[56]
[Source: Analysys Mason, company websites, 2016]

Operator	Peak downlink bandwidth – Residential	Peak uplink bandwidth– Residential	Business services over HFC offered?	Peak downlink bandwidth – Business	Peak uplink bandwidth – Business
Virgin Media, UK	200Mbit/s	12Mbit/s	Yes	152Mbit/s	12Mbit/s
Rogers, Canada	1Gbit/s	50Mbit/s	Yes	250Mbit/s	20Mbit/s
Ziggo, Netherlands	200Mbit/s	20Mbit/s	Yes	500Mbit/s	40Mbit/s
Cablecom, Switzerland	500Mbit/s	50Mbit/s	Yes	200Mbit/s	20Mbit/s
Telenet, Belgium	200Mbit/s	12Mbit/s	Yes	240Mbit/s	20Mbit/s
Telemach, Slovenia	200Mbit/s	6Mbit/s	Yes	200Mbit/s	6Mbit/s
Com Hem, Sweden	1Gbit/s	100Mbit/s	No[57]	-	-
UPC, Ireland	360Mbit/s	36Mbit/s	Yes	250Mbit/s	Not specified

4.4 HFC technology roadmap

Cable operators are already widely offering more than 100Mbit/s (downlink) broadband services using DOCSIS 3.0 and the bonding of additional channels is able to push this capacity towards 500Mbit/s.

However, the foreseeable development of HFC networks will be based on the DOCSIS 3.1 specification. The development of the DOCSIS 3.1 was accelerated to help meet the requirements of cable operators to compete with emerging networks using copper and fibre technologies. According to CableLabs, the specification was completed 40% faster than previous specifications.

The technology roadmap of HFC, which focuses on the introduction of DOCSIS 3.1 is described in Figure 4.11.

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[56] Where service providers show a speed range, the highest speed is shown.

[57] No specific Com Hem business services marketed.

Figure 4.11: HFC technology roadmap [Source: Analysys Mason, 2015]

	2000	2005	2010	2015	2020	2025

Evolution of the active layer

▲ DOCSIS 3.0

▲ DOCSIS 3.1

Max D/L capacity per user[1]	50Mbit/s	200Mbit/s	500Mbit/s	1Gbit/s	10Gbit/s
Max U/L capacity per user[1]	10 Mbit/s	20 Mbit/s	50 Mbit/s	100Mbit/s	2Gbit/s

[1] This is the aggregate capacity per node and is shared between end users

Key

The shaded boxes indicate the expected start year of deployment, with an approximate end year(s).

▲ Time of standards ratification

It should be noted that the above HFC roadmap is not necessarily representative of the market in Australia, but is provided as a generic guide to what we will expect worldwide.

4.4.1 DOCSIS 3.1

Key features

The key features and improvements to the existing DOCSIS 3.0 specification highlighted by CableLabs are in the areas of:

- *Bandwidth* – ultimately support for 10Gbit/s downlink and 1Gbit/s uplink services.

- *Quality of experience* – reduction in network latency in the cable access network by implementing active queue management, which is intended to improve responsiveness for applications that require low latency, such as online gaming.

- *Higher capacity* – more efficient data encoding algorithms offer the potential to increase the data transmission capacity by up to 50% using the same spectrum. The available capacity can be extended further by using the additional spectrum defined by the DOCSIS 3.1 specification.

- *Flexible migration strategy* – DOCSIS 3.1 equipment is designed to co-exist with older DOCSIS versions, enabling DOCSIS 3.1 to be introduced incrementally in line with market demand.

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- *Energy efficiency* – DOCSIS 3.1 protocols have been implemented to increase the energy efficiency of cable modems.

By working closely with technology suppliers, CableLabs has also attempted to reduce the period between release of the specification and the availability of the first products in the marketplace. There have been recent indications that both Comcast and Liberty Global, major players in USA and Europe will launch DOCSIS 3.1 services during 2016.[58]

Work on the DOCSIS 3.1 specification has focused on developments in two key areas in the physical layer related to increasing the bandwidth supported by the network:

- *Frequency planning* – the spectrum allocated to uplink and downlink bandwidth is increased.

- *Data encoding* – the introduction of OFDM encoding provides an environment for increasing the bandwidth for a given amount of spectrum.

DOCSIS 3.1 also provides improvements above the physical layer covering control of the use of OFDM encoding, enhancements to OFDM and SC-QAM channel bonding, QoS implementation and data traffic queue management, to help reduce network delay. It also introduces improved cable modem energy management to reduce the amount of power required by the cable modem when it is in idle mode.

Downlink bandwidth

DOCSIS 3.1 specifies a *normal* downlink frequency range of 54–1002MHz, which is similar to the 50–1002MHz range defined in DOCSIS 3.0 (with an upper limit of 862MHz for EuroDOCSIS). However, DOCSIS 3.1 also includes *extended* ranges, with lower downlink edges of 108MHz and 258MHz and upper downlink edges of 1218MHz and 1794MHz. The larger lower downlink edge values enable the spectrum allocated to uplink bandwidth to be increased, while the higher upper downlink edge values significantly widen the spectrum available for downlink services. The frequency range edges are summarised in Figure 4.12.

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[58]   http://www.lightreading.com/cable/docsis/docsis-31-enables-rapid-deployment-of-gigabit-broadband/a/d-id/716814?itc=lrnewsletter_cabledaily

Figure 4.12: Options for DOCSIS 3.1 downlink frequency range [Source: Analysis Mason, 2015]
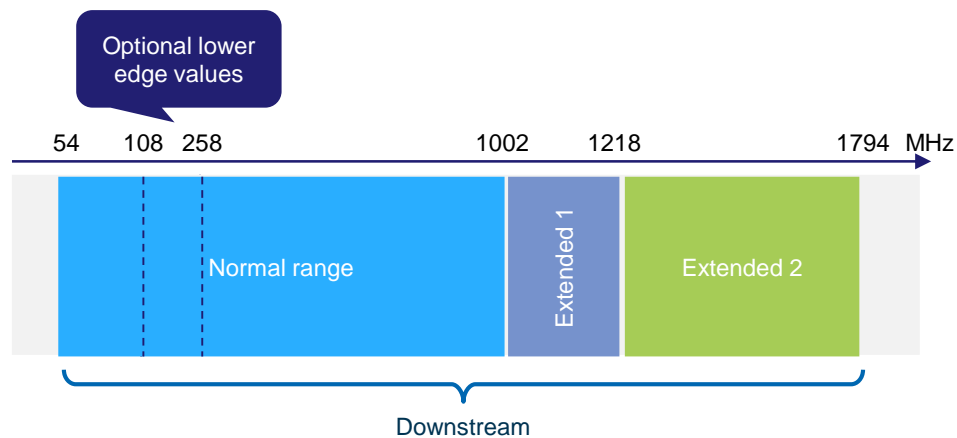
The DOCSIS 3.1 downlink channel spacing can be between 24 and 192MHz, which provides significantly larger channels than the 8MHz used in EuroDOCSIS 3.0. A minimum of two independently configurable channels must be supported by the CMTS and the cable modems that use DOCSIS 3.1-based services.

Uplink bandwidth

DOCSIS 3.1 specifies a normal uplink frequency range of between 5MHz and either 42MHz or 65MHz, as compared to between 5MHz and either 42MHz or 85MHz for DOCSIS 3.0 (or 65MHz for EuroDOCSIS). The 85MHz value now becomes one of the uplink upper-edge options in the extended operating range (other options being 117MHz and 204MHz), as shown in Figure 4.13 below. The higher upper-edge options provide the opportunity to significantly increase the uplink bandwidth supported. Each uplink channel can occupy up to 96MHz, with the CMTS and the cable modem needing to support a minimum of two channels.

Figure 4.13: Options for DOCSIS 3.1 uplink frequency range [Source: Analysis Mason, 2015]
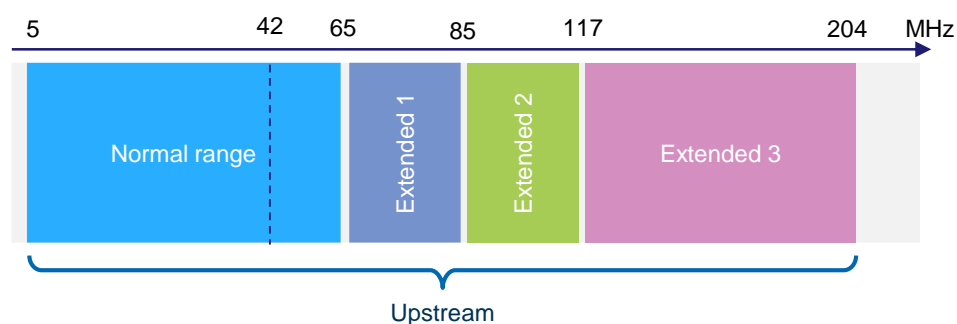
PHY layer data encoding

The DOCSIS 3.0 PHY layer is based on SC-QAM operation, and this capability is carried forward into DOCSIS 3.1 to maintain backwards compatibility with DOCSIS 3.0. However, DOCSIS 3.1

also introduces OFDM into the PHY layer, which provides the potential for more efficient encoding, and hence higher data bandwidth.

OFDM has a number of advantages over a single-carrier approach, including:

- Greater robustness to interference (including specific external sources) – as there is greater potential to control the signal at a subcarrier level to avoid interference.

- Better operation in low-SNR environments – the introduction of more advanced encoding techniques to enable more efficient and robust use of the spectrum.

- Greater flexibility in spectrum allocation – because OFDM involves smaller incremental subcarriers and provides the ability to adjust the overall channel size, it offers more flexibility in how the spectrum is used.

- Improved spectrum efficiency – the higher encoding rates enabled by the use of OFDM and low-density, parity-check, forward error correction, rather than the Reed-Solomon forward error correction used in DOCSIS 3.0, will improve spectrum efficiency.

Flexibility of DOCSIS 3.1 to meet evolving service demands from end-users

In practice, the larger channel widths of DOCSIS 3.1 will mean that a 'bigger IP pipe' is available for the delivery of converged IP services to end-users, compared to the more constrained environment of DOCSIS 3.0. This is likely to accelerate the convergence of all services over IP, including the deployment of IPTV over DOCSIS (VDOC).

While DOCSIS 3.1 will provide a more flexible and improved system for the delivery of services, it is likely to take some time to come to fruition. Industry sources we have spoken to foresee a long period of parallel running of DOCSIS 3.0 channels alongside DOCSIS 3.1 channels, both in the uplink and downlink direction. They see a full migration to an all-IP infrastructure as a long and expensive task, requiring the replacement of end-user equipment and an upgrade of applications and content platforms and processes.

4.4.2 Beyond DOCSIS 3.1

The DOCSIS 3.1 specification was released in October 2013, after a significant amount of intense development work. Since that time the prime focus has been on developing products to meet the requirements of DOCSIS 3.1.

It should be noted that as well as implementing the DOCSIS 3.1 specification, cable operators have the opportunity to introduce architectural changes to the network, such as:

- implementing M-CMTS/D-CMTS to introduce new modulation schemes to increase the bandwidth available

- node splitting, and deploying fibre closer to end-users, to reduce the number of premises that share the same spectrum
- deploying new IP- or fibre-based access technologies in specific 'high-traffic' locations, thus further developing the HFC network architecture to meet end-user demand.

The third option includes new developments such as DOCSIS Ethernet over coax (DOCSIS EoC), Ethernet passive optical network (EPON) protocol over cable (EPoC), and radio frequency over glass (RFoG). However, these all involve significant capital investment in civil infrastructure and are therefore less likely to be implemented in the short term.

The rapid development of DOCSIS 3.1 and earlier releases of the DOCSIS specification demonstrate that the industry is capable of evolving and developing the features needed to keep pace with end-user demand.

We also note that as the coaxial access network (currently the bottleneck) is continually improved through the upgrades detailed above, the limiting factor will begin to move towards the core network. An example of this may be the limiting factors associated with fibre backhaul from the optical node to the local head-end. Current optical transmission technologies in the HFC network use analogue amplitude modulation, which could, for example, be upgraded to digital optical transmission technologies such as broadband digital return (BDR), to improve SNR performance within the network and allow the use of even higher modulation schemes.[59]

4.5 Ability of HFC technology to meet evolving bandwidth demand

This section examines the uplink and downlink capability of DOCSIS 3.0 and DOCSIS 3.1 technology and how this relates to the headline bandwidth that can be offered and the sustained bandwidth that can be supported by the network.

4.5.1 Sharing of broadband spectrum among end-users

Headline bandwidth

The bandwidth available using the spectrum allocated to broadband services needs to be converted to a headline bandwidth offered to an end-user. In examples we have seen, the headline bandwidth offered to end-users typically equates to between one quarter and one half of the total bandwidth available in the system. This figure can depend on:

- **Type of service** – a higher bandwidth may be offered to business end-users that use the network during the day. This can happen where the bulk of the end-users are residential and many of them do not use the service during the day: business end-users therefore face less contention in the network.

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[59]   *Examining the Future Evolution of the Access Network*, ARRIS, 2013.

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- **Positioning of service** – operators can decide to either attach greater importance to the value of peak bandwidth an end-user can achieve or the consistency with which it can achieve its sustainable bandwidth. If it is the former, it will offer higher-bandwidth packages, but the maximum bandwidth may not be available at peak usage periods. If it is the latter, then the operator will offer lower-bandwidth packages, but with a higher likelihood that the bandwidth can be achieved at peak usage periods.

As an example of how the bandwidth available may relate to headline speeds offered, consider the following operator's network configuration. It has 16 bonded channels using 256-QAM (an available bandwidth of over 800Mbit/s), and offers 500Mbit/s services to businesses that use the network predominantly during the day and 200Mbit/s services to residential end-users. The operator prefers to offer bandwidths that have a reasonably high likelihood of being achieved at peak times.

4.5.2 Achievable downlink headline bandwidth

DOCSIS 3.0 heralded a significant increase in both uplink and downlink bandwidth by allowing bonding of the 8MHz RF channels used for broadband delivery. The bandwidth of an operator's DOCSIS 3.0 downlink channel is dependent upon both the number of channels that are bonded and the modulation scheme employed, for example, eight bonded 8MHz RF channels using 256QAM will provide circa 400Mbit/s (i.e. eight channels at 51Mbit/s using 256QAM = ~400Mbit/s). The bandwidth available in each RF segment for different DOCSIS 3.0 and 3.1 configurations is shown in Figure 4.14.

Figure 4.14: Available bandwidth for different DOCSIS downlink configurations [Source: Analysys Mason, 2015]
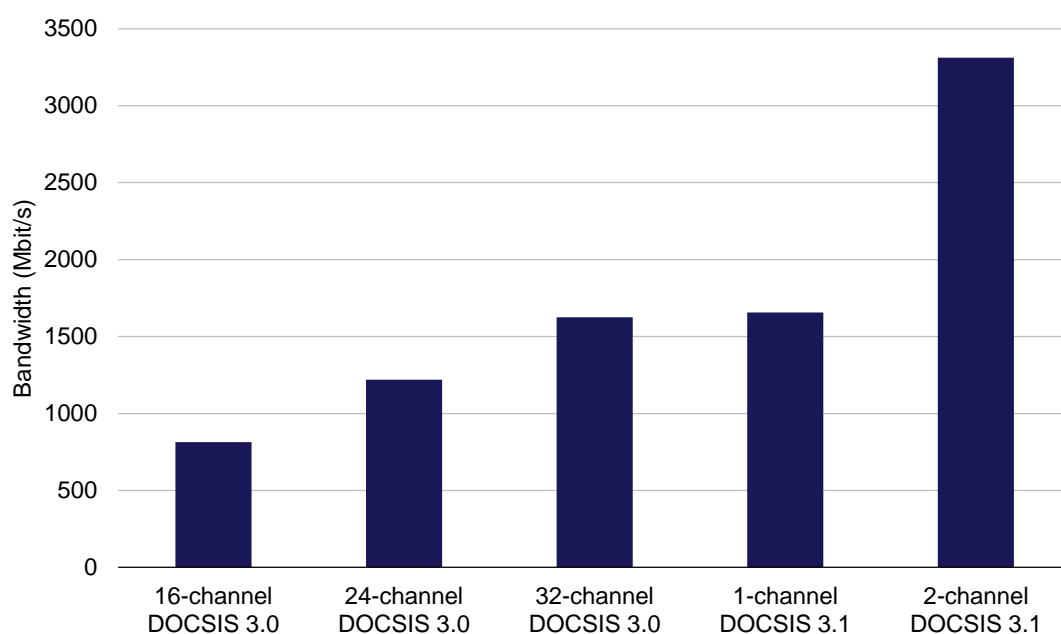
The figures assume 256-QAM encoding for DOCSIS 3.0 and 192MHz channels for DOCSIS 3.1 with 1024-QAM encoding.

As stated in Section 4.5.1, cable operators will not usually offer downlink bandwidth equal to the whole of the bandwidth available in the RF segment, but more usually 25% or 50%. Figure 4.15 and Figure 4.16 show how the different DOCSIS configurations will be able to support the required bandwidth demand identified in Section 3.5.2 for the top 1% of users in Australia.

Figure 4.15: Comparison of downlink bandwidth demand estimates for top 1% of end-users with bandwidth provided by different DOCSIS configurations (50% of total bandwidth) [Source: Analysys Mason, 2015]
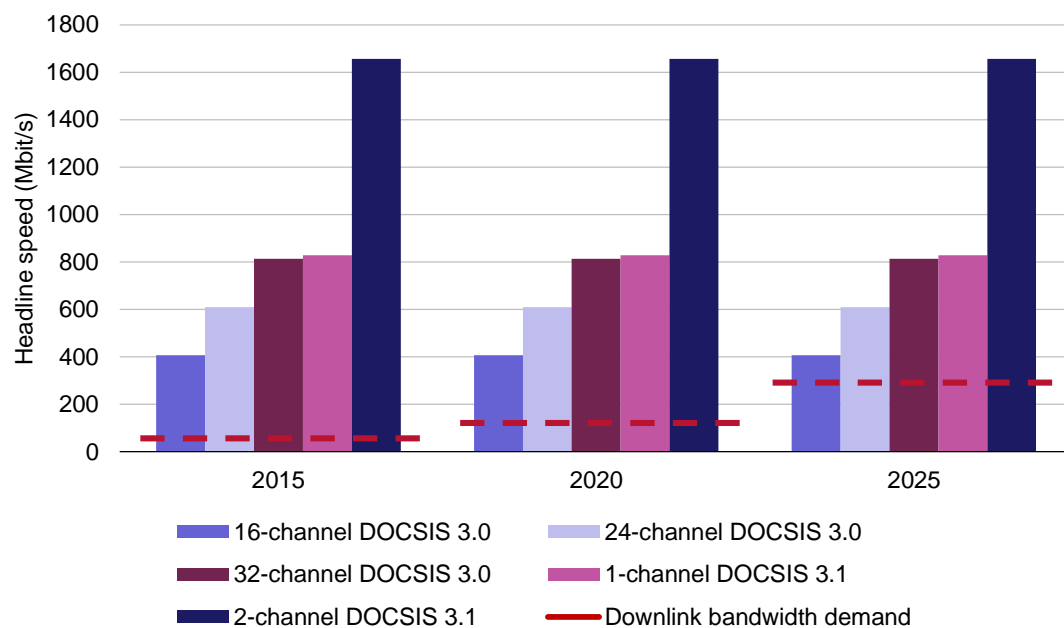
Figure 4.16: Comparison of downlink bandwidth demand estimates for top 1% of end-users with bandwidth provided by different DOCSIS configurations (25% of total bandwidth) [Source: Analysys Mason, 2015]
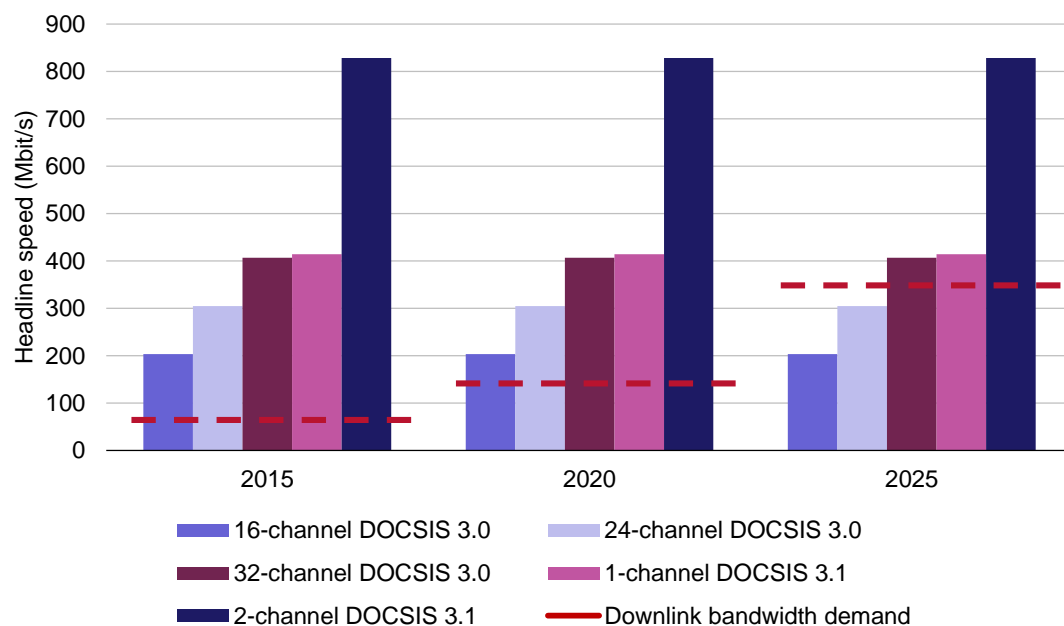
If operators were to offer services to the top 1% of their end-users with a headline bandwidth of 50% of the segment bandwidth, then all the DOCSIS configurations listed will meet traffic requirements up to 2025. If only 25% of the segment bandwidth is offered, then both the 16- and 24-channel DOCSIS 3.0 versions will be insufficient by 2025. However, there are options available to upgrade the network to 32-channel DOCSIS 3.0 or the deployment of DOCSIS 3.1 would be able to overcome this issue.

If international market competition considerations are taken into account, then it may become necessary to be able to offer a 1Gbit/s service by 2025. This is likely to require the deployment of two DOCSIS 3.1 192MHz bonded channels, which is feasible given the implementation of a suitable network upgrade programme. However, it should be noted that if services are offered to businesses with guaranteed bandwidth at all times, this will also need to be considered in assessing the peak downlink bandwidth that can be offered to all end-users.

4.5.3 Achievable uplink data bandwidth

As with the downlink channel, the bandwidth of an operator's DOCSIS 3.0 uplink channel is dependent upon both the level of channel bonding and the modulation scheme employed. The bandwidth available in each RF segment for different DOCSIS 3.0 and 3.1 configurations is shown in Figure 4.17.

Figure 4.17: Available bandwidth for different DOCSIS uplink configurations [Source: Analysys Mason, 2015]
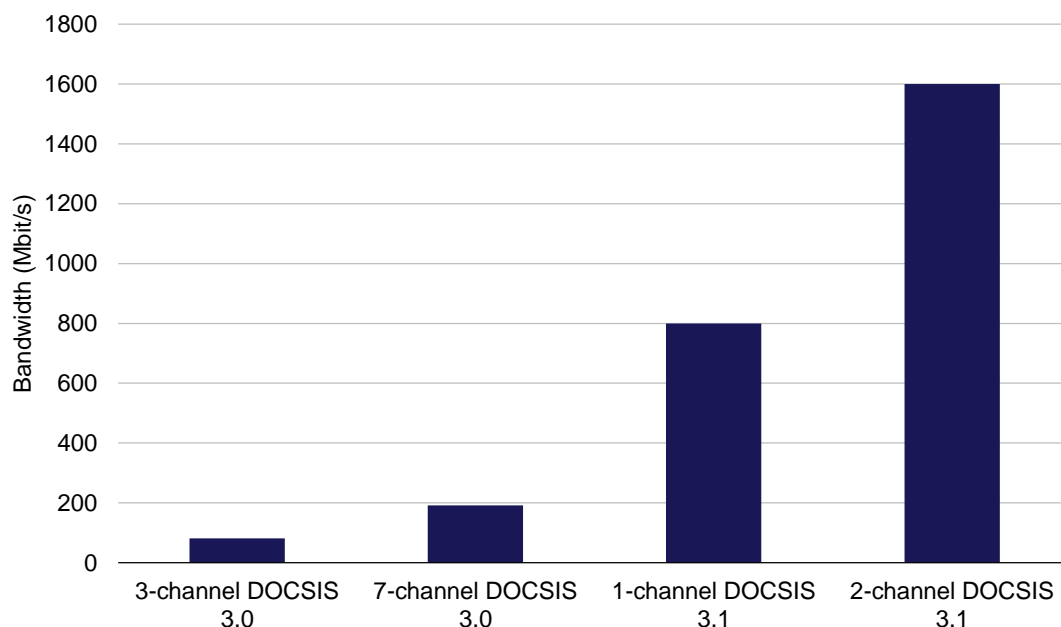
The figures assume 64-QAM encoding for DOCSIS 3.0 and 96MHz channels with 256-QAM encoding for DOCSIS 3.1.

As discussed in Section 4.5.1, cable operators will not usually offer downlink bandwidth equal to the whole of the bandwidth available in the RF segment, but more usually 25% or 50%.

Figure 4.18 and Figure 4.19 show how the different DOCSIS configurations will be able to support the required headline bandwidth described in Section 3.5.2 for the top 1% of households in Australia, assuming the uplink bandwidth offered is one-fifth of the downlink bandwidth.

Figure 4.18: Comparison of uplink bandwidth estimates for top 1% households with DOCSIS configurations (50% of total bandwidth) [Source: Analysys Mason, 2015]
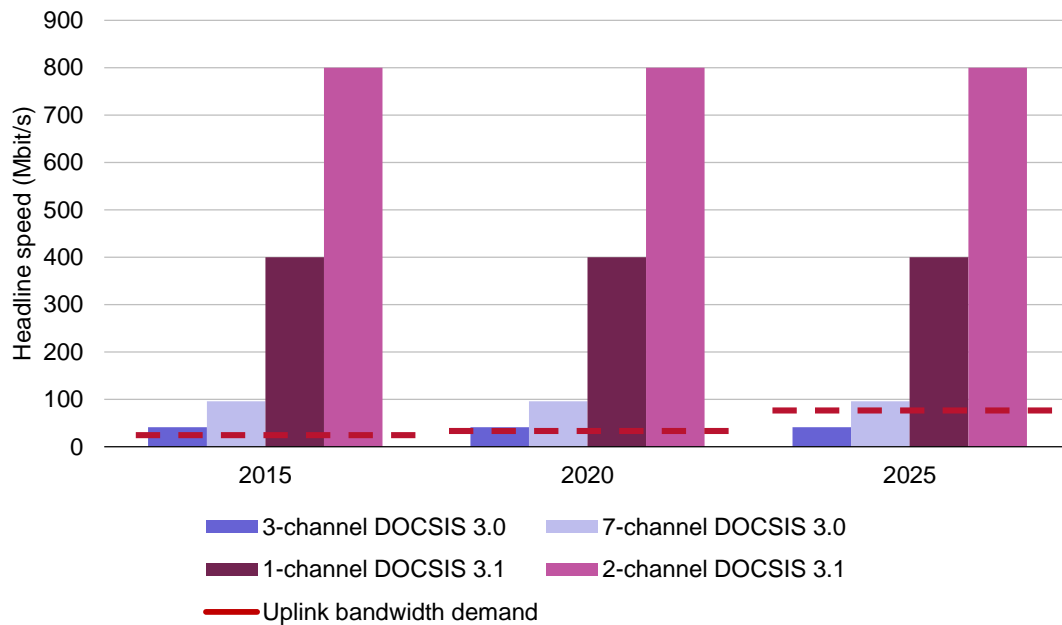
Figure 4.19: Comparison of uplink bandwidth estimates for top 1% of households with DOCSIS configurations (25% of total bandwidth) [Source: Analysys Mason, 2015]
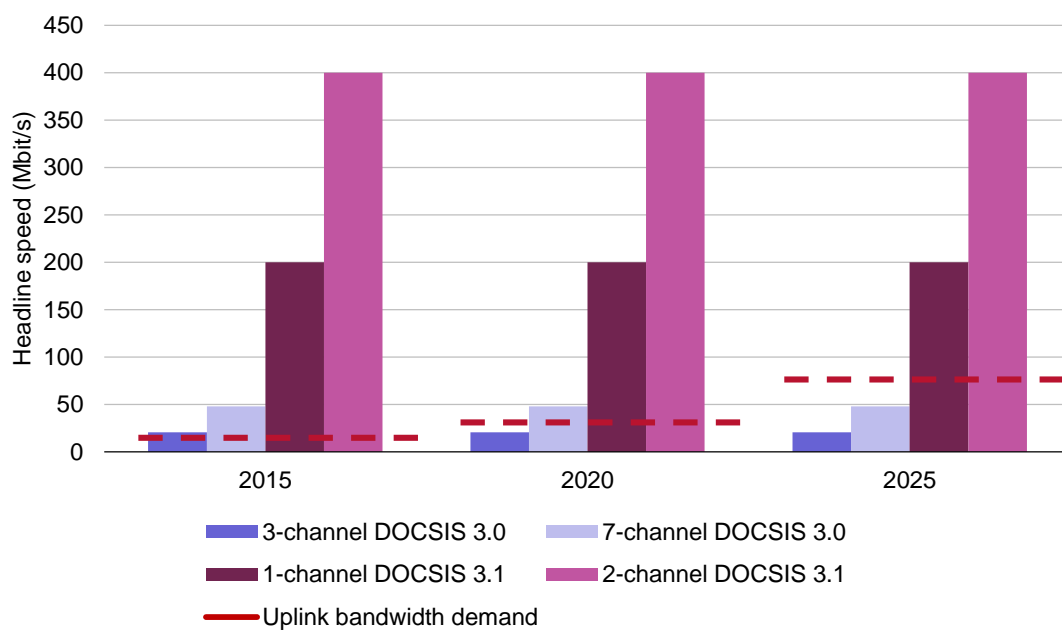
If operators were to offer services to the top 1% of their end-users with a headline bandwidth of 50% of the segment bandwidth available then all the DOCSIS configurations listed will meet traffic requirements up to 2025 except for the three-channel DOCSIS 3.0 version, which is only planned to be offered by nbn during the transition to nbn ownership in any case. If only 25% of the segment bandwidth is offered, then both three- and seven-channel DOCSIS 3.0 versions will be insufficient by 2025. Deployment of a DOCSIS 3.1 96MHz channel and a change in the uplink/downlink frequency will be required to serve the top 1% of end-users by 2025. It should be noted that the implementation of a DOCSIS 3.1 uplink channel will require expansion of the uplink bandwidth, which is a significant upgrade as described in Section 4.6.2.

If international market competition considerations are taken into account, then it may become necessary to be able to offer a 200Mbit/s uplink service by 2025 (assuming a 1Gbit/s downlink service and maintaining a downlink-to-uplink ratio of 5:1). This can also be supported by the deployment of a DOCSIS 3.1 96MHz bonded channel. However, it should be noted that if services are offered to businesses with guaranteed bandwidth at all time, this will also need to be considered in assessing the peak uplink bandwidth that can be offered to all end-users.

4.6 Operational considerations for technology upgrades

HFC operators have a number of options for upgrading their networks to increase the broadband service bandwidth available to end-users. Upgrades can include changes of network configuration while maintaining DOCSIS 3.0, the introduction of parts of the DOCSIS 3.1 specification and the introduction of D-CMTS. The actual network upgrades that an HFC operator might undertake will depend on the current configuration of the network and what the operator hopes to achieve from the upgrade.

This section describes each of the potential network upgrade options and examines the benefits, and challenges of introducing each option.

4.6.1 DOCSIS 3.0 upgrades

A number of potential upgrades can be made to a DOCSIS 3.0 HFC network to maximise broadband service bandwidth, prior to the upgrade to DOCSIS 3.1:

- reducing the number of homes per fibre node (node splitting)
- increasing the use of channel bonding
- extending the spectrum width, to a limited extent
- reallocating existing spectrum.

Reducing homes per node/node splitting

Reducing the number of households served by a single combined spectrum coverage area (by reducing the size of the optical node's catchment area) increases the capacity available for each

customer premises, as a smaller number of customer premises are able to share the same amount of aggregate bandwidth.

Broadband services are combined with other services via the RF combiner at the local FAN site, with a unique integrated broadband data stream i.e. integrated multiple broadband channels, formed for each optical node. The data capacity of the available DOCSIS channels is therefore shared between all the active users beyond the optical node. Under a typical HFC network architecture, as shown in Figure 4.20, the optical node generally serves between 250 and 1500 households.

Figure 4.20: HFC architecture prior to node splitting [Source: Analysys Mason, 2015]
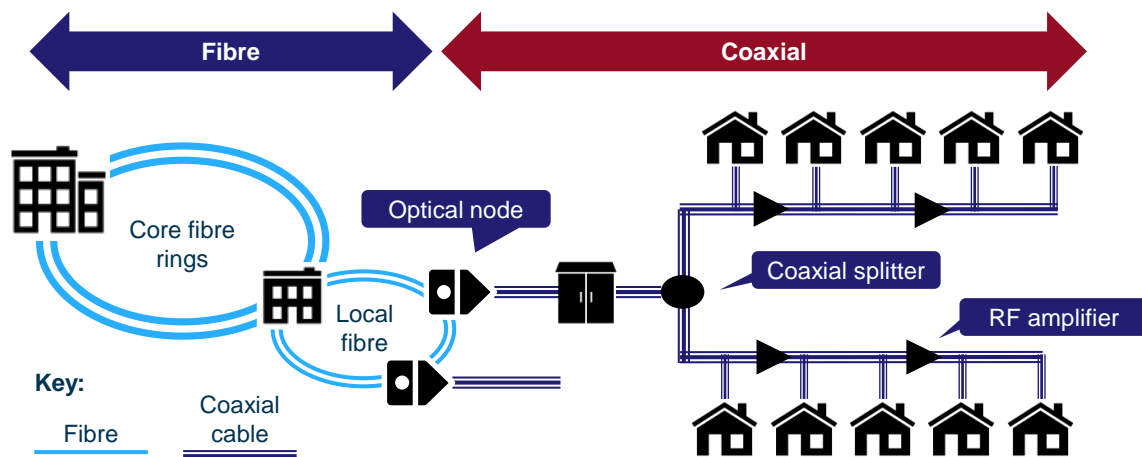
The best and often implemented way to reduce the number of customer premises per optical node is to split the node. This is achieved by replacing a single optical node with two nodes, each of which serves a subset of the original node's customer premises, as shown in Figure 4.21. Each of these two new sub-networks has the same equivalent number of available DOCSIS channels as the original single sub-network, but this bandwidth serves fewer customer premises. Additional fibre will also be required to connect to the new optical node.

Figure 4.21: HFC architecture following node splitting [Source: Analysys Mason, 2015]
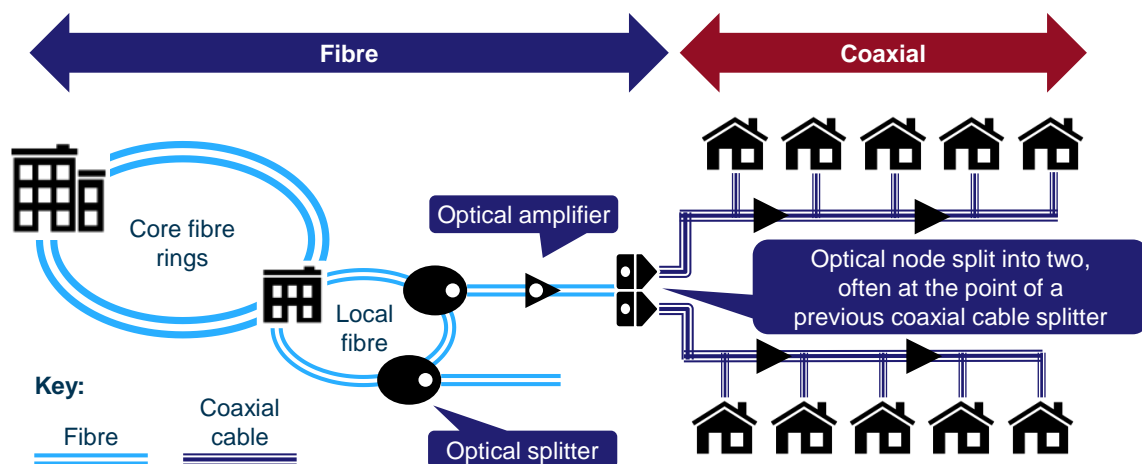
Optical nodes can be split by installing a new node alongside the existing node and sharing the premises that each serves or by adding new optical nodes deeper into the network towards the customer premises, such as at an RF splitter location. The process of node splitting can continue into the access network towards the customer premises, addressing smaller and smaller groups of customer premises. Generally, these split nodes occur at points in the network where previous active electronic components were present, due to the pre-existence of a power source and street furniture (cabinet, manhole, chamber, etc.) at these locations. The logical end point for node splitting occurs when the fibre path is extended to the last active piece of equipment within the coaxial chain, i.e. the last repeater prior to any group of households. This is referred to as 'deep fibre', or node plus zero (N+0), as shown in Figure 4.22, with optical nodes serving approximately 50–150 customer premises.

Figure 4.22: HFC architecture following N+0 deep fibre deployment [Source: Analysys Mason, 2015]
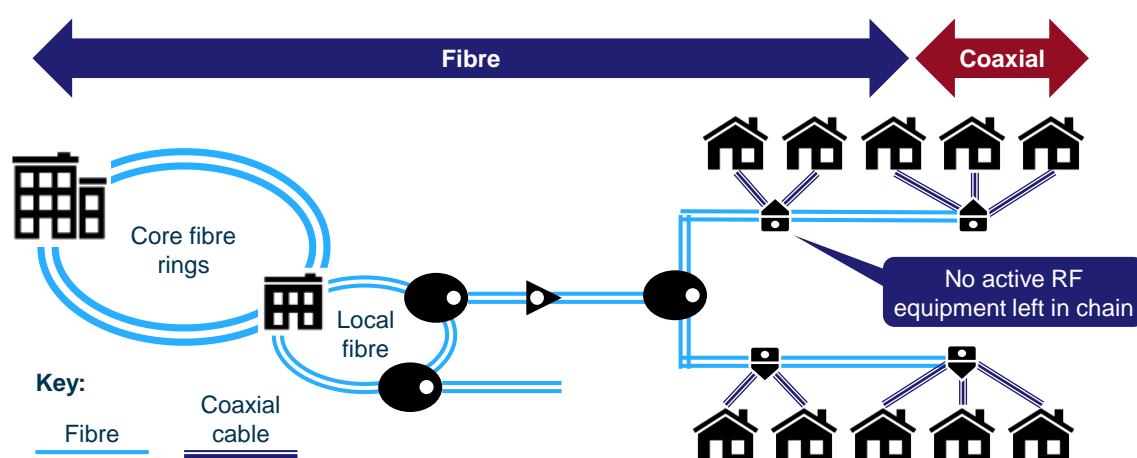
The roll-out of fibre deeper into the network leads to a reduction in complexity of the HFC network, often producing power and maintenance cost savings. This is because greater signal attenuation occurs in coaxial cable than in fibre, requiring a larger number of amplifiers over a set distance. Furthermore, as mentioned before, each amplification of the RF signal adds new noise to the signal, and more significantly, amplifies any existing noise which has accumulated over its prior journey. Therefore, a deeper fibre network can lead to better SNR properties, potentially allowing for increased QAM rates (especially on the uplink) and reducing consumer connectivity issues related to noise.

This type of upgrade is independent of DOCSIS versions and does not need any additional CPE or changes to customer premises. However, it does require new optical nodes and will need fibre extensions to replace the coaxial cable and new power sourcing if the optical node is moved to a new location closer to the customer premises. New CMTSs, which may be in the form of D-CMTS (see Section 4.6.3), are also likely to be required as this functionality is moved closer to the customer to allow higher modulation schemes to be used.

Increasing the use of channel bonding

Increasing the number of bonded channels provides both efficiency gains and improvements in headline bandwidth. As such, increasing the level of channel bonding is an obvious step for operators in dealing with increased data traffic demand.

Although any number of channels can technically be bound together, the network equipment must be able to support the number of channels bound at both the CMTS and cable modem to ensure successful transmission at that number of channels. However, the system will still operate if a cable modem (or CMTS) is unable to encode/decode the total number of channels bonded, with data transmission occurring at the maximum number of channels that both pieces of equipment are able to support. Furthermore, the number of uplink channels that can be bonded will be limited by the maximum size of the uplink (e.g. seven 6.4MHz channels for DOCSIS 3.0).

It is possible to upgrade the CMTS or cable modem independently, for example during a typical CPE refresh cycle, without significantly degrading the quality of the network. However, this can cause load balancing losses, as any cable modem that is unable to support larger bonded channels will be unable to use the top channels of a bonded data stream.

Increasing the number of 8MHz RF channels to 24 or 32, for example, will significantly increase available bandwidth and could delay the need to invest in DOCSIS 3.1. However, this approach is dependent on access to sufficient spectrum within the existing total HFC spectrum band (considering spectrum required for other services such as TV) to support the increased number of broadband channels.

Limited extension of the spectrum width (within DOCSIS 3.0 bounds)

Another key method for increasing bandwidth in both uplink and downlink directions is to increase the width of the total spectrum band used, and so increase the number of available channels.

This is limited under DOCSIS 3.0 to an upper bound of 862MHz. However, for some operators which currently only use spectrum to a lower upper bound limit, this can be a relatively easy upgrade (as it falls within current equipment operating specifications), and may only require the replacement of a limited amount of legacy equipment within the network. However, for other operators where the upper limit is beyond existing equipment cut-off frequency operating specifications, a significant upgrade would be required (notably for replacing all amplifiers and taps).

The extension of uplink spectrum is not supported beyond 65MHz under EuroDOCSIS 3.0, but given that equipment is frequently co-designed for both DOCSIS and EuroDOCSIS deployment it may be relatively easy to extend the uplink spectrum as DOCSIS equipment supports up to 85MHz in the upstream direction.

Reallocating existing spectrum

In some circumstances, it may make sense to increase the spectrum allocated to a specific service at the expense of another less widely used service. Assuming the spectrum is currently used by multiple services, the number of channels used by any particular service can easily be increased, at the expense of another (less utilised) service, as shown in Figure 4.23. As a result, one of the major considerations for a modern cable operator is the relative proportions of spectrum to dedicate to each of its services.

In some countries, the switch-off of analogue TV can free up significant amounts of RF spectrum, which can be reallocated to other services. However, this would not be an option in Australia as no analogue TV services remain in the Australian cable networks.

Figure 4.23: Service trade-offs on RF spectrum [Source: Analysys Mason, 2015]
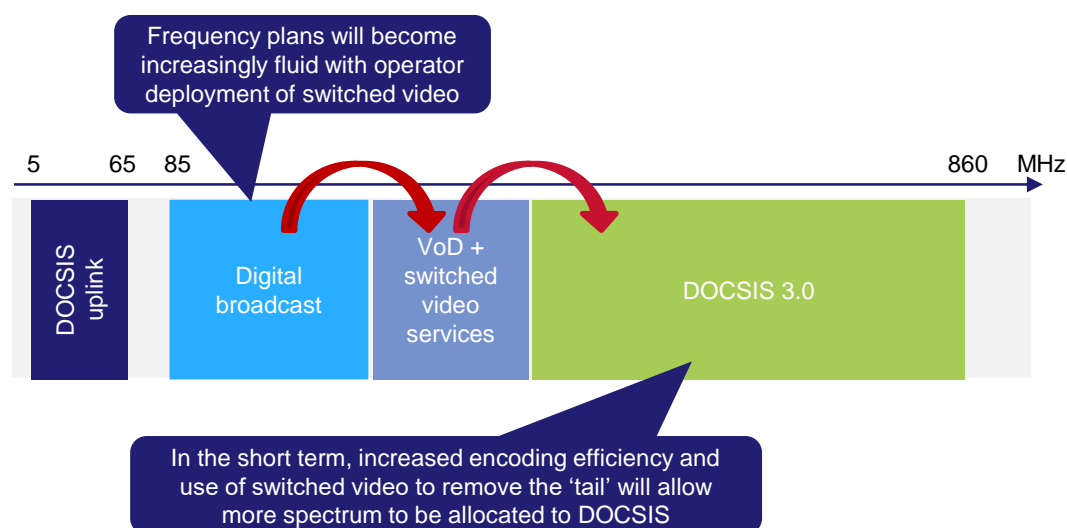
Following the removal of analogue services, operators are seeing growing demand for TV driven by an increasing number of HD digital channels and narrowcast VoD services, leading to an increase in the spectrum used for digital TV. If operators improve the efficiency of their TV service provision, they can make additional spectrum available for data services (as well as reducing the need to make a 'one or the other' choice between the services). The main methods for increasing digital TV spectrum efficiency are using more efficient encoding technologies e.g. moving from MPEG2 to MPEG4 and moving to new transmission methods such as switched video services that only allocate space to TV channels that users are watching at any point in time.

4.6.2 DOCSIS 3.1 upgrades

A cable operator could implement a number of potential upgrades relating to DOCSIS 3.1:

- moving to OFDM channels and undertaking OFDM channel bonding
- extending the spectrum width
- introducing new MAC-level features

- introducing D-CMTS.

Although we consider these upgrades independently, it is likely that more than one of them would be implemented simultaneously as part of a programme to introduce DOCSIS 3.1 functionality.

However, it should also be remembered that while there is significant potential for network capacity expansion in the DOCSIS 3.1 specification, it is likely that legacy DOCSIS 3.0 cable modems will need to be supported for some considerable time. Therefore, spectrum will need to be reserved for DOCSIS 3.0-compatible services, which could limit the potential for rolling out DOCSIS 3.1 services, where there are spectrum constraints. Managing the use of spectrum will be a key issue for cable operators, although to some extent this can be addressed by extending the spectrum available as defined in the DOCSIS 3.1 specification.

Moving to OFDM channels and undertaking OFDM channel bonding

As detailed in Section 4.4.1, DOCSIS 3.1 channels are based on OFDM rather than SC-QAM. As such the move to DOCSIS 3.1 allows for the introduction of new OFDM channels, alongside existing SC-QAM channels. Further benefit can be gained from OFDM channels being bonded with existing SC-QAM channels ('OFDM to SC-QAM'), similar in principle to SC-QAM-to-SC-QAM channel bonding under DOCSIS 3.0. Once an operator has deployed multiple OFDM channels on its spectrum, multi-channel OFDM-to-OFDM bonding can also be introduced, which will provide even more capacity.

Introducing OFDM and channel bonding with SC-QAM provides more capacity by more efficient use of spectrum as OFDM is capable of more 'bits per Hz'. As with all DOCSIS 3.1 implementations, upgraded or new CMTS and cable modem equipment will be needed and spectrum will need to be available.

Extending the spectrum width (within DOCSIS 3.1 bounds)

Another key method for increasing bandwidth in both uplink and downlink directions is to increase the width of the spectrum band used, and so increase the number of available channels. However, the availability of this option can be limited by the current set-up of equipment within the network, and so may require significant network investment to derive the full benefit.

► *Uplink band frequency expansion*

One of the limitations of cable broadband compared to other technologies (such as DSL or mobile broadband) is the higher degree of asymmetry and the limitations on relative uplink versus downlink bandwidth. Significant effort has been made by the standards bodies recently to consider methods for increasing uplink bandwidth. Given the limited potential for cable operators to re-allocate their uplink spectrum usage (given its minimal size and the fact that the majority of their spectrum is already allocated to DOCSIS) and implement channel bonding on the uplink band, the operators have been focusing on increasing the uplink band edge above 65MHz.

Two key uplink band extensions are discussed by operators and vendors: mid-split (5–85MHz) and high-split (5–200MHz). However, expansion of the uplink spectrum under each option is complicated by the following factors:

- *Inappropriateness of current filters* – currently, many of the active components in the network, such as amplifiers and optical nodes, use diplex filters to separate the downlink and uplink signals prior to amplification/transmission. The current cut-off frequencies within the diplex filter are fixed at the time of installation, so these filters would need to be adjusted to deal with a higher-frequency split between uplink and downlink components. We note that while modern equipment is already designed with easily replaceable filter modules, older active equipment (with integrated diplex filters) will need to be replaced entirely.

- *Lack of current specifications* – while DOCSIS 3.0 already allows for uplink frequency of up to 85MHz, no provision exists in EuroDOCSIS 3.0 for an uplink band beyond 65MHz. However, within DOCSIS 3.1 an uplink band maximum of 208MHz is possible.

- *Legacy frequency issues* – significant amounts of legacy CPE may require replacement, to prevent them from interfering with (or receiving interference from) uplink transmissions on unexpected channels. For example, the out-of-band control channel (used for programme guides and cable card control on STBs) is generally located between 70MHz and 130MHz, so would interfere with the uplink band. To change this channel would require the replacement of many STBs within a network. This may also have an impact on the choice of deployment strategy (i.e. whether to upgrade all customer premises in a node at the same time or on a premises-by-premises basis).

Downlink band frequency expansion

While there are other methods for increasing the available bandwidth for cable networks in the downlink, an increase in spectrum is still an important factor. An increase in downlink bandwidth, under DOCSIS 3.1, implies an increase in the overall RF frequency band above 862MHz (the limit for DOCSIS 3.0) – generally either to a new 1214MHz downlink upper boundary or ultimately to a higher 1794MHz downlink upper boundary.

In addition to similar issues to those detailed above for the uplink band, the downlink band will suffer issues related to the use of frequencies higher than those for which the network was designed. This can lead to three main issues:

- Cable networks will generally have been designed with particular frequency attenuation characteristics in mind (given the spectrum specifications of the network). As higher frequencies are used the level of attenuation may increase to an extent that cannot be addressed by increasing the amplification at existing amplifiers, but requires the addition of new amplifiers with a shorter spacing along the cable (and hence a potentially costly network redesign). These issues will be particularly prevalent in a network upgrade to 1794MHz upper boundary.

- RF passive equipment (such as splitters and taps) is designed with specific operating frequency limits in mind, and increasing the upper frequency bound above 1214MHz is likely to lead to issues when operating outside the design limits, especially in cable taps. It would be a costly undertaking to replace these taps, given the large number in the network (approximately one tap for four customer premises).

- As the frequencies used in cable networks are expanded there is likely to be an increase in the number of high-power wireless bands with which cable networks share frequencies. For example, increasing the upper frequency bound of a network to 1214MHz would require a crossing of the 900MHz band, which is typically used for mobile networks worldwide.

4.6.3 Introducing D-CMTS

The introduction of D-CMTS reduces the importance of the local head-end, and means that operators only have to convert once from RF to optical signals (whereas the current system involves converting both at the optical node and within the head-end). This reduces signal losses and allows higher modulation schemes to be deployed. The fibre feeder between the local head-end and the fibre node now becomes a digital link which is able to support standard Ethernet interfaces, typically 1Gbit/s and 10Gbit/s. The actual benefit of moving from an RF to a digital fibre feeder will depend on the length of the fibre feeder, with shorter fibre feeders experiencing lower signal loss and hence less benefit from moving to a digital fibre feeder. However, an RF fibre feeder can typically account for half or more of the signal transmission power loss and so has a strong impact on the level of encoding supported.

The move to a D-CMTS architecture can be achieved using DOCSIS 3.0 technologies, but the maximum benefit is gained in a DOCSIS 3.1 environment, because the reduced SNR profile allows a significant increase in the modulation scheme up to 4096-QAM (whereas this is limited by the DOCSIS 3.0 specification to a maximum of 256-QAM).

It should be noted that the move to a D-CMTS architecture could also be undertaken as part of a deep-fibre (or N+0) architecture deployment, creating smaller fibre nodes.

The introduction of D-CMTS will move CMTS encoding to the fibre node. This will have benefits but there are some barriers to introduction, as such deployments require a significant upgrade.

4.7 Conclusions

HFC networks provide leading broadband services today and have the future roadmap to be able to support end-users' requirements well into the future. When required, cable operators have a number of options for increasing capacity in their broadband network. They vary from those that can be implemented on today's networks, to those that require the implementation of DOCSIS 3.1 and/or require significant network investment.

The upgrade path chosen by a particular operator will depend on a combination of:

- current network configuration
- end-user demand for increased bandwidth and sustained bandwidth, as well as the need to respond to competitive pressures
- availability of cost-effective DOCSIS 3.1 products
- availability of funds and appetite for capital investment
- desire to move to an IP-oriented service execution environment.

Each operator's particular priorities will govern which activities it undertakes and the order in which they are implemented. Our understanding is that cable operators' focus is now shifting from a strong emphasis on overall peak bandwidth (as has been the case over the last five years or so), to an increased focus on data transmission efficiency, to meet the expectations of significant future traffic growth (i.e. maximising the amount of data that can be transmitted to consumers on each node).

Given this focus, and the methods available for increasing data capacity, we believe DOCSIS 3.0 will remain a dominant presence for the next five years, before the additional encoding efficiency available from DOCSIS 3.1 (combined with natural equipment replacement cycles) allows operators to switch technologies in a cost-efficient manner.

5   Review of nbn's methodology and processes for MTM network selection

The Australian Government's SoE gives nbn a mandate to design and deploy an MTM NBN. Although the Australian Government's direction to nbn provides nbn with flexibility regarding technical, operational and network design decisions to implement the network, it expects nbn to:

- Deliver the network within the constraint of a public equity capital limit of AUD29.5 billion specified in its funding agreement with the Australian Government and the Australian Government's broadband policy objectives.

- Determine which technologies are utilised on an area-by-area basis so as to minimise peak funding, optimise economic returns, and enhance the company's viability.

- Be guided by the Australian Government's policy objectives of providing download data rates (and proportionate upload rates) of at least 25Mbit/s to all premises and at least 50Mbit/s to 90% of fixed-line premises as soon as possible.

In making these decisions, nbn also has to have regard to a broader range of considerations, such as long-term NPV considerations and its strategy associated with exercising its rights (under the revised agreements with Telstra) to acquire some of the copper network assets from Telstra, as well as some of the HFC network assets from Telstra and Optus. In the case of the HFC network assets that nbn can acquire from Telstra and Optus, nbn has to determine whether to utilise both networks within a single geographical area or whether to use a single network, in which case it will also need to decide which one of these networks it will use.

In this section, we first analyse the methodology and processes used by nbn to select the network type it will deploy in each area and assess the prudency and efficiency of this methodology and processes.

We then consider nbn's HFC network selection strategy for each area.

5.1   nbn's network selection methodology and processes

nbn has adopted a two-step approach for determining which type of MTM network it will deploy in a particular geographical area. This approach comprises the strategic modelling process and the strategic overlay process:

- **Strategic modelling process**: the optimum network type for each area is determined based on a linear programme model (the 'MTM Optimiser'), which considers financial and non-financial business rules, as well as SoE principles, to derive the optimal technology to be used for that area.

- **Strategic overlay process**: once the optimum network type has been determined by the MTM Optimiser, nbn then applies a strategic overlay to review the outcome of the MTM Optimiser to address practical issues associated with the deployment of that particular network in the relevant geographical area.

We describe each of these steps in more detail in the following sections.

5.1.1 Strategic modelling process

Description of the strategic modelling process

The strategic model is implemented using a tool developed by nbn called the MTM Optimiser. The MTM Optimiser is based on a linear programme model that concurrently considers the various outcomes of a wide array of parameters for each geographical area.

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5.1.2 Strategic overlay process

Description of strategic overlay process

Once the optimum network type has been determined by the MTM Optimiser, nbn then applies a strategic overlay to review the outcome of the MTM Optimiser to address practical issues of deploying such technology in the considered area.

To ensure the MTM Optimiser meets the SoE and overall objectives in a realistic and deliverable plan, nbn uses a series of business rules as part of the strategic overlay process.

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5.1.4 Preliminary distribution of premises per network type

Based on its initial calculations mentioned in the previous section, nbn was able to estimate the total number of premises to be served by the different network types. This is shown in Figure 5.3.

Figure 5.3: Multi-technology mix of premises [Source: nbn,[62] 2016]

Network type	# premises at end of roll-out (millions)	% of premises at end of roll-out (rounded)
FTTP	2.4	20%
FTTN/FTTB	4.5	38%
HFC	4.0	34%
FWA	0.6	5%
Satellite	0.4	3%

As shown in the above figure, nbn expects to serve more than a third of premises (i.e. ~4.5 million premises) using FTTN/FTTB, another third (i.e. ~4 million premises) using HFC and approximately one fifth of premises (i.e. 2.4 million premises) with FTTP. The remaining premises, located in more remote areas, will be either served by FWA and/or satellite.

Understanding the distribution of network types is crucial for estimating the total end-to-end service availability across the network as the characteristics of each network vary leading to different availability figures for each technology type. The combination of each network type to provide an overall end-to-end service availability is described in Section 7.2.4, Figure 7.12.

5.2 Assessment of nbn's decisions

Analysys Mason's assessment of nbn's network selection methodology

We believe that the methodology and processes used by nbn for determining which type of MTM network it will deploy in a particular geographical area is prudent and efficient. The two-step process (i.e. the strategic modelling and the strategic overlay processes) used by nbn leads to a prudent and efficient methodology to determine which type of MTM network it will deploy in each geographical area.

We are satisfied with the methodology used for the strategic modelling process to determine the optimum type of MTM network to deploy. nbn's methodology is based on a series of parameters that have been developed in line with SoE principles.

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[62]   http://www.nbnco.com.au/content/dam/nbnco2/documents/nbn-corporate-plan-2016.pdf

The strategic overlay process considers practical and operational issues in the deployment of the relevant network type for every individual area. It is based on a series of business rules that consider a wide range of relevant factors, including the minimisation of peak funding, optimising economic returns and enhancing nbn's viability. In addition, the methodology also incorporates a long-term NPV consideration. We believe this process to also be prudent and efficient as it is critical to consider the different constraints in the different areas to ensure an efficient deployment of the network. **[C-I-C]**

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6 Review of the efficiency and prudency of nbn's FTTN/FTTB network design

In this section, Analysys Mason sets out its assessment of the extent to which nbn's design for its FTTN/FTTB network is efficient and prudent, based on the strategy of taking over ownership of Telstra's copper network and transforming it into an FTTN/FTTB network. Many decisions have to be made as part of the development of an efficient and prudent FTTN/FTTB network architecture and associated infrastructure. These decisions can be grouped as follows:

- *Service and technology choices* relating to how the services proposed by nbn can be delivered using the selected technology.

- *Architectural choices* relating to the allocation of resources, topology and dimensioning of the network, taking into account the constraints of the existing networks.

- *Infrastructure choices* relating to the specific physical components of the network and the establishment of different sections and nodes of the network.

In this section, we consider the following decisions, which we believe will have the most impact:

- Services and technology (assessed in Section 6.1):

  - the FTTN/FTTB network technology selected by nbn to support its wholesale service portfolio, in accordance with the Australian Government's SoE
  - the Layer 2 protocol used to interconnect with RSPs.

- Architecture (assessed in Section 6.2)

  - the end-to-end architecture between customer premises and the PoI to meet service requirements while following international best practice
  - the spectrum allocation for xDSL, and any interference with existing services
  - network dimensioning to meet the service requirements
  - approach to network resilience (i.e. end-to-end service availability) and ability to meet end-to-end service availability targets
  - options to increase capacity to meet future service requirements.

- Infrastructure (assessed in Section 6.3)

  - customer premises
  - the existing CAN
  - street cabinet
  - distribution fibre network (DFN)
  - FAN

–   transit network

–   aggregation node and POI.

Figure 6.1 below summarises the critical decisions faced by nbn in respect of the design of its FTTN/FTTB network from a technology, architecture and infrastructure perspective.

Figure 6.1: FTTN/FTTB networks – technology, architecture and implementation options [Source: Analysys Mason, 2016]
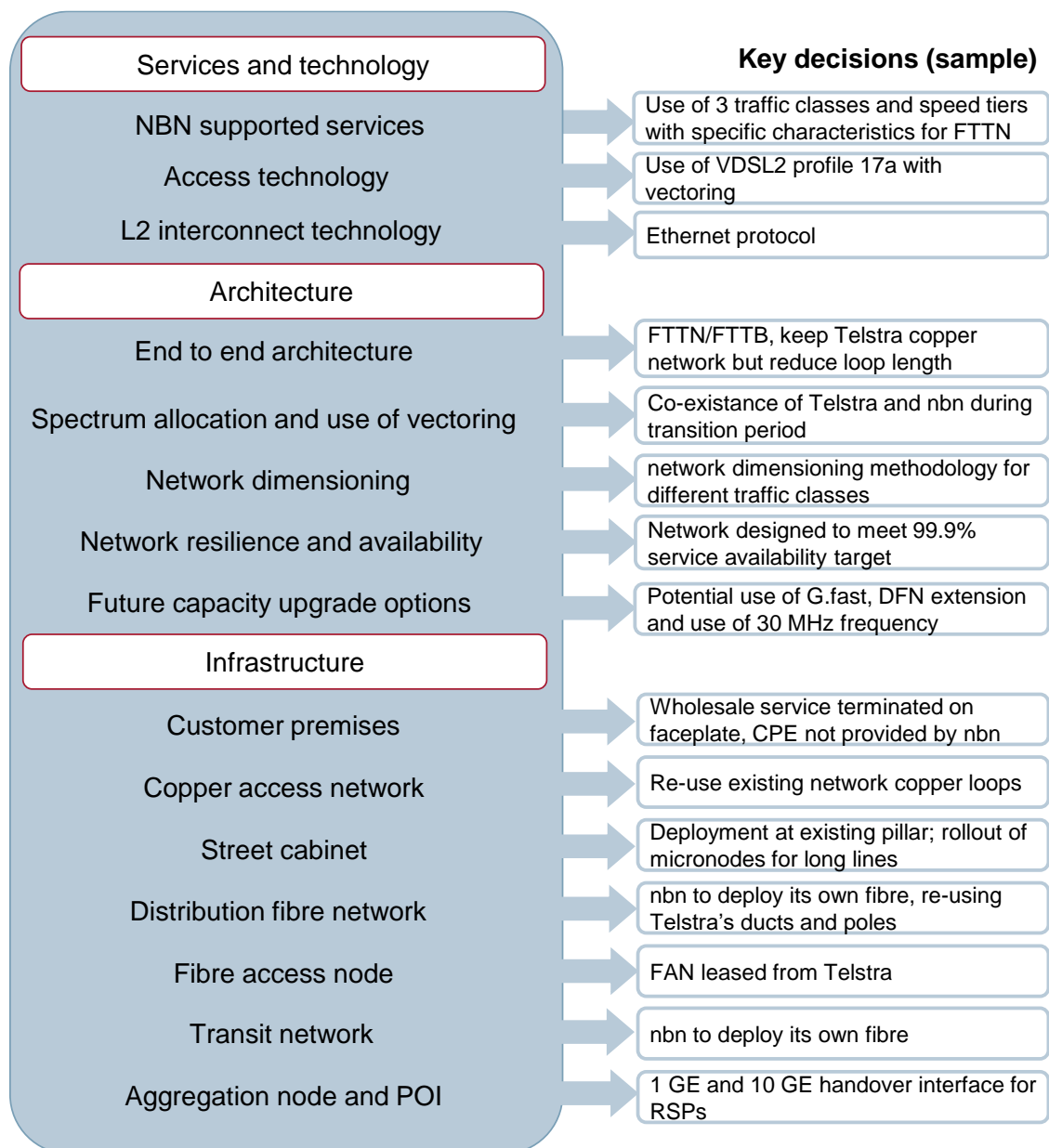
It is the *combination* of these individual design choices and decisions that together determine whether the FTTN/FTTB network design as a whole is efficient and prudent. Therefore, we have assessed the efficiency and prudency of individual design choices and decisions, and have then – based on this assessment – provided our overall conclusion on the extent to which nbn's design of its FTTN/FTTB network is efficient and prudent as a whole.

It should also be noted that some of the key design choices have been specified or influenced by the Australian Government in its SoE. In accordance with our instructions, this report does *not* examine the merits of any specifications given by the Australian Government, but only those specific choices that have been made by nbn within the overall parameters established by the Australian Government at a policy level through its SoE.

6.1 Assessment of FTTN/FTTB services and technology

6.1.1 Services supported by the NBN

Key issues

To meet the various requirements of different end-users, the nbn network supports three different traffic classes for its FTTN/FTTB wholesale access product, defined by nbn as Traffic Class 1 (TC-1), Traffic Class 2 (TC-2) and Traffic Class 4 (TC-4). The characteristics of these are summarised in Figure 6.2 below. TC-1 is intended to support real-time voice applications, while TC-2 is aimed at businesses that require services with a guaranteed bandwidth at any time when the service is available (see Section 6.2.4 for a discussion of service availability). TC-1 and TC-2 are specified by nbn in terms of a committed information rate (CIR), meaning that the end-user can expect to receive at least these minimum speeds at any time.

TC-4 is intended to support high-speed internet services, and is specified by nbn in terms of peak information rate (PIR), meaning that the end-user can expect to receive these maximum speeds but not at all times: the bandwidth is expected to reach 90% of this peak bandwidth for 90% of the time. The rest of the time, end-users can expect to obtain at least 60% of the peak bandwidth. It should be noted that the above definition only applies to lower speed tiers in the FTTN/FTTB network as described in Figure 6.4.

Figure 6.2: Summary of traffic classes defined by nbn for areas served by FTTN and FTTB technology [Source: nbn, 2015]

	TC-1	TC-2	TC-4
Bandwidth profile	150kbit/s 300kbit/s 500kbit/s 1Mbit/s 2Mit/s 5Mbit/s	5Mbit/s 10Mbit/s 20Mbit/s	12Mbit/s (downlink) and 1Mbit/s (uplink) 25/5Mbit/s[55] 25/5–10Mbit/s[63] 25–50/5–20Mbit/s[63] 25–100/5–40Mbit/s[63]
Dimensioning rules	150kbit/s and 300kbit/s: 0.08 Erlang of traffic for residential end-users 0.18 Erlang of traffic for business end-	Symmetrical services ranging from 5Mbit/s to 20Mbit/s – uncontended	For 12/1Mbit/s and 25/5Mbit/s profile: End-users to obtain 90% of peak speed for 90% of the time and at least 60% of peak at other times

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[63]   These are subject to different minimum PIRs during the co-existence period.

	TC-1	TC-2	TC-4
	users 500kbit/s to 5Mbit/s – uncontended		For 25/10Mbit/s profile and above: End-users to reach a peak speed between 25Mbit/s and the tier specify speed depending on copper loop characteristics

RSPs will procure wholesale access services from nbn with various traffic classes, and these will be used to provide retail services to end-users, depending on the end-user's requirements. For example, businesses are most likely to be the only type of end-users taking retail services based on TC-2, for example, to provide virtual private network connectivity between multiple sites. In comparison, some residential users will take a TC-1-based retail service for fixed voice services, if required. TC-4-based services will typically be used to provide internet access services that do not require the same stringent quality and/or availability parameters as those aimed at businesses.

The finite bandwidth available within each section of the nbn network will be shared between the different services being provided to end-users. As illustrated in Figure 6.3, this bandwidth will be dynamically allocated between the different services being used, to help meet the performance targets for the corresponding traffic classes. This means, for example, that end-users will only be able to obtain the instantaneous peak speed specified for TC-4-based services if they do not use other traffic classes at the same time. However, the minimum bandwidth, the CIR, specified for the TC-1 and TC-2 traffic classes will be guaranteed.
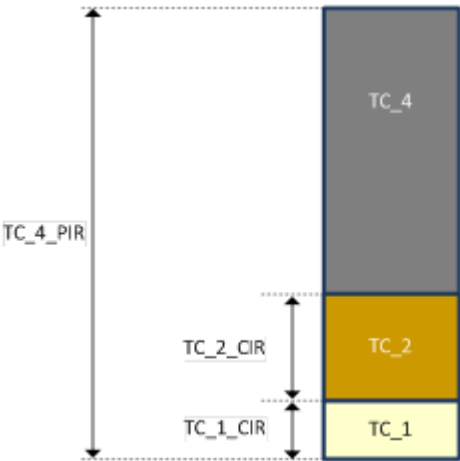
Figure 6.3: Access service bandwidth specification [Source: nbn, 2015]

nbn's position

Due to technology constraints, nbn is planning to offer a number of different speed tiers for TC-4 traffic in areas served by different network types. Figure 6.4 summarises the characteristics of these speed tiers provided in areas served by FTTN and FTTB.

Speed tiers (peak speed for downlink/uplink)	Characteristics
12/1Mbit/s	End-users to reach 90% of peak speed for 90% of the time and 60% of peak at other times
25/5Mbit/s	End-users to reach 90% of peak speed for 90% of the time and 60% of peak at other times
25–50/5–20Mbit/s	End-users to reach a peak speed between 25Mbit/s and 50Mbit/s in the downlink depending on copper loop characteristics
25–100/5–40Mbit/s	End-users to reach a peak speed between 25Mbit/s and 100Mbit/s in the downlink depending on copper loop characteristics

Figure 6.4: Characteristics of TC-4 speed tiers [Source: nbn, 2015]

A number of limitations are specific to TC-4 services provided in areas served by FTTB/FTTN:

- **High speed tier service limitations**: high speed tiers (i.e. services with higher downlink bandwidth than 25Mbit/s and with higher uplink bandwidth than 5Mbit/s) will not be designed to peak at a fixed maximum bandwidth target but will be designed to peak to a bandwidth within a defined range, depending on local condition of the CAN and copper loop length. The range specifies the maximum PIR that may be achieved for the relevant bandwidth profile, with the PIR falling anywhere in the range for the relevant bandwidth profile (i.e. they are not minimum/maximum PIR ranges).

- **Co-existence period limitations**: during the co-existence period with Telstra, nbn will supply services on its FTTB and FTTN networks that are, in some cases, subject to a wider PIR range than would otherwise apply under normal conditions. In particular, for areas served by FTTN, the lower end of any PIR range for an AVC TC4 bandwidth profile (except in regard to the 12/1Mbit/s profile) will be 12/1Mbit/s.

High speed tier service limitations

As identified in Section 3.2.1, the bandwidth that can be provided by xDSL systems is dependent upon the copper sub-loop length and the condition of the copper network. Therefore, since the characteristics of the copper network will vary from premises to premises, the network will not be able to deliver the same bandwidth to every user (e.g. end-users connected to a short sub-loop and served by high-quality copper cable will have access to higher-bandwidth services than end-users connected to longer sub-loops and served by a lower-quality copper cable). Based on this constraint, nbn has decided to implement higher speed tiers (i.e. services with higher downlink bandwidth than 25Mbit/s and with higher uplink bandwidth than 5Mbit/s) based on bandwidth ranges rather than fixed PIR targets. For example, for the 25–50/5–20Mbit/s service, nbn will design the service to a PIR target of between 25 and 50Mbit/s for the downlink and to a PIR target of between 5 and 20Mbit/s for the uplink, whatever the characteristics of the local network enables

it to deliver. However, in any case, nbn will design the network to meet the minimum speeds specified by the Government (i.e. 25/5Mbit/s).

In addition, nbn has developed a dimensioning methodology that estimates the combined present and future traffic requirements for each service (see Section 6.2.3). This methodology will be used as the basis of nbn's plans to re-configure and/or upgrade the FTTN/FTTTB network to meet the expected future traffic demand.

Co-existence period limitations

nbn defines the co-existence period in its Wholesale Broadband Agreement to be *the period during which, to ensure quality of service to Customers, NBN Co is required to adjust the normal operations of the NBN Co FTTB Network or NBN Co FTTN Network by way of a Downstream Power Back-off, including to accommodate the simultaneous supply of NEBS* [nbn Ethernet bitstream services] *supplied by means of the NBN Co FTTB Network or NBN Co FTTN Network (as the case may be) and exchange-fed services, Special Services or other services to Premises using the public switched telecommunications network.*

During the co-existence period, for its VDSL2 services, nbn is planning to use power back-off in the ADSL2+ frequency band (up to 2.2MHz) to mitigate the interference which would be caused to the ADSL2+ signal coming from Telstra's exchange (see description of power back off principles in Section 3.6.1). A decrease in the launch power of the VDSL2 signal will reduce the SNR and therefore will reduce the bandwidth associated with the VDSL2 signal.

Analysys Mason's assessment

The downlink and uplink bandwidth delivered over the FTTN/FTTB network will depend upon the characteristics of the copper loop, particularly the length of the sub-loop and whether vectoring can be used or not. Based on plant records provided by Telstra and on nbn's modelling of the CAN based on the samples available to date, nbn should be able to meet the SoE target download data rates of 25Mbit/s to 100% of premises and 50Mbit/s to 90% of premises (and proportionate upload rates) in areas served by FTTN/FTTB technology after the end of the co-existence period.

For low speed tiers (12/1Mbit/s and 25/5Mbit/s) in respect of the TC-4 traffic class, nbn has a network design objective of providing end-users with 90% of peak bandwidth for 90% of the time and 60% of peak bandwidth at other times.

However, it should be noted that:

– Due to constraints inherent in the FTTN and FTTB, for higher speed tiers (25–50 or 25–100Mbit/s for the downlink and 5–20Mbit/s or 5–40Mbit/s for the uplink), the design objective for peak bandwidth provided will fall within the specified range (i.e. services may not be able to attain the maximum bandwidth value specified for the range, depending on local condition of the CAN and copper loop length). We believe that the strategy associated with higher speed

tiers is prudent and reasonably accounts for uncertainties regarding the actual physical characteristics of the existing CAN.

– During the co-existence period with Telstra, nbn will supply services on its FTTB and FTTN networks using ranged bandwidth profiles that are, in some cases, subject to wider PIR ranges than would otherwise apply under normal conditions. In particular, for areas served by FTTN, the lower end of any PIR range for an AVC TC-4 bandwidth profile (except in regard to the 12/1Mbit/s profile) will be 12/1Mbit/s.

6.1.2 Access technology

Key issues

As presented in Section 3.3, a number of incumbent PSTN operators around the world with CANs similar to Telstra's use VDSL2 technology (with a 17a frequency profile) to provide broadband services to their end-users using the legacy PSTN CAN. Examples include Openreach, Belgacom, Telekom, TIM and AT&T. The majority of these operators (i.e. Belgacom, Telekom and AT&T) use vectoring technology to increase the bandwidth they can provide. Openreach is conducting trials with the objective of implementing vectoring in the near future, where it is feasible. However, TIM is experiencing some difficulties in deploying the technology, mainly due to the presence of third-party RSPs using unbundled sub-loops to deliver their broadband service. (Sub-loop unbundling can pose problems because – as explained in Section 3.2.5 – a vectoring system will function only if a single operator controls all the copper pairs (sub-loops) at the cabinet.)

nbn's position

nbn is planning to use VDSL2 technology with profile 17a for its FTTN/FTTB network, and wherever feasible to deploy vectoring technology to extend the reach and performance of its FTTN network.

Analysys Mason's assessment

Analysys Mason believes that the use of VDSL2 (profile 17a) technology by nbn is prudent. VDSL2 is a mature technology which has been successfully deployed by many incumbents around the world, such as Openreach and AT&T, and is also a cost-efficient technology as it allows the re-use of the existing CAN infrastructure, avoiding costly civil engineering or the deployment of an overlay network.

nbn's approach to vectoring is prudent as it is considering all the potential issues which could affect its deployment. As further discussed in Section 6.2.2, nbn is working in close collaboration with the Communications Alliance WC58 to address potential interference issues where there are multiple VDSL2 systems (from different providers) using copper cables in the same sheath in the FTTB context.

6.1.3 Technology for Layer 2 interconnection

Key issues

The original SoE (of December 2010) stated the Australian Government's choice of wholesale service provision at Layer 2. In particular, it stated that NBN Co *"will offer open and equivalent access to wholesale services, at the lowest levels in the network stack necessary to promote efficient and effective retail level competition, via Layer 2 bitstream services"*. The provision of wholesale access at Layer 2 usually refers to providing access seekers with access to the electronic layer of the network (i.e. the data link layer within the OSI model).[64]

This choice has not explicitly been carried forward into the latest SoE, though that does state that *"the Government intends the NBN to be a wholesale-only access network available on equivalent terms to all access seekers, that operates at the lowest practical levels in the network stack"*. There is still a need for nbn to provide interconnection to the FTTN and HFC networks.

Worldwide, Ethernet is now the ubiquitous Layer 2 protocol, not only for LANs but also for metropolitan and national networks. It has been recommended or prescribed by a number of standards bodies (e.g. the Broadband Forum and the Metro Ethernet Forum) and regulators as the preferred Layer 2 broadband access technology. In line with this international best practice, nbn has already implemented Ethernet as the Layer 2 interconnect technology for its existing networks. Further downstream, Ethernet is also used for interconnecting to Internet peering and transit service providers for connection to the World Wide Web.

nbn's position

nbn plans to adopt Ethernet as the Layer 2 protocol to interconnect with access seekers for all of its offered wholesale services, irrespective of the access network technology used.

Analysys Mason's assessment

We consider that nbn's choice of Ethernet as a Layer 2 protocol to interconnect to access seekers to provide its wholesale services is prudent. The choice of Ethernet aligns with global standards and is a proven technology, and will facilitate competitive vendor pricing and minimise technology risk and the risk of stranded assets. Also, since Ethernet technology is adopted worldwide, its selection by nbn is also cost-efficient and will allow the operator to exploit the economies of scale associated with the production of Ethernet equipment worldwide.

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[64]   If additional background on Layer 2 service delivery is needed, a full discussion of the impact of providing wholesale services at different layers in the OSI model can be found in Analysys Mason's report for Ofcom, *GPON Market Review - Competitive Models in GPON: Initial Phase*, Ref: 15340-512, 26 October 2009. This is available at http://stakeholders.ofcom.org.uk/binaries/research/technology-research/Analysys_Mason_GPON_Market_1.pdf.

analysys mason

6.2 Assessment of the FTTN/FTTB architecture

This subsection provides our assessment of the issues relating to the selection of the proposed FTTN/FTTB network architectures, including:

- end-to-end architecture
- spectrum allocation
- network dimensioning
- network resilience and availability
- options for future capacity upgrades.

6.2.1 End-to-end architecture

Key issues

nbn has to design its FTTN/FTTB network to provide a set of wholesale broadband services with the characteristics described in Section 6.1.1. Since the bandwidth capable of being provided to customer premises connected to an FTTN/FTTB network is a function of the copper loop length, the location of the DSLAM serving those premises has to be carefully considered to ensure that the copper loops are short enough to provide the required bandwidth.

Also, the network must be resilient enough to reliably provide the required services. For this, nbn has to define an end-to-end wholesale service availability target, and design its network to meet this target. The target will be a compromise between the costs associated with increasing service availability and the number of end-users affected by a single fault.

In addition, all links in the network have to be dimensioned appropriately so that there is no capacity bottleneck and that each end-user receives a broadband service that meets the performance targets for uplink and downlink speeds.

Finally, since nbn has the right to acquire some of the assets that comprise Telstra's copper network, the design of the network is aimed at maximising the re-use of existing infrastructure where possible to ensure a cost-effective solution.

nbn's position

To provide wholesale broadband services with the characteristics described in Section 6.1.1, nbn will deploy an FTTN/FTTB architecture in selected areas. The logical blocks of this architecture are illustrated in Figure 6.5 below.

Figure 6.5: Generic end-to end architecture for nbn's FTTN/FTTB network[65] [Source: Analysys Mason, 2015]
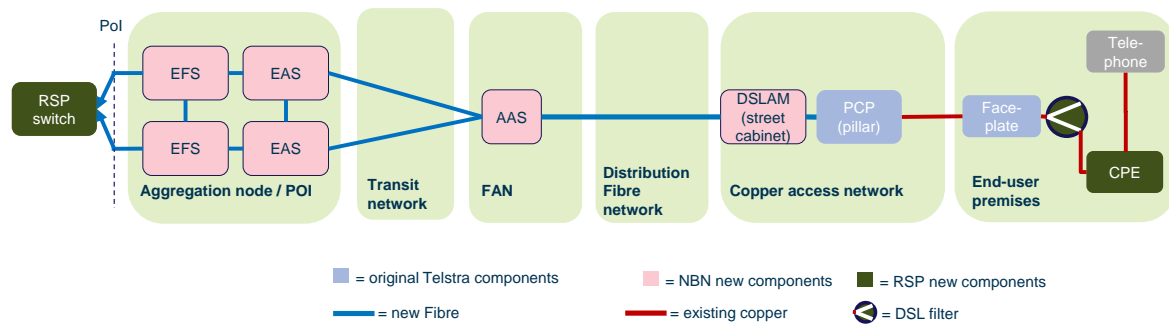
As shown, the architecture can be understood in terms of six segments:

- end-user premises
- CAN
- DFN
- FAN
- transit network
- aggregation node/POI.

We provide a brief overview of each of these segments below, but provide more granular details for each of these segments in Section 6.3.

At the customer premises, nbn will physically terminate its wholesale service at the face plate. nbn does not expect to provide any CPE – this will be owned either by the RSP or by the end-user.

nbn intends to re-use Telstra's CAN, including where technically and financially feasible, the PCP pillar, which provides a useful interconnection point within the CAN. nbn is also planning to deploy new street cabinets, close to the PCP location where technically and financially feasible. It plans to offer wholesale broadband access services by deploying VDSL2 DSLAMs, hosted either (a) in the new street cabinets located close to the PCP location (for the FTTN network); or (b) in small cabinets (i.e. pillars) or in the basement of MDUs (for the FTTB network).

To interconnect the DSLAM to the FAN, nbn will deploy a DFN, wherever possible re-using Telstra's ducts and poles to deploy its own fibre cables. This will help minimise the deployment costs of the DFN.

In the FAN, nbn will deploy – where appropriate – an access aggregation switch (AAS) to aggregate the traffic from several DSLAMs to minimise the number of physical connections to the transit network, and therefore costs.

The transit network will connect the AAS to a pair of EASs hosted in an aggregation node. The transit network will comprise a fibre network plus active equipment to ensure reliable

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[65]   For the avoidance of doubt, nbn is not offering voice services based on POTS emulation.

transmission. nbn will use WDM technology to ensure that the capacity deployed in the transit network is cost-effectively scalable with growth in end-user demand (note that for simplicity, this WDM equipment is not shown in Figure 6.5 above). Also, nbn plans to deploy its own fibre infrastructure in the transit network; in areas where dark fibre is available, the operator may take dark fibre from other operators if this makes commercial sense.

Aggregation nodes will aggregate the traffic from several FANs: there will be 121 aggregation nodes in the whole network. To aggregate the traffic, a pair of resiliently configured EASs will be deployed in each aggregation node. The EASs will connect to a pair of EFSs which will provide the interfaces for RSPs to connect to, namely the PoIs.

Analysys Mason's assessment

nbn is being prudent and efficient by maximising the re-use of Telstra's network, particularly the CAN, including the PCP pillar. The FTTN/FTTB architecture is fundamentally a standard design similar to other FTTN/FTTB networks in the world, as evidenced in our case studies.

6.2.2 Spectrum allocation and use of vectoring

Key issues

nbn has a number of options regarding its spectrum plan for its VDSL2-based services. As documented in Section 3.2.3, a number of VDSL2 frequency profiles have been defined by the standards bodies, each with different performance characteristic depending on the length of the copper loop (e.g. higher-frequency profiles enhance broadband performance better on shorter loops). However, the frequency ranges that operators can use in the CAN are typically managed to avoid interference issues, and the optimum frequency profile may not be available or authorised in some particular cases.

In Australia, Working Committee 58 (WC58) was created within the Communications Alliance to investigate all issues with the deployment of VDSL2 within the FTTN/FTTB architecture. In particular, WC58 is responsible for the industry codes of practice and standards that ensure harmonious deployment of xDSL technology on copper access cables in the Australian market. It focuses on the following issues:

- crosstalk and other forms of interference
- transmit power levels
- rules to facilitate coexistence of services sharing the same cables.

As described in Section 3.2.5, vectoring technology mitigates FEXT and therefore provides significant gains in terms of bandwidth in VDSL2 systems. This in turn allows the reach of VDSL2 systems to be extended and therefore allows operators to serve end-users using fewer nodes, thereby reducing capex requirements. However, to enjoy the full benefits of vectoring, the technology has to be applied to all the VDSL2 signals transmitted within a single cable binder. In

Australia, the use of vectoring could be limited by two constraints: (a) the requirement for nbn to support existing Telstra broadband customers[66] during the co-existence period, and (b) the need to support infrastructure sharing within MDUs.

WC58 has been considering the introduction of VDSL2 and FTTN technology in light of the Australian Government's policies by:

- understanding the role of VDSL2 vectoring
- considering how to manage VDSL2 spectrum in cables
- considering the transition from today's network to FTTN and FTTB
- exploring the technical implications of having more than one VDSL2 DSLAM sharing cables.

Regarding the last point, a key issue acknowledged by WC58 is when DSLAMs from different operators (e.g. nbn and another operator) are deployed in different locations but use copper pairs within the same cable binder to provide broadband services to end-users. This situation, which may give rise to interference problems, is illustrated in Figure 6.6.

Figure 6.6: Example of two DSLAMs located in different locations causing interference [Source: Analysys Mason, 2015]
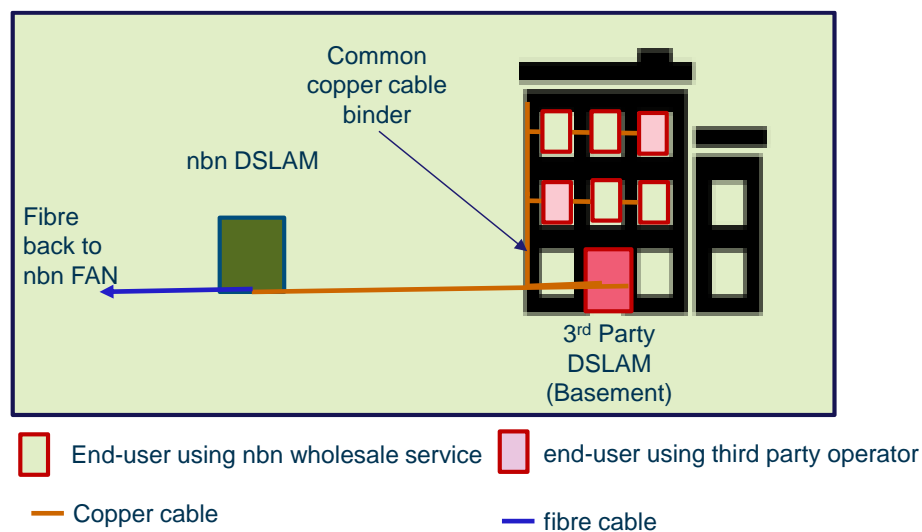
In the situation illustrated, the signal from the cabinet provided by nbn will become weaker through attenuation as it travels to the MDU building, while the signal generated by the third-party DSLAM (located in the basement of the MDU) will be much stronger. Unless spectrum is managed so that the systems do not use overlapping spectrum, this arrangement will create unequal crosstalk levels such that the strong third-party signal will detrimentally impact the performance of nbn's broadband service more than nbn's signal will affect the other operator's service.

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[66]   Using ADSL2+ from the FAN.

Based on theoretical analysis, WC58 has determined that the download bandwidth of a vectored VDSL2 service delivered from a remote cabinet to an end-user in an MDU would be reduced by as much as 75% if a third-party DSLAM is located in the MDU basement using the same spectrum and internal MDU wiring infrastructure. This analysis is illustrated in Figure 6.7 for an nbn FTTN node located 400m from the MDU. From Figure 6.7, it can be seen that, depending on the length of cable within the MDU itself, the downlink bandwidth could fall below the 25Mbit/s required by the Australian Government.[67]

Figure 6.7: Impact of sharing spectrum on download bandwidth (raw rate) for a VDSL2 cabinet located 400m from an MDU [Source: Communication Alliance, 2015]
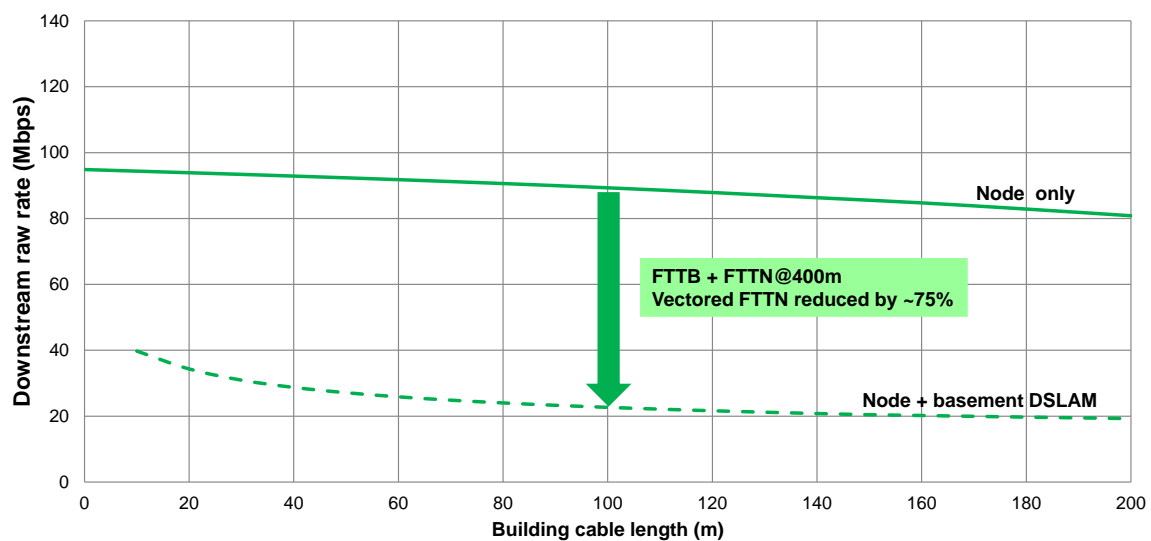
Furthermore, during the co-existence period, it will be necessary to support both Telstra ADSL2+ services provided from Telstra's exchange *and* nbn VDSL2 wholesale services provided from the street cabinet. If not carefully implemented and managed, this may also lead to mutual crosstalk that would significantly affect the performance of services provided by both Telstra and nbn.

To mitigate the above issues, WC58 has put forward four different options, which we discuss below:

- Option 1: spectrum separation
- Option 2: spectrum shaping
- Option 3: segregated cables
- Option 4: single VDSL2 operator per designated area.

► *Option 1: spectrum separation*

Option 1 assigns separate spectrum bands to each system or location to avoid interference, as illustrated in Figure 6.8 below.

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[67]   Specified in the SoE: see item 2 in Section 2.2 above.

Figure 6.8: Option 1: spectrum separation [Source: Communication Alliance, 2015]
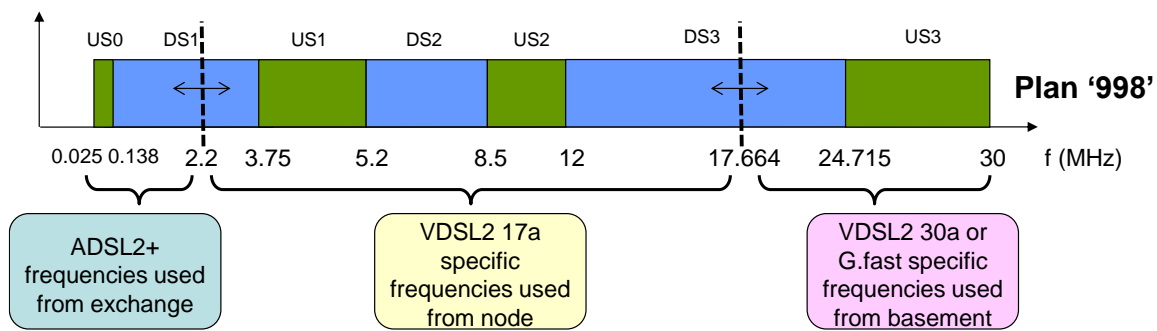
However, there is a major issue associated with spectrum separation: it significantly reduces the amount of spectrum available to each DSL system. In practice, the bandwidth associated with un-vectored VDSL2 lines longer than 200m could be reduced by half because the available spectrum is halved.

► *Option 2: spectrum shaping*

As mentioned in Section 3.2.1, spectrum shaping[68] reduces the power of the VDSL2 signal from the cabinet in the ADSL2+ frequency band, to minimise the crosstalk caused to existing ADSL2+ signals transmitted from the exchange. Spectrum shaping is therefore mainly aimed at protecting legacy services from interference from VDSL2, and does not address the case where two operators both deploy VDSL2 using copper pairs within the same cable binder.

► *Option 3: segregated cables*

This option deploys separate copper cables from the DSLAM to the end-user premises for each operator. That way, each operator has full control of all lines within their own cable and can therefore fully take advantage of the bandwidth gains provided by vectoring. However, this would require the deployment of new cables in the MDU, a solution which is both costly and which potentially requires the co-operation of the building owners.

► *Option 4: single VDSL2 operator per designated area*

This option would designate a single operator within each area which would provide open-access bitstream services to other operators wanting to serve customers in that area. However, this approach would have an impact on the prospect of facilities based competition as it removes the option for an alternative operator to use its own active equipment (i.e. its own DSLAM) to provide broadband services to its customers.

► *Recommendation from WC58*

WC58 has recommended Options 3 and 4 to the industry and the Government as these options are less technically challenging to implement and would maximise the benefits of VDSL2 vectoring in terms of bandwidth gains. However, Option 3 would potentially require more far-reaching changes

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68   Spectrum shaping can take the form of "uplink or downlink power back-off" (U/DPBO).

regarding the deployment of copper cables in MDUs, while Option 4 would raise broader issues about the model for competition in the telecoms sector, which could be significant.

WC58 is currently developing an approach along the lines of spectral separation (Option 1). The outcome is expected to be constrained by the limitations of spectral separation described above. However, the code of practice has not yet been finalised by WC58 at the time of writing and any changes in recommendations from WC58 will impact nbn's technical strategy.

nbn's position

nbn is planning to use VDSL2 technology using a 17MHz spectrum profile (profile 17a), The Communications Alliance has also developed a framework for the use of profile 17a in Australia.

► *Use of vectoring with FTTN architecture*

nbn is currently considering whether to use vectoring to extend the reach of its FTTN network whether the copper cable is shared with other operators or not. This decision is motivated by the following considerations:

- It is expected that the industry code being formulated by the Communications Alliance will stipulate spectrum separation (Option 1) to avoid interference, where separate spectrum bands are allocated to the VDSL system of each operator that is seeking to serve MDU premises using copper pairs that are contained within a shared cable. This way, if nbn were to deploy an FTTN node to serve premises in an MDU building, then Operator B wanting to thereafter serve premises in that MDU building and using copper pairs contained within a copper cable being used by nbn, would have to deploy a solution which does not use nbn spectrum (i.e. which does not use the first 17MHz of the cable spectrum). For example, Operator B could deploy G.fast technology using spectrum between 17MHz and the maximum frequency standardised for G.fast technology (i.e. 106MHz today or 212MHz in the future).

- Conversely, it is expected that if Operator B had already deployed some infrastructure in the MDU basement, and if nbn were to deploy an FTTN node to serve premises in the same building, then it is expected that Operator B would be asked to vacate some spectrum so that both the nbn FTTN node and Operator B's basement system would each have exclusive access to some of the spectrum each (i.e. high/low spectrum split).

However, this position is still evolving and may change with WC58's future findings and associated recommendations. In any case, nbn will be able to turn vectoring off if the interference generated by nbn is detrimental to the performance of Operator B and vice-versa.

► *Use of vectoring with FTTB architecture*

For MDUs, where nbn has to share the copper cable with another operator, nbn plans to use vectoring. This is applicable in cases where nbn provides services using a compact DSLAM hosted just outside the MDU, and where nbn provides services using a compact DSLAM hosted in the basement of the MDU.

Of course, for MDUs where nbn does not have to share the copper cable with another operator, nbn will also use vectoring.

► *Mitigation of interference between VDSL2 and ADSL2+*

During the co-existence period, for its VDSL2 services, nbn is planning to use power back-off in the ADSL2+ frequency band (up to 2.2MHz) to mitigate the interference which would be caused to the ADSL2+ signal. The Communications Alliance estimates that the degradation in vectoring gain associated with this situation is less than 10% for most vectored VDSL end-users,[69] which means that the performance of nbn's VDSL2 service will be minimally impacted during the co-existence period.

Analysys Mason's assessment

We believe that nbn's use of 17MHz spectrum is prudent: profile 17a is being used to provide VDSL2 services by many incumbent operators worldwide (e.g. Openreach, Telekom, TIM and AT&T). The Communications Alliance has also developed a framework for the use of profile 17a in Australia.

We acknowledge the work conducted by WC58 of the Communications Alliance regarding interference issues in xDSL systems. This process is still on-going at the date of this report but we note that the current preference appears to support the use of spectrum separation (Option 1) to avoid interference, where separate spectrum bands are allocated to the VDSL system of each operator that is seeking to serve MDU premises using copper pairs that are contained within a shared cable.

nbn's current default position is to enable vectoring for all FTTB and FTTN architectures. nbn will be able to turn vectoring off in areas where interference with other operators causes an issue regarding the performance of the service. We believe this decision to be prudent and efficient because:

– For the FTTN architecture, it will allow each street cabinet to serve a larger footprint, thereby reducing the number of cabinets and compact DSLAMs needed. However, for the special case when nbn customers in an MDU are served from an nbn street cabinet and nbn has to use copper pairs within the same cable binder being used by another operator also serving the building, nbn's strategy for addressing interference issues will be dependent to some extent on the outcome of the Communications Alliance process referred to above. If vectoring has to be turned off due to interference issues, there may be a case where a new FTTN micro-node may have to be installed closer to end-users to ensure the SoE objectives are met in terms of service speeds.

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[69]   Communications Alliance, Managing Interference in a Vectored VDSL2 environment: Communications Alliance WC58 18 November 2014, page 10. See http://www.commsalliance.com.au/__data/assets/pdf_file/0020/46901/Managing-Interference-in-a-Vectored-VDSL2-environment-final.pdf

– For the FTTB architecture, nbn has decided to also use vectoring when the copper cable has to be shared with another operator located in the MDU building on the basis that there are service stability benefits with this approach, with nbn having the flexibility to turn vectoring off if it causes performance degradation to nbn's service or to the other operator's services.

– nbn may re-consider its strategy regarding vectoring in line with future findings and recommendations from WC58 of the Communications Alliance.

It is a prudent decision to use power back-off in cabinet locations to mitigate interference caused to the ADSL2+ signal on Telstra's broadband lines during the co-existence period. Power back-off is a mature feature in VDSL2 DSLAMs and has been used by many operators worldwide to mitigate this particular issue. In addition, the Communications Alliance has developed a framework for the use of this solution and believes that the degradation in bandwidth caused to nbn services will be marginal (e.g. approximately 10%).

6.2.3 Network dimensioning

[C-I-C]

[C-I-C]

6.2.4 Network resilience and availability

Key issues

The SoE states that "*nbn will take proportionate responsibility for the quality, consistency and continuity of service experienced by RSPs and their end-users*". We interpret this statement as requiring nbn to provide an end-to-end service availability sufficient to ensure the wholesale service provides adequate quality to RSPs and ultimately to end-users.

End-to-end service availability is defined as the amount of time the service will be operational for the end-user under normal operating conditions. Typically, any *planned* service downtime (e.g. for network maintenance or upgrades) is not counted as network downtime. Network resilience is the ability of the network to continue operating normally, typically in the case of a single service-affecting network fault.

Operators normally define end-to-end service availability based on the type of products provided and the market segment targeted. Once the end-to-end service availability is defined, operators have then to design their network architecture in such a way that this level of availability is met, taking into account any network redundancy that is required for passive network elements (i.e. alternative diverse physical paths) and active components (e.g. hot-standby configured or pooled network elements). Defining end-to-end service availability is always a compromise between service availability (quality) and costs: it is more expensive to build a resilient network supporting a high end-to-end service availability, mainly because additional redundant links and network components are required.

In the case of nbn, we highlight that the service availability of the FTTN/FTTB access network will be heavily influenced by the design of the existing Telstra CAN which will be acquired by nbn, since a significant proportion of the CAN will be re-used.

As mentioned in Section 5, it is estimated that the FTTN/FTTB network will serve approximately 38% of premises in Australia. Therefore, the availability performance of this network will make a significant contribution when calculating the overall average service availability of nbn's wholesale products.

nbn has calculated the end-to-end service availability of the FTTN/FTTB network considering four different variables, which we discuss below:

- type of FTTN/FTTB end-to-end architecture
- type of copper access infrastructure used (i.e. aerial or underground)
- type of DSLAM used (i.e. ISAM 7330 or ISAM 7367 SX48)
- provisioning of battery backup for the DSLAMs
- resilience characteristics of the other components in the network.

► *Type of FTTN/FTTB end-to-end architecture*

The four end-to-end architectures defined and considered by nbn for the FTTN/FTTB network are the following (explained in more detail in Annex C):

- **FTTN Option 1:** direct connection of DSLAM to POI with fibre
- **FTTN Option 2a:** direct connection of DSLAM to POI with WDM
- **FTTN Option 2b:** connection of DSLAM to AAS deployed at the POI
- **FTTN Option 3:** connection of DSLAM to AAS deployed at the FAN.

► *Type of copper access infrastructure*

Depending on the area, the existing CAN is deployed either aerially or underground. In urban areas and new developments it is usually deployed underground (in ducts), whereas in outer urban and rural/remote areas it is more common to find aerial deployments being used. Overall, nbn believes that 70% of the CAN infrastructure is underground and 30% aerial.

Aerial infrastructure is typically less reliable than underground infrastructure, because it is more prone to faults due to external conditions (e.g. bad weather) and therefore requires significantly more operational interventions (e.g. repair). This implies that services provided via aerial infrastructure are potentially less reliable (e.g. reduced availability) and that operational costs associated with repairs and maintenance are greater per unit route length for aerially deployed cables.

nbn has had no influence in the design of Telstra's established network, but must take into consideration its actual and forecast performance characteristics to ensure that the QoS targets for the wholesale services provided over this network are met, and that operational costs are minimised. A business case including opex, capex and QoS objectives for any new or replacement access infrastructure should consider aerial and underground deployment on a case-by-case basis, and be able to choose the most efficient and prudent solution.

► *Type of DSLAM*

nbn is planning to use two main types of DSLAM, depending on the number of premises being served. ALU ISAM 7330 units will typically be deployed in a street cabinet and configured with either 64, 128 or 384 VDSL2 ports. ALU ISAM 7367 SX-48 units will be deployed on a pillar or in a manhole; they have 48 VDSL2 ports.

We highlight that the ISAM 7330 models will typically be deployed when there are more than 40 premises to be served (typically within FTTN architecture) and that ISAM 7367 units will be used where there are less than 40 premises to be served. Also, the ISAM 7367 is a compact unit and its availability specification is lower than that of the ISAM 7330.

► *Provisioning of battery backup for the DSLAMs*

For both types of DSLAMs there is an option to include battery backup in the cabinet or pillar to mitigate mains power outages and improve availability. nbn is planning to include four hours of battery backup in each DSLAM. We note that the provisioning of battery backup is not explicitly mentioned in the SoE, although the SoE asks nbn to "take proportionate responsibility for the quality, consistency and continuity of service experience by retail service providers and their end-users".

nbn's position

nbn has set a design target across all its networks to achieve an average end-to-end availability of 99.9%. Some end-users served using one technology (e.g. FTTN or aerial cables) may experience a service availability lower than 99.9%, while others served by another technology may experience a higher availability.

nbn has calculated the expected end-to-end service availability associated with different FTTN architecture options, type of CAN, type of DSLAM, and DSLAM battery backup. It should be noted that the nbn calculation excludes the following factors:

- probability of mains power outages
- state of the DSL line, including periods of DSL line re-synchronisation
- customer CPE (this is owned by the RSP or end-user).

The results of the availability calculation are provided in Figure 6.11 (for the ISAM 7330) and Figure 6.12 (for the ISAM 7367). It should be noted that the results assume the provision of four hours of battery back-up for all DSLAMs.

Figure 6.11: End-to-end service availability for ISAM 7330 [Source: nbn, 2015]
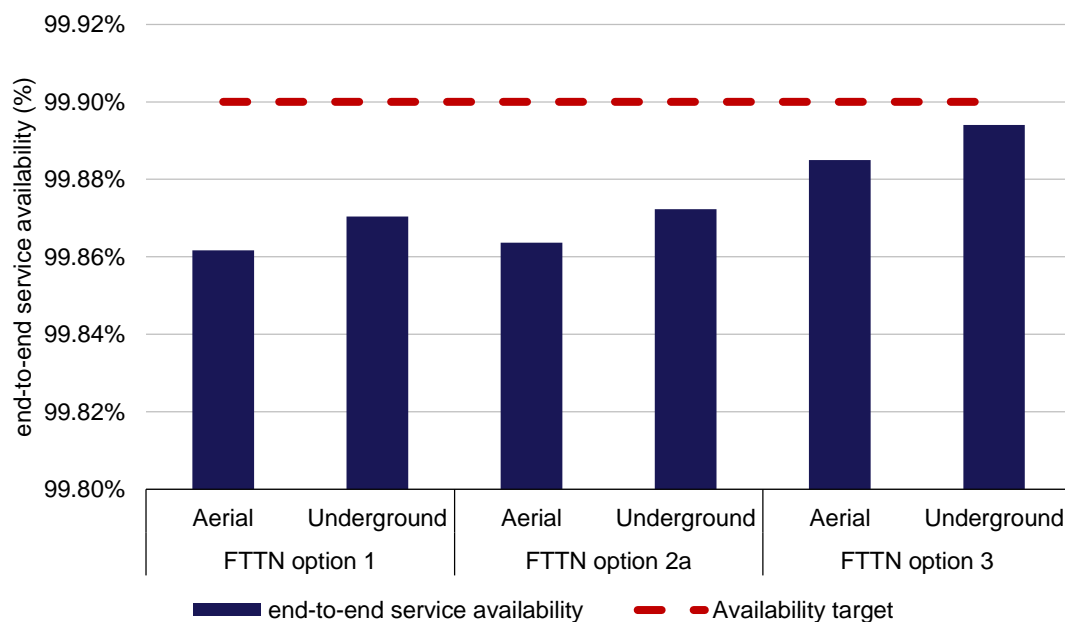
Figure 6.12: End-to-end service availability for ISAM 7367-48SX [Source: nbn, 2015]
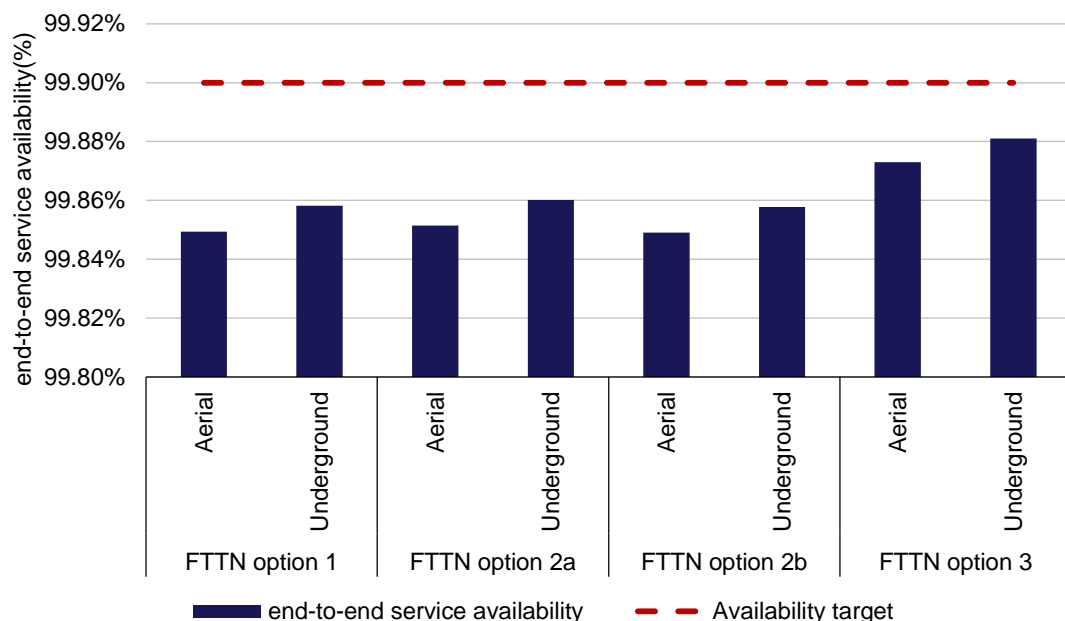
As illustrated in the above figures, none of the architectures proposed will achieve nbn's target for average end-to-end-service availability. Also, as expected, availability will be lower in areas where the CAN is deployed aerially than in areas where it is deployed underground.

To better understand what each network component contributes to the end-to-end availability, nbn has calculated the contribution in downtime from each component in the access network. Unfortunately, the timeframe for our review did not permit us to assess the detailed calculation of

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availability for each configuration envisaged by nbn. The results are illustrated in Figure 6.13 for an underground CAN and Figure 6.14 for an aerial CAN. In both cases, the DSLAMs are assumed to be ISAM 7330 units with four-hour battery backup.

Figure 6.13: Downtime contribution of each access network component for underground CAN infrastructure [Source: nbn, 2015]
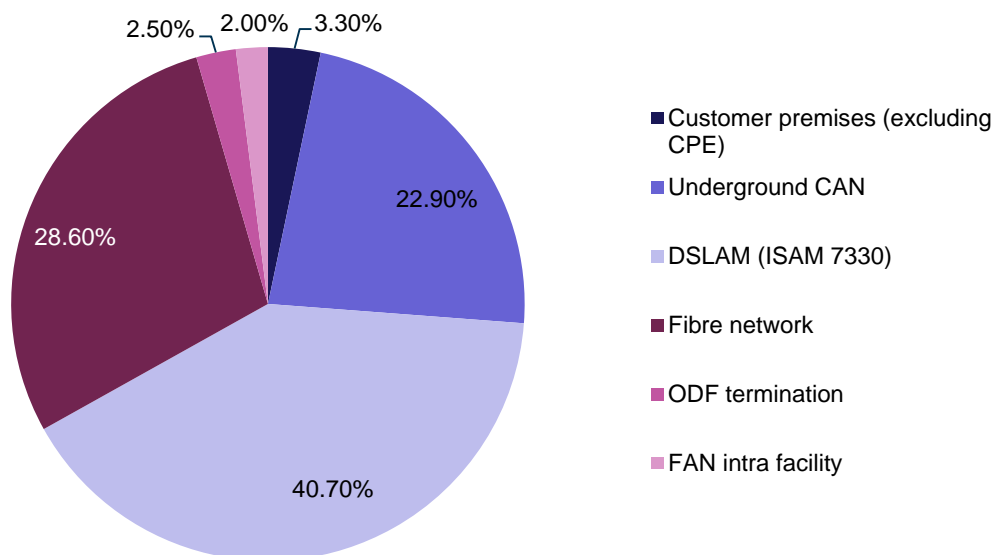
Figure 6.14: Downtime contribution of each access network component for aerial CAN infrastructure [Source: nbn, 2015]

It can be seen that the three major contributors to downtime are:

- **the DSLAM**, which contributes more than one third of the total downtime of the access network
- **the CAN**, which contributes 30% of downtime for aerial CAN and 22.9% for underground CAN
- **the distribution fibre network** (connecting the DSLAM to the FAN), which contributes 26% of downtime in the case of overhead CAN and 28.6% in the case of underground CAN.

Analysys Mason's assessment

nbn's design target for average end-to-end service availability of 99.9% (across all access networks) is prudent, and is in li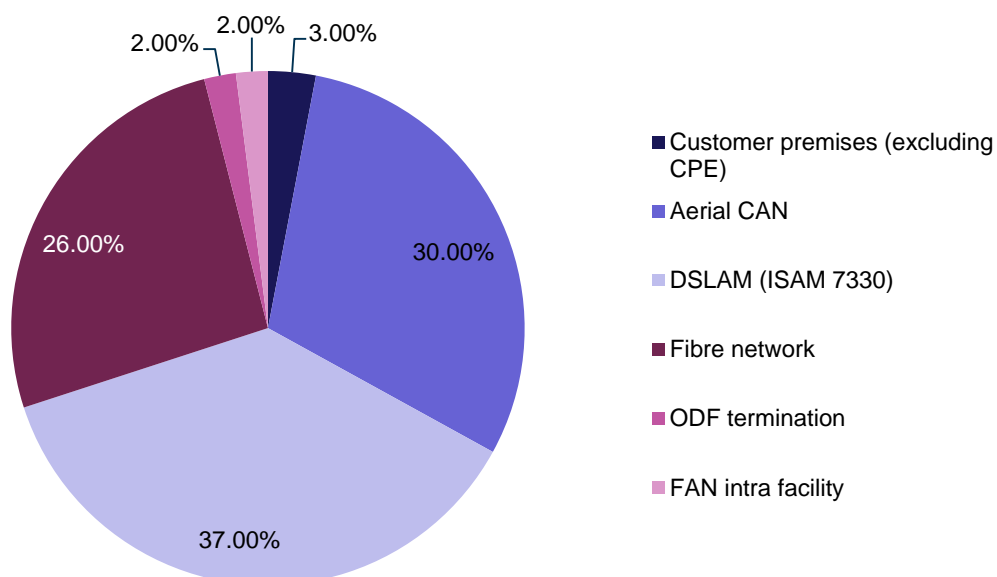ne with international best practice. The overall approach to assuring availability through the network design is in line with the approach we have seen from other large-scale operators.

nbn has undertaken calculations of end-to-end service availability to the best of its ability given the level of information available.[72] Based on these calculations, the end-to-end availability of the FTTN/FTTB networks will be lower than the design target for national average availability (across all access networks), depending on the infrastructure and type of DSLAM used. These figures reflect an average across the FTTN/FTTB access network as a whole.

The largest contributor of downtime in the access network is typically the DSLAM. We believe that nbn's decision to implement four-hour battery backup in every DSLAM is prudent, as it will improve the availability of the DSLAM. In our experience, operators usually equip DSLAMs with 2–6 hours of backup, depending on the reliability of local mains power).

nbn's calculations in relation to availability of the CAN, which is also a major contribution to downtime in the access network, are based on Telstra's figures, but these relate to the average availability of the customer access network at a national level whereas the performance of particular lines will vary for different locations. nbn's overall approach to assuring availability through its network design is in line with what we would expect. For example, we would not expect resilient links from a DSLAM to the AAS and EAS as the number of subscribers involved (less than 400 end-users) is too low to justify the costs of redundant interfaces and links. However, we would expect the deployment of redundant links between the AAS and the EAS as these links will carry aggregated traffic from several DSLAMs serving a significant number of end-users.

In general, the network has been designed so that no more than 4000 end-users will be affected by a single service-affecting network fault (such as a fibre break or equipment failure). This is prudent. Our experience of incumbent operators in developed markets in the Asia–Pacific region and Western Europe suggests that the number of end-users affected by a single point of failure can vary across the network, due to design rules flexibility and geographical constraints. However, our experience typically suggests that this figure will typically be in the range 5000 to 40 000 end-users.

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[72]   The timeframe for our review of nbn's network did not allow us to assess the detailed calculation of availability for each configuration envisaged by nbn.

Finally, although the estimated end-to-end availability of services provided over the FTTN infrastructure will fall short of the average national design target of 99.9%, when considering the mix of networks, the expected average service availability across all networks will be 99.897%,[73] which is just 0.003% short of the design target.[74] We believe this to be reasonable in the circumstances given the uncertainty in relation to the availability rates of the different acquired networks at the time of writing this report.

6.2.5 Options for further capacity upgrades

Key issues

The Australian Government's SoE states that "*nbn will ensure that any network upgrade paths are made available as required*". Over time, end-user demand for higher-bandwidth services will increase, and this will need to be supported by the network. In Section 3.5.2 we discussed the likely bandwidth need of the top percentile of households (110Mbit/s by 2020 and 313Mbit/s by 2025), and noted that momentum is growing in developed countries for services with downlink bandwidths of 500Mbit/s and 1Gbit/s services are also becoming common. This greater bandwidth demand will lead to nbn's FTTP/FTTB access network needing to be re-configured or upgraded.

nbn's position

At this stage, nbn does not yet have a clearly established roadmap for the upgrade of its network to support future products and the expected growth in bandwidth demand. However, the operator is considering the following options for upgrading its network in the future:

- exploiting the evolving xDSL standards, and potentially using G.fast technology
- using the 30a frequency profile for VDSL2, which extends the spectrum available from 17MHz to 30MHz
- extending the DFN to reduce the copper loop length (e.g. by deploying FTTdp architecture)
- using other technologies coexisting and overlapping in the MTM network
- upgrading to FTTP.

The extension of the spectrum from 17MHz to 30MHz will allow the provisioning of higher bandwidth on the relatively short copper loops, as explained in Section 3.2.3. The Communications Alliance has not yet developed a framework for the use of 30MHz spectrum (profile 30a) in Australia.

The extension of the DFN to reach closer to the end-user will allow nbn to reduce the copper loop length, and therefore to provide higher-bandwidth services. Amongst other options, extending the DFN to the DP will enable nbn to use G.fast technology, making possible a combined bandwidth in excess of 500Mbit/s, depending on the length of the last drop. Ultimately, the fibre could be

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[73]   See Figure 7.12.

[74]   Equivalent to 26 minutes of downtime per year.

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extended to the end-user premises and nbn could migrate the FTTN/FTTdp network to an FTTP solution. As described in Section 6.3.4, the cost of such a migration will be minimised by the fact that the current DFN is designed to be scalable, with significant spare fibres at the FTTN node.

Overall, nbn plans to assess the most appropriate upgrade paths depending on its forecasts for network traffic demand and its view on the most prudent and efficient option to take, bearing in mind the relative upgrade costs and benefits.

Analysys Mason's assessment

Despite the fact that nbn does not currently have any clearly established roadmap for the upgrade of the FTTN/FTTB network, it is considering a number of options to ensure that its network continues to meet service requirements as demand for bandwidth increases in the future. These options – which have been deployed by other operators internationally – include the extension of VDSL2 spectrum from 17MHz to 30MHz (though this is not currently within the framework developed by the Communications Alliance); the use of new xDSL technologies such as G.fast;[75] the extension of dark fibre to the DP to further reduce the copper loop length; and ultimately a prudent incremental extension of the fibre access network towards the customer premises to achieve an FTTP architecture in the longer term.

nbn will provision a 12-fibre cable for each DSLAM, which means that the network can cost-effectively and straightforwardly be upgraded to an FTTP (i.e. GPON) architecture. In our review, we have not identified any issues in the way that the FTTN/FTTB network is designed which would prevent efficient and prudent upgrades to increase network capacity to address future market demand where required.

We believe that the options considered by nbn to support future services are prudent: they are in line with international best practice – a number of operators around the world are currently considering the same options to support future bandwidth demand. We also consider that nbn's approach to network upgrade is efficient, as it relies on incremental upgrades to the existing network rather than the deployment of a new network, thereby maximising the return on its investment in existing assets.

nbn's ability to undertake upgrades will be dependent to some extent on the outcome of the current Communications Alliance process that seeks to deal with the interference issues caused by the co-existence of different xDSL systems. Resolving interference caused by the co-existence of different ADSL systems may become a greater issue when FTTN/FTTB networks are upgraded to new xDSL technologies, such as G.fast over FTTdp, that will increasingly rely on vectoring to deliver their full bandwidth potential and ensure maximum return on investment.

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[75]   At the time of writing, nbn has not yet made any decisions regarding the use of the G.fast technology.

6.3 Assessment of the FTTN/FTTB infrastructure

In this section, we consider each of the physical locations in the FTTN/FTTB network, from the customer premises to the PoI, describing the features of the architecture that relate to each location and the equipment deployed at each location. We consider the following locations, illustrated in Figure 6.15 overleaf:

- customer premises
- CAN
- street cabinets
- DFN
- FAN
- transit network
- aggregation node and RSP handover (PoI).

6.3.1 Customer premises

Key issues

We believe there are two issues to consider when specifying the technical strategy for the customer premises: the demarcation point for the wholesale service, and the number of UNI ports on the CPE. Each of these issues is discussed below.

► *Demarcation point for the wholesale service*

First, it is important to differentiate between two different types of CPE, namely:

- VDSL2 modems, which are designed to terminate the electrical signal originating at the DSLAM
- residential gateways (RGWs), which are designed to provide Wi-Fi access to end-users as well as LAN and telephony ports to allow end-users to connect their devices (e.g. PCs and telephones) with cables.

In general three CPE technology options exist to provide broadband connectivity to end-users:

- *CPE Option 1*: standalone VDSL2 modem owned by the wholesale service provider to terminate the wholesale service, plus standalone RGW owned by the RSP or end-user.

- *CPE Option 2:* combined VDSL2 modem and RGW, a single device owned by the wholesale service provider.

- *CPE Option 3:* physical (i.e. non-electrical) termination of the wholesale service on a wall plate, often referred to as a 'wires only' solution.

Figure 6.15: Location of physical network assets in the FTTN/FTTB network [Source: nbn, 2015]

GLOSSARY

AAS: Access Aggregation Switch
AN: Aggregation Node
BMPT: Branch Multiport
BNG: Broadband Network Gateway

CJL: Copper Joint Location
DJL: Distribution Joint Location
DSLAM: Digital Subscriber Line Access Multiplexer
DWDM: Dense Wave Division Multiplexing

EAS: Ethernet Aggregation Switch
EFS: Ethernet Fanout Switch
FAN: Fibre Access Node
ODF: Optical Distribution Frame

PCD: Premises Connection Device
POI: Point of Interconnect
PoP: Point of Presence
TLS: Telstra

The main advantage of Option 1 (separate VDSL2 modem and RGW) is that the wholesale provider has full control of the xDSL line, and the VDSL2 modem provides a natural demarcation point[76] between the wholesale provider and the RSP – this helps to identify the responsible party when a broadband service fails. However, Option 1 requires two devices in the premises, which is more costly. Also, having two separate devices in the customer premises may affect end-to-end service availability, as the inclusion of an additional device introduces another component into the supply chain that may potentially fail.

Option 2 combines the VDSL2 modem and RGW into a single device owned by the wholesale service provider. This reduces the cost of the overall solution, and still provides the wholesale service provider with full control of the broadband service.

Option 3 is significantly different from Options 1 and 2 as the wholesale provider does not own any devices in the customer premises. Instead, the combined VDSL2 modem and RGW is supplied and owned by the RSP or the end-user, and is directly physically connected to a wall plate. This option significantly reduces the costs associated with the wholesale service, but requires the RSP or end-user to supply and connect a CPE that is compatible with the wholesale provider's DSLAM, to operate correctly and identify faults when they occur.

We highlight that Openreach in the UK provides both Option 1 and Option 3.[77] For Option 3, Openreach provides CPE specifications which the RSP or end-user must adhere to if the broadband service is to operate correctly.

► *Number of UNI ports on the CPE*

The previous SoE (December 2010) mandated that all types of CPE (FTTP, FWA and satellite) should support multiple RSPs. The latest SoE (April 2014) does not require nbn to support multiple RSPs in a given customer's premises through a single CPE.

nbn's position

nbn will terminate its wholesale service at a wall plate in the end-user premises and will therefore not provide any CPE (i.e. Option 3 above). Instead, the CPE will be provided by the RSP or end-user. To ensure that the CPE integrates effectively with nbn's DSLAMs, nbn has published the specifications for compatible CPEs, which RSPs and end-users will need to comply with to ensure that they can receive specified levels of support. nbn has also established a process that permits RSPs to register CPE against the published specification, which in turn will allow nbn to better support the use of that registered device on its network.

nbn is also planning to re-use existing copper lead-ins from the Telstra network, whenever these are available.

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[76]   The demarcation point is usually at the LAN port of the VDSL2 modem.

[77]   http://www.sinet.bt.com/sinet/SINs/pdf/498v6p0.pdf for more details on Openreach's products.

Analysys Mason's assessment

We consider that nbn's decision to terminate its wholesale service at the wall plate is prudent and in line with other international operators (e.g. Openreach). Our experience is that RSPs like the option to provide their own network termination device in a single device to end-users, as this enables them to differentiate themselves and allows a single CPE to be installed on the customer premises, which is also preferred by end-users.

The decision of nbn not to provide a network termination device is efficient from a cost point of view as it will remove significant costs from the wholesale solution. It is also efficient for nbn to publish specifications for CPEs provided by RSPs or end-users and establish a process that permits RSPs to register CPE against the published specification. In addition, nbn may also wish to consider initiating a testing programme to validate which CPEs can be supported by its network to provide the required functionalities.

By terminating the wholesale service at the wall plate, nbn will only be able to support the provision of different services by multiple RSPs at the same time in an end-user premises through the use of separate copper pairs. The use of a single NTD to service multiple RSPs is not mandated by the latest SoE.

However, it should be noted that FTTN/FTTB is the only network types for which nbn does not provide any CPE to end-users, meaning that the service provisioning process is different from other network types. nbn has designed a specific service provisioning process for FTTN/FTTB to account for this.

We also believe that re-using lead-ins from Telstra whenever possible is prudent and efficient, as it will accelerate the provisioning process and will be cost-effective.

6.3.2 CAN

Key issues

The SoE states that nbn has flexibility and discretion in operational, technology and network design decisions, within the constraint of a public equity capital limit of AUD29.5 billion.

nbn is in the process of acquiring some of the assets from Telstra's CAN, which will become the basis of nbn's FTTN/FTTB access network. The condition of this CAN will significantly influence the performance levels that nbn will be able to deliver. Where the copper infrastructure is of insufficient quality to provide the required broadband services, new copper cables and joints will need to be installed. Also, as explained in Section 3.2.1, certain components which were introduced by Telstra to support legacy voice services may need to be removed, to ensure nbn can provide services which are compliant with the SoE. These components include bridged taps, party lines and pair-gain systems, and loading coils.

In addition, it is expected that in some areas there will not be enough cable pairs to serve all customer premises. In these areas, new copper cables will have to be deployed containing an increased number of copper pairs.

nbn's position

nbn will endeavour to re-use the existing Telstra infrastructure as much as possible where technically and financially feasible, to help ensure that its network design and operation is prudent and effective. However, it may not always be possible to re-use the existing copper cables as they may be faulty or not be suitable to provide VDSL2-based services. nbn has already identified this issue and its current strategy is to rehabilitate different components of the CAN network, in two different stages: rehabilitation before the ready-for-service (RFS) date, or post-RFS rehabilitation. This strategy is designed to minimise the capital investment in the copper network.

Pre-RFS rehabilitation will include the removal of pair-gain systems, as nbn believes that pair gain systems may not allow it to deliver the minimum speed tier (i.e. 25/5Mbit/s) specified in the SoE to end-users. Lines affected by pair-gain systems will initially be identified based on the plant records provided by Telstra.

Once the network is operational in a particular area and provides at least the minimum expected service tier (i.e. 25/5Mbit/s), post-RFS rehabilitation will further improve the performance of the network by:

- removing loading coils
- replacing faulty cables and joints
- replacing untwisted aerially deployed cables
- replacing faulty pillars.

The network components that are causing degradation in performance will be identified by physically testing each of the copper lines once they are in service.

nbn also plans to augment the CAN in areas where not enough copper pairs are available. The key principles in augmenting the CAN will be as follows:

- Faulty copper cables will be replaced on a like-for-like basis (i.e. faulty aerial cable will be replaced by new aerial cable, and faulty underground cable will be replaced by new underground cable).

- A cable section will be augmented with a cable that has a sufficient number of copper pairs to accommodate growth of 20% (assuming utilisation not greater than 80%), and will allow for at least two copper pairs per premises located in the cable serving area.

- Where augmentation is required for only a section of a cable area, all the cables in the section not augmented will allow for at least one copper pair per premise located in the cable serving area.

- Copper cable sizes for underground deployment will be 2, 10, 30, 50, 100, 200 or 400 pairs.

- Copper cable sizes for aerial deployment will be 2, 10, 50 or 100 pairs.

Analysis Mason's assessment

We believe that nbn's decision to maximise the re-use of the existing Telstra CAN is both prudent and efficient. The CAN is already deployed, so nbn will avoid costs associated with civil engineering and expedite the RFS date, should Telstra's records be accurate.

We also believe that nbn has correctly identified the primary types of remedial work that are likely to be needed on the CAN to ensure the required performance of VDSL based services. The two-stage rehabilitation strategy is efficient, ensuring that no undue investment will be needed to deliver the minimum service bandwidth stated in the SoE. However, the plant records from Telstra may be inaccurate in locating the lines affected by components which have an adverse effect on performance, which may lead to longer provisioning times as unforeseen components may have to be removed to ensure that the line can, in fact, deliver the minimum service required.

We believe that the principles guiding the augmentation of the CAN are sound and will lead to efficient use of funds.

However, at this stage, nbn does not have enough empirical evidence or data on the Telstra network to be able to evaluate the extent to which remedial and augmentation work will be required. Depending on the local condition of the CAN, if the extent of remedial and augmentation work is significantly different from what has been allowed for, then this may potentially raise cost issues from both a capex and opex perspective. However, as the network roll-out proceeds, further real data regarding the condition of the CAN will become available which may enable nbn to change its strategy as required to reduce its costs.

6.3.3 Street cabinets/pillars and MDU basement location

Key issues

We define a DA to be an area comprising a group of premises connected to a single PCP pillar. The set of DAs served by the same DFN is defined as a service area module. Therefore, a FAN will serve several service area modules.

The positioning of the DSLAM cabinet is a compromise between the broadband bandwidth that can be achieved at the customer premises and the number of end-users which can be served from a single cabinet. In general, allowing a larger distance between the cabinet and the customer premises means that the cabinet can be used to serve more premises. Fewer cabinets will be then deployed to serve the premises in a particular area and consequently the deployment is more cost-effective. However, the greater distance between the cabinet and the customer premises leads directly to lower broadband bandwidth available at that premises due to the progressive signal attenuation along the length of the copper loop. Therefore, when designing its FTTN network, nbn has to carefully consider the location of street cabinets to host the DSLAMs. It needs to:

- consider suitable existing locations for interconnecting with the CAN
- optimise the number of customer premises served from a single cabinet/DSLAM
- ensure the copper loop length between the DSLAM and the customer premises is of an appropriate distance to be able to deliver the broadband bandwidth advertised

- endeavour to minimise costs by maximising the re-use of existing infrastructure.

nbn's position

In the FTTN network, nbn will deploy new street cabinets to host the DSLAMs (ideally, to minimise costs, these new cabinets should be located close to existing PCP pillars to cost-effectively gain access to the copper loops). As mentioned previously, nbn is planning to use two types of DSLAMs (i.e. the ISAM 7330 hosted in a cabinet and the ISAM 7367 SX-48 hosted in a pillar). These DSLAMs will be interconnected to the existing CAN following the below decision flow chart:

Figure 6.16: Decision flow chart for interconnection to the CAN [Source: Analysys Mason, 2015]
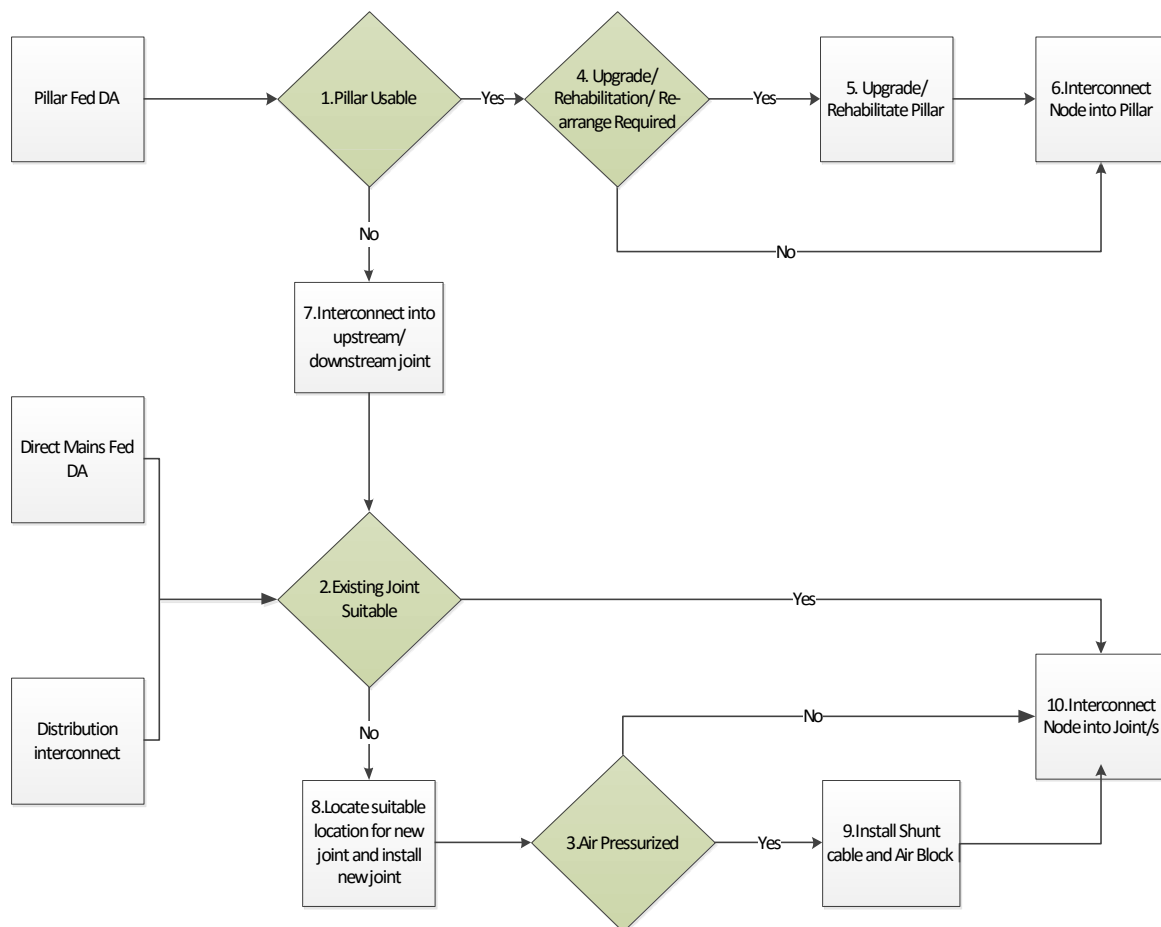
► *Location and connection of DSLAMs*

The interconnection between the DSLAMs and the CAN will be at the following locations (in order of preference):

- For the FTTN network:

  – at an existing PCP pillar location
  – at an existing joint or control joint

– at a newly installed joint.

- For the FTTB network:

  – at an existing MDF within an MDU building
  – at an existing joint or control joint
  – at a newly installed joint.

nbn anticipates that in the majority of cases the DSLAM will be connected to the existing PCP pillar. If the pillar requires remedial work or needs augmenting, nbn will rehabilitate or upgrade it. However, if the pillar is not useable, such as if there are no suitable nearby locations capable of accommodating a node cabinet, nbn will look for a suitable joint to interconnect the street cabinet DSLAM to the CAN. If no such joint is available, a new joint will be created.

► *Design rules to provision the minimum 25/5Mbit/s service*

Once a suitable position for the DSLAM cabinet has been found, nbn has to ensure that the copper loop from the DSLAM can achieve the minimum downlink bandwidth of 25Mbit/s, to comply with the SoE. As the network is being designed on an area-by-area basis, nbn will analyse the attenuation along each copper loop within each DA. Based on the expected characteristics of Telstra's CAN, nbn has determined the maximum attenuation per line for meeting different uplink and downlink bandwidth requirements, compatible with meeting the uplink and downlink bandwidth targets for the various speed tiers (see Section 6.1.1). It should be noted that the attenuation values provided assume the use of vectoring technology.

Figure 6.17: Maximum attenuation for different bandwidth requirements [Source: nbn, 2015]

Peak speed for downlink/uplink	Maximum attenuation at 3.75MHz
<25/5Mbit/s	>50dB
Potentially 25/5Mbit/s	>43dB ≤50dB
25/5Mbit/s	>27.5dB ≤43dB
50/20Mbit/s	≤27.5dB

As shown in the table, to provide the minimum 25/5Mbit/s service, the attenuation of the copper loop must be 43dB or less. Since the network is designed to meet the minimum Australian Government requirements of 25Mbit/s in the downlink and 5Mbit/s in the uplink for 100% of premises, 43dB attenuation represents an upper limit. nbn has defined a number of design rules to ensure 100% of premises can obtain the minimum 25/5Mbit/s service:

- Lines with an attenuation of 43dB or less will be served from the DSLAM in the street cabinet as they achieve the minimum requirements.

- Lines with an attenuation of between 43dB and 50dB are considered to be 'marginal', as nbn believes they could potentially achieve the minimum 25/5 line speed, depending on the individual characteristics of each line. These lines will be served by the newly installed DSLAMs in street cabinets, but rehabilitation or augmentation of the copper loops may be

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considered for these lines to ensure they meet the minimum 25/5Mbit/s requirements, if a compact DSLAM is not being deployed close to these lines (see next bullet).

- Lines with attenuation in excess of 50dB cannot meet the minimum bandwidth requirements. Where more than 20 lines in a particular area have an attenuation of more than 50dB, nbn will deploy an ISAM 7367-48SX (a compact DSLAM with 48 ports) to serve these lines. These DSLAMs will be deployed on pillars or in manholes.

Figure 6.18: Deployment of an ISAM 7367-48SX for line with attenuation more than 50dB [Source: nbn, 2015]
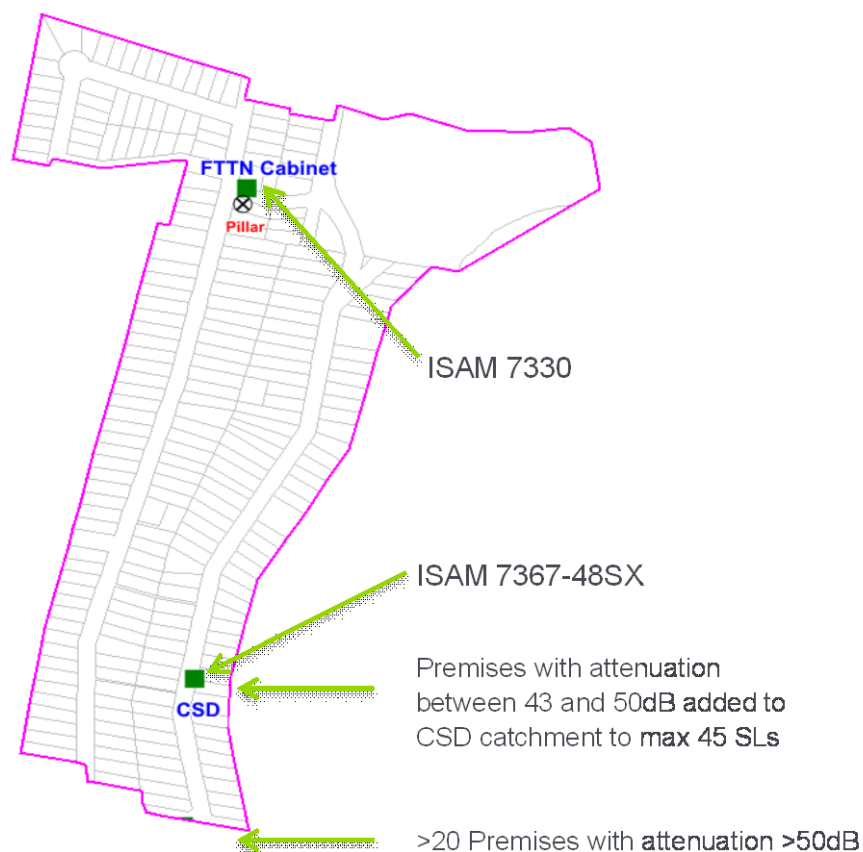
Also, when a compact DSLAM is deployed, any nearby lines with attenuation between 43dB and 50dB may also be served by this DSLAM, to ensure these lines will also provide the minimum 25/5Mbit/s service.

When fewer than 20 lines have attenuation in excess of 50dB in a given DA, it will not be economically viable for nbn to deploy an additional compact DSLAM to serve them. Instead, nbn will investigate, on a case-by-case basis, whether remedial work could be carried out to improve copper quality and reduce the attenuation of the lines. nbn is still investigating the best possible solution to cost-effectively address cases where fewer than 20 lines in a DA have attenuation greater than 50dB.

► *Expected service performance*

Based on the above design rules and on the available information from Telstra on the CAN, nbn has estimated the distribution of uplink and downlink bandwidth for premises served with and without the deployment of compact DSLAMs. Note that this analysis is based on Layer 2 traffic, which includes overhead data which is not used to transmit end-user data, and therefore the actual bandwidth that end-users will experience will be slightly less than that shown.

Figure 6.19: Distribution of expected bandwidth provided to FTTN/FTTB served premises with and without the deployment of compact DSLAMs [Source: nbn, 2015]
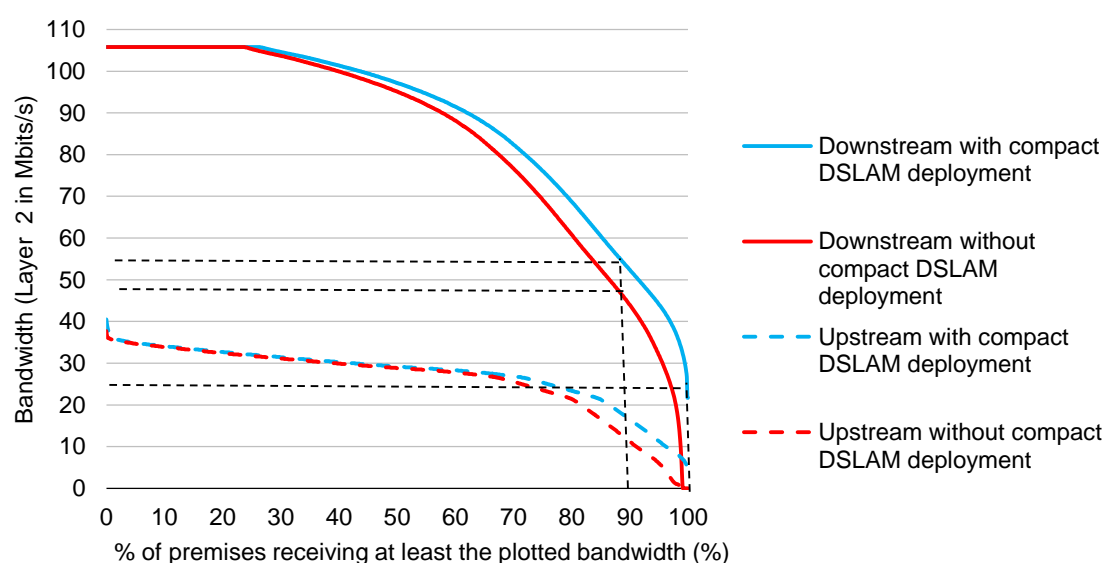
It can be seen that if compact DSLAMs are not deployed to serve lines with attenuation greater than 50dB, 97% of premises will receive a downlink bandwidth of 25Mbit/s or more, and 86.6% will receive 50Mbit/s or more. By deploying compact DSLAMs, 100% of premises will be able to receive 25Mbit/s or more in the downlink, and 91.3% will be able to receive 50Mbit/s or more. From this analysis, it is obvious that if nbn wants to meet the Australian Government objectives, compact DSLAMs will have to be deployed according to the design rules described above.

Analysys Mason's assessment

We believe that nbn's decision to maximise the re-use of Telstra's PCP pillars and implement separate street cabinets for the FTTN network to be both prudent and efficient. This approach is adopted by many incumbents worldwide and therefore represents best practice.

nbn's analysis of the expected bandwidth based on the level of attenuation in the loop is sound, and we agree that nbn will have to deploy compact DSLAMs to serve the longer lines if it is to meet the Australian Government's targets of providing 25Mbit/s in the downlink for 100% of premises upon launch, and 50Mbit/s for 90% of premises as soon as possible. In fact, the proposed design will achieve both objectives after the co-existence period.

However, we highlight that nbn has based its calculations on Telstra's records of the characteristics of the CAN, so nbn is reliant on these records being accurate. As nbn starts operating the network, it will be able to collect actual data on the CAN and adjust its strategy if records are not correct.

6.3.4 Distribution fibre network

Key issues

The DFN provides fibre connectivity between the FAN and DAs. The DFN was designed to be agnostic to the access technology being used, and will allow the following access networks to be connected: FTTP, FTTN, FTTB, HFC, FWA.

nbn's position

nbn will design and build its own DFN for the FTTN/FTTB access networks to connect each of its DSLAMs to a FAN. The DFN is configured in a star topology, which means that the fibre path connecting the FAN and the DSLAM will be unprotected (i.e. not resilient). nbn's key design principle for the DFN is to re-use existing infrastructure (e.g. ducts) as much as possible. This will mean using Telstra ducts wherever technically feasible, and implies that the cost of the DFN will have a direct relationship with the level of spare duct space in appropriate Telstra ducts.

The architecture of the DFN is illustrated in Figure 6.20 below; it comprises five segments:

- DFN aggregation (where required)
- DFN trunk
- DFN branch (where required)
- DFN feeder
- hub sheath distribution.

Figure 6.20: Logical architecture of the DFN [Source: nbn, 2015]
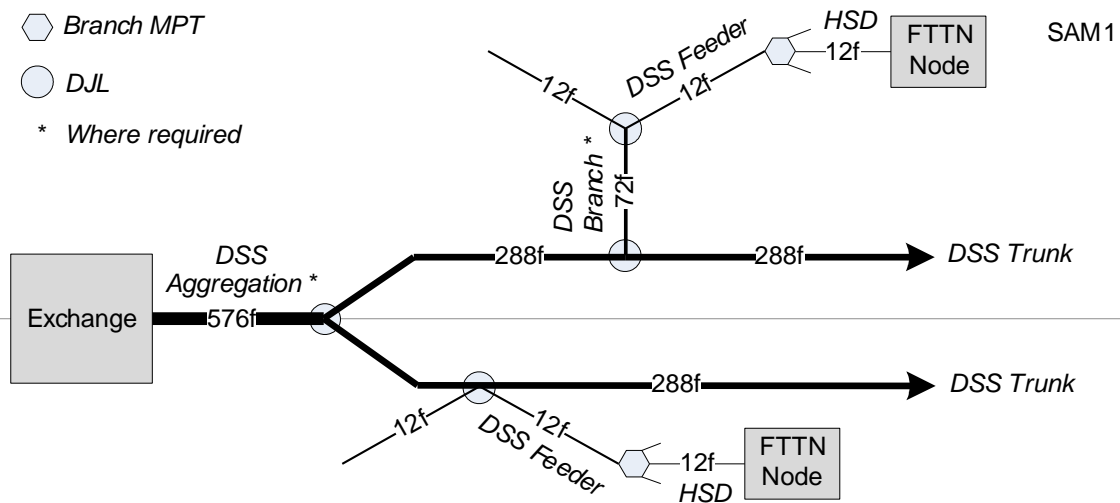
► *DFN aggregation*

This segment aggregates fibres from different service area modules. nbn uses standard cable sizes for the DFN aggregation segment which vary between 288 and 864 fibres, depending on the number of DAs. Aggregated DFN cables are terminated on the optical distribution frame at the FAN. It should be noted that the DFN is designed in such a way that a single fibre break would not affect more than 4000 end-users.

► *DFN trunk*

The DFN trunk cable will typically follow the existing Telstra main duct route, and extend to the furthest point in the service area module. nbn uses standard size cables for DFN trunk cables which vary between 144 and 432 fibres.

► *DFN branch (where required)*

nbn uses a DFN branch cable only when the DFN feeder or the hub sheath distribution connection between the DFN and the DSLAM cannot connect directly to the DFN trunk cable in a cost-efficient manner. Each branch cable is designed to serve no more than four DAs. nbn uses 72-fibre cables for the DFN branches. If a 72-fibre branch cable is installed to serve four DAs, then 24 spare fibres will be available across the four DAs for future use (assuming each DA is assigned 12 fibres).

► *DFN Feeder*

A DFN feeder cable is used between the branch distribution joint (referred to as DJL in the above figure) and branch multiport. nbn uses 12-fibre cables for the DFN feeder. Each feeder cable serves a single branch multiport (i.e. is capable of serving more than one node).

► *Hub sheath distribution*

The connection between the DFN and a single node (e.g. DSLAM) is referred to as the hub sheath distribution. nbn uses a 12-fibre cable to connect to the DSLAMs. It should be noted that two fibre pairs are dedicated to connect each DSLAM (i.e. two Gigabit Ethernet connections). In the future the ISAM 7330 DSLAMs will be able to support a Gigabit Ethernet backhaul connection on a single fibre, which will free up more fibre at the DSLAM.

Analysys Mason's assessment

We believe that the architecture of the DFN is prudent and efficient from a resiliency and scalability perspective. In terms of resiliency, the DFN is designed in such a way that a single fibre break would not affect more than 4000 end-users. This is prudent compared with industry standards (in our experience, operators generally design their network so that a single point of failure affects between 5000 and 40 000 end-users).

In terms of scalability and ease of upgrade, the provisioning of a 12-fibre cable to connect the DSLAM to the FAN is prudent. It means that there are currently 10 spare fibres at the node, which facilitates a number of upgrade options for nbn. These can be used either for point-to-point fibre connections or to upgrade the FTTN network to a GPON FTTP network, or for additional capacity on the DSLAM, if required.

Also, the use of the same design rules for different types of access network leads to consistent planning, and makes it relatively easy to upgrade the FTTN network to FTTP if this is required.

6.3.5 Fibre access node

Key issues

In general, incumbents' FANs (often referred to as 'local exchanges') are located to serve a particular area in an optimal way from a physical/geographical perspective. Furthermore, duct infrastructure for a particular area is generally configured to terminate in local exchanges. Given this situation, it is common for incumbents to provide co-location services in their exchanges, usually in the form of a lease arrangement whereby client operators can co-locate their equipment and connect it to the incumbent's infrastructure (e.g. copper lines).

From the point of view of the alternative operator, it is important to ensure that the contract terms provide sufficient notification time in the case where the incumbent plans to close the exchange (the operator will then need to relocate all of its active and passive equipment to an alternative site). In the case of nbn, which uses co-location space in Telstra exchanges, the situation would be further exacerbated by the fact that nbn's DFN uses Telstra's ducts, which all terminate in the exchange (FAN). If a FAN were to be closed, nbn might have to carry out major civil works to connect its FDN to a new FAN location.

nbn's position

nbn has a long-term contract with Telstra to use co-location space within selected FANs for nbn to host its equipment.

nbn plan to use FANs for three main purposes:

- to terminate its DFN to the DSLAM
- to host AASs
- to host WDM equipment, if appropriate.

Analysys Mason's assessment

We believe that nbn's use of co-location space in Telstra's FANs (exchanges) is both prudent and efficient. This is because the FANs are already operational facilities and are therefore fit for purpose to host passive and active equipment. The FANs also provide natural locations for the installation of aggregation nodes in the network, upon which all the infrastructure converges – this will enable a rapid network deployment.

We understand that nbn's arrangements with Telstra provide for long-term access to FAN sites, minimising the risk associated with the potential closure of FANs were nbn operates.

Analysys Mason usually recommends operators to aggregate traffic as soon as practically possible within their networks as this saves capacity further downstream. We therefore believe that aggregating the traffic from all DSLAMs connected to a FAN into an AAS is efficient.

6.3.6 Transit network

The architecture of the transit network was reviewed as part of our previous report[78] and we understand that no material changes in terms of architecture and design has been made for the implementation of the MTM strategy. Therefore we have not re-assessed the transit network.

6.3.7 Aggregation node and PoI

The architecture of the aggregation node and PoI was reviewed as part of our previous report. In this section, we only comment on new information made available by nbn regarding aggregation nodes and PoIs noting that the architecture of the network in the POIs is not dependent on the nature of the access infrastructure connecting to it.

nbn's position

nbn is planning to deploy two EASs at each POI which will aggregate the traffic from all types of access networks (i.e. FTTP, FTTN/FTTB, HFC, FWA and satellite), plus EFSs which will provide the interface for RSPs to interconnect to the nbn network. As mentioned previously, nbn plans to

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[78]   *Review of the efficiency and prudency of NBN Co's fibre and wireless network design*, Analysys Mason, Sept 2012.

provide redundant EASs and EFSs to ensure that there is no single point of failure in the POI. nbn will make available 1GE or 10GE interfaces to RSPs to interconnect to the network.

Analysys Mason's assessment

We consider nbn's approach regarding aggregation nodes and POIs to be prudent and efficient, as it is agnostic as to the different types of access networks deployed in different areas, and therefore results in a unified architecture and consistent interconnection points for RSPs.

7 Review of the efficiency and prudency of nbn's HFC network design

In this section, Analysys Mason sets out its assessment of whether nbn's design for its HFC network, based on the strategy of taking ownership of some of the existing assets that comprise the Telstra and Optus HFC networks, is efficient and prudent. Many decisions have to be made as part of the development of an efficient and prudent HFC network architecture and associated infrastructure. The key choices can be grouped as follows:

- *Technology choices* which relate to the roll-out strategy in accordance with the broadband requirements of DOCSIS for HFC networks.

- *Architecture choices* relating to the allocation of resources, topology and dimensioning of the network, taking into account any constraints of the existing networks.

- *Infrastructure choices* which relate to the specific components and implementation of the various sections and nodes of the network.

In this section, we consider the following decisions, which we believe will have the most impact:

- Services and technology (assessed in Section 7.1)

  – the ability of the HFC architecture to support nbn's wholesale service portfolio
  – the Layer 2 protocol used for interconnecting with the networks of RSPs.

- Architecture (assessed in Section 7.2)

  – the ability of the end-to-end architecture to meet service requirements while following international best practice
  – HFC spectrum allocation for broadband services
  – network dimensioning to meet service requirements
  – the approach to network resilience (i.e. end-to-end service availability) and ability to meet targets
  – options to increase capacity to meet future service requirements.

- Infrastructure (assessed in Section 7.3)

  – customer premises
  – design rules and roll-out of the coaxial access network
  – optic node
  – DFN
  – FAN
  – transit network
  – aggregation node (including CMTS) and PoI.

Figure 7.1 below summarises the critical decisions faced by nbn in designing its HFC network.

Figure 7.1: HFC network – technology, architecture and infrastructure options [Source: Analysys Mason, 2015]

Key decisions

Services and technology

NBN supported services and access technology → Use of three traffic classes and speed tiers compatible with DOCSIS 3.0 HFC

L2 interconnect technology → Ethernet protocol

Architecture

End to end architecture → Centralised CMTS and existing component re-use

Spectrum allocation → Medium term 24 downstream and 7 upstream channels

Network dimensioning → Target of 500 subscribers per segment

Network resilience and availability → 99.9% availability target

Future capacity upgrade options → Use of node splits, increasing spectrum, DOCSIS 3.1, mid-split

Infrastructure

Customer premises → Part of NBN solution, DOCSIS 3.1 compatible

Coaxial network → Re-use existing networks

Optic node → Re-use existing optic nodes

Distribution fibre network → Re-use existing operator equipment and plant

Fibre access node → Houses RF combiner. FAN leased from Telstra

Transit network → nbn to deploy its own fibre

Aggregation node and PoI → 1G and 10GE handover interface for RSPs

It is the *combination* of these individual design choices and decisions that together determine whether the HFC network design as a whole is efficient and prudent. Therefore, we have assessed the efficiency and prudency of individual design choices and decisions, and have then – based on this assessment – provided our overall conclusion on the extent to which nbn's design is efficient and prudent as a whole.

Finally, we highlight that some of the key decision choices that have an impact upon the efficiency and prudency of nbn's HFC network have been specified or influenced by the Australian Government in its SoE. In accordance with our instructions, this report does not examine the merits of the specifications given by the Australian Government, but instead examines the key choices or decisions that have been made by nbn in the design of its network within the overall parameters established in the SoE.

7.1 HFC services and technology assessment

7.1.1 Supported services and access technology

Key issues

The physical characteristics of an HFC network are fundamentally different to those of an FTTN/FTTB network. For example, the performance of services delivered over HFC architecture is less sensitive to the length of the copper/coaxial cable linking the end-user to the rest of the network. As such, there can be differences in the way services are specified for an HFC network compared to an FTTN/FTTB network.

nbn's position

The services that will be supported by nbn's HFC network are expected to be similar to those described in Section 6.1.1 of this report and comprise the following traffic classes:

- TC-4 based services represent low-priority traffic and are used for non-time-sensitive applications such as web browsing.

- TC-1 based services represent high-priority traffic and are used for time-sensitive applications such as voice services.

- TC-2 based services represent high-priority traffic and are used for symmetrical business applications.

As with services offered over FTTN/FTTB networks, TC-1- and TC-2-based services will be offered with a CIR in areas covered by the HFC network. This means that the end-user can expect to receive at least the stated minimum speed at all times.

By contrast, services based on TC-4 will be provided with a specified PIR. This is different from services offered in FTTN and FTTB areas where high speed tier services (i.e. services with a speed higher than the minimum 25/5Mbit/s) offered by nbn are specified in terms of PIR ranges, based on the characteristics of the FTTN/FTTB network. TC-4 based services expected to be provided over the HFC network are summarised in Figure 7.2.

Speed tier	Downlink speed	Uplink speed
1	12Mbit/s	1Mbit/s
2	25Mbit/s	5Mbit/s
3	25Mbit/s	10Mbit/s
4	50Mbit/s	20Mbit/s
5	100Mbit/s	40Mbit/s

Figure 7.2: Expected characteristics of TC-4 speed tiers for HFC services [Source: nbn, 2015]

nbn plans to initially use DOCSIS 3.0 to deliver broadband services over the HFC network. However, DOCSIS 3.0 is a highly asymmetrical technology in which the typical downlink-to-uplink bandwidth ratio is 10:1, and this asymmetry is reflected in the services offered by cable operators throughout the world (see Section 4.3 above).

nbn has stated that in the future it is likely to want to launch additional, premium business services with higher headline speeds of up to 1Gbit/s, while maintaining a downlink-to-uplink ratio of 2.5 to 1. These will be in line with the higher FTTP speed tiers, namely 250Mbit/s (downlink) / 100Mbit/s (uplink), 500/200Mbit/s and 1000/400Mbit/s. These form part of nbn's HFC product roadmap, although no dates for release have been formally defined.

nbn has a methodology for forecasting future traffic demand and dimensioning the HFC network accordingly. This estimates the combined future traffic requirements for each service, as described in Section 6.2.3 above, and these forecasts are then used as the basis for its plans to re-configure and upgrade the HFC network to meet evolving traffic demand. DOCSIS 3.0 technology is capable of meeting the foreseeable future speed requirements, and nbn's acquisition of the assets that comprise the Telstra and Optus HFC networks provides a quick implementation route. nbn expects to be able to upgrade its HFC network to meet future network capacity requirements: the upgrade will include physical and logical re-configurations of the network and upgrading it with higher-capacity DOCSIS 3.1 technology in the second half of 2017.

Analysys Mason's assessment

Overall, we consider that DOCSIS 3.0-based HFC networks provide a prudent and efficient way to roll out services that meet the requirements of the services to be provided by nbn. HFC networks using DOCSIS 3.0 are used widely throughout the world to provide *downlink* services equal to or in excess of the speed that nbn will offer as part of its standard product set, and such networks are able to meet the SoE's downlink requirements (as shown in our analysis in Sections 4.3 and 4.5). nbn's traffic forecasting and network dimensioning methodology takes into account the fact that the DOCSIS 3.0 bandwidth available is shared between end-users on each RF segment.

DOCSIS 3.0 is also in principle capable of meeting the maximum *uplink* speed of 40Mbit/s currently planned by nbn, as shown in Section 4.5. However, we highlight that cable operators typically offer services with a downlink-to-uplink speed ratio of 10:1, whereas nbn has a consistent set of wholesale products across access networks where the ratio is as low as 2.5:1. The high ratio normally used by other operators is due to the strongly asymmetric nature of DOCSIS 3.0 and the greater susceptibility of the uplink signal to interference, since it is carried in the bottom part of the HFC spectrum. In particular, there is a risk that nbn will only be able to meet the 40Mbit/s uplink target by carrying out a significant number of network upgrades if there are high levels of take-up of the 100/40Mbit/s speed tier. This will become an even more significant issue if higher-speed services are offered in the future. However, the introduction by nbn of DOCSIS 3.1 in the second half of 2017 will alleviate this risk. This issue is covered in more detail in Section 7.2.3 and 7.2.5.

In addition, the bandwidth requirements of TC-1 and TC-2 traffic need to be taken into account. Both of these services are symmetrical and so will have a proportionally higher impact on the uplink bandwidth available. However, given the small bandwidth requirement of TC-1 traffic and the relatively small numbers of nbn connections that include TC-2 elements (based on estimates provided by nbn), this should not become a key factor in traffic management.

Careful traffic forecasting and a proactive approach to network re-configuration will be an important part of nbn's approach to managing the HFC network. From our discussions with nbn, we are confident that this is well understood and is being incorporated into the company's business and operational processes. The acquisition of some of the assets that comprise the Telstra and Optus HFC networks provides the quickest and most cost-effective route to providing nbn services in areas where these networks have already been deployed, allowing services to be offered as soon as possible and making it a prudent and efficient path to take.

7.1.2 Layer 2 interconnect technology

As described in Section 6.1.3, nbn plans to adopt Ethernet as the Layer 2 protocol to deliver all its wholesale services, across all the different types of access network being deployed by nbn, including the HFC access networks.

Analysys Mason's assessment

As stated in Section 6.1.3, we consider that nbn's choice of Ethernet as a Layer 2 protocol is prudent.

7.2 Assessment of the HFC network architecture

This section provides our assessment of nbn's proposed HFC network architecture, including:

- end-to-end architecture
- spectrum allocation
- network dimensioning
- network resilience and availability
- options for future capacity upgrades.

7.2.1 End-to-end architecture

Key issues

The HFC network is based on the existing Telstra and Optus HFC networks, and will use a combination of the existing infrastructure plus nbn's own equipment. The architecture is summarised in Figure 7.3.

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Figure 7.3: End-to-end architecture of the HFC network [Source: Analysys Mason, 2015]
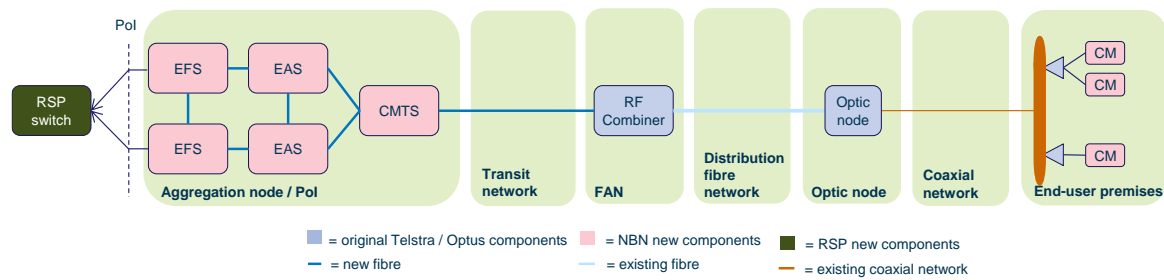
The network will deploy its own cable modem, but utilise the existing access network from the customer premises to the RF combiner, including the coaxial outside plant (including amplifiers and taps) and the optic node. The fibre from the optic node to the RF combiner will be obtained from Telstra and Optus once ownership is transferred to nbn as part of a long-term agreement.

nbn will deploy its own CMTS which will connect to the RF combiner, with fibre backhaul to the PoI for the RSPs being provided via Ethernet switches – EASs and EFSs.

nbn's position

nbn has taken the approach of combining its own backhaul network with the existing access networks. This allows maximum re-use of the extensive existing HFC access network components (covering 4 million customer premises), while enabling the backhaul and interconnect strategy to follow the same rules as for other access networks. The backhaul and interconnect strategy then ensures the alignment of access aggregation regions (AARs), the local area that each customer premises is allocated to, and the connectivity serving area (CSA), which defines the PoI that a particular group of AARs is allocated to. The AARs have previously been defined to align with Telstra's CAN pillar serving areas, which do not necessarily align with the serving areas of HFC optic nodes. nbn's backhaul network is configured to ensure that the AAR/CSA relationship is maintained in line with the original definition, by the use of a service connectivity network routing function in the Ethernet backhaul network.

Analysys Mason's assessment

nbn is being prudent and efficient by maximising the re-use of the existing assets that form part of the Telstra and Optus networks, particularly the access networks from the RF combiner site to the end-users. The cable networks are fundamentally of standard design, similar to other HFC networks throughout the world delivering a combination of broadband and TV services. nbn's decision to make its own arrangements for backhaul from the RF combiner site (i.e. in the transit network), rather than mirroring the existing networks back to head-end sites, is prudent as it will be more cost-effective and will provide nbn with more flexibility for future upgrades. It will also allow nbn to maintain the AAR/CSA relationship.

nbn has good reasons for insisting on the use of its own cable modem (CPE) at the customer premises and the provision of CPE by the network provider in an HFC context is common practice in other markets. However, our experience is that RSPs do like the option of providing their own CPE in a single device as it enables them to differentiate themselves and allows a single CPE to be installed on the customer premises. nbn may wish to move to this model in the future, while stipulating the minimum requirements of the cable modem part of the CPE to meet the requirements of nbn's network.

7.2.2 Spectrum allocation

Key issues

Spectrum allocation needs to be considered in two parts:

- *During the coexistence period* – the 18 months following the RFS date, during which Telstra and Optus will continue to offer broadband and TV services over the same network infrastructure as nbn.

- *After the coexistence period* when the Telstra and Optus spectrum will be handed over to nbn completely (although third-party pay-TV services will still have to be accommodated).

► *During the coexistence period*

During this time, the HFC spectrum will be shared between Telstra/Optus and nbn.

During the coexistence period, nbn has been allocated 16×8MHz channels for its DOCSIS 3.0 downlink on the Telstra forward path. The rest of the spectrum is split between the Foxtel pay-TV service and Telstra's own DOCSIS 3.0 service.

The situation with Optus is more complex. For the downlink, an initial allocation will be made of 64MHz. This will be followed by another contiguous allocation of 64MHz, no later than six months later. For the uplink, Optus will make an initial allocation of 20MHz from the upper end of the upstream spectrum.

► *After the coexistence period*

After the coexistence period, Telstra and Optus will stop offering broadband services directly and will need to take services for their end-users via a wholesale agreement with nbn. Their end-users will therefore need to transfer from a service that uses the Telstra/Optus cable modems and CMTSs to an nbn service using nbn's own new cable modems and CMTSs. The spectrum used for the earlier Telstra services will then transfer to nbn.

At this point, nbn will gain another 128MHz of downlink spectrum from the Telstra DOCSIS service, giving 256MHz of spectrum in total or 32×8MHz channels. nbn will also gain five currently unallocated channels, and will have access to all upstream spectrum between 5MHz and 65MHz. Assuming that spectrum below 20MHz is difficult to use due to interference issues, there

will be enough capacity for 7×6.4MHz, a standard bandwidth for uplink channels. For the Optus network, more than 32×8MHz downlink channels will be provided, plus the uplink frequencies between 5MHz and 65MHz. The Foxtel pay-TV service will continue to be delivered on the Telstra network,[79] although that may change in the future.

nbn's position

nbn plans to use a separate RF segment for each optic node, so all end-users connected to an optic node will share the same bandwidth, but the bandwidth will not be shared with any other end-users beyond that optic node.

nbn's plans for how it will use its spectrum before and after the coexistence period are shown in Figure 7.4 below.

Figure 7.4: nbn planned spectrum usage during and after the coexistence period [Source: Analysys Mason, 2015]

Link type	During coexistence period	After coexistence period
Downlink	**813Mbit/s** (16×8MHz channels at 256 QAM)	**1220Mbit/s** (24×8MHz channels at 256 QAM)
Uplink	**82Mbit/s** (3×6.4MHz channels at 64 QAM)	**192Mbit/s** (7×6.4MHz channels at 64 QAM)

We highlight that initially only eight downlink channels will be available on the Optus network, so the downlink bandwidth will be 406Mbit/s (50.75MHz×8). nbn has no specific plans beyond the coexistence period, but will be looking to make the most appropriate use of the spectrum to meet the traffic demand of end-users. In the longer term, more of the existing capacity may be made available, depending on the plans for the delivery of Foxtel's pay-TV service.[80] In addition, nbn could consider expanding the spectrum either to the limits of DOCSIS 3.0 (862MHz) or to a value defined by DOCSIS 3.1 (e.g. 1214MHz), although there will be network upgrade implications, particularly for network amplifiers (see Section 7.3.2).

Analysys Mason's assessment

We consider nbn's approach to the use of spectrum to be prudent as it makes appropriate use of available spectrum both during and after the coexistence period. nbn will also have the option to expand the use of DOCSIS 3.0 to 32 channels in the downlink, or to introduce DOCSIS 3.1.[81] Future downlink plans will depend on whether the spectrum currently used by Foxtel's pay-TV service becomes available, and whether nbn decides to expand the spectrum to the limits of DOCSIS 3.0 or in line with values specified by DOCSIS 3.1. Network upgrades will be required to accommodate this approach (see Sections 7.3.2 and 7.3.3).

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[79] At the end of the co-existence period, Foxtel's TV services will not be provided on the Optus network.

[80] After the co-existence period, Foxtel's pay-TV services will be available on the Telstra HFC network but not on the Optus HFC network.

[81] nbn has already taken the decision to implement DOCSIS 3.1 in the second half of 2017.

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The use of the maximum 256 QAM in the downlink and 64 QAM in the uplink maximises capacity and is also realistic as the plans do not depend on using spectrum below 20MHz for the uplink (the 0–20MHz range is more susceptible to interference and is likely to only support lower encoding levels and be more susceptible to QoS issues).

The delayed release of eight of the Optus downlink channels will mean that using the first eight channels will only provide 406Mbit/s downlink bandwidth compared to 813Mbit/s on the Telstra downlink. Any capacity issues will need to be monitored, but as initially the number of customers per RF segment is likely to be low, this is unlikely to become a major issue.

During the coexistence period, on both networks the upstream bandwidth will be limited to 82Mbit/s (for all end-users sharing an optic node). This could potentially cause a performance problem, but will be mitigated by not launching TC-2 services until after the end of the coexistence period, meaning it is unlikely to become a major issue (see Section 7.2.3).

It could be argued that it would be more capex-efficient if end-users could continue to use Telstra/Optus cable modems and CMTSs when they migrate their service to nbn, rather than having to install new nbn devices. However, this approach would introduce significant technical design and operational complexity that would very likely have a negative impact on the overall process.

After the coexistence period, Telstra and Optus will stop offering broadband services directly and will need to take services for their end-users via a wholesale agreement with nbn. Their end-users will therefore need to transfer from a service that uses Telstra/Optus cable modems and CMTSs to an nbn service using nbn's own new cable modems and CMTSs. The spectrum used for the earlier Telstra services will then transfer to nbn. We consider nbn's approach to service migration to be prudent and efficient, as it ensures that nbn will not need to support a large range of legacy cable modems that are not able to support high-bandwidth services.

7.2.3 Network dimensioning

Key issues

The key elements that need to be considered for dimensioning HFC networks are the headline speed and the peak average bandwidth required on each RF network segment (in both uplink and downlink directions) to support all the end-users on the segment. We have already discussed the relationship between RF segment bandwidth and headline speeds in Section 4.5, but in the present section, we provide more detail of the nbn context. We also discuss how peak average bandwidth (i.e. average bandwidth required during the busy hour) is determined, and the key issues surrounding this for the nbn network.

nbn is planning for the maximum number of active services per RF segment and optic node to be approximately 500. At present, the number of active services is forecast to exceed this amount in around 42% of Optus's optic nodes that nbn will use and 37% of Telstra's optic nodes that nbn will use.

► *Headline speed*

To put the headline speed requirements into context, we will consider an example of a typical RF segment requirement for TC-1, TC-2 and TC-4 traffic. nbn has developed service take-up forecasts up to 2022. Assuming a typical RF segment covering 500 customer premises and a take-up rate of 75%, this would result in 375 end-users needing to be served.

The TC-1 and TC-2 traffic classes are symmetrical and assume the 'equivalent circuit rate' approach[82] and a reduced reserved bandwidth requirement, as described in Section 6.2.3. To calculate how much bandwidth can be assumed to be available for TC-4 services, the TC-1 and TC-2 bandwidth requirements must be calculated and removed from the bandwidth available. As an example, assuming 50Mbit/s needs to be reserved per RF segment for TC-1 and TC-2, the remaining available bandwidth for TC-4 traffic is provided in Figure 7.5.

This figure of 50Mbit/s may vary and will in particular increase if a particular RF segment area has a high concentration of businesses using TC-4 services, but Figure 7.5 shows the proportion of uplink and downlink traffic that this will represent for the planned DOCSIS 3.0 post-coexistence spectrum usage stated in Figure 7.4 (as we are considering traffic requirements in 2022, we do not need to consider the impact during the coexistence period, which will have ended by then).

Figure 7.5: Impact of TC-1 and TC-2 traffic on available bandwidth per RF segment by 2022 [Source: Analysys Mason, 2015]

Link type	Bandwidth available (Mbit/s)	TC-1 and TC-2 requirement (Mbit/s)	TC-1 / TC-2 proportion of total bandwidth	Remaining bandwidth (Mbit/s)
Downlink	1220	50	4.1%	1170
Uplink	192	50	26.0%	142

We stated in Section 4.5 that cable operators typically offer headline speeds to their end-users at 25% or 50% of the available bandwidth in the RF segment. If we take the more conservative view of 25%, then in this case, nbn would be able to offer speeds up to around 300Mbit/s in the downstream and 38Mbit/s in the upstream. This is comfortably above the headline downlink requirements, but below the uplink speed required for the premium 100/40Mbit/s service. It is also below most of the suggested speeds in nbn's HFC product roadmap for business services, namely 250/100Mbit/s, 500/200Mbit/s and 1Gbit/s/400Mbit/s.

► *Peak average bandwidth per user*

Another important metric related to speed is the maximum sustained bandwidth that can be achieved per user if all users on the same fibre node attempt to use the network in the same way at the same time (i.e. during the busy hour). This is also known as the peak average bandwidth per user. The total peak average bandwidth for an RF segment is the peak average bandwidth per user multiplied by the number of end-users on that segment. At the end of 2014, the typical average

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[82] This calculates the required number of virtual channels of a given bandwidth which would be required for a blocking probability of 0.5%, using the Engset formula. See Section 6.2.3 above.

peak average bandwidth used by end-users in Australia was around 400kbit/s, which compares to around 800kbit/s in the USA and represents a market lag of around two to three years. Analysys Mason forecasts that in Australia the peak sustained downlink bandwidth could rise to around 2.1Mbit/s by 2020.[83] This would equate to just under 800Mbit/s (375×2.1Mbit/s = 787.5Mbit/s) per RF segment assuming 375 end-users per segment. TC-1 and TC-2 traffic is considered in addition to these figures. If we assume the uplink traffic is 20% of the downlink traffic, then this would equate to around 160Mbit/s in the uplink by 2020.

The relation between peak average bandwidth and the bandwidth available after the coexistence period according to nbn plans is shown in Figure 7.6. This assumes a tripling of traffic between 2020 and 2023, and also assumes that nbn will meet its target of 500 premises per RF segment by the end of the coexistence period.

Figure 7.6: Forecast TC-4 peak average bandwidth per RF segment in 2020 and 2023 [Source: Analysys Mason, 2015]

Link type	Bandwidth available (Mbit/s)	Estimated peak average traffic in 2020 (Mbit/s)	Estimated peak average traffic in 2023 (Mbit/s)[84]
Downlink	1220	800	2400
Uplink	192	160	480

It can be seen that based on our forecasts, the proposed post-coexistence RF segment configuration will start to come under pressure soon after 2020 for both the downlink and uplink. This may even happen a little sooner, depending on nbn's approach to providing additional headroom in the network to maintain a high QoS in line with its traffic management product commitments. We note that the TC-1 and TC-2 traffic will also need to be added to these figures (though they will have less of an impact). It will be at this point that the network upgrades described in Section 4.6 are likely to need to be considered.

It should also be noted that while this section specifically examines the traffic requirements of the RF segment, which transports traffic over coaxial fibre cable back to the CMTS, the backhaul from the CMTS will also need to be considered, and upgrades undertaken when additional capacity is required.

nbn's position

nbn intends to reduce the number of customer premises per optic node to 500 by the end of the coexistence period, while its target at the RFS date is 900 customer premises per optic node. nbn is well aware of the need to closely monitor traffic trends and be ready to evolve the network to provide the necessary capacity to address growing traffic demand. To this end, it has developed a detailed traffic model to forecast likely network upgrade requirements on a node-by-node basis, and will use this model to determine when upgrades will be needed. The modelling approach has

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[83]   *Fixed network data traffic worldwide: forecasts and analysis 2015–2020,* Analysys Mason, May 2015.

[84]   Assumes a doubling of demand every three years.

been discussed in Section 6.2.3. It is intended that the model algorithms will develop over time to reflect any ongoing changes to traffic trends, taking into account actual network performance.

Also, nbn is planning to upgrade its network to DOCSIS 3.1 in the second half of 2017.

Analysys Mason's assessment

We believe that nbn's approach to the network dimensioning process is similar to that being taken by cable operators throughout the world, and provides a prudent and efficient approach to upgrading to account for additional traffic capacity in an HFC network.

The RF segment configuration in the post-coexistence period will likely be able to support service demands up to around 2020 in terms of headline bandwidth and peak average bandwidth, if take-up is in line with nbn forecasts and assuming nbn's target of 500 end-users per RF segment is met by the end of the coexistence period. nbn's decision to implement DOCSIS 3.1 in the second half of 2017[85] will ensure that, by 2020, there will not be any bottleneck regarding headline bandwidth.

nbn has also stated it may want to launch premium business services with higher headline speeds of up to 1Gbit/s, while maintaining a downlink-to-uplink ratio of 2.5 to 1. It may be possible to accommodate such services in a limited way, particularly if business usage is mainly during the daytime (most residential end-users are more active during the evening) and where the HFC nodes are typically subject to less load from residential users. Even so, deploying such services with a downlink-to-uplink ratio of 2.5 to 1 may be challenging, and possibly unfeasible for the higher uplink speeds envisaged (200Mbit/s+) without expansion of uplink spectrum in line with DOCSIS 3.1 specifications (as discussed in Section 7.1.1).

From the perspective of peak average bandwidth, Analysys Mason's own forecasts (which broadly align with nbn forecasts) suggest that network upgrades such as node splitting, greater channel bonding or the introduction of DOCSIS 3.1 features are likely to have to be introduced from 2020 – or earlier in areas with particularly high traffic or market penetration. This is in line with nbn strategy to implement DOCSIS 3.1 in the second half of 2017.

It should be noted that this is an 'on-average' assessment: individual nodes may require upgrades at an earlier or later date depending on their actual traffic characteristics. It also depends on nbn achieving its target of reducing the number of end-users per RF segment to 500. It appears that nbn fully understands these issues and intends to address network upgrades as required utilising a prudent combination of traffic modelling and analysis of actual network performance data.

7.2.4 Network resilience and availability

Key issues

As mentioned in Section 6.2.4, nbn has defined the overall end-to-end service availability target to be 99.9% in all areas, and across all the different access networks used. To calculate the overall end-to-end availability across the HFC network, nbn has calculated the end-to-end availability of both the Optus and Telstra networks for a mix of five physical architectures (weighted according

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85   http://www.nbnco.com.au/blog/the-nbn-project/nbn-wraps-up-HFC-pilot-steam-ahead-to-launch.html

to their expected proportion across the network). An overview of the different types of architecture and their occurrence in the network is shown in Figure 7.7.

Figure 7.7: Summary of architecture types used for modelling of end-to-end availability [Source: Analysys Mason, 2015]

Architecture type	Key features	Proportion of overall network
1	Combined FAN and aggregation node with RF combiner, CMTS and PoI to RSPs	17.73%
2	Separate FAN (with RF combiner) and aggregation node with CMTS and PoI to RSPs	40.91%
3	Separate FAN (with RF combiner) and aggregation node with CMTS and PoI. Service connectivity network functionality to address AAR overlap issues where optic nodes cover more than one AAR. Backhaul and PoI for RSPs on separate site from CMTS	0.86%
4	Combined FAN and aggregation node with RF combiner. CMTS service connectivity network functionality to address AAR overlap issues where optic nodes cover more than one AAR. Backhaul and PoI to RSPs on separate site to CMTS	9.52%
5	FAN with RF combiner and CMTS, but separate aggregation node for backhaul and handover to RSPs	30.99%

The two most common architectures are illustrated in Figure 7.8 (Architecture 2) and Figure 7.9 (Architecture 5). In Architecture 2, the RF combiner and CMTS are located on separate sites, with the CMTS being co-located with the PoI. In Architecture 5, the RF combiner and CMTS are on the same site, while backhaul aggregation and PoI are on separate sites.

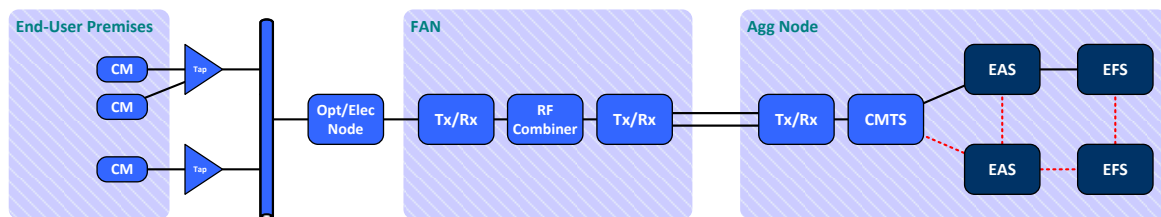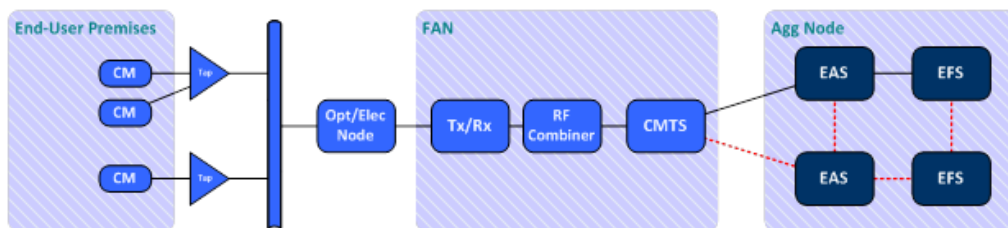*Figure 7.8: HFC end-to-end Architecture 2 [Source: nbn, 2015]*

Figure 7.9: HFC end-to-end Architecture 5 [Source: nbn, 2015]

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The Telstra and Optus networks have been modelled separately as they have different characteristics. The following points are important to note:

- Optus's HFC coaxial network has a 100% aerial deployment between the customer premises and the optic node. Optus has not provided an availability figure for this network, so a figure of 99.9% has been assumed by nbn in the modelling.

- Telstra's HFC coaxial network is 70% underground and 30% aerial deployment for the link between the customer premises and the optic node. Telstra has not provided an availability figure, so 99.925% has been assumed by nbn – this is greater than for the Optus network due to the presence of a significant amount of underground infrastructure.

- Optus has deployed protected RF optics between the optic node and the RF combiner site, while Telstra uses unprotected RF optics in this part of its network. nbn also intends to deploy unprotected optics when it rolls out its own fibre network.

- Telstra's power supplies are mounted on utility poles even when the coaxial network is underground, and are not provided with battery back-up. Optus's power supplies are also mounted on utility poles, but have battery back-up. nbn intends to use battery back-up in relation to the Optus network but does not immediately plan to undertake upgrades to the Telstra coaxial network to introduce battery backup given the acceptable levels of availability that currently exist on that network notwithstanding the lack of battery back-up. nbn plans to review the requirement for battery back-up once the roll-out is complete.

The availability modelling has been completed in two stages, first assuming no power outages and then taking into account power outage factors. We note that the modelling has been undertaken *excluding* any impact on availability from the cable modem, as relevant actual availability data in relation to the types of cable modems that will be used by nbn as a long-term solution are not available at the time of writing.

The results for each of the five architectures, assuming no power outages, are summarised in Figure 7.10. The Telstra network generally exceeds the 99.9% target, but the starting assumption that the Optus HFC access network has an availability of 99.9% inevitably means it will fall short of the target when the other elements of the calculation are added. However, when the values are weighted by the number of premises served by each architecture, the overall availability figure is 99.900%, which meets the target. Unsurprisingly, the best performance is where the RF combiner, CMTS and backhaul components are all on the same site.

Figure 7.10: End-to-end availability by architecture and network type (excluding power outages) [Source: Analysys Mason, 2015]
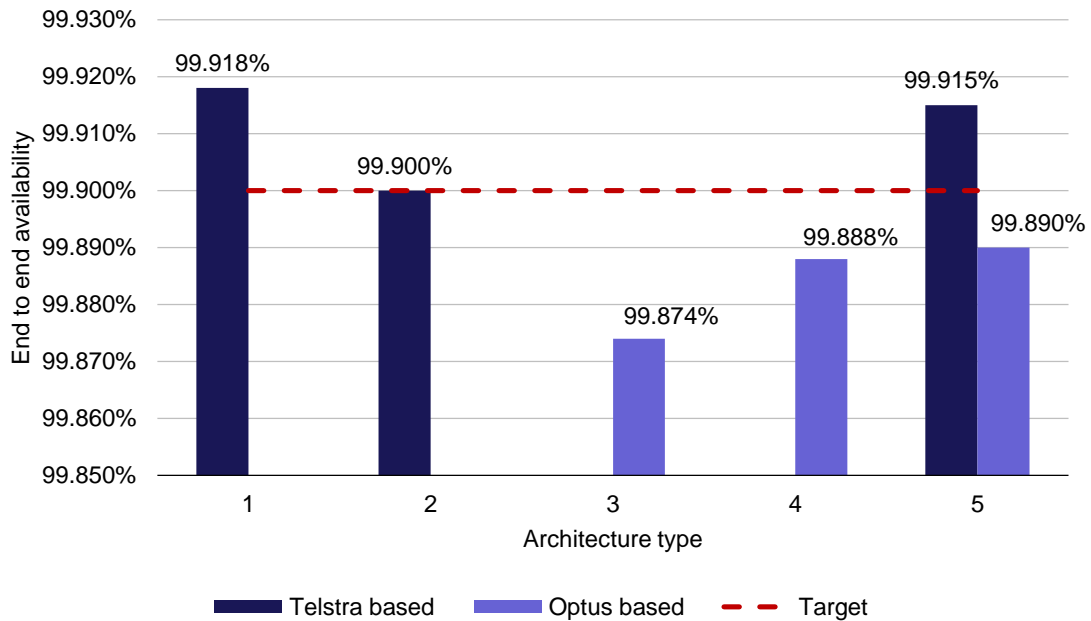
The modelling has also been undertaken taking potential power outages into account. The results are summarised in Figure 7.11, taking into account weighted averages for the contribution of each network. Including power outages in the calculations and using the weighted average, overall HFC network availability is 99.900%. If nbn added battery back-up at each site, this would increase to 99.906%.

Figure 7.11: End-to-end availability by architecture and network type (including power outages) [Source: Analysys Mason, 2015]
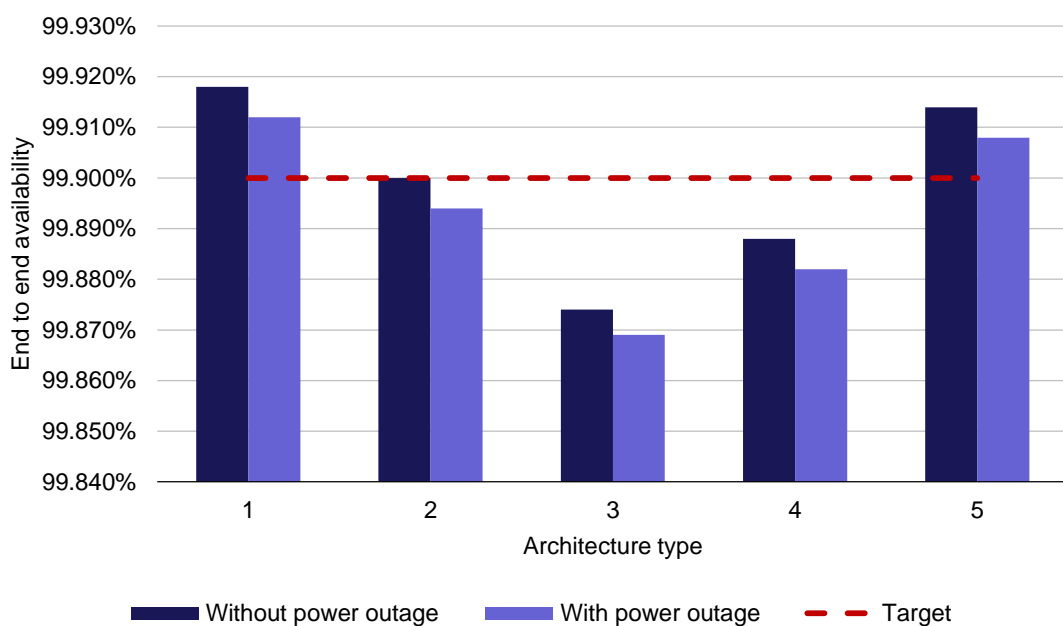
It should be noted that the availability calculations assume the more resilient 'diverse chassis redundancy mode' option, whereas most service providers take the less resilient 'single chassis redundancy mode' option. The use of the 'diverse chassis redundancy mode' option has a slight positive impact on the availability values compared to the version used by most service providers.

The furthest point up the network from the customer premises which presents a single point of failure is the RF combiner. This typically supports eight optic nodes and so its failure or unavailability could have an impact on around 4000 subscribers.

nbn's position

nbn has completed its network availability modelling exercise to the best of its ability considering the information available at this time. It intends to update its model with additional information from Telstra and Optus on the availability of their networks once this information is provided. It will also update the modelling to include the cable modem component when data becomes available.

nbn has also examined the HFC network availability in the context of the overall availability of the FTTP, FTTN, FTTB and HFC networks when battery backup is included. The results of this analysis are summarised in Figure 7.12. As can be seen, if four-hour battery backup is included, overall end-to-end availability in all of the networks comes close to the 99.9% target.

Figure 7.12: Overall network end-to-end availability [Source: nbn, 2016]

Network type	Proportion	Availability (power availability excluded)[86]	Total annual downtime (hours)	Availability (power availability Included)[87]	Total annual downtime (hours)
FTTP	21.48%	99.930%	6.13 hours	*99.930%	6.13
FTTN/FTTB	37.92%	99.893%	9.37 hours	99.852%	12.96
HFC	34.35%	99.897%	9.02 hours	99.877%	10.77
FWA	3.63%	99.894%	9.29 hours	*99.894%	9.29
Satellite	2.61%	99.700%	26.28 hours	*99.700%	26.28
Weighted national availability	100.00%	99.897%	8.99 hours	99.875%	10.96

* Power availability not taken into account.

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[86]   Excludes power availability from all access network technologies. Please note but fixed wireless and satellite availability figures do not take into account power availability as yet.

[87]   Includes power availability for FTTP, FTTN, FTTB and HFC, but using the excluded values for fixed wireless and satellite.

Analysys Mason's assessment

nbn has undertaken network availability modelling to the best of its ability given the level of information available at this time. However, the actual availability figures for the HFC networks of Telstra and Optus have not been made available to date. They are the biggest influencing factors in the availability calculations, and up to this point, nbn has only been able to estimate these values. Therefore, depending on the condition of the actual component networks, the actual availability of the overall HFC network may be different from nbn's estimate. Further information about the availability of the HFC networks from Telstra and Optus will provide the basis for nbn to further develop and refine its availability modelling and to compare against real world data.

In addition, nbn has not yet been able to include in its modelling the availability of the cable modem, which is the element that typically has the highest impact on service and which will inevitability reduce the availability figure further. It should also be noted that the availability calculations assume the more resilient 'diverse chassis redundancy mode' option, whereas most service providers take the less resilient 'single chassis redundancy mode' option. The use of the 'diverse chassis redundancy mode' option has a slight positive impact on the availability values compared to the version used by most service providers.

Overall, nbn's approach to availability in the network design is in line with what we would expect and is a prudent approach. For example, we would not expect resilient links from the optic node to the RF combiner, but we would expect any links between an RF combiner site and a remote CMTS site to be redundantly configured. These are both nbn policies. We also consider it prudent that the RF combiner represents the highest-impact single point of failure in the HFC network, affecting around 4000 end-users. As stated in Section 6.2.4, in our experience, incumbent operators typically design their networks so that a single point of failure will affect between 5000 and 40 000 end-users. In this respect, nbn's decision is prudent.

As the calculations currently stand, nbn is very close to meeting its overall average availability target across all access networks, and we consider that nbn is being prudent in its approach to ensuring network availability targets are adhered to as closely as possible.

7.2.5 Options for future capacity upgrades

Key issues

It is a requirement of the SoE that nbn designs its network to have appropriate upgrade paths to deal with expected growth in traffic demand (see Objective 3 in Section 2.2 above). Over time, end-users' service requirements will evolve to require higher bandwidths from the network. In Section 3.5.2, we considered the likely bandwidth demand of the top percentile of end-users (110Mbit/s by 2020 and 313Mbit/s by 2025) and noted that momentum is growing in developed countries for services of 500Mbit/s and 1Gbit/s.

More specifically, we discussed in Section 7.2.3 that it is highly likely that nbn will need to take steps to provide sufficient capacity in the network. A first step is to ensure that all optic nodes

serve no more than 500 end-users, but further upgrades will be required over time. In Section 4.6, we discussed the various upgrade options open to HFC operators, ranging from the physical re-configuration of a DOCSIS 3.0 network to the introduction of DOCSIS 3.1 functionality.

nbn's position

nbn's detailed design considerations are currently focused on the shorter-term challenges of acquiring some of the assets from the Telstra and Optus HFC networks and setting them up to deliver the required broadband wholesale services. It has not currently defined a detailed roadmap of future upgrades to the HFC network, though it has identified a number of steps that it will consider in future to meet capacity demand, which include:

- re-use of incumbent operator spectrum and ultimately pay-TV spectrum
- roll-out of DOCSIS 3.1, including use of OFDM and OFDMA encoding
- use of D-CMTS to move the RF interface closer to the customer, reducing RF losses and allowing higher encoding levels
- building out nbn's own fibre network (DFN) within the HFC footprint, giving it access to more cost-effective fibre
- optic node splits, either logical node splits at existing optic nodes or by rolling out fibre closer to customers
- increasing the mid-band split to provide additional upstream bandwidth.

nbn will assess the most appropriate upgrade paths depending on network traffic requirements and will identify the most prudent and efficient option to take, bearing in mind the relative costs and benefits. In addition, nbn has also suggested that in the longer term it could ultimately replace the RF section of the network with incremental investments in fibre until an FTTP solution is reached, if market demand for bandwidth required this.

Analysys Mason's assessment

nbn has considered a number of upgrade options for ensuring that the HFC network can continue to meet service requirements as demand for bandwidth increases in the future. In particular, it needs to ensure that demand for *upstream* bandwidth can be met. The options include the potential deployment of DOCSIS 3.1, which will enable nbn to offer downlink services in excess of 1Gbit/s, thereby competing with products offered by FTTP networks.

Understandably, nbn does not yet have detailed plans for the upgrade of its HFC network in the longer term, as it is concentrating on the more immediate challenges of getting the network operational. However, there are a number of DOCSIS 3.0- and DOCSIS 3.1-based options that can be evaluated to determine the most prudent and efficient way to provide more capacity in the future.

7.3 Assessment of the HFC infrastructure

In this section, we consider each of the physical locations in the HFC network, from the customer

premises to the POI, describing the network features that relate to each location and the equipment that is deployed or planned to be deployed there. We consider the following locations, as illustrated in Figure 7.13:

- customer premises
- coaxial network
- optic node
- DFN
- FAN
- aggregation node and RSP handover (PoI).

Figure 7.13: Key infrastructure locations within the HFC network [Source: nbn, 2015]

GLOSSARY

AN: Aggregation Node
AMP: Amplifier
BMPT: Branch Multiport
BNG: Broadband Network Gateway

CMTS: Cable Modem Termination System
DOCSIS: Data Over Cable Service Interface Specification
EAS: Ethernet Aggregation Switch
EFS: Ethernet Fanout Switch

FAN: Fibre Access Node
HFC: Hybrid Fibre Coax
ODF: Optical Distribution Frame
PCD: Premises Connection Device

POI: Point of Interconnect
PoP: Point of Presence
TLS: Telstra

7.3.1 Customer premises

Key issues

The lead-in and cable modem configuration will utilise the existing infrastructure where available, which varies between operators and in the case of Telstra depends on the specific area of the network. The options are shown in Figure 7.14.

Figure 7.14: Configuration options for customer premises* [Source: nbn, 2015]
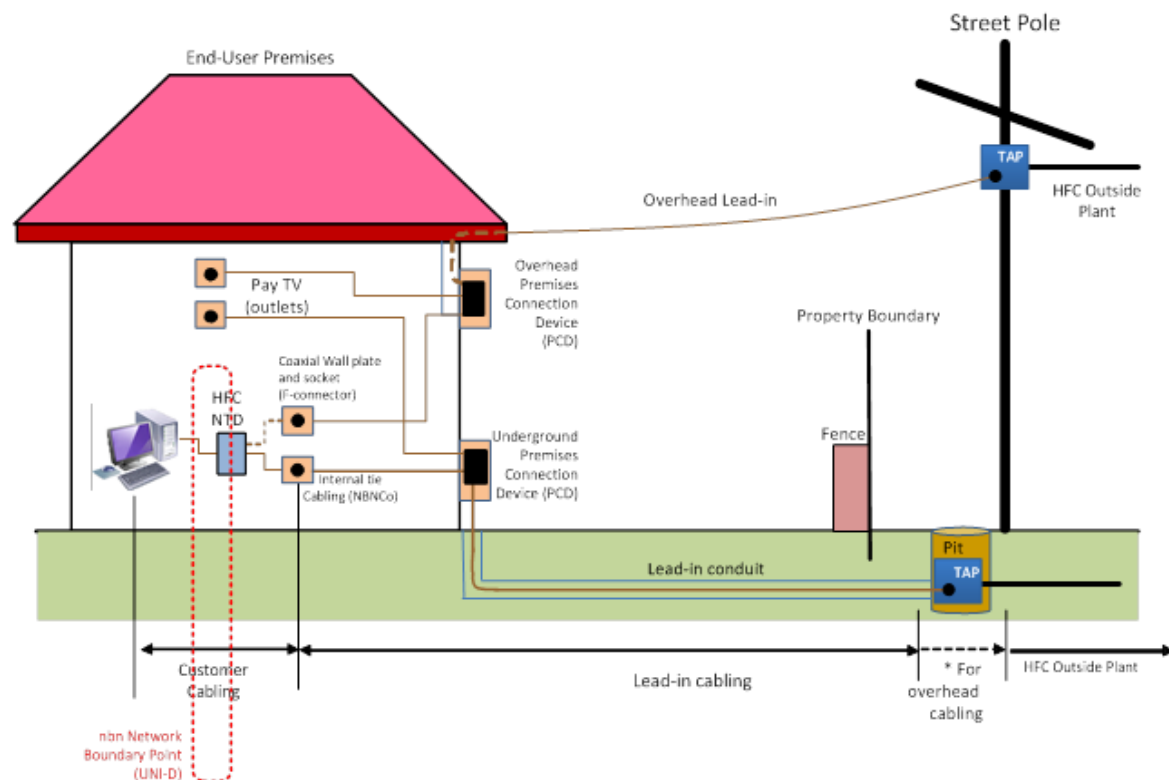
The Optus access infrastructure is deployed entirely overhead and so in each case there is an overhead coaxial lead-in from a network tap on a pole to an overhead premises connection device (PCD).

The Telstra coaxial infrastructure is 70% underground and 30% overhead deployment, and so has a mixture of overhead and underground PCDs. The overhead delivery infrastructure is similar to that of Optus, but underground delivery is from a network tap located in a pit outside the premises via a lead-in conduit, in which the lead-in coaxial cable is deployed. The lead-in cable is standard 0.3- or 0.4-inch cable (depending on the length of the lead-in), with overhead cable also including a messenger wire to ensure a more robust delivery. The same specification equipment is used for both networks.

The PCD is typically located on the outside of customer premises and is the demarcation point between internal and external infrastructure. It contains an isolator that eliminates the risk of

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equipment being damaged by power surges or lightning strikes, as well as a splitter that can be used to split broadband and TV services. An internal tie cable is provided between the PCD and a wall-plate on which a coaxial F-connector is mounted, which the cable modem is connected to.

nbn's position

nbn will utilise the existing lead-ins, PCDs and internal tie cables where possible, and in line with the single HFC network strategy (i.e. Optus lead-ins in Optus-only areas and Telstra lead-ins in other areas) described in Section 5.1.3 of this report. Where such lead-ins do not exist, nbn will use the same methods and components as in the surrounding areas.

nbn has decided to procure its own cable modem to give it control over the functionality of this device and the services delivered to it. The cable modem will be specified to include support for a single RSP. The key requirements are:

- DOCSIS 3.1 capability, which will give the cable modem flexibility for upgrading end-users and managing traffic requirements as they increase.

- Functionality to provide Layer 2 VPN business services over DOCSIS (BSOD), which is used in constructing the Layer 2 wholesale service provided to RSPs.

If end-users or RSPs were allowed to provide their own cable modem then it is possible that products without the above functionality would be used, which could cause operational difficulties for nbn as they would have to support a wider range of cable modems with different levels of speed and functionality.

Analysys Mason's assessment

nbn is taking a prudent and efficient approach to the deployment of customer lead-ins by using existing lead-ins where possible. This will save both time and cost compared to using new connections. Telstra and Optus use industry-standard cables and components, and nbn plans to continue to use the same approach for new network connections, an approach which we consider to be prudent and efficient.

nbn has good reasons for deciding to use its own cable modem. The provisioning of the cable modem by the network provider in an HFC context is not uncommon, though in our experience RSPs also like the option to provide their own CPE in a single device as this enables them to differentiate themselves, and allow a single CPE to be installed on the customer premises. nbn may wish to move to this model in the future, while stipulating the minimum requirements for the cable modem part of the CPE to meet its own requirements.

nbn has decided to limit the cable modem to the support of a single RSP, rather than the multiple RSPs supported for the FTTP service. Support for multiple RSPs is not a requirement in the SoE in relation to MTM services; it does not reflect common practice internationally in the context of HFC deployments and is generally not supported by cable modem manufacturers. It is also the case that end-users still have the option of acquiring additional services through the installation of an additional connection. We also note that the use of multiple ports in the FTTP network has had a limited impact to date due to the nature of wholesale pricing approaches and the buying habits of consumers at the retail level.

7.3.2 Coaxial network

Key issues

In addition to the different mix of underground and overhead infrastructure used by Telstra and Optus, the two operators also take a different approach to the design of their coaxial distribution networks from the optic node to the customer premises. The Telstra plant is based on an N+3 amplifier configuration, where a maximum of three amplifiers are deployed in cascade between the optic node and the customer premises. In contrast, Optus uses an N+5 configuration. These differences are illustrated in Figure 7.15.

Figure 7.15: Architectures of the Telstra and Optus coaxial networks [Source: Analysys Mason, 2015]
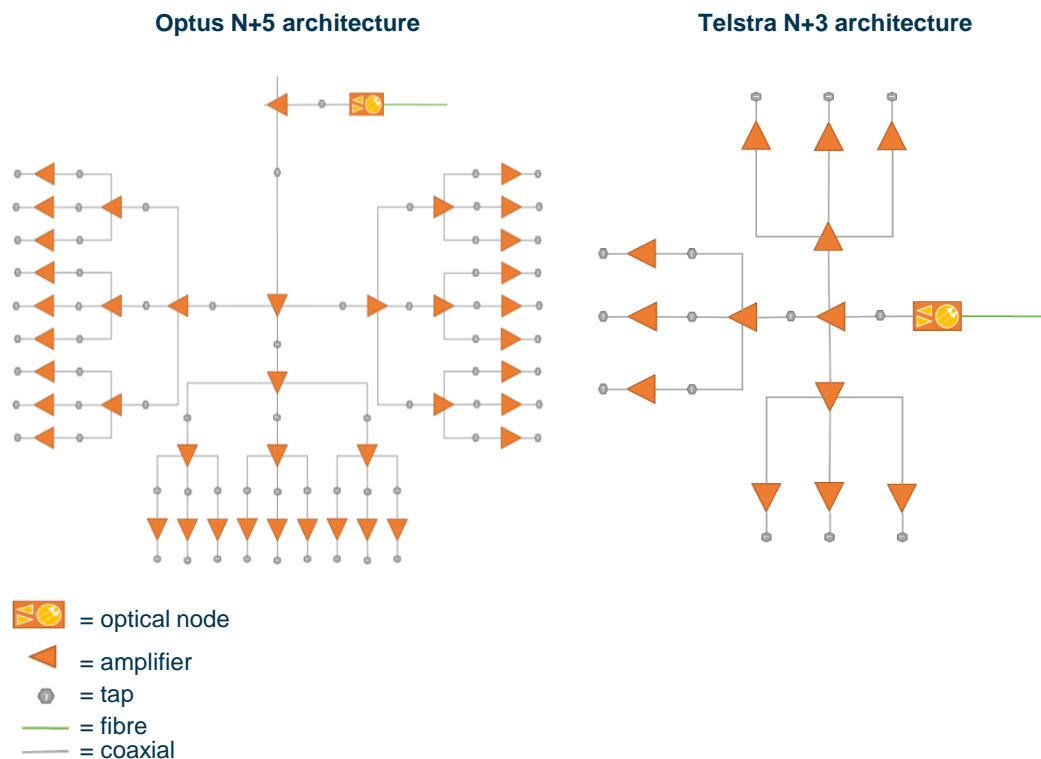
Optic nodes and amplifiers in the HFC plant require external power, which may be provided by local power supplies (if available) or may be transmitted alongside the HFC plant. The Optus optic

nodes have four-hour battery back-up, whereas the Telstra equipment has no battery back-up protection in the coaxial network. nbn plans to review the requirement for battery back-up in the future once the roll-out is complete. The impact on network end-to-end availability of this approach has been described in Section 7.2.4.

The Telstra standard amplifiers are Philips Magnavox models with an upper frequency boundary of 750MHz and a mid-point split of either 65MHz or 85MHz. Telstra has also deployed amplifiers in apartments that have an upper frequency boundary of 862MHz, also with a 65MHz or 85MHz mid-point split. The specifications of the Optus amplifiers are not yet available.

Network taps are situated at the location where the customer premises drop cable connects to the HFC coaxial distribution network. The taps come in two-, four-, and eight-way variants, and the version deployed depends on the number of customer premises to be serviced from the tap location.

Telstra and Optus use a mixture of gauges of overhead and underground cables depending on specific requirements. For example, for longer cable runs, wider-gauge cable is used to reduce losses. In the Telstra coaxial network, the most commonly used cable is CX-50, which has a gauge of 0.5 inches. Optus's most commonly used cable is CX-625, which has a wider gauge of 0.625 inches.

nbn's position

nbn intends to re-use the existing Telstra and Optus coaxial networks in their current form. nbn does not currently plan to provide battery back-up at the Telstra power nodes in light of the already acceptable levels of end-to-end availability achieved by the Telstra network in the absence of battery back-up. nbn plans to review the need for battery back-up in the future.

For any new build that it undertakes, nbn plans to deploy equipment that will support a wider spectrum plan, with an uplink spectrum range of 5MHz to 85MHz and a downlink range of 105MHz to 1GHz. It also wishes to deploy an N+1 amplifier architecture to decrease the noise floor of the uplink path.

Analysys Mason's assessment

nbn intends to use parts of the existing Telstra and Optus coaxial networks to provide its services, and this is a prudent and efficient approach to roll-out as it uses the existing spectrum plans and makes extensive use of existing infrastructure.

The designs of the two coaxial networks differ, but both are within the bounds of standard design practice and will meet short- and medium-term bandwidth requirements. The Telstra N+3 amplifier design is preferable to the Optus N+5 design as it will more readily support higher encoding schemes, and hence greater service bandwidth. The limitations of the Optus N+5 design could be overcome by reducing the coaxial section by deploying fibre nearer to end-user premises, but this would need significant investment.

nbn's plans for new-build infrastructure highlight the limitations of the existing infrastructure for offering higher-capacity services in the longer term, particularly in the area of the upper frequency boundary. The current extensive use of 750MHz amplifiers in the Telstra network means that a significant network upgrade will be required if the spectrum is extended in the future in line with DOCSIS 3.1. This may drive nbn to consider other upgrade possibilities such as node splitting and other options discussed in Section 7.2.5, in preference to spectrum expansion. Nevertheless, it is likely that spectrum expansion will need to be considered in the longer term.

At this stage, nbn does not have enough empirical evidence or data on the condition of the Telstra and Optus HFC networks to be able to evaluate the extent to which remedial and augmentation work will be required. Depending on the local condition of the HFC network, if the extent of remedial and augmentation work is significantly different from what has been allowed for, then this may potentially raise cost issues from both a capex and opex perspective. However, as the network roll-out proceeds, further real data regarding the condition of the HFC network will become available which may enable nbn to lower its costs.

7.3.3 Optic node

Key issues

The optic node is the aggregation point for all customer premises to be connected to the coaxial plant in the area that it serves. It is the demarcation between the coaxial cable plant and the optic cable plant and converts between optic and electrical signals for the downlink connection, and vice versa for the uplink connection. There are currently around 6000 optic nodes across the HFC footprint.

We understand that both Telstra and Optus are upgrading their optic nodes to Arris Optimax OM4100 equipment, which supports up to 1000MHz downlink capacity and various uplink splits up to 105MHz (the equipment can be upgraded to support different band splits). The product also supports up to four RF segments per optic node, and supports CWDM multiplexing on the RF optic fibre so that all RF segments can be backhauled on the same fibre. The support of higher uplink and downlink frequencies will help with any future spectrum expansion plans, while the support of multiple RF segments will be useful for node splitting.

Telstra is upgrading from legacy Philips Diamond Hub equipment while Optus has been upgrading from Antec equipment, although exact details of what proportion of the network has been upgraded have not been made available.

The optic nodes are either located on a utility pole (for the overhead infrastructure) or in a pit (for underground infrastructure).

nbn's position

nbn is planning to re-use the Telstra and Optus optic nodes for the initial deployment, but expects the number of nodes to grow as the numbers of end-users per RF segment are reduced and capacity

requirements increase. nbn estimates that the number of optic nodes will increase to between 12 000 and 14 000 by 2021.

Analysys Mason's assessment

nbn is taking a prudent and efficient approach by re-using the existing optic nodes from Optus and Telstra, which are industry-standard deployments. Where nbn undertakes upgrades to optic nodes to newer equipment as per its current plans, then this should enable nbn to undertake subsequent upgrades such as node splitting and spectrum changes without changing the optic node equipment. We expect that this will help to provide cost-efficient upgrades relative to a situation where nbn is re-using existing nodes from Optus and Telstra.

We expect that for its new optic nodes, nbn will deploy nodes that can facilitate capacity upgrades, making possible re-configuration activities such as changing the mid-split and expanding the spectrum band without the need for additional physical equipment upgrades. This will ensure that such upgrades can be conducted in a prudent and efficient manner.

7.3.4 Distribution fibre network

Key issues

Within the overall nbn network, the DFN delivers fibre between key outside plant locations. In the HFC network, it connects the RF combiner and the optic node, and this will initially consist of fibre supplied by Telstra and Optus.

Optus has installed its fibre between its optic nodes in a ring configuration, providing resilience in the event of a fibre break between the optic node and the RF combiner. Telstra, however, has deployed logical point-to-point links and so does not have this level of resiliency.

The optical-to-electrical conversion equipment is part of the optic node and is a specific piece of equipment at the FAN (see Section 7.3.5).

nbn's position

Initially, nbn plans to acquire access to Telstra and Optus single fibres to connect its RF combiners and the optic nodes. In the future, nbn may deploy its own fibre if it is required either for additional capacity or for other architectural reasons. This approach may also be more cost-effective than taking dark fibre from other operators. If this does happen, nbn does not intend to follow the Optus approach of providing resilient links, but rather will provide logical point-to-point links (Telstra's approach). nbn's approach to future DFN deployment is described in Section 6.3.4.

When nbn lays fibre to an optic node via its DFN, it plans to allocate 12 fibres per optic node (four fibres for the node itself, four for a nearby FTTB site and four spare).

Analysys Mason's assessment

nbn will initially utilise existing Telstra and Optus fibre to connect the RF combiner and the optic node. We consider this approach prudent and efficient as it will enable service to be established quickly and cost-effectively as no additional capital investment will be required.

nbn may deploy its own fibre if more capacity is required in the future (e.g. due to node splitting, which will require one additional fibre per new optical node). This approach may also be more cost-effective than taking dark fibre from other operators. We consider this a prudent and efficient approach to future fibre deployment.

We note that when additional fibre is required, nbn intends to follow the Telstra approach to DFN network deployment, using a point-to-point architecture rather than the more resilient ring approach of Optus. This will provide the most efficient approach, but nbn does need to consider network resiliency targets and might need to reconsider its approach if there were any future changes to the network resilience strategy as the result of more data on the availability of the Telstra and Optus networks becoming available (see Section 7.2.4).

7.3.5 Fibre aggregation node

Key issues

The FAN is the location of the RF combiner and the optic transmission equipment that connects the RF combiner to the optic node. In some cases, the CMTS is also situated in the FAN, such as in the end-to-end Architecture 4 shown in Figure 7.9 above. The CMTS is covered in Section 7.3.6 below on the aggregation node. There are 261 FAN sites across the HFC footprint within the nbn network.

► *RF combiner*

The RF combiner aggregates services from upstream sources onto a single RF bearer. In nbn's case, the RF combiner will aggregate services from the following sources during the coexistence period:

- nbn CMTS
- Telstra or Optus CMTS
- Optus voice service
- Foxtel pay-TV
- telemetry and maintenance equipment.

► *RF optical transmission equipment*

The optical transmission equipment connects the output of the RF combiner to the optic node via the DFN. It may also be used to carry the signals between the RF combiner and CMTS if they are located on separate sites. In some cases, it can multiplex signals using CWDM to reduce fibre requirements (CWDM functionality is supported by the Arris OM4100 optic node). The Telstra RF optic transmission equipment has the capabilities listed in Figure 7.16.

Figure 7.16: Capability of Telstra's RF optic transmission equipment [Source: nbn, 2015]

Tx / Rx area	Capability
Forward bandwidth	85MHz to 862MHz
Return bandwidth	5MHz to 200MHz
Narrowcast return transmitters	200MHz 1550nm, DWDM capable
Narrowcast forward transmitters	862MHz 1550nm, DWDM capable
Forward path receivers	862MHz wideband
Return path receivers	200MHz wideband

nbn's position

nbn intends to use the existing RF combiners, although there may come a time when they become redundant if broadband services are the only services being provided over the infrastructure. nbn also intends to use the existing RF optic transmission equipment, although it will need additional equipment in line with its planned expansion of the optic nodes and CMTSs. Any future RF optic transmission strategy will be influenced by nbn's expansion strategy. For example, if D-CMTSs are deployed in the future, then RF optic transmission equipment may become redundant, as it will be replaced by digital transmission to the D-CMTS. It also needs to be noted that it is not compatible with spectrum expansion beyond 862MHz.

As described in Section 6.3.5, as part of the long-term contract between Telstra and nbn, co-location space within selected FANs is provisioned for nbn to host its equipment.

Analysys Mason's assessment

nbn's intention to use existing RF combiners and RF transmission equipment is both prudent and efficient, as their specifications are compatible with the spectrum requirements of nbn's network roll-out plans.

When nbn considers the choice of RF combiner and transmission equipment for network expansion, this will need to be compatible with its overall spectrum strategy, including matching the spectrum capability with its planned new amplifiers (up to 1GHz).

7.3.6 Transit network

The architecture of the transit network was reviewed as part of our previous report[88] and we understand that no material changes in terms of architecture and design has been made for the implementation of the MTM strategy. Therefore we have not re-assessed the transit network.

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[88] *Review of the efficiency and prudency of NBN Co's fibre and wireless network design*, Analysys Mason, Sept 2012

7.3.7 Aggregation node and PoI handover

Key issues

The aggregation node can be combined with other nodes, such as the FAN, but in general it will house the following equipment:

- CMTS
- EAS Ethernet aggregation equipment
- EFS Ethernet aggregation equipment.

There are approximately 121 aggregation nodes across the nbn network, of which 77 are planned to have HFC access network equipment connected.

► *CMTS*

The CMTS forwards and receives traffic between the Ethernet aggregation function and the cable modems. It is responsible for DOCSIS encapsulation and RF modulation/de-modulation towards and from the cable modems, and plays a key role in traffic performance enforcement as it controls access to the RF bandwidth allocated to DOCSIS services.

It is a key requirement that the CMTSs support the DOCSIS features that will enable capacity expansion, and they also need the capability to be expanded to provide more capacity as the number of RF segments in the network increases. nbn will use CMTSs that are new and owned by nbn from Day 1. nbn's preferred CMTS equipment is Arris's E6000 product, which is being developed with DOCSIS 3.1 functionality. The initial generation hardware does not have full DOCSIS 3.1 functionality, although it will support 96MHz of DOCSIS 3.1 plus 32 channels of DOCSIS 3.0. The support of five 192MHz blocks of DOCSIS 3.1 will require the second generation of hardware. Uplink functionality up to 204MHz is supported by both versions of the hardware.

nbn is targeting an absolute maximum of 56 RF segments per CMTS, equating to 33 600 end-users (600 end-users per RF segment). Beyond this level, additional CMTS will be required.

► *Ethernet aggregation and PoI handover*

The EAS connects and aggregates multiple CMTS devices and may also be used for aggregation of traffic from other network types. However, the HFC network needs additional functionality to allow 'any-to-any' mapping between an optic node serving area and a POI, to resolve AAR overlap issues. It does this by using the service connectivity network, as shown in the end-to-end Architecture 3 illustrated in Figure 7.17 below.

Figure 7.17: End-to-end Architecture 3 [Source: Analysys Mason, 2015]
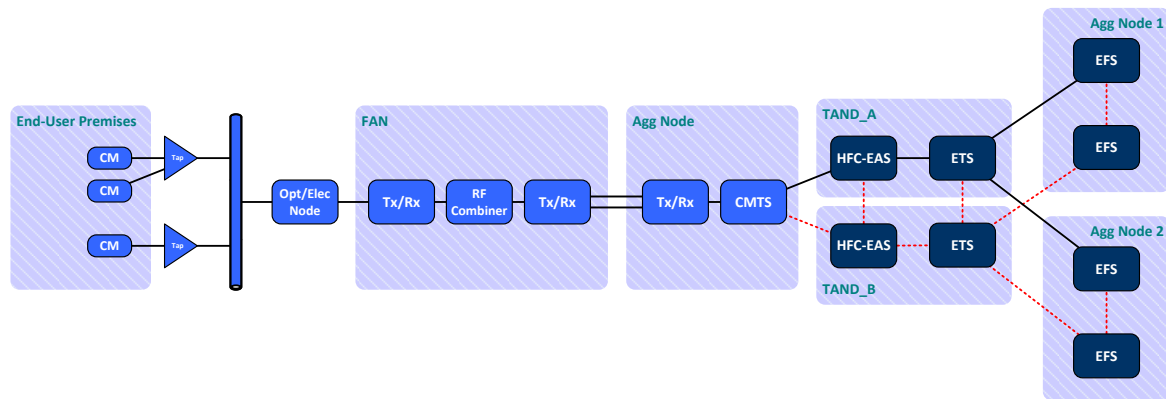
This approach allows end-users served by the same optic node, but in different AAR areas, to be directed to the correct PoI locations, as each AAR area is linked to a specific PoI location. This is done by connecting the CMTS to specific HFC-EASs, which are configured along with the ETS to identify and route specific end-user traffic to the PoI with which its AAR is associated.

nbn's position

nbn is working closely with its CMTS vendor to ensure its CMTS equipment is aligned with nbn's future capacity and functionality needs. It has designed its Ethernet aggregation network for HFC to be common with other access networks were possible, and to address the AAR overlap issue where necessary.

Analysys Mason's assessment

nbn is using equipment from a leading CMTS vendor and is working closely with it to ensure its likely roadmap requirements are being addressed as well as possible, while ensuring its roll-out targets can be met. We consider the approach of working with a leading equipment vendor to provide CMTS functionality to be prudent.

As far as the Ethernet aggregation network and PoI are concerned, nbn is aiming to be as consistent as possible with the approaches used for other access networks, while also addressing the overlapping AAR issue. We consider this to be an efficient and prudent approach to maintaining consistency with existing deployments and meeting requirements for AAR/PoI alignment.

Annexes

The following material is provided as annexes to the report:

Annex A   Principal authors of this report

Annex B   Declaration
B.1   Declaration
B.2   Disclosure of work conducted for Department of Communications

Annex C   Network selection process for MDU buildings

Annex D   FTTN architectures considered by nbn

Annex A   Principal authors of this report

Amrish Kacker

Position: Senior Partner, Head of Asia–Pacific Operations, Analysys Mason

Project role: Project Director

Qualifications: MBA, B.Eng.

Amrish leads the Asia–Pacific operations of Analysys Mason and is based in Singapore. He has worked across the region, specialising in the support of board-level investment and strategy decisions. He was the Project Director for this report and previously undertook a review of the prudency and efficiency of nbn's FTTP, fixed wireless and satellite networks.

Amrish has successfully delivered a number of projects involving NGA/government interventions in the Asia–Pacific region.

Key projects include the following:

- Support to a wireless operator in developing its TD-LTE migration strategy and a board-level assessment of NGN investment for a multi-play operator.

- Advice to a quad-play operator in the Asia–Pacific region on its strategic approach to a new FTTH network.

- Support to a large mobile operator in a South-East Asian market on developing its regulatory strategy for wholesale broadband access, including:

  – developing a detailed understanding of the building blocks of wholesale broadband access, both for legacy, DSL-based networks and for next-generation, fibre- or VDSL-based networks planned in the country

  – conducting a thorough review of the terms proposed by the incumbent in its wholesale offer, and developing a negotiating position to put forward to the incumbent;

  – providing high-level insight into the economics of the portfolio of wholesale products available to the mobile operator, and recommending a strategy to reach a positive negotiation outcome, engaging with the regulators and policy makers, as well as other operators in the market.

- Strategic consultancy support on Singapore's next-generation national broadband network (NGNBN), for the IDA, including:

  – the development of a cost model for deploying the NGNBN, looking at different technologies and network architectures

- considering a range of operational structures for the NGNBN and the possible procurement strategies to deliver the network. Amrish was responsible for assessing the role for wireless technologies in the NGNBN.

Amrish has also successfully delivered a number of NGA/government projects in Europe, including:

- Directing the development of a regional broadband intervention strategy in the UK.

- Managing the development of a transformation roadmap for a European incumbent to migrate to an NGN.

- Working closely with the UK Cabinet Office in developing a proposal for the aggregation of public-sector demand for broadband over a 10- to 15-year period.

- Managing the development of a framework for an intervention plan to extend broadband availability in a rural English country; the framework provided a basis for costs as well as potential benefits.

- Managing the development of a roadmap for a European incumbent operator to migrate its current legacy system to an NGN.

Amrish has an M.B.A. from the Indian Institute of Management and a B.Eng. Degree in Computer Science from the Birla Institute of Technology and Science (Pilani).

Dr Franck Chevalier

Position: Co-Head of Technology Consulting, Analysys Mason

Project role: Project Manager and FTTN/FTTB review lead

Qualifications: Ph.D., B.Eng. (Honours), IET Chartered Engineer

Franck was the Project Manager for this report, and as such was responsible for the day-to-day running of the project and preparation of the deliverables.

Franck is Analysys Mason's Co-Head[89] of Technology Consulting and is one of the most experienced technical consultants in the technical analysis of NGA networks. Franck has 15 years' experience in telecoms, spanning research, pre-sales and consulting. Franck's experience includes providing specialist strategic and technical advice to operators and governments. He has extensive knowledge of due diligence processes and business-case development. Projects of note include the following:

- Managing the previous independent expert review of the efficiency and prudency of NBN Co's fibre, wireless and satellite network design, which was used by NBN Co to support its original Special Access Undertaking application to the ACCC.

- Lead technical adviser to the Irish Government for the National Broadband plan since January 2015, which aims at delivering NGA broadband services to 100% of the population in Ireland.

- Managing a project for Spark in New Zealand to assess the resiliency of its network.

- Managing a number of projects for Chorus in New Zealand to review its FTTH and FTTN network design to ensure it was cost-effective and met the Crown's objectives for the ultra-fast broadband network and the rural broadband initiative network.

- Working on a number of relevant projects for Ofcom (the UK regulator), including on GPON competition models. He managed a highly technical report on the capacity of future optical access networks, which was used by Ofcom to inform its review of wholesale local access. He also managed the duct survey projects commissioned by Ofcom in 2008 and in 2009, and the development of operational models in shared infrastructure, which resulted in Ofcom mandating duct and pole access in the UK to remove entry barriers for NGA alternative operators.

- In addition, in the past three years, Franck has been involved in over five technical reviews of fixed national networks and three technical due diligences of mobile networks, throughout the world.

Prior to joining Analysys Mason in 2005, Franck worked for Nortel Networks as the design authority for optical networks in the UK, France, the Middle East and Africa.

Franck has a Bachelor of Engineering (Honours) and a Ph.D. in Optical Transmission from the University of Strathclyde (UK). He was a member of the Ofcom Advisory Committee for Scotland till May 2012.

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89   The other Co-Head of Technology Consulting at Analysys Mason is Rod Parker, mentioned below.

Rod Parker

Position: Co-Head of Technology Consulting, Analysys Mason

Project role: HFC review lead

Qualifications: B.Eng. (Honours), IET Chartered Engineer

Rod was the technical advisor for this report. In this role, Rod primarily contributed to the review of nbn's design of its HFC networks.

Rod is Analysys Mason's Co-Head[90] of Technology Consulting and is one of the most experienced technical consultants in the technical analysis of HFC networks. Rod has 25 years' experience in telecoms, spanning system design, pre-sales and consulting. Rod's experience includes providing specialist strategic and technical advice to operators and governments. Projects of note include the following:

- Managing a study into the capability of cable network architectures, particularly focusing on their ability to deliver broadband services for the UK regulator, Ofcom. The study reviewed the capability of cable network architectures and the capability of the DOCSIS 3.0 specification and the potential capability of the DOCSIS 3.1 specification and its potential to meet evolving broadband needs over the coming years.

- Leading a network due diligence project of an Indian broadband operator with hybrid fibre–coax (HFC), gigabit passive optical network (GPON) and Ethernet access networks, on behalf of a private equity company in India.

- Developing a broadband deployment strategy for a South-East Asian fixed operator considering the relative merits of FTTP, HFC and FTTN network roll-out.

- Managing the technical work stream for the development of an FTTH strategy for an electricity company in the Middle East.

- Leading a detailed design review of an FTTN-based NGN (covering access, core transport and MPLS and voice network) for an incumbent operator in the Middle East which required an independent view of its design strategy.

- Managing projects for Ofcom, the European Commission, the Welsh Government and the European Investment Bank examining areas relating to broadband network deployment, plus national mobile roaming and VoIP.

- In addition, in the past three years, Rod has been involved in eight technical reviews of fixed national networks and seven technical due diligences of mobile networks, throughout the world.

Prior to joining Analysys Mason in 2006, Rod was a network design consultant in the UK and Asia, while working for Marconi.

Rod has a Bachelor of Engineering (Honours) in Electrical and Electronic Engineering from the University of Birmingham (UK).

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[90]   The other Co-Head of Technology Consulting at Analysys Mason is Dr Franck Chevalier, mentioned above.

Rupert Wood

Position: Research Director, Analysys Mason Research

Project role: industry developments in NGA and FTTx traffic forecast

Qualifications: Ph.D., B.A. (Honours)

Rupert is lead analyst for Analysys Mason's *Fixed Networks* and *Wireless Networks* research programmes.

His primary areas of specialisation include next-generation networks, long-term industry strategy and forecasting the dynamics of convergence and substitution across fixed and mobile networks. Rupert relevant recent publications include:

- *Fixed network data traffic worldwide: forecasts and analysis 2015–2020*, Analysys Mason, 2015.

- *Wireless network traffic worldwide: forecasts and analysis 2014–2019*, Analysys Mason, 2014.

- *Harnessing the value of TWDM-PON*, Analysys Mason 2015.

- *FTTx roll-out and capex worldwide: forecasts and analysis 2014–2019*, Analysys Mason, 2014.

Rupert regularly contributes to the international press on a wide range of telecoms subjects and has been quoted by *The Times*, *The Economist*, *Business Week*, *Telecommunications Online* and *La Tribune*.

Rupert has a PhD from the University of Cambridge, where he was a Lecturer before joining Analysys Mason.

Annex B   Declaration

B.1   Declaration

Analysys Mason has made all the inquiries that Analysys Mason believes are desirable and appropriate and that no matters of significance that Analysys Mason regards as relevant have, to Analysys Mason's knowledge, been withheld from the ACCC or the Court.

Analysys Mason declares that each of the opinions expressed in this report is wholly or substantially based upon Analysys Mason's specialised knowledge.

Amrish Kacker for Analysys Mason Ltd

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Date: 1 April 2016

Disclosure of work conducted for the Department of Communications

We would like to declare that we are currently working with the Department of Communications, assisting it in defining the cost of implementing a universal service obligation for broadband services in Australia.

In particular, our scope of work is to:

• provide input into the design, development and quality assurance of a financial model to quantify the magnitude of the losses from NBN non-commercial services by providing expert advice on a broad range of technology-based assumptions relating to nbn FWA and satellite networks.

• provide input into the development and quality assurance of a draft and final report considering funding options for NBN non-commercial services, including by validating the accuracy and robustness of claims regarding long term strategic issues relating to nbn FWA and satellite networks.

We have already informed the Department of Communications of our involvement with Webb Henderson/nbn and its legal team has confirmed that it does not see a conflict of interest in our undertaking this project for nbn. Similarly, we have informed Webb Henderson, the legal advisor to nbn on this project, which has also confirmed that it does not see a conflict of interest in our undertaking this project.

# Annex C   Network selection process for MDU buildings

[C-I-C]

[C-I-C]

Annex D   FTTN architectures considered by nbn

nbn has defined four different architectures for the FTTN /FTTB network, which are described below and illustrated in Figure D.1:

- **FTTN Option 1:** Direct connection of DSLAM to POI with fibre
- **FTTN Option 2a:** Direct connection of DSLAM to POI with WDM
- **FTTN Option 2b:** Connection of DSLAM to AAS deployed at the POI
- **FTTN Option 3:** Connection of DSLAM to AAS deployed at the FAN.

Figure D.1: nbn's FTTN/FTTB architecture options [Source: Analysys Mason, 2015]
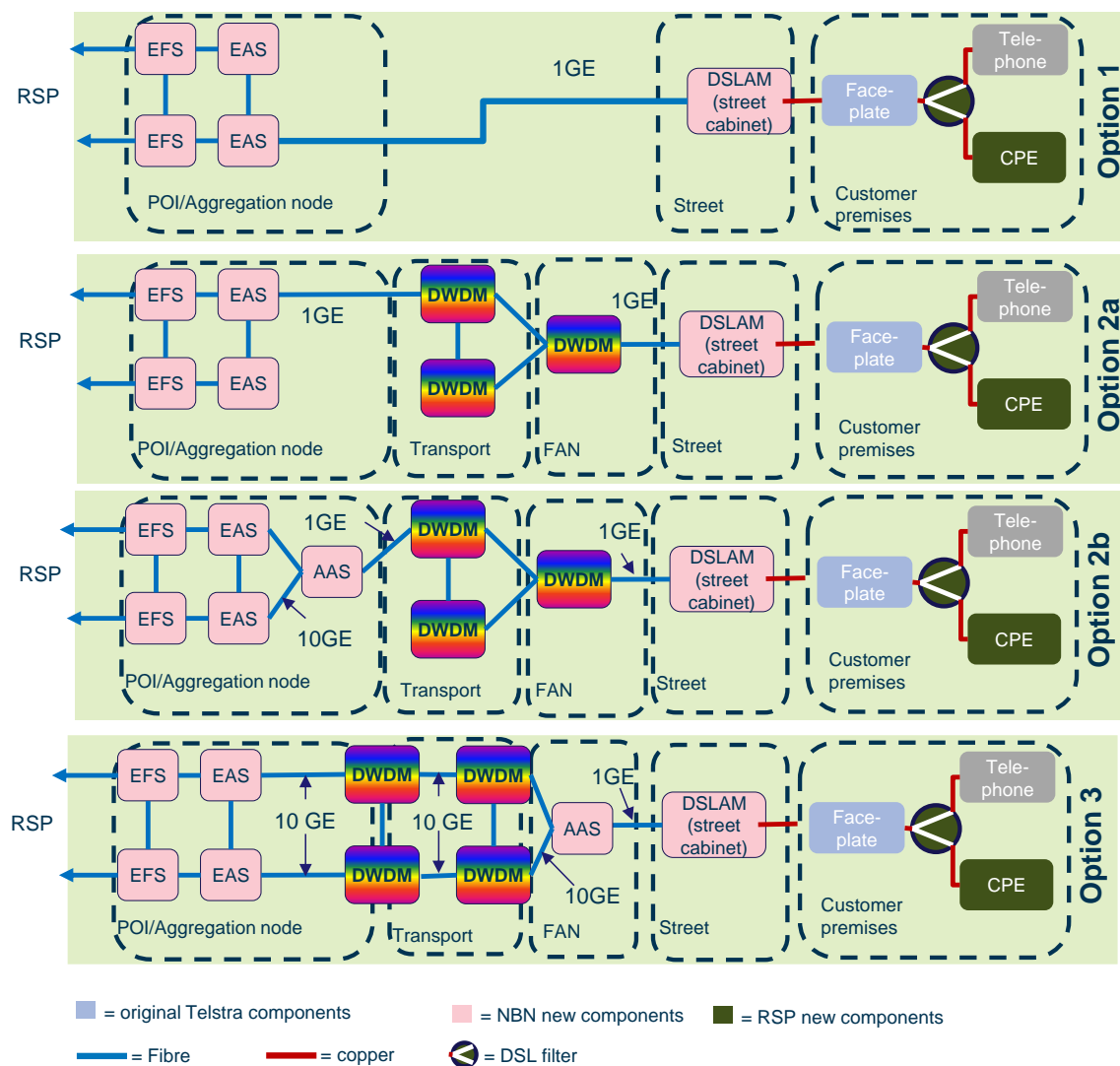
FTTN Option 1: consists of connecting the DSLAM directly to an Ethernet Aggregation Switch (EAS) at a POI site using fibre connectivity. This scenario assumes that a DSLAM is connected to the EAS using a single link (i.e. the fibre link between the DSLAM and the EAS represents a single point of failure for all end-users served by the DSLAM).

FTTN Option 2a: is similar to Option 1 except that the transport of data between the DSLAM and the EAS is provided through the DWDM transport network, using a dedicated wavelength for transporting the 1Gigabit Ethernet (1GE) signal. There is a single 1GE link between the DSLAM and the DWDM OADM located in the FAN and also a single 1GE link between the EAS and the DWDM OADM located in the POI. It should be noted that in the WDM network each 1GE wavelength is protected using a 1+1 configuration.

FTTN Option 2b: is similar to Option 2a except that an Access Aggregation Switch (AAS), located in the POI, aggregates the traffic coming from several DSLAMs before transmitting the signal to the EAS and to the EFS. The AAS connects to a pair of EAS, providing some resilience if one of these links fails.

FTTN Option 3: consists of aggregating the traffic of several DSLAMs at the FAN using an AAS. The AAS is then connected to a pair of DWDM OADMs using 10GE wavelength, which transports the traffic to a pair of EASs located in the POI. In the transport network, the 10GE links are protected using the DWDM system, ensuring that there is no single point of failure in the WDM network.