Roberson and Associates, LLC
Technology and Management Consultants ®

FUTURE BANDWIDTH REQUIREMENTS IN AUSTRALIA

INDEPENDENT EXPERT REPORT

This report has been prepared subject to, and in accordance with, the Expert Evidence Practice Note (GPN-EXPT) issued by the Federal Court of Australia on 25 October 2016.

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Roberson and Associates, LLC

Contributors:

Bill Alberth

Mark Birchler

Pepe Lastres

Tom MacTavish

Nat Natarajan

Dennis Roberson

EXECUTIVE SUMMARY

The focus of this assessment report is to evaluate the methodology used by nbn to model and forecast future network requirements and specifically to respond to the following three fundamental questions:

> 1. Do you consider nbn's traffic modeling methodology, as set out in the White Paper, the Forecast Presentation and the Need for Speed Presentation, to be a reasonable modeling methodology from a technical perspective?
>
> 2. Do you consider nbn's 10-year usage and speed forecasts, as set out in the Forecast Presentation and the Need for Speed Presentation, to be a reasonable prediction of usage and speed requirements for Australian end-users over the next 10 years?
>
> 3. Do you consider nbn's 10-year usage and speed forecasts, as set out in the Forecast Presentation and the Need for Speed Presentation, are broadly consistent with prevailing reputable forecasts on these matters in other comparable international jurisdictions?

We find that the nbn model is a reasonable and conservative means of producing estimates of future capacity needs. We also observe that modeling networks, and especially a country wide network like that provided by nbn, has become very complex. This increased complexity is due to the scale of the network, the diversity and criticality of the applications served and the migration from classic circuit switch networks to packet switch systems.

With historic circuit switched systems it was possible to merely stack average circuit channel usage to estimate network capacity needs. This simplistic methodology is completely incompatible with modern packet switched networks. Traffic on packet switched networks is inherently bursty in nature. Restricting the traffic throughput on packet switched networks results in applications restricting peak usage (by changing encoders, or reducing video resolution, etc. – all of which reduce user satisfaction). For example, the Transmission Control Protocol (TCP) uses a "slow start" algorithm where the TCP application will significantly reduce data throughput after a packet loss event and then slowly increase the allowed traffic rate.

nbn utilizes a model for predicting traffic that should provide realistic expected data usage given current user trends. A significant inflection point for network capacity is the current transition of video from 1K to 4K screens (i.e., 4x the data required for communicating the screen content) which is reasonably handled in the nbn model.

We find that the usage and speed modeling results from nbn are reasonable, and we agree with the predictions derived. The model reflects current usage paradigms and correctly accounts for evolving 4K and future 8K video usage predictions.

We find the modeling effort both valid and appropriate. In fact, we consider it conservative in the sense that nbn could benefit in the future from reviewing potential inflection points and new usage patterns as predicted by groups such as the Institute for the Future. The model currently used by nbn could miss increases in usage from new technologies or new uses of old technologies in the outer years of the model which could increase the usage of the network and speed requirements. As such we view the predictions nbn is using as reasonable, but also potentially conservative in the 5–10 year timeframe.

We find that the predictions for broadband usage and speed for other markets are generally in line with the predictions from the nbn model. As an example, we note that the U.S. FCC recently filed a notice of inquiry to increase the definition of broadband to at least 100/20 Mbps (downlink/ uplink). The current definition of broadband is 25/3 Mbps (downlink/uplink). Changing to 100/25 will change future maps of areas that have broadband available and may change subsidies to underserved locations.

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1 INTRODUCTION

1.1 Background

The "Brief for Expert Advice" document[1] (pp. 4) defines the technical scope for this independent expert report as:

> 1. Do you consider nbn's traffic modeling methodology, as set out in the White Paper, the Forecast Presentation and the Need for Speed Presentation, to be a reasonable modeling methodology from a technical perspective?
>
> 2. Do you consider nbn's 10-year usage and speed forecasts, as set out in the Forecast Presentation and the Need for Speed Presentation, to be a reasonable prediction of usage and speed requirements for Australian end-users over the next 10 years?
>
> 3. Do you consider nbn's 10-year usage and speed forecasts, as set out in the Forecast Presentation and the Need for Speed Presentation, are broadly consistent with prevailing reputable forecasts on these matters in other comparable international jurisdictions?

Thus, the two primary areas of expertise directly applicable to this scope are: (1) link dimensioning of fibre, fixed wireless, satellite and multi-technology mix (MTM) networks and (2) end-user experience prediction and relationship to network performance capabilities.

The RAA team contains a unique set of individuals with integrated skills that cover this technological scope. The group has long, deep experience in the performance assessment of terrestrial and satellite communication networks and in end-user experience research and development (see team biographies in Appendix A for details).

Section 2 contains detailed technical assessments for each of these three questions.

1.2 Legal Acknowledgement

This report is prepared subject to, and in accordance with, the Expert Evidence Practice Note (GPN-EXPT) issued by the Federal Court of Australia on 25 October 2016.

2 TECHNICAL QUESTION ASSESSMENTS

2.1 Traffic Modelling Methodology Reasonable?

This section addresses the fundamental aspects of modeling telecommunication networks that have been used across the globe for most of the past century. This includes both classes of networks, namely, circuit-switched networks that have been in use since the introduction of voice telephony and packet-switched networks that came about sixty years ago with the introduction of the ARPANET and subsequent design and deployment of commercial networks and the Internet

[1] Brief for expert advice - Need for speed (16.09.2022).docx.

based on TCP/IP protocols. The analysis and design of communication networks rely on one or more aspects involving a combination of the following techniques: analytical, simulation, optimization and measurement / validation of networks.

Our conclusion for this section is based primarily on a comparison with existing real-world approaches to traffic modelling in large scale packet networks.

Section 2.1.1 discusses the traffic modeling methods prevalent across the globe and highlights the key characteristics that must be considered in a successful design and evaluation.

Section 2.1.2 presents the highlights of the main decisions and approaches to traffic modeling used by nbn to analyze performance and design (link sizes and other network parameters).

In addition, we assess whether nbn has taken all key factors into account, ensured the accuracy of model outputs for validation of their approach and adopted a closed loop mechanism for ensuring model parameters are refined on a periodic basis as these could change with time and growth of end user population.

We compare the nbn approach with traffic modeling practice across the industry and around the world. We draw our overall conclusion that nbn has adopted a reasonable and practical methodology approach to traffic modeling its network. The rest of this section will describe our findings in more detail.

2.1.1 Typical Modeling Approaches Across the Industry

Traffic modeling is a well-established science that has been successfully used for well over seventy years in the classical world of circuit-switched telephone networks. The first analytical formulas were derived well over a century ago. It has enabled telephone companies to engineer their networks to carry expected offered load (voice call connection requests) in an efficient manner. The key factors that had to be considered were: a) frequency with which calls are placed and b) the amount of time taken or connection resources consumed for a call. A typical telephone network would include switches and trunks distributed physically over a wide geographic area. The physical network is fixed while the traffic that it is designed to carry is subject to random demands. The times at which calls are generated and the lengths of time the call will last are both unpredictable except in a statistical sense. The main tasks of a network designer included: how many resources to provide to accommodate the random demand at an acceptable level of performance to end users. If the network is under engineered (i.e., not enough resources), telephone calls may be blocked (or lost). If the network is over engineered (i.e., too many resources), the resources may be under-utilized (i.e., wasted resources) resulting in high network costs (i.e., poor economics). While the first telephone call was made by Alexander Graham Bell in 1876 and the circuit-switched networks came into being in 1878, the field of traffic modeling and engineering had an early start with ground-breaking works of A. K. Erlang and T.O. Engset starting around 1917 onwards.[2] [3] The circuit-switched networks reserved a dedication channel (or

[2] A. K. Erlang, Solution of Some Problems in the Theory of Probabilities of Significance in Automatic Telephone Exchanges, published in Elektroteknikeren, Vol. 13, 1917, p 5., https://web.archive.org/web/20110719122546/http://oldwww.com.dtu.dk/teletraffic/erlangbook/pps138-155.pdf

[3] Moshe Zukerman, Introduction to Queueing Theory and Stochastic Teletraffic Models, page 191 on Engset Loss Formula, http://www.ee.cityu.edu.hk/~zukerman/classnotes.pdf.

network resources) for the entire duration of a voice call. Electronic signals pass through several switches before a connection is established and network resources are reserved for the duration of the call.

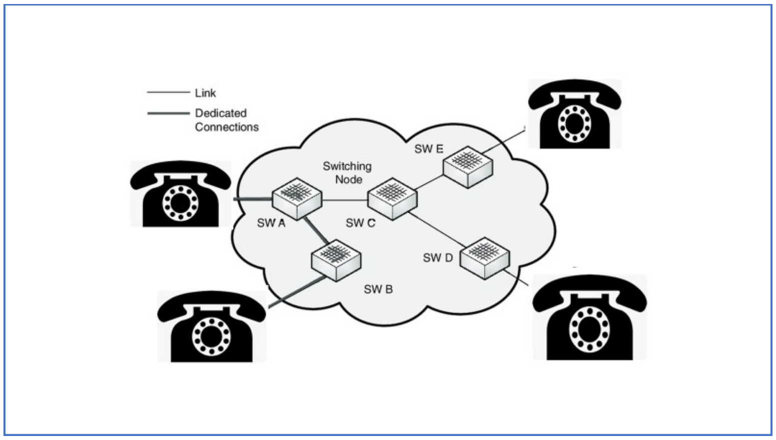

Figure 1. A Circuit-Switch Network (Voice Calls used an end-to-end path with circuit reservation)

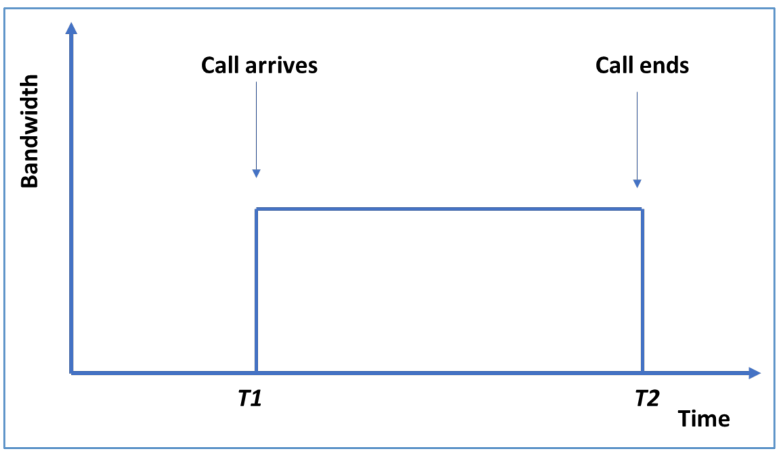

Figure 2. Resource Consumption by a Circuit Switched Call

In general, the design of an efficient network to serve end user demands with an acceptable level of performance involved one or more of the following subproblems:

- Network Topology Design (Mesh / Tree / Star)
- Trunk Sizing (how much capacity to provision for each trunk)
- Route design and selection (what paths to use between two end points and how to select)

In specific cases, the design of an efficient network may be reduced in scope to solving a subset of the above problems. As an example, the network topology may be fixed and the design may involve trunk sizing and route selection.

The subject of traffic engineering in circuit-switched networks has been well-studied and effective approaches for tele-traffic performance analyses and capacity planning methods have been developed over the past century. Call arrivals are modeled as Poisson processes for analysis simplicity and have been validated in traffic measurements. Classic references for traffic engineering in telephone networks based on circuit-switching are cited below. [4] [5] [6] [7] [8] [9]

2.1.1.1 Traffic Intensity Variations

Practical experience in operating circuit-switched networks has shown that call attempts vary with time of day. The term *Busy Hour* [10] is defined as a period of sixty consecutive minutes during which telephone traffic is the highest. Measurements are taken during peak periods (or *Busy Hours*) so that the Grade of Service (GoS) will be achieved through an entire day. This concept is common to most communication systems.

There is a tendency for peaks in the morning and afternoon due to business activity, and likely another peak in the late evening due to personal communications, resulting in multiple busy hours in a day. More generally then, the distribution of calls in a given area is not uniform over time but varies sometimes widely with time of day. In telephone communications peaks typically last for one to two hours and one hour is taken as standard measurement unit.

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[4] R. B. Cooper, Introduction to Queueing Theory, 2nd edition, North-Holland (Elsevier), New York, 1981.

[5] R. Syski, Introduction to Congestion Theory in Telephone Systems, 2nd Edition, Elsevier, New York, 1986.

[6] Andre Girard, Routing and Dimensioning in Circuit-Switched Networks, Addison-Wesley Publishing Company, Reading, Massachusetts, ISBN 0-201-12792-X, 556 pages, 1990.

[7] D. W. Hill and S. R. Neal, Traffic Capacity of a Probability-Engineered Trunk Group, Bell System Technical Journal, Vol.55, pp. 831-842, 1976.

[8] C. J. Truitt, Traffic Engineering Techniques for Determining Trunk Requirements in Alternate-Routine Trunk Networks", Bell System Technical Journal, Vol. 33, pp. 277-302, 1954.

[9] R. J. Harris, "Comparison of Network Dimensioning Models", Australian Telecommunication Research, Vol. 18, pp. 59-69, 1984.

[10] busy hour - TIA's Glossary of Telecommunication Terms (tiaonline.org) - In a communication system, the sliding 60-minute period during which occurs the maximum total traffic load in a given 24-hour period.

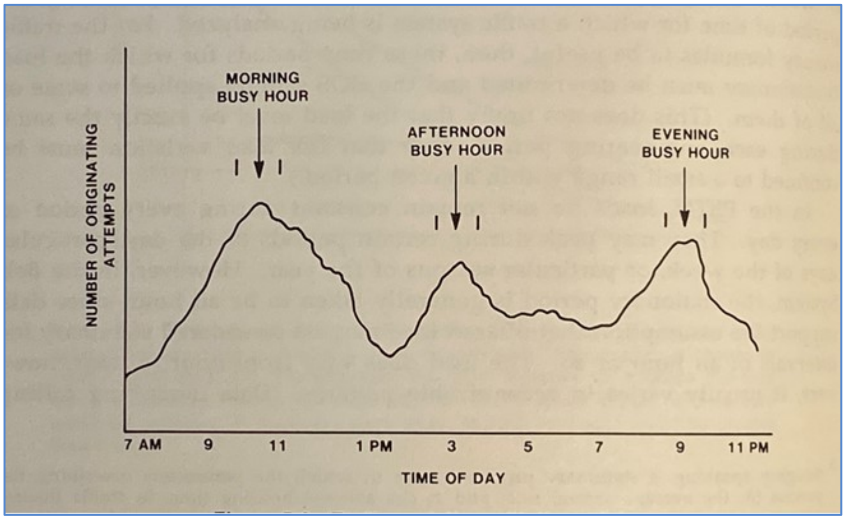

Figure 3. Time of Day Traffic Variation in a Circuit-Switched Telephone Network [11]

The busy hour may also depend on location due to factors such as:

1. Network spans a wide geographic area and with multiple time zones (e.g. USA, Canada).
2. Holiday resort areas (with a seasonal variation dependent on visitors).

In addition, special days (likely country dependent) in a year may contribute to higher than average busy hour traffic (e.g., Mother's Day and Christmas days in the USA).

Several practical approaches to the dimensioning of circuit-switched networks have been published. These address the problem of design networks that satisfy performance requirements for: a) more than one busy hour [12] [13] or b) operate under different potential operating scenarios [14].

2.1.1.2 Packet Switched Network Traffic

Today, most networks have transitioned to use digital data-oriented Packet-switched networks. These networks move data in separate, small blocks (i.e., packets) based on the destination address in each packet. Packets received at the destination are reassembled in the proper sequence to make up the message. The messages sent via streams of independent packets do not require a dedicated chain of circuits to be in place for the complete duration of the communication. Rather, each packet follows routes that are the least congested. This flexibility serves several important functions.

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[11] Engineering and Operations in the Bell System, Second Edition, Reorganized and Rewritten Telecommunications in the Bell System 1982-1983, AT&T Bell Laboratories, R. F. Rey (Technical Editor) AT&T Bell Laboratories, Murray Hill, N.J., USA ISBN No. 0-932764-04-5, First Printing 1984. Page 152.

[12] Eisenberg, M., "Engineering Traffic Networks for More Than One Busy Hour," B.S.T.J., 56, No. 1, January 1977, pp. 1-20.

[13] Elsner, B., "A Descent Algorithm for the Multihour Sizing of Traffic Networks," B.S.T.J., 56, No. 8, October 1977, pp. 1405-1430.

[14] K. S. Natarajan, D. H. Walters and B. Maglaris, "Design of Survivable Circuit-Switched Communication Networks", Proc. of IEEE MILCOM Conference, 16.2-1 – 16.2-6, October 1982.

1. If some individual link in the chain of circuits from A to B breaks or is congested, packets are automatically rerouted on a real time basis onto alternative paths to their destination.
2. If no superior reroutes are available, new fiber optic technology makes it much quicker to add to existing circuit capacity than old copper technology. These expansions can sometimes be completed in just a few hours in urban areas and perhaps longer in rural areas.
3. If in spite of engineering's best efforts, congestion does appear, network technology and its underlying software directs the sender of the packets to pace its rate of transmissions in order to prevent packet bottlenecks from building-up. Congestion in today's increasingly virtualized networks may no longer mean blocked calls or a connection failure.
4. If one link in the network is consistently congested, that link can be upgraded without requiring the whole network to be upgraded.

It is common for the time duration of a packet transmission to be less than 1 millisecond and for thousands of packets to arrive in a second. The interarrival time between packets from a source are dependent and packet arrivals are bunched together, which is called ***bursty traffic.*** Buffers are provided to accommodate the temporary peaks in packet arrivals. Packet waiting times and buffer overflow probabilities are the primary performance measures of interest at the packet level. Some common protocols that are or have been used to transport broadband packet traffic include ATM, Ethernet and TCP/IP.

The burstiness of traffic can be shown by plotting the arrival rate of packets as a function of time. Figure 4 shows 30-second segments of packet data traces for four different applications including: an Internet data session (e.g., web browsing), a video conference and movies with two different encodings. Note that the data traces are application dependent and do not resemble each other. [15] [16] [17] Internet session end points are typically an end user at one end and a server at the other end of a connection. A video conference session may have two end users at either end of the session.

Internet data rate alternates between high and low packet arrival rate (sometimes dropping to zero). Video traces are influenced by the number of frames per second, number of bits in each frame and the encoding scheme(s) used. It is important to note that each application data source is bursty and characterized by significant variation in speed requirement (peak and average values differ significantly). Reserving bandwidth required to accommodate the traffic based on peak traffic will result in considerable unused bandwidth. Alternatively, if a reservation is based on average value of arriving traffic, it will lead to degraded quality because considerable information will be lost during peak periods. Packet switching enables statistical sharing of multiple video streams in a way that both the efficiency and the quality of service are maintained.

[15] Robert Cooper and Daniel Heyman, Encyclopedia of Telecommunications, Vol. 16, pp. 453-483, Marcel Dekker, Inc. 270 Madison Avenue, New York, NY.

[16] L Kleinrock, Queueing Systems, Vol. I, Addison Wesley, NY, 1975

[17] L. Kleinrock, Queueing Systems, Vol. II, Addison Wesley, NY, 1975

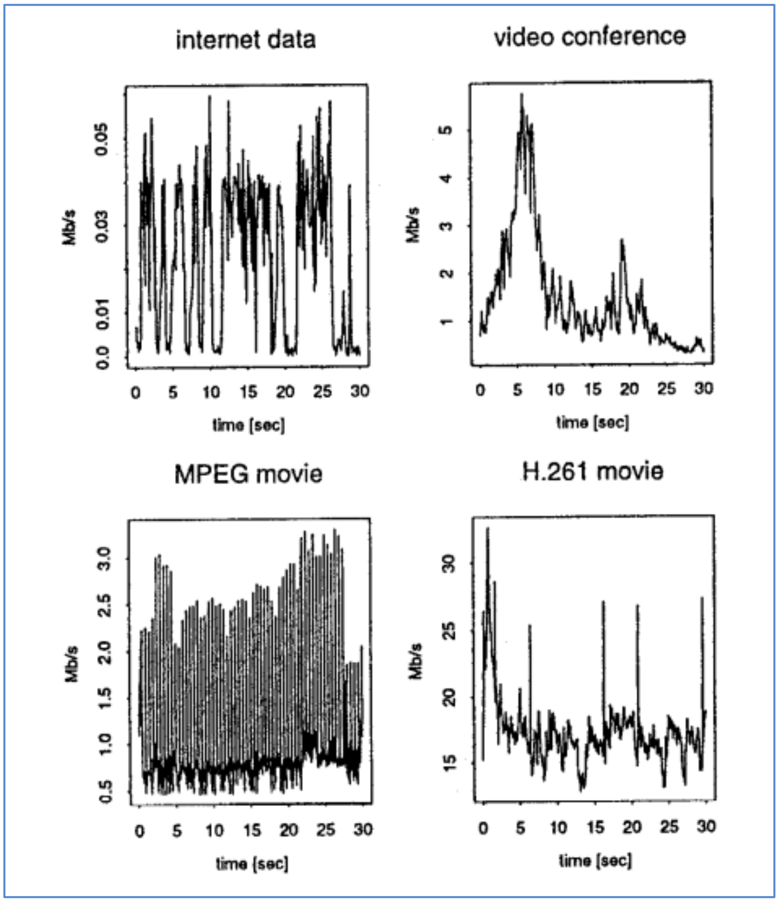

Figure 4. Example Traffic Magnitude vs. Time for Various Types[15]

Traffic studies in packet networks [18] [19] [20] have shown that packet interarrival times are not exponentially distributed (i.e., not Poisson arrivals) [21]. Various traffic studies have shown that both local-area and wide-area network traffic, the distribution of packet interarrivals clearly differs from exponential. [22] [23] [24] It has been argued convincingly that LAN traffic is better

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[18] Anick, D. Mitra, M.M. Sondhi, "Stochastic Theory of a Data-Handling System with Multiple Sources", Bell System Technical Journal, 61, 1871-1894m 1982.

[19] Beran, R. Sherman, M. S. Taqqu, W. Willinger, "Variable-Bit-Rate Video Traffic and Long-Range Dependence", IEEE Trans. on Communication, 1992.

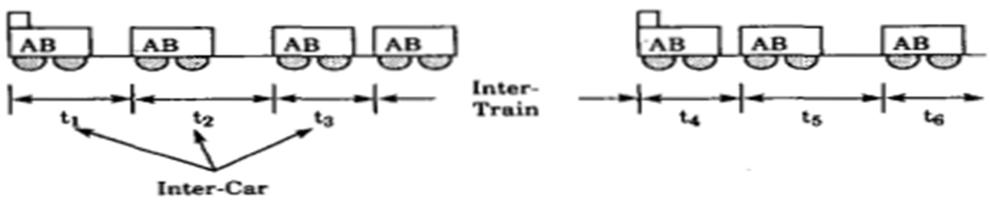
[20] Beran, "Statistical Methods for Data with Long-Range Dependence", Statistical Science 7, No. 4, 1992.

[21] Vern Paxon and Sally Floyd, "Wide Area Traffic: The Failure of Poisson Modeling", IEEE/ACM Transactions on Networking, Vol. , No. , June 1995, pp. 226-244 .

[22] R. Jain and S. Routhier, "Packet trains – Measurements and a new model for Computer Network Traffic", IEEE Journal on Selected Areas in Communications, Vol. 4, pp. 986-995, Sept. 1986.

[23] H. Fowler and W. Leland, "Local Area Network Traffic Characteristics with Implications for Broadband Network Congestion Management", IEEE Journal on Selected Areas in Communications, Vol. 9, pp. 1139-1149, Sept. 1991.

modeled as statistically self-similar processes[25] [26] which have different theoretical properties compared to Poisson processes. For self-similar traffic there is no natural length for a "burst" and traffic bursts appear on a wide range of time scales. Wide Area Network (WAN) traffic arrival processes are better modeled using self-similar processes. Analyses of wide area TCP traffic sources have shown that Poisson models often seriously underestimate the burstiness of TCP traffic over a wide range of time scales. Poisson arrival processes are quite limited in their burstiness, especially when multiplexed to a high degree. Wide-area traffic is much burstier than Poisson models predict, over many time scales. This higher level of burstiness has major implications for congestion control, traffic performance and engineering.



The packet train model consists of a sequence of packets traveling between a given pair of nodes. The intercar interval is much smaller compared to the intertrain interval.

Figure 5. Packet Train Model of Bursty Traffic[22]

The time-of-day variation with busy hour (one or more per day) that was observed first in circuit-switched telephone networks has been observed (and measured) in practice in packet-switched data networks over the past several years. The busy hours as well as the magnitude of packet traffic are dependent on the country (or geographic location) and types of popular data applications used. However, the basic traffic pattern resembles the traffic variation curve shown in Figure 5.

2.1.1.3 Observations on Modeling Practice in Industry

Sound use of traffic modeling is essential for *satisfying end-user traffic and performance* expectations with a *well-designed or engineered network that both satisfies customer needs and is cost optimized*. The *validity of traffic modeling* needs to be assessed by *ongoing measurement and calibration efforts.*

Traffic engineering tools are used by operators of networks as part of an overall program of network management. US Telecommunication companies [27] (such as AT&T, T-Mobile, Verizon

[24] P. Danzig, S. Jamin, R. Caceres, D. Mitzel and S. Estrin, "An Empirical Workload Model for driving wide-area TCP/IP Network Simulations", Internetworking Research Experience, Vol. 3, No. 1, pp. 1-26, March 1992.

[25] W. E. Leland, Murad S. Taqqu, Walter Willinger and Daniel Wilson, "On the Self-Similar Nature of Ethernet Traffic (Extended Version)", IEEE/ACM Transactions on Networking, Vol. 2, No. 1, February 1994, 15 pages.

[26] B. Mandelbrot, The Fractal Geometry of Nature, New York, Freeman, 1983.

[27] https://www.ustelecom.org/research/network-performance-data/

and several dozen other carriers) continuously monitor traffic offered and bandwidth usage on their networks with tools that analyze and correlate network statistics, which reveal network trends, and provide performance and capacity reports used to manage and as appropriate upgrade their networks. The data reported for the network compares performance achieved between sample weeks and the baseline week (typically using traffic the same day or set of days in a week with a special focus on the busy hour, or increasingly even finer grained busy periods).

Even with substantial growth in use as more and more Americans stayed home during Covid-19, U.S. communications networks have managed significant increase in traffic by and large without a hiccup. As one would expect, US Telecom members reported traffic increases — some significantly so — especially in residential areas, over traffic levels prior to mid-March 2020 (onset of COVID-19 and associated widespread lockdowns and resultant shift to home-based lifestyles for work, education, healthcare, etc.). The ability to absorb additional traffic and the avoidance of a worst-case traffic scenario is a design feature of America's modern broadband networks incorporating sound traffic engineering practices that contributed to the resiliency, security and stability of the networks. The most significant factor is that America's broadband providers have invested heavily and consistently over the last several decades to ensure their networks have the capacity to handle the ever-increasing demand for data, especially during peak times of day.

It is important to note there are objective measurements of internet speeds reported on a monthly basis by Ookla and similar companies. [28] Specifically, Ookla publishes Speedtest Global Index rankings that are based on median download speed to best reflect the speeds a user is likely to achieve in a market. Australia ranks quite well (12th globally) when median ***mobile*** download speeds are compared. In contrast Australia ranks 67th rank if median ***fixed broadband*** download speeds are compared. The following table illustrates the rankings of top-25 countries as per the Ookla speedtest measurements (middle of August 2022).

[28] https://www.speedtest.net/global-index
https://www.speedtest.net/global-index/australia#mobile Australia Median Speeds August 2022

Mobile Broadband			Fixed Broadband		
Global Download Speed 30.70 Mbps			Global Download Speed 69.14Mbps		
#	Country	Mbps	#	Country	Mbps
1	**Norway**	**122.77**	1	**Singapore**	**219.01**
2	United Arab Emirates	118.42	2	Chile	211.43
3	Qatar	114.28	3	Thailand	188.75
4	**South Korea**	**112.26**	4	Hong Kong (SAR)	179.58
5	**Denmark**	**103.5**	5	China	178.73
6	**Netherlands**	**102.06**	**6**	**United States**	**167.36**
7	Bulgaria	95.76	7	Macau (SAR)	157.54
8	Kuwait	94.86	**8**	**Denmark**	**156.06**
9	China	92.53	**9**	**New Zealand**	**133.44**
10	Saudi Arabia	91.81	10	Japan	131.86
11	Luxembourg	86.94	11	Spain	131.55
12	**Australia**	**83.59**	12	United Arab Emirates	127.16
13	**Switzerland**	**81.11**	13	Monaco	126.72
14	Brunei	79.5	14	Romania	123.31
15	Bahrain	76.16	**15**	**Switzerland**	**122.76**
16	**Sweden**	**74.35**	16	Taiwan	115.07
17	**Finland**	**70.29**	17	Kuwait	114.17
18	**Singapore**	**69.04**	**18**	**Canada**	**111.76**
19	**Belgium**	**67.42**	19	Liechtenstein	110.77
20	Maldives	66.63	**20**	**South Korea**	**109.1**
21	Cyprus	66.16	21	Panama	107.86
22	**New Zealand**	**62.95**	**22**	**Netherlands**	**106.51**
23	North Macedonia	62.47	**23**	**France**	**105.23**
24	**United States**	**61.95**	24	Moldova	104.92
25	**Canada**	**61.34**	25	Hungary	101.08
			67	**Australia**	**52.62**

Table 1. Comparison of International Internet Speeds

In the context of US Telecom marketplace, the following observations have been noted with respect to peak demands and time of day dependence and importance of streaming services.[29]

> Evening hours typically represent the peak demand time in residential networks, with a small handful of streaming services such as Netflix, Google's YouTube and Amazon Prime accounting for 60–80 percent of all broadband traffic during those hours. During these peak hours, traffic is commonly 3–5 times higher than during an average hour of the day, which means huge amounts of unused traffic capacity are regularly available during the off-peak hours.

The traffic increases associated with telework, telemedicine, and distance learning tend to occur during daytime hours — when unused traffic capacity is the greatest. As a result, these COVID-19 increases in traffic have been readily accommodated by U.S. broadband networks allowing the lines of news, public safety, healthcare, daily communications, and entertainment to remain open and running smoothly.

Most countries in Europe and East Asia (Japan, S. Korea and others) appear to have handled the pandemic traffic demands for broadband reasonably well. A recent report asserts that internet speeds in the US were more than twice as fast the European Union's in 2021. [30] A reasonable compilation of broadband facts and figures for Europe is available.[31]

2.1.2 Assessment of the nbn Modeling Approach

nbn's traffic modeling methodology is described in a white paper [32]. Numerous documents related to the traffic modeling white paper are available [33] [34] [35] [36]. The overall purpose of traffic modeling is to accurately estimate bandwidth and service capacity, as well as scalability requirements across the nbn network, to aid in network design, construction and augmentation to achieve a positive and consistent end-user experience. This section summarizes the main aspects of the methodology and its use of traffic modeling tools.

The most fundamental ideas and assumptions of the nbn traffic modeling methodology are summarized below.

- Traffic Forecasts – This includes expected end user data consumption over a ten-year horizon. The traffic forecasts are determined as accurately as possible from secondary

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[29] Designed for Demand: How Networks Keep Your Data Flowing, https://ustelecom.medium.com/designed-for-demand-how-networks-keep-your-data-flowing-b21d74d8df0c

[30] https://fairinternetreport.com/research/usa-vs-europe-internet-speed-analysis Annual Report: Europe vs US Broadband Performance 2022, Fair Internet Report.

[31] https://www.statista.com/topics/3729/broadband-in-europe/#dossierKeyfigures

[32] Traffic Modeling Methodology, a nbn white paper dated !5 June 2017, F0020- 31-15173.

[33] Wholesale Broadband Agreement – Product Technical Specification: NBN Company Ethernet Bitstream Service.

[34] M. Mathis, et al, The Macroscopic Behavior of the TCP Congestion Avoidance Algorithm, Computer Communication Review, Vol. 27, No. 3, July 1997, ISSN 0146-4833.

[35] J. Padhye et al, Modeling TCP Throughput: A Simple Model and its Empirical Validation, Proc. of ACM SIGCOMM '98 on Applications, technologies, architectures and protocols for computer communication, pages 303-314.

[36] M. Allman, V. Paxson and E. Blanton, RFC 5681: TCP Congestion Control, September 2009.

research (e.g., industry reports from Cisco, Sandvine and others) and from nbn traffic data collected from the live network. The long-term forecast estimates the expected usage of applications likely to consume significant bandwidth and other resources. A detailed discussion of traffic forecasting and the methodology used by nbn is in Section 2.2 of this document.

Use of traffic engineering tools for forecasting growth includes a periodic cycle of network analysis and/or predictions of network traffic growth. This process is fed and driven by first gathering network statistics from network nodes or intermediate collection devices. This data is then used as input into intermediate traffic engineering analysis processes that may determine if any adjustment to either the physical or the logical configuration of the network is required. The mechanisms are used to collect and view traffic engineering data from network nodes (sometimes referred to as a traffic matrix in the industry).

- Our description of packet network traffic characteristics (Section 2.1.1) had indicated the self-similar nature of wide area and local area traffic that reflected the burstiness of packet traffic. The packet data consumption rates vary considerably over time (both over the long-term lasting several minutes as well as short-term bursts lasting a few seconds). For the purposes of traffic modeling, with a statistically large population, nbn can assume average values for packet data rather than deal with an entire distribution (or range) of packet data values. For the purpose of capacity planning, it is necessary to assess the total data consumption of all end users put together. The use of statistical multiplexing of resources (including shared links, switches etc.) tends to smoothen out the bursty nature of individual user traffic over the short periods of interest here. The use of average values of packet data values (e.g., data consumption over a long duration like a month) of individual end users is a good indicator of aggregate capacity needs over a link.
- Packet traffic exhibits long- and short-term variations of data speeds. This has been modeled by incorporating a well-established notion of busy hour traffic modeling as well as random instantaneous bursts.
- TC-1 and TC-2 traffic classes are used to carry business voice calls and video conference calls. These applications can be reasonably modeled as constant (or nearly constant) bit rate traffic. nbn has taken a reasonable approach to modeling such traffic using well-established voice telephony models using Erlang models.

The following figure shows the major steps involved in nbn's modeling approach.

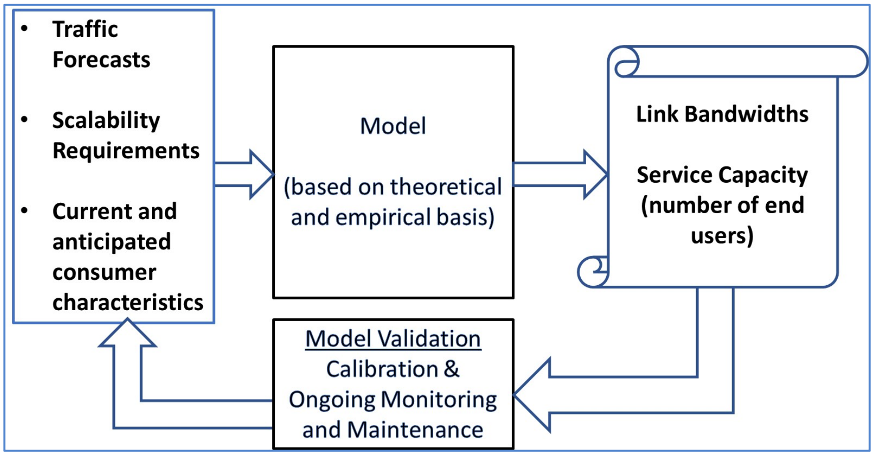


Figure 6. nbn Traffic Modeling Steps

The accuracy of the modeling approach is considered important for the following reason. Without a suitable validated traffic model, there is substantial risk that capacity is under provisioned resulting in end user dissatisfaction because of an inability to get the maximum throughput they have contracted to receive. If the model overprovisions the network, it is bad as well because it results in expensive underutilized links. The costs incurred in building and operating an inefficient network (with one or more underutilized links) are ultimately passed down and borne by the end users. An accurate traffic model is essential to gain confidence that a) consumers are adequately supplied bandwidth resource and b) costly link bandwidth resources are not wasted with underutilized links and consumers are spared unnecessary cost.

nbn has sought to assess the accuracy of link capacity predictions based on its modeling algorithms by comparing against the measured value of live optical line terminations (see Figure 7). Ideally the ratio of modeled (or estimated) maximum throughput to measured maximum throughput should be as close to 1 as possible. A ratio greater than 1 would indicate that the link is over engineered while a ratio less than 1 would indicate that the link bandwidth is underestimated by the model. Figure 7 shows that the ratio increases with the number of end users sharing a link and about 20% excess capacity is estimated. This is a reasonable amount of overengineering that will be useful over time, especially if the traffic forecasts are conservative. Historical results on validation of models used by nbn are included in Appendix B.

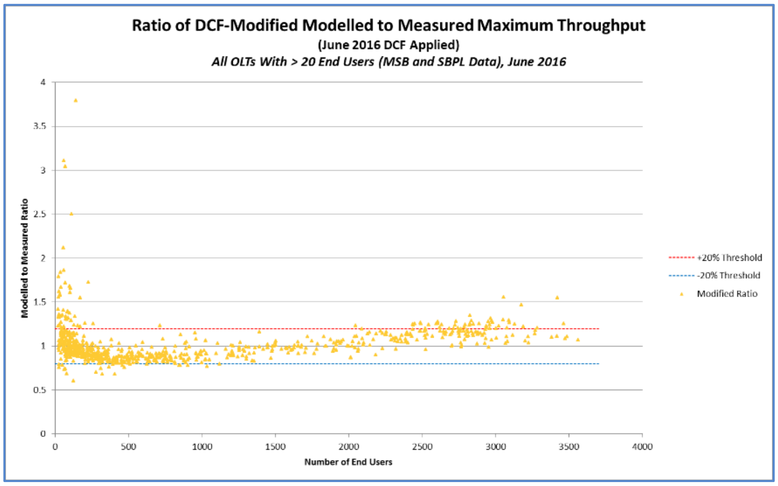


Figure 7. Validation of Link Level Model Estimates[32]

nbn uses traffic models to determine the required dimensions of:

- Shared network resources, such as backhaul links between network elements
- Shared bandwidth pools used to artificially restrict best-effort traffic (TC-4) when traffic of many users is pooled.

The cumulative effort of end-user traffic is taken in the aggregate based on statistical parameters representing an emergent group of end-users.

The presence of multiple end-users simultaneously active at a given time is abstracted for use in the model by a factor called "Concurrency".

The main performance attributes of a link are:

- the number of end-user services it can support at a given performance level; and
- the bandwidth of the link.

Link bandwidth that are considered include:

- Ethernet Layer 1 bandwidth is raw physical resource of the link or line speed (often described as the "throughput").
- Ethernet Layer 2 bandwidth is the proportion of the physical link that is available for use by a Retail Service Provider or End-user.

Figure 8 shows the Layer 1 and Layer 2 bandwidth components in an Ethernet frame. Layer 2 bandwidth is referred to a nbn product bandwidth while Layer 1 bandwidth is called Link bandwidth.

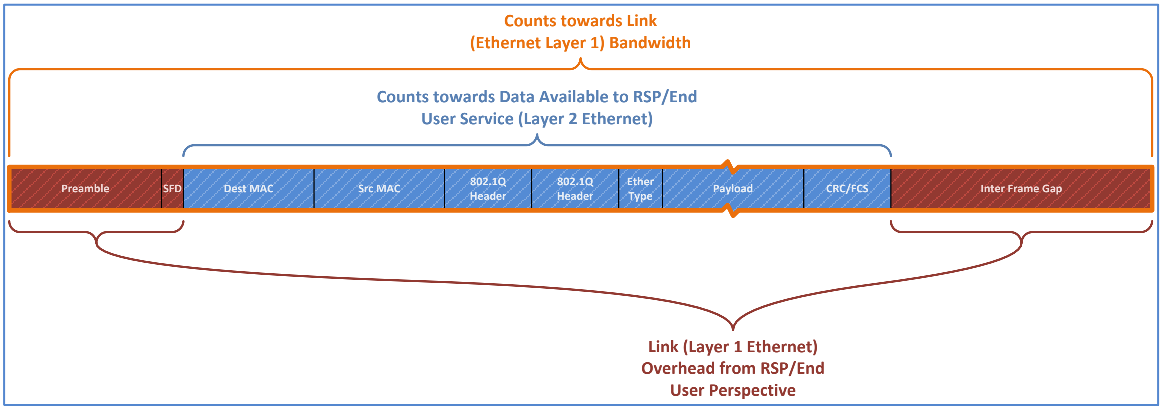


Figure 8. Layer 1 and Layer 2 Components in Ethernet Frames[32]

With respect to modeling best-effort (TC-4) traffic, the following assumptions are made in the evaluation of Ethernet L2 throughput (i.e., product bandwidth or goodput).

- Each user consumes an average amount of data in a fixed period (e.g. month)
- Most of the data consumption is in the downstream direction (mostly videos) and there is a parameter called downlink-to-upstream ratio to calculate uplink traffic
- Data traffic variations result in peaks of usage. There are two types of peaks: a) long-period peaks (e.g. busy hour peaks during a day) and short-period peaks (e.g. instantaneous peaks).
- Simultaneous consumption of data by end-users is modeled with a parameter "Concurrency" further classified as instantaneous concurrency and periodic concurrency (over time periods lasting 5 minutes to an hour). Short-term peaks are also described by a Peak-to-Average factor which has been observed to be about 1.7 (see Figure 9). The factor tends to be higher if the number of end users is smaller with less benefit of statistical multiplexing.

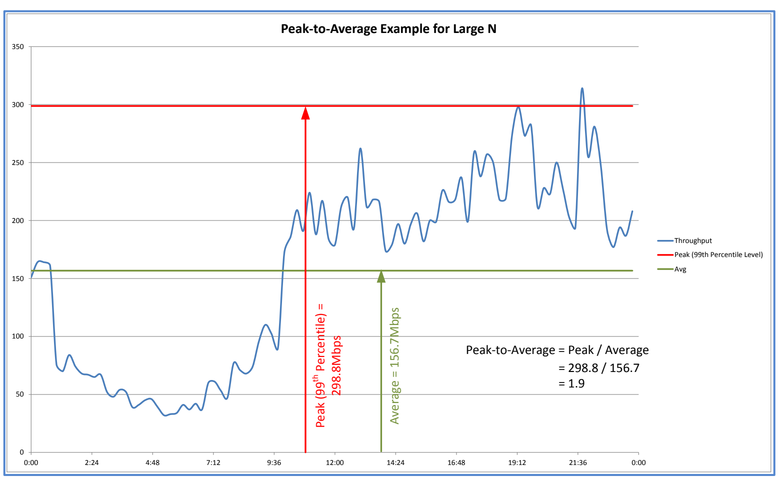


Figure 9. Peak-to-Average Example for a Large Number of End-Users[32]

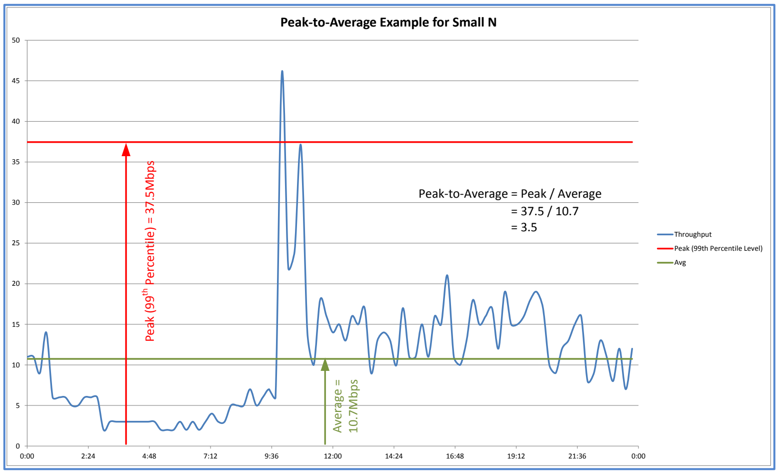


Figure 10. Peak-to-Average Example for a Small Number of End-Users[32]

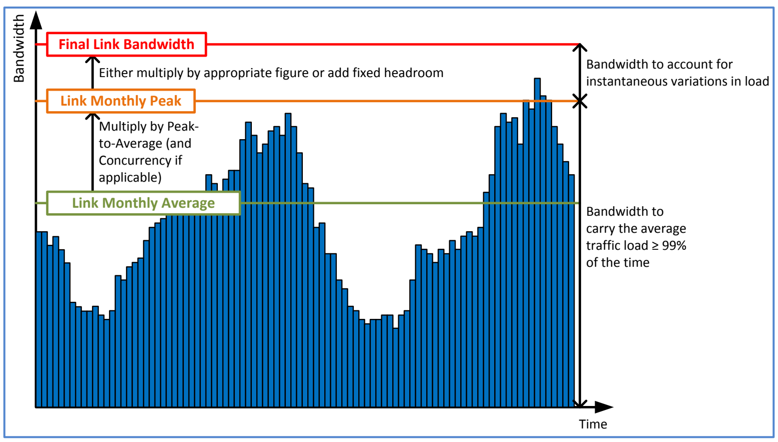


Figure 11. Estimating Peak Information Rate[32]

2.1.2.1 Modeling Best-Effort Traffic (TC-4 class)

nbn has defined an internally used performance metric called the X/Y/Z metric. Three thresholds (X, Y, Z) are used to define service levels of TC-4 traffic. The following text explains well the methodology (source: Traffic Modeling White Paper).

1. The X threshold, which indicates the percentage of the top TC-4 speed tier that an end-user would be able to burst to at some point during a session during the non-busy hours of a day.
2. The Y threshold, which indicates the percentile of the day that has the lowest usage (i.e., the non-busy hours).
3. The Z threshold, which indicates the minimum percentage of the top TC-4 speed tier that an end-user is able to burst to at some point during a session during the busy hours of a day.

> To meet the X/Y/Z metric, both X and Z speed thresholds have to be met. For example, a 90/90/60 metric means a user on the top TC-4 speed tier should be able to burst to 90% of their top speed during the non-busy hours (the bottom 90% of the hours in the day in terms of load), and should also be able to burst to 60% of their top speed during the busy hours (the top 10% of the hours in the day in terms of load).
>
> The key term in this metric is "burst to". An end user is defined as having burst to their X or Z metric when their average throughput over a minimum of 500ms reaches the X or Z threshold, as this indicates that there is potentially bandwidth available.

The above is a reasonable attempt to model the important TC-4 class of traffic in the nbn network. The white paper gives a good explanation with relevant figures. The X/Y/Z metrics are a well-defined, proprietary way to account for the various real-world factors that characterize best-effort traffic including burstiness, peak-to-average variations versus number of end users, concurrency at the link and user level, busy hour compared to non-busy hours, and a goal of achieving prescribed performance levels (expressed in percentages of maximum speed, number of users, busy vs non-busy hours). There is no universally accepted analytical modeling approach in industry to solve this problem. The nbn approach is a reasonable and practical way to systematically estimate performance and plan link dimensions.

2.1.2.2 Modeling of Constant Bit Traffic Classes (TC-1 and TC-2 class)

Business Voice and Video Conferencing applications traffic is modeled as TC-1 and TC-2 respectively.

The traffic patterns are reasonably deterministic (in terms of bandwidth required per second for the duration of the calls). nbn has chosen to use the classic tele-traffic models (specifically the Engset algorithm) which have been practically proven and validated over the past several decades in circuit-switched networks. These are well described in Section 4.1 of the traffic modeling white paper (see footnote 28). The Engset algorithms extend Erlang theory by taking into account a finite number of sources. Erlang theory by itself assumes an infinite number of sources, so the Engset algorithm was chosen because the number of end-users is a big factor in all of the traffic models.

The Engset algorithm takes three parameters and is run for each TC-1 and TC-2 speed tier. The total bandwidth output of all the runs can then be used to determine the total bandwidth required for TC-1 and TC-2. The three inputs required for the algorithm are:

1. The **Grade of Service** (GOS) required. This is also called the **Blocking Probability** (or Probability of Blocking). The Blocking Probability is the probability of attempting to make a call (or data connection) and not finding a circuit (or bandwidth) available. Typical Blocking Probabilities are of the order of 0.5% or 1%. In the modelling the default is 0.5% for residential and 1% for business.
2. The **Busy Hour Offered Traffic** per End-user in Erlangs. An Erlang is a dimensionless unit that in this case defines the proportion of a circuit that needs to be held over a period of time (usually an hour) for each end-user. In the modelling, the default is 0.08 Erlangs for residential and 0.18 Erlangs for business. (For example, in the busy hour a residential (or business) End-user will use a circuit for 4.8 (or 10.8 minutes respectively).
3. The **Number of End-users** (or number of sources).

The model is used to calculate the number of circuits and equivalently the total capacity needed for handling the TC-1 and TC-2 classes of traffic. The above approach to modelling these two classes of traffic is very reasonable.

2.1.2.3 nbn Traffic Models

nbn uses a variety of dimensioning models and applies them under different context and constraints to model all 3 traffic classes currently in use (TC-1, TC-2 and TC-4). Table 2 summarizes the various methods in use.

<table>
<tr><th>Model</th><th>Description</th><th>End User Limits</th><th>Model Inputs and Outputs</th></tr>
<tr><td>Link Dimensioning Model (LDM)
(Section 4.2 of traffic modeling white paper, footnote 32)</td><td>Specifically used for link dimensioning without considering performance.</td><td>No Limit</td><td rowspan="3">• Ethernet Layer 1 bandwidth per link (Mbps or Gbps)
• Average user throughput (kbps or Mbps) consumed over a month
• Number of users and service characteristics
• Link efficiencies and overheads due to link control operations.</td></tr>
<tr><td>End-User Throughput Estimation Model (ETEM)
(Section 4.3 of white paper footnote 32)</td><td>Link dimensioning with performance considerations.</td><td>200 – 4000 End-Users</td></tr>
<tr><td>Temporal Distribution Model (TDM)
(Section 4.4 of white paper footnote 32)</td><td>Link dimensioning with performance considerations</td><td>Less than 200 end-users</td></tr>
</table>

Table 2. nbn Traffic Models

The design of a large national communication network presents itself with a range of topology options (see Figure 12). Each option is suitable depending on geographic scope and traffic, performance and reliability requirements. In practice a network design will utilize a combination of such topologies. For a representative sample of logical topology diagrams in the nbn network, please see Appendix C.

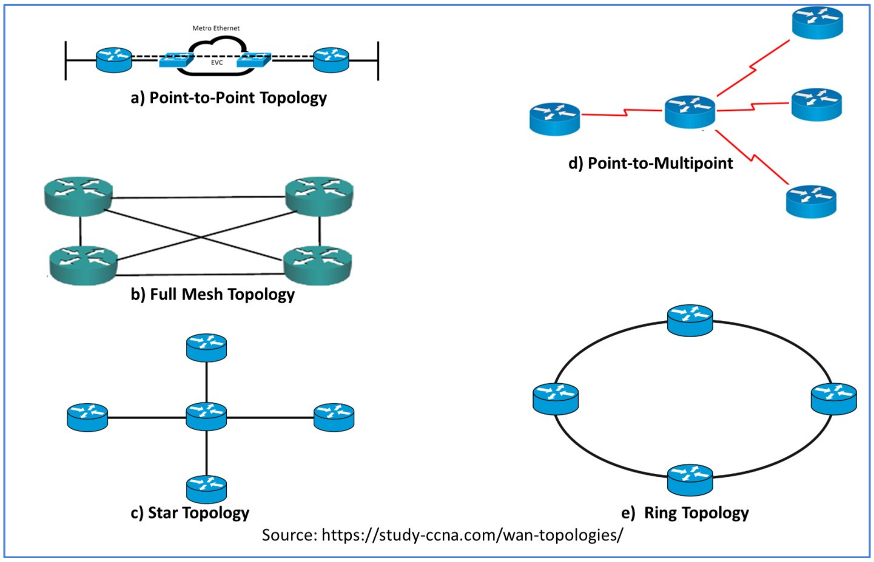


Figure 12. Topology Alternatives for a Communication Network

2.1.2.3.1 Link Dimensioning Method (LDM)

The LDM is used for large links, such as those found within the nbn Point of Interconnect (POI) aggregation networks. No direct consideration is given to factors such as time of day or busy hour or number of simultaneously active users. It does not consider performance constraints and is used solely for estimating maximum throughput expected. Table 3 of the Traffic Modelling white paper describes the various parameters used in the model. The main outputs of the LDM Model are the peak required throughput on the link in the downstream and upstream directions.

2.1.2.3.2 End-User Throughput Estimation Model (ETEM)

This method estimates the bandwidth required on a link to sustain a specified number of users based on pre-defined characteristics of their usage. ETEM takes into account the bursty nature of Internet-type traffic, such as Web browsing, file transfers, peer-to-peer communications and gaming. The method is technology agnostic as to type of link under consideration and is used when number of users is between 200 and 4000.

Amongst the model's inputs are:

- The average amount of data consumed by a user in a month (typically in GB).
- The number of TC-4 users (services) that will be using the link.
- User concurrency (a measure of how many of the link's users are expected to be active at any one time).
- The performance required based on the X/Y/Z metric.
- TC-1 and TC-2 usage based on the modelling methodology detailed above.

ETEM model is used to simulate an entire day's worth of traffic, and the most in-depth implementations of the model provide the data in hourly increments. An example output of the model is graphed in Figure 13.

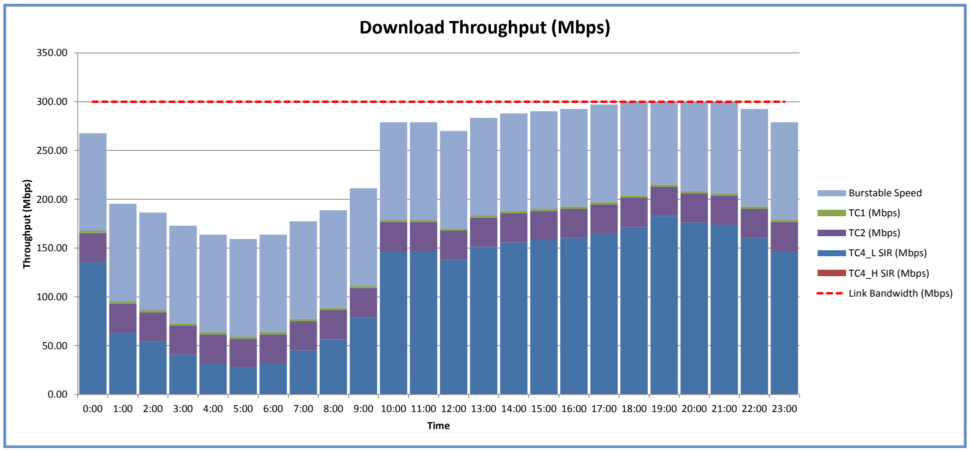


Figure 13. Example of ETEM Output[32]

2.1.2.3.3 Temporal Distribution Model (TDM)

Link size is most often dimensioned according to what needs to be consumed during busy hours. The TDM model uses only the busy hour in order to make its determination. The model assumes a base throughput during the busy hour based on the total number of services, the average TC-4 throughput during the busy hour and any TC-1 or TC-2 throughput added on top of it. It also adds an extra TC-4 component based on an instantaneous concurrency figure of 8% to come up with a total expected maximum throughput. A Burstable Speed factor, added on top of this figure, is a reasonable heuristic to get the final required link dimensioning.

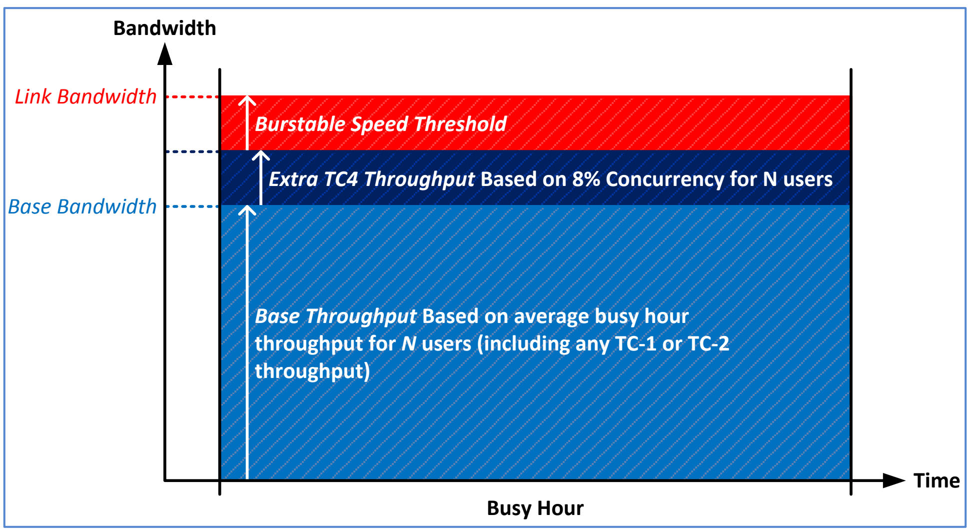


Figure 14. Temporal Distribution Model[32]

Main inputs to the TDM are the same or similar to inputs from the other models:

- The average amount of data consumed by a user in a month (typically in GB).
- The number of TC-4 users (services) that will be using the link.

- User concurrency (a measure of how many of the link's users are expected to be active at any one time). Unlike the other concurrencies in the other models, this is an instantaneous concurrency of 8%.
- The performance required is based on the X/Y/Z metric with the TDM using only the Z threshold.
- TC-1 and TC-2 usage based on the modelling methodology detailed earlier.

Tables 13 and 14 of the Traffic Modeling white paper (see footnote 32) describe the TDM model inputs and algorithm steps respectively.

2.1.2.3.4 Packet Loss and Congestion Avoidance / Control Schemes in TCP/IP Networks

The traffic modelling white paper describes a combination of all modelling methodologies used in either building a new system or maintaining existing systems. Packet Loss and Congestion Avoidance is an overlay on TDM, LDM and ETEM used by the traffic engineering tools and are designed to assist capacity planning and performance measurement. Once the estimation of end user performance is calculated using ETEM techniques a packet loss calculation is performed to temper the models outputs. Section 5 of the nbn traffic modeling white paper (footnote 31) describes the above techniques applicable to packet loss and congestion avoidance in TCP/IP networks.

2.1.2.4 Validation of the Model

As stated previously model validation including calibration of measured and model outputs and appropriate refreshing of relevant parameters on a periodic basis (e.g. at least once in six months) is essential to have accuracy and confidence in the model results. nbn has a regular program to refresh model values including the following parameters. The details are found in Section 6 of the white paper.

1. Peak-to-Average Ratio
2. TC-4 Upstream and Downstream Usage per Month per End-User (based on CTO 10-year forecast)
3. Concurrency
4. Downstream / Upstream Ratio
5. Mean Busy Hour Throughput Percentage
6. Drift Correction Factor

Appendix B contains a graph (Figure 25) that shows the historical accuracy of nbn predictions over a period of about ten years. The graph shows a relatively close match between the network traffic (in Gbytes per month) that was forecast by the nbn model and the actual measured network traffic. This nbn validation process is an important step in achieving accuracy over the ten-year prediction window.

All the above factors are important to reflect difficult real-world characteristics of a packet data network that is continually subject to growing traffic demands and increased end-user expectations.

2.1.2.5 Summary

Based on a review of classical techniques for traffic modeling and engineering in the real-world and techniques practiced by many carriers across the globe, we believe that the nbn traffic modeling methodology takes into account key real-world parameters and uses proprietary home-grown engineering tools to manage its network so that the long-term interests of end-users are satisfied, and the network is well-utilized to make the operations economically effective. The nbn modeling is a reasonable approach that takes into account all key factors important for modeling packet traffic, utilizes a mix of analytical and approximation methods to solve a complex traffic engineering problem and validation based on modeling, measurement and feedback for refinement of model inputs on a periodic basis.

2.2 10-Year Usage and Speed Forecasts Reasonable?

2.2.1 Overview of Methodologies

The sources that provide the information basis for the nbn usage and speed forecasts reflect a variety of perspectives including respected government bureaus, well-established industry research organizations, and respected third-party analysts. The resource topics are focused on network traffic related aspects including demographics, user behaviors, usage trends, and technology eco-systems. Given this context, the basis for the nbn forecasts is reasonably qualified and diverse for the creation of valuable perspectives on the nature of network traffic.

The nbn forecasting methodology is based on describing historical usage and traffic data, and extrapolating future demand from it while acknowledging assumptions and risks for technology improvements, shifting demographics, changing usage patterns (e.g., moving from Free to Air to streaming), and seasonality. In addition, the forecast methodology allows for adjustments attributable to irregular and one-time events such as migration to new platforms or ready acceptance of more favorable solutions.

There are other methodologies available that could be considered to add a more complete description of alternative futures, especially those that are not easily foreseen because they are:

1. not sufficiently measurable
2. the result of external influences
3. combinations of seemingly unrelated events, or
4. arriving so quickly that recognition and response times are limited.

Given these contributing factors, relevant foresight practices may include methodologies such as scenario planning, inflection point identification, and PEST (political, economic, social, and technology) analysis.

Peter Schwartz pioneered the use of scenario planning and analysis, and his work is well documented in his book, *The Art of the Long View*.[37] His process entails developing consciously

[37] Schwartz, Peter, The Art of the Long View: Planning for the Future in an Uncertain World, Doubleday, 1991.

diverse descriptive scenarios of plausible alternate futures with an emphasis on challenging assumptions, including outliers, and examining contingencies.

Peter F. Denning addresses the challenge of forecasting the future when we live in times of exponential change that occurs simultaneously in multiple technologies. He recommends the inflection point analysis approach used by such leaders as Intel Corporation's legendary former Chairman, Andy Grove, and Stanford affiliated futurist, Tony Seba to gain foresight into eras where there are rapid shifts in user behavior as they adopt new solutions due to dramatically favorable cost or performance curves.[38] Well-known market disruptions that exemplify these types of inflections include the shifting of analogue TVs to smart TVs, cellphones to smartphones, and film-based cameras to digital cameras. All benefited from the convergence of notable S-curves of adoption rates for silicon storage, graphics processors, and wireless communications.

S-curves describe the curvilinear adoption rates that new products take as novel solutions that might be initially too expensive and low performing, but eventually gain a level of cost, performance and feature improvement that overtake the incumbent solution and create new rapid growth markets. A classic S-curve pattern was demonstrated in the slow adoption rate of early mobile phones in the 1970's that peaked in the 2000's and were replaced rapidly by smartphones that, in addition to traditional voice telephony, offered dramatically new capabilities for internet access and hundreds of convenient "apps."

Organizations such as the Institute for the Future have adopted methodologies to forecast futures by using means such as PEST analyses to identify and clarify aspects that may shape the future. The IFTF is well-known for its expertise in these type analyses and describe their own expertise, below.

> Institute for the Future is the world's leading futures organization. For over 50 years, businesses, governments, and social impact organizations have depended upon IFTF global forecasts, custom research, and foresight training to navigate complex change and develop world-ready strategies. IFTF methodologies and toolsets yield coherent views of transformative possibilities across all sectors that together support a more sustainable future.[39]

Of particular interest to the present question is a recent description by the IFTF of a future networked world entitled, "The Hyperconnected World of 2030-2040."[40] The report was created by an expert panel that comprised noted research leaders from academia, industry, futurist, and policy organizations. The work was made possible by support from the Office of the Director of National Intelligence (USA).

The focus of the IFTF's two-part report is described in the introduction:

> What exactly does the hyperconnected world of 2030–2040 look like? The hyperconnected world is a future in which 5G networks have been widely and globally deployed, and in

[38] Denning, Peter F., Navigating with Accelerating Technology Change, Communications of the ACM, September 2018, Vol. 61, No. 9, pg 28

[39] Monaco, N., The Hyperconnected World of 2030–2040, Institute for the Future, Palo Alto, CA, 2020, pg iii.

[40] ibid, pg iii

which the normal, day-to-day functioning of society depends on billions of connected devices having highly reliable, low-latency connectivity.[41]

Part I[42] discusses probable and possible areas of concern in a hyperconnected world and touches on several areas that will enable or impact network usage: theft-prone vulnerabilities, medical care protocols, proliferating cryptocurrencies, digital deception, synthetically generated media, disinformation-driven fragmented world views, and new human/computer action paradigms such as conversational agents.

Part II groups and discusses the key findings of the workshop in four key element categories below and continues by using canonical scenarios advocated by Professor James Dator's (Professor Emeritus and former Director of the Hawaii Research Center for Futures Studies). His four scenario categories of continued growth, collapse and decline, constraint and limits, and transformation are used to explore hyperconnected technology and to develop general guidelines for those futures.

1. Conversational Computing and AI
2. Immersive User Experiences
3. Robots, Autonomy Vehicles, and Drones
4. Networks – Fast, Quick, Adaptive, Versatile

In the current network traffic forecast, nbn may be able to lower the risk of underestimating network demands in outer years by systematically creating an inventory of use case scenarios developed through established foresight methodologies that would then be refined in conjunction with subject matter experts.

2.2.2 Assessment of nbn Forecast

The nbn forecasting methodologies are focused on collecting historical and current network traffic data in a detailed and thorough manner and, as such, they should yield reasonable results for time spans that encompass periods of stable product offerings and human behaviors (e.g., the 0–5-year timeframe). When disruptive factors are introduced (potentially in the 5–10-year timeframe), whether or not those factors are political, economic, social, or technological, there is a likelihood that the network traffic forecasts will not sufficiently anticipate them unless there is a methodology that regularly provides early detection of emerging signals and their relationship to other evolving factors.

[41] ibid, pg 1

[42] ibid, pp 5-15

2.3 10-Year Usage and Speed Consistent with Reputable Forecasts?

2.3.1 Overview of Other Industry Forecasts

2.3.1.1 General Industry Forecasts

Technology forecasts, no matter the technology, are made up of many component parts each of which contribute to the growth of the resulting supply curve. The supply curve is predictable due to the relative continuity of development of those components acting together over time. In this case the technology supply curve is defined by the current and future technologies used to deliver broadband internet services. This underlying technology makes up the network which supplies that internet data.

The end-users and the applications they use are what drives internet data demand. Understanding the uptake of new applications, games, services, as well as devices such as TVs, mobile phones, etc. will help in the development of the internet data demand curve. This demand curve will be used to determine the predicted usage and desired speed to provide an acceptable end-user experience over the planning horizon.

It is the meeting of the supply and demand that will dictate the requirements for speed and the associated usage forecasts. In this case the usage and speed forecasts from other international jurisdictions will be used to test the consistency of nbn forecasts. While each international jurisdiction will have their own forecast of usage and speed, the growth trends in each should be consistent with the overall global trends. As expected, there will be outliers but the extenuating circumstances that caused that situation should be identifiable and appropriate judgment can be used to determine whether to include that data in the analysis.

While we have discussed the more traditional forecasting techniques, we also should consider risk mitigation techniques that make the forecast more robust and resilient over time. These techniques address how to handle the uncertainty in a future outcome as was demonstrated during the COVID-19 pandemic. While this was a global natural event there are also technological inflection points that also can be modeled and taken into consideration when producing a forecasting model. The next section addresses this topic.

2.3.1.2 Risk Mitigation Forecasting

The nbn reports address incremental network traffic increases based on historical and current traffic generated by existing products and services. From a usage perspective, the reports consider three primary traffic categories: 1) current (e.g., voice/video conferencing, IP cameras) and emerging video streaming capabilities (4K and 8K), 2) game-related traffic for installations, updates, and purchases, and 3) traffic generated by general work from home scenarios. The reports do consider the network traffic impact resulting from changing social behavior such as COVID lockdowns, ‘out of home’ activities, and networked mobile computing. And there are acknowledgements that new products (e.g., IP Cameras) will impact upstream video traffic generation.

2.3.2 Assessment of nbn Consistency with Other Forecasts

2.3.2.1 International Industry Forecasts

This section covers the consistency of the nbn forecast usage and speed forecasts with other international jurisdictions including various global, U.S., and European forecasts. Sources of forecast information include, but are not limited to: CableLabs, Cisco, CTIA, DataReportal, Ericsson, FCC, ITU, NAB, NCTA, Nokia, Omdia (Ovum), Ookla, OpenVault, and Strategy Analytics.

Global demand for broadband connections has been strong for several years. The broadband market can be divided into fixed and mobile.

From a global subscription perspective, the mobile broadband market is substantially larger than the fixed broadband market: approximately 6 billion mobile broadband subscriptions versus 1.18 billion fixed broadband subscriptions as of November 2020. Globally, the fixed broadband market is still growing according to the ITU.[43] The continued growth in the number of subscriptions shown in Figure 15 will in turn increase data demand.

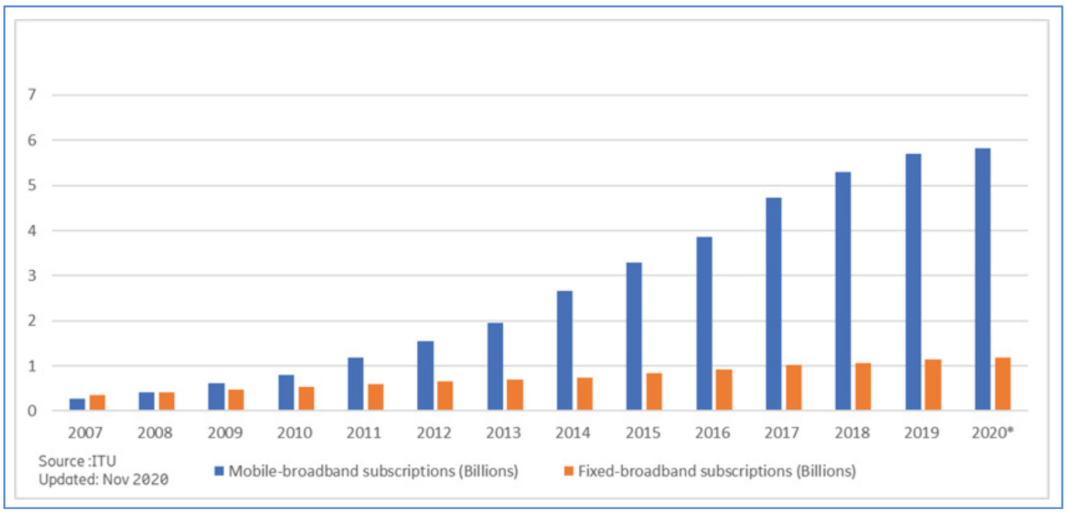
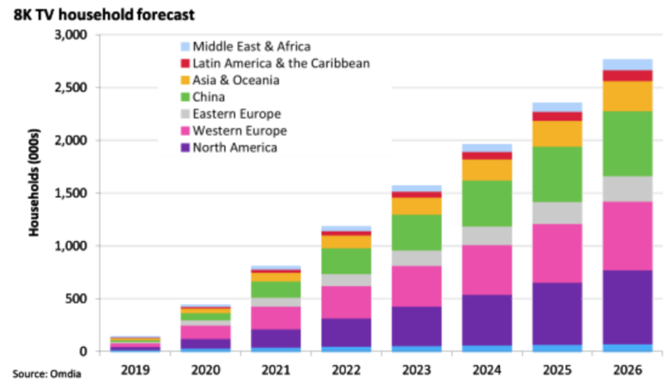


Figure 15. Global broadband subscription growth (ITU)

2.3.2.1.1 TV Format by Household

TV Household formats are a useful proxy for video data usage. As with 4K UHD, and more so with 8K, TVs will drive demand for higher data usage. An April 2022 blog from Omdia[44] (see Figure 16 below) highlighted a slower than expected uptake of 8K TV with a forecast of 2.7 million households by the end of 2026 worldwide. They attribute this softening of the market to lack of native content, price pressure, and lack of demand in China.

43 Avalable: https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx.
44 Omdia research finds consumers remain sceptical about the benefits of 8K :: Omdia (informa.com) April 28, 2022



8K TV households (000s)

Region	2019	2020	2021	2022
Japan	16	32	42	48
North America	30	92	171	269
Western Europe	35	127	216	305
Eastern Europe	13	50	85	115
China	15	66	155	244
Asia & Oceania	20	46	82	121
Latin America & the Caribbean	4	13	28	43
Middle East & Africa	5	15	27	37
World	**139**	**440**	**804**	**1,181**

Source: Omdia

Figure 16. Worldwide 8K TV Household Forecast – Omdia (April 2022)

With the economics of 4K UHD struggling with their own content issues, the growth of 8K TV will be delayed relative to previous forecasts such as the Strategy Analytics report from April 2021 that predicted Global 8K TV household adoption reaching 72 million by 2025.[45]

[45] Strategy Analytics: 8K TV Owning Households to Reach 72 million Worldwide by 2025 | Business Wire April 7, 2021

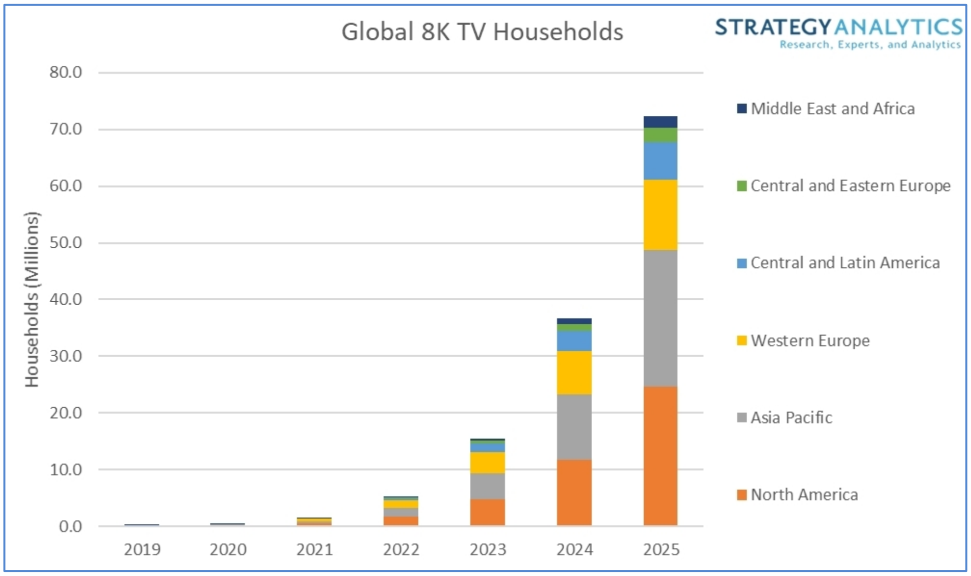


Figure 17. Global 8K TV Households - Strategy Analytics (April 2021)

The discrepancy between these two forecasts points to the fact that there is no consensus on the uptake of 8K TV over the planning period. Further, this does not speak to the take up of 16K TV which may make an entrance into the TV market by the end of the planning period (2028).

2.3.2.1.2 Pay TV and Over-the-Top Subscriptions

The primary market drivers for 4K UHD and later 8K TVs is the growth of Over-the-Top (OTT) subscriptions versus Pay TV (see Figure 18).

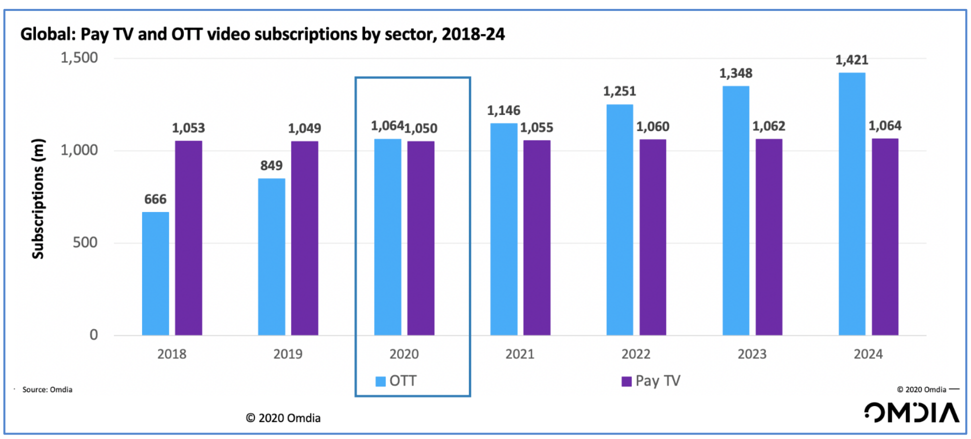


Figure 18. Global: Pay TV and OTT video subscriptions by service 2018-2024 (Omdia)

2.3.2.1.3 Video Streaming Applications

Price and TV screen size (discussed above) are also factors.[46] OTT services have been driven by the sales of new Smart TVs where access to streaming video services is available, see Figure 19.

CATEGORY TRAFFIC SHARE

TOTAL TRAFFIC

	Category	Total Volume
1	Video	53.72%
2	Social	12.69%
3	Web	9.86%
4	Gaming	5.67%
5	Messaging	5.35%
6	Marketplace	4.54%
7	File Sharing	3.74%
8	Cloud	2.73%
9	VPN	1.39%
10	Audio	0.31%

GLOBAL APP TRAFFIC SHARE

TOTAL TRAFFIC

	Category	Total Volume
1	YouTube	14.61%
2	Netflix	9.39%
3	Facebook	7.39%
4	Facebook video	4.20%
5	Tik Tok	4.00%
6	QUIC	3.98%
7	HTTP	3.58%
8	HTTP Media Stream	3.57%
9	BitTorrent	2.91%
10	Google	2.79%

Figure 19. Category and Global App Traffic Share – January 2022

"Our data show in the first half of 2021 bandwidth traffic was dominated by streaming video, accounting for 53.72% of overall traffic, with YouTube, Netflix, and Facebook video in the top three.[47] "

8K TV resolution is 7680 X 4320 or 33,177,600 pixels which requires at least a ~100 Mbps services to accommodate the streaming content. It will also require substantial buffering. 4K resolution has 3840 X 2160 or 8,294,400 pixels which only requires ~25 Mbps data stream with some limited buffering to ensure no interruption of content. The move from 4K UHD to 8K today leads to the requirement for a higher priced internet service and TVs.

2.3.2.1.4 Average Screen Time Usage

Another important component of the video forecast is related to the amount of time spent looking at screens. Average screen time for Americans is ~7 hours per day with ~50% on Smart TVs and desktops and ~50% on mobile screens. The screen time metric has been relatively flat year-over-year (2022 over 2021).[48]

Over the planning horizon there will be other technologies at play that will lead to increased demand for higher resolutions and therefore higher data demand, e.g., 16K and even 32K displays. These technologies include VR/AR headsets which requires 32K resolution to give 3D perspectives as well as 16K resolution screens and to support future 16K content.

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[46] Omdia: 4K TV sales on the up as OTT overtakes pay TV - Digital TV Europe November 17, 2020

[47] The Global Internet Phenomena Report, January 2022, page 12-13

[48] Comparitech Article - Screen Time Statistics: Average Screen Time in US vs. the rest of the world; Screen Time Statistics: Average Screen Time in US vs. the rest of the world - Comparitech using data from DataReportal; DataReportal – Global Digital Insights

2.3.2.1.5 Broadband Network Data Traffic

U.S. Broadband Network data traffic is revealing shifting usage patterns among subscribers on usage-based billing (UBB) plans, who are adopting higher-ARPU speed tiers and whose usage pattern growth is surpassing that of subscribers on flat-rate billing (FRB).[49]

The U.S. monthly weighted average data consumed by subscribers in 2Q22 was 490.7 GB, up 13.1% from 2Q21's weighted average of 433.5 GB, and down 4.5% sequentially (quarter-over-quarter) from 1Q22. This is in line with historical second quarter seasonal patterns. Weighted averages combine data from FRB and UBB subscribers (see Figure 20). Annual upstream data usage growth (10.5%) was outpaced by downstream data usage growth (13.4%) in 2Q22.

UBB networks realized greater annual growth in upstream usage, up 18.5%, as compared to FRB networks, which saw relatively flat growth in upstream data usage.

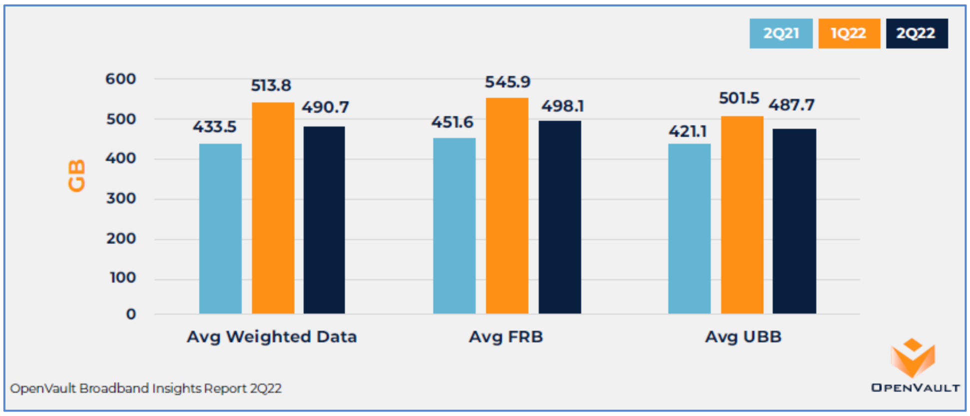

Figure 20. Data Usage Trends by Billing Type – 2Q22 (OpenVault[50])

2.3.2.1.6 Broadband Data Usage Trends

In 2Q22 European vs. North American Data Usage (see Figure 21).

- European average data usage (212.1 GB) declined close to 8% from 1Q22 (230.3), highlighting seasonal usage patterns similar to what were seen in North America.
- North American median data usage (313.9 GB) approached 3x that of European median data usage (109.1 GB) in 2Q22.

[49] OpenVault Broadband Insights Report - US and Europe Data OVBI_2Q22_Report, page 4
[50] ibid, page 5

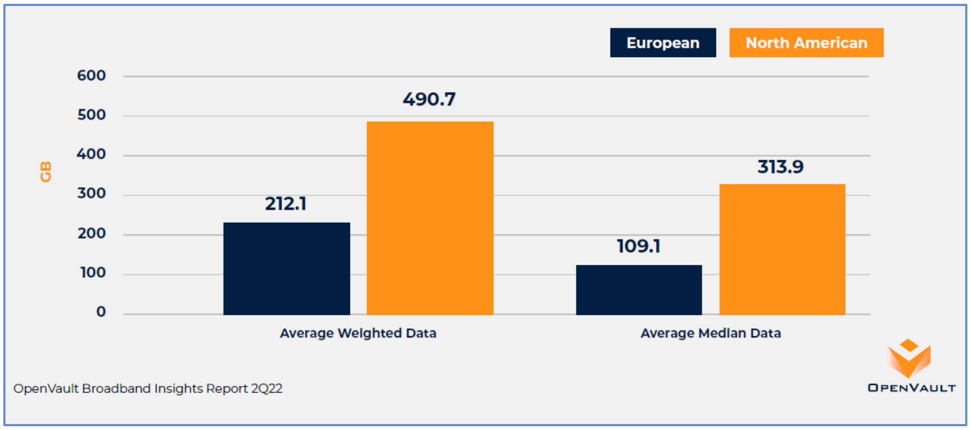

Figure 21. European vs. North American Data Usage – 2Q22 (OpenVault[51])

UBB subscribers are accelerating their data usage, thanks in large part to those subscribers adopting faster broadband speed tiers. This faster growth in subscribers' data usage has UBB operators closing the historical data consumption gap with FRB operators.

2.3.2.1.7 Broadband Subscriber Speeds

Three out of four U.S. subscribers now receive broadband speeds of 200 Mbps or higher (see Figure 22).

- The gigabit subscriber tier in 2Q22 reached 14.2% of all subscribers, up more than 35% from a year ago (10.5%).
- With 55% of subscribers in 2Q22, the 200 – 400 Mbps speed tier is by far the most popular tier.
- The slowest speed tier of less than 50 Mbps continues to shrink; in 2Q22 it was 5.7% of all subscribers, down nearly 25% from 1Q22 (7.6%).

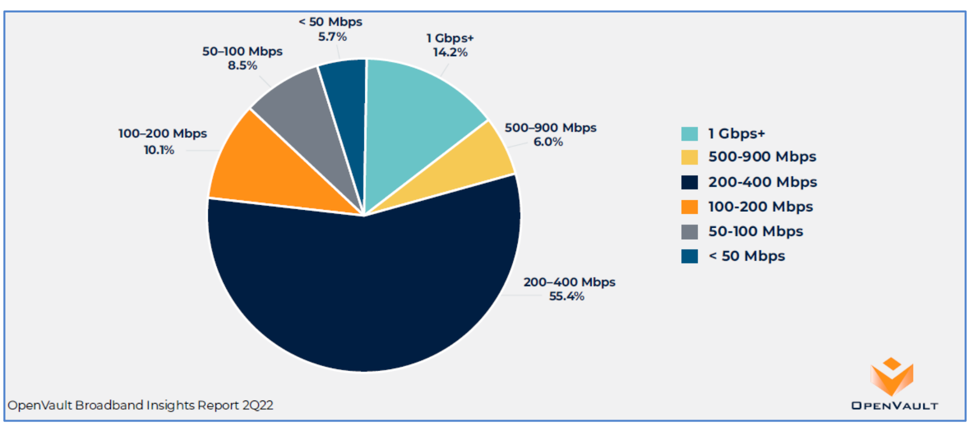

Figure 22. Provisioned Speed Tiers — 2Q22 (OpenVault[52])

[51] ibid, page 9

Ookla®, Speedtest® Global Index rankings (see Figure 23) are based on median download speed to best reflect the speeds a user is likely to achieve in a market.[53]

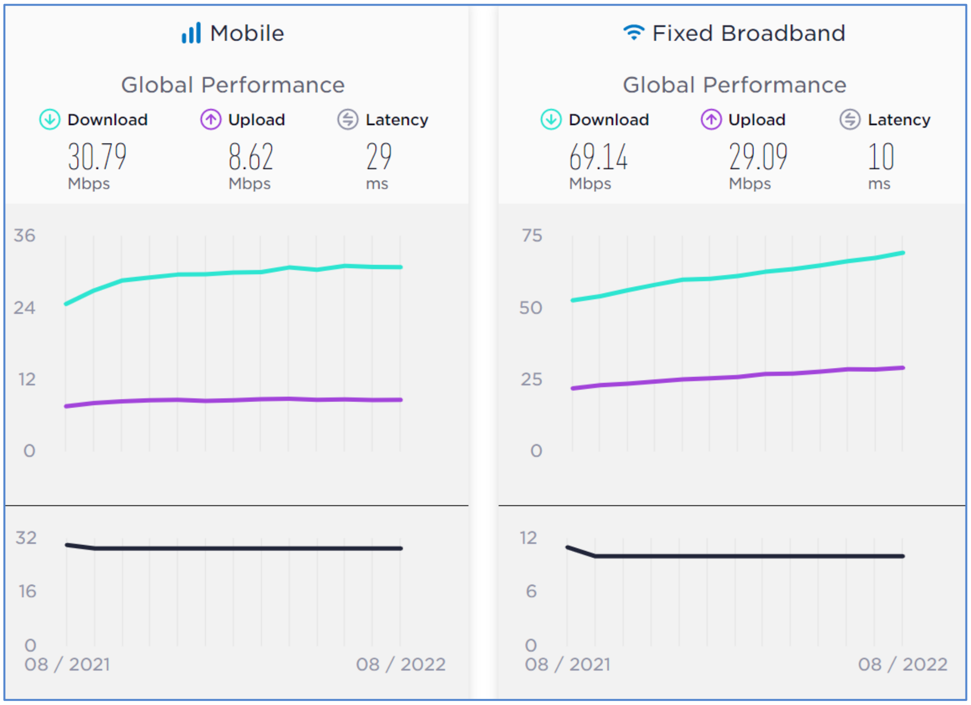

Figure 23. Global Median Speeds August 2022(Ookla®, Speedtest®)

FCC analysis of fixed broadband deployment data revealed that fixed line-based technologies are limited to a small portion of the geography, no more than 20% of U.S. urban census blocks. Figure 24 shows the current median speeds across ISP technologies in rural U.S. markets against the FCC broadband criteria. [54] It also shows that fiber, cable, and satellite exceed the current FCC speed metric (25/3 Mbps) for broadband service. In July, FCC Chairwoman Jessica Rosenworcel proposed in a Notice of Inquiry to increase the speed metric to 100/20 Mbps.[55] She stated:

> The 25/3 metric isn't just behind the times, it's a harmful one because it masks the extent to which low-income neighborhoods and rural communities are being left behind and left offline. That's why we need to raise the standard for minimum broadband speeds now and while also aiming even higher for the future, because we need to set big goals if we want everyone everywhere to have a fair shot at 21st century success.

The Notice of Inquiry proposes to set a separate national goal of 1 Gbps/500 Mbps for the future.

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[52] ibid, page 7
[53] Ookla, Speedtest Global Index – Internet Speed around the world – Speedtest Global Index
[54] FCC, "Form 477 Broadband Deployment Data - June 2019 (version 2)," June 2019. [Online]. Available: https:// www.fcc.gov/form-477-broadband-deployment-data-june-2019-version-2
[55] FCC, Chairwoman Rosenworcel Proposes to Increase Minimum Broadband Speeds | Federal Communications Commission (fcc.gov)

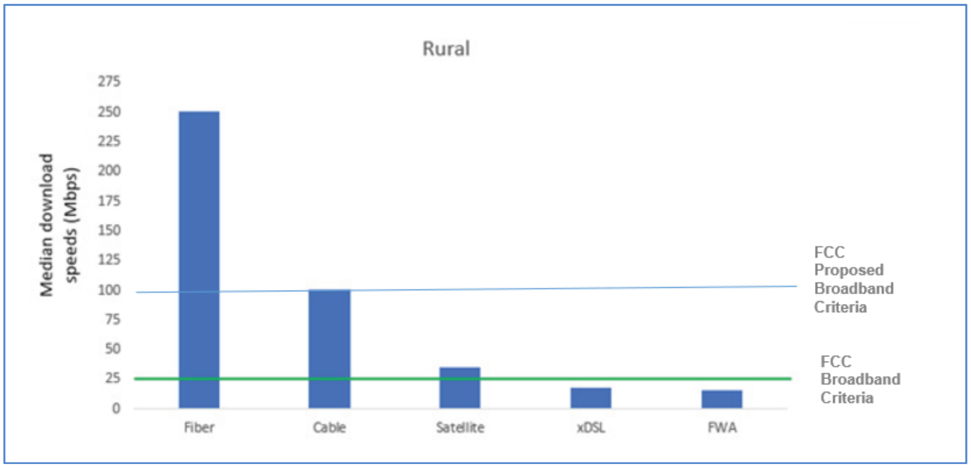

Figure 24. Median speeds across ISP technologies (FCC)

2.3.2.2 Assessment of the nbn Traffic Forecast

Collectively these international sources align well and are broadly consistent with the current nbn traffic forecasts. Breaking down the application usage of these traffic forecasts into their key drivers the most critical element is video. Video is the largest single contributor to application traffic worldwide accounting for approximately 80% of internet traffic.

Much of that video traffic is in turn driven by video from household devices. The largest component of video traffic in the home is directly related to Household TV resolution specifically 4K and now 8K TVs. The nbn Household TV resolution projections are in-line with global forecast noted above although the uptake of 4K and 8K may be slower than has been modeled.[56] The current global and U.S. forecast show that 4K's uptake will be slower than nbn modeled and thus will delay the increase in traffic derived from 8K by 1 to 2 years. [57]

While TV Household resolution is a key driver of the global and nbn traffic forecasts, the amount of time all screens are active will also contribute to the video traffic forecast. The nbn screens active during the day forecast is in general agreement with other global and U.S. sources. The average American spending ~7 hours per day looking at screen while in the average adult in the U.K. spent ~6.5 hours per day[58] and Australian spent 6.1 hours[59]. This metric saw a significant increase due to the 2020 – 2021 COVID lockdowns but this metrics forecast shows a relatively flat growth profile over the forecast period.

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56 Omdia research finds consumers remain sceptical about the benefits of 8K :: Omdia (informa.com) April 28, 2022

57 Strategy Analytics: 8K TV Owning Households to Reach 72 million Worldwide by 2025 | Business Wire April 7, 2021

58 Ofcom: Lockdown leads to surge in TV screen time and streaming - Ofcom – August 5, 2020 and

59 Comparitech Article - Screen Time Statistics: Average Screen Time in US vs. the rest of the world, March 21, 2022; Screen Time Statistics: Average Screen Time in US vs. the rest of the world - Comparitech using data from DataReportal; DataReportal – Global Digital Insights

Daily Usage per Active Screen show growth as the mix shifts to more video intense applications. This is also consistent globally as 4K content is added by YouTube, Netflix, as well as the recent uptake of TikTok. Content per Device Resolution is again consistent given the increased number of applications allowed by higher screen resolutions.[60]

The global speed requirements both downstream and upstream continue to increase with even more emphasis being placed globally on higher performance. In July 2022, the U.S. FCC Chairwoman Jessica Rosenworcel proposed in a Notice of Inquiry to increase the speed metric from 25/3 Mbps to 100/20 Mbps across U.S. rural communities. She also stated the goal is to reach 1 Gbps / 500 Mbps in the future, most likely in the 2030s. This FCC initiative adds to nbn's position that increasing the speed delivered to its customers beyond the BCAR estimate of homes needing 56 Mbps or less by 2023 is a requirement.[61]

In conclusion the sources that form the basis of the nbn usage and speed forecasts are consistent with international sources utilized. A variety of reputable international sources including government agencies, industry-led reports, and third-party analysis were used to validate the nbn forecast. These sources focused on network traffic with special emphasis on the video, which is the single biggest driver of traffic, but also included user behaviors, usage trends, and technology advancements. Given this analysis, the nbn forecast is in-line with international sources and is an accurate reflection of the Australian network traffic growth over the forecast period.

2.3.2.3 Mitigating Forecasting Risk

The earlier referenced IFTF and ITU reports describe future scenarios where reliable, secure, and fast network traffic is a key factor in delivering and/or capturing user experiences. Alternate human/computer interaction paradigms (e.g., audio, haptic, immersive) are explored that go far beyond the keyboard/visual domains that dominate today's interactions. And there are scenarios where computer-enabled devices (e.g., drones, autonomous vehicles) will require high-quality network connections as a fundamental capability regardless of human participation. In many cases, the emerging technologies are leveraging each other's capabilities so that new products and services are creating demand inflection points that are not easily determined by extrapolating from existing trend lines. Engaging new methodologies as described in Section 2.2.1 can improve an understanding of these difficult-to-foresee sources of increased network traffic.

3 CONCLUSIONS

Returning to the three fundamental questions posed for this report:

> 1. Do you consider nbn's traffic modeling methodology, as set out in the White Paper, the Forecast Presentation and the Need for Speed Presentation, to be a reasonable modeling methodology from a technical perspective?

[60] The Global Internet Phenomena Report, January 2022, page 12-13

[61] FCC, Chairwoman Rosenworcel Proposes to Increase Minimum Broadband Speeds | Federal Communications Commission (fcc.gov)

> 2. Do you consider nbn's 10-year usage and speed forecasts, as set out in the Forecast Presentation and the Need for Speed Presentation, to be a reasonable prediction of usage and speed requirements for Australian end-users over the next 10 years?
>
> 3. Do you consider nbn's 10-year usage and speed forecasts, as set out in the Forecast Presentation and the Need for Speed Presentation, are broadly consistent with prevailing reputable forecasts on these matters in other comparable international jurisdictions?

Our response to question 1 is that we find that the nbn model is a reasonable, potentially conservative estimate for future usage needs. The model accounts for the complexity of a nationwide network, the typical requirements and vagrancies of a packet network and, given the dominance of video traffic, supports the current migration to higher video resolutions (4K and 8K) which will significantly impact required speeds and data usage.

In response to question 2, the predictions from the nbn 10-year usage and speed forecasts are reasonable given current usage trends and may be somewhat conservative for the 5-10 year timeframe.

In response to question 3, the nbn 10-year usage and speed forecasts are broadly consistent with the reputable forecasts for broadband needs from other global jurisdictions.

4 SIGNATURES

Signed for and on behalf of Roberson and Associates, LLC:

Dennis Roberson, President and CEO

William Alberth, Vice President, Mobile Technologies

A. Author Bios

William Alberth, Vice President, Mobile Technologies

Mr. Alberth joined Roberson and Associates in 2013. With more than 170 patents issued or pending, he is a leading innovator in the wireless communications field and is presently consulting to several startups and established corporations on topics of technology, wireless technology, and intellectual property. Mr. Alberth is passionate about developing and commercializing new technology, and his patent portfolio covers mobile communications across hardware, software, network, end-to-end services, and various aspects of wireless technologies.

Mr. Alberth created and led a team responsible for a majority of the intellectual property filed by Motorola Mobility, which included use and construction of a watch phone device. He was the Top Inventor at Motorola Mobility. As Mobile Devices Chief Technology Officer, Mr. Alberth was responsible for developing differentiating technologies. He was a Dan Noble Fellow and a Member of Motorola's Science Advisory Board where he led the technical ladder and served on Motorola's Patent Committee. He regularly consults on technology licensing, technology investment, and acquisitions and also served as an expert legal witness. He is a regular consultant to carriers on wireless connectivity and emerging technologies and has presented to the Federal Communications Commission on spectrum and other topics.

Prior to his current assignment, Mr. Alberth was responsible for leading new product development and introduced various analog and digital mobile communication products. He has over 30 years' experience in digital communications, radio frequency systems engineering, digital signal processing, new technology introductions, and has product development experience in Long-Term Evolution (LTE), Code Division Multiplex Access (CDMA), Universal Mobile Telecommunications System (UMTS), Third Generation (3G), Personal Digital Cellular (PDC), and analog technologies.

Mr. Alberth graduated with a Bachelor of Science in Electrical Engineering from the University of Illinois in Urbana-Champaign and a Master of Science in Electrical Engineering from Illinois Institute of Technology. He is an advisor to Northwestern University's Electrical and Computer Engineering Department.

Mark Birchler, Senior Principal Investigator

Mr. Birchler joined Roberson and Associates in March 2011. He led the development and deployment of long-term spectrum observatory systems, supported Federal Communications commission (FCC) policy development on issues, such as spectrum utilization, and provided consultation on dynamic spectrum access coexistence issues. Mr. Birchler led programs relating to technology and standards associated with Department of Defense (DoD)/commercial spectrum sharing in the 3.5 GHz and Advanced Wireless Services (AWS)-3 bands, as well as a Defense Advanced Research Projects Agency (DARPA) program which focuses on evaluation of spectrum situational awareness technology. More recently, Mr. Birchler has contributed to spectrum assessment for satellite systems and the testing of geotargeted broadcast technology with a focus on advancement in the FCC regulatory process.

Prior to joining Roberson and Associates, Mr. Birchler was a Fellow of the Technical Staff in the Applied Research Center at Motorola Mobility, serving as a Research Department Manager and Senior Technical Leader. Mr. Birchler was a primary technical contributor to research and development of the iDEN wireless communication system. He held engineering and management positions in Motorola Labs and Land Mobile Products Sector Research. He has over 39 years' experience in wireless technology, including optimized video transport, commercial solutions in licensed and unlicensed bands, public safety solutions, techno-business analysis, geolocation solutions, system simulation, and strategic program development.

Mr. Birchler has 23 issued patents, including a Motorola Regional Patent of the Year and was recognized as a key technical leader through induction into Motorola's Science Advisory Board. He has extensive experience in wireless standards and FCC policy development and has published numerous technical papers, book contributions, and presentations.

Mr. Birchler received his Bachelor of Science in Electrical Engineering degree from the University of Minnesota and his Master of Science in Electrical Engineering from Illinois Institute of Technology.

Pepe Lastres, Senior Marketing Consultant

Mr. Lastres joined Roberson and Associates as Senior Marketing Consultant in July, 2016, with 31 years' experience in the industry. He also serves as the Vice President of Marketing at BroadView Communications.

Previously, Mr. Lastres served as the Head of Marketing and Corporate Affairs North America within Nokia Solutions and Networks (NSN), now Nokia Networks, reporting directly to the NSN Chief Marketing Officer (CMO). There, Mr. Lastres led all aspects of mobile industry marketing and corporate affairs in support of the NSN regional Head of Customer Operations North America. Specific duties included development and implementation of annual and long-range marketing plans, account sales support plans, channel management, branding, lead generation, marketing metrics, internal communications, analyst and press relations, trade show participation, government relations, and association management.

Prior to NSN, Mr. Lastres served as the Senior Director of Wireless Networks Solutions Marketing supporting the Mobile Broadband business reporting directly to the Motorola

Solutions' CMO. He has extensive international experience, having held positions both in Hong Kong and the United Kingdom in addition to the United States.

Mr. Lastres holds a Master of Business Administration from the University of Chicago Booth School of Business and a Bachelor of Science degree from Florida Institute of Technology.

Tom MacTavish, Senior Principal Investigator

Mr. MacTavish joined Roberson and Associates in June 2018. Recently, he retired as a Research Assistant Professor at the Illinois Institute of Technology's Institute of Design (ID) where he taught courses and conducted research related to human/computer interaction design and design research methods. During his 13 years at ID, his individual research was focused on Persuasive Interaction Design and understanding the theories, methods, and techniques that can be used to provide people with computer-assisted support for achieving their behavioral goals.

Prior to joining ID, Mr. MacTavish directed Motorola Labs' Center for Human Interaction Research for nine years with research laboratories in Phoenix (AZ), Schaumburg (IL), and Shanghai (China). Before Motorola, for seven years he led the Human Interface Technology Center based in Atlanta (GA) for NCR Corporation, and for 5 years he served as director of engineering for NCR's wireless communications and networking engineering group in Utrecht, The Netherlands. Earlier in his career, he led software development teams for NCR's point of sale and transaction processing products.

As a member of the human/computer interaction research community, Mr. MacTavish has participated in the full range of product conceptualization and development phases including strategy formulation, user and technology research, concept development, and product implementation. These activities resulted in delivered projects and products using many methods and technologies including recognition technologies (handwriting, speech, and image), interaction technologies (synthetic speech, multimodal interaction, and context aware systems), and experience design and prototyping (design research, user centered design, usability evaluations, and rapid prototyping). Also, he served for 10 years as a member of the scientific committee of the International Conference on Persuasive Technologies, a conference that is held annually in locations around the world.

Mr. MacTavish holds a Master of Arts in Library and Information Science (AMLS) from the University of Michigan and a Master of Arts in English from the University of Iowa. He has a Bachelor of Arts in English from Central Michigan University.

Nat Natarajan, Principal Engineer III

Dr. Natarajan joined Roberson and Associates in 2014 and has 36 years' industry experience in wireless communication and networking systems. Dr. Natarajan is an accomplished master network innovator with work experience covering the entire technology life cycle of widely- deployed wireless systems. In his current position, he has been engaged in serving customers with innovative and efficient spectrum sharing strategies that serve business, as well as public interests.

Previously, Dr. Natarajan worked as a Mobility Network Consulting engineer and architect at Cisco Systems, and his work included commercial customer deployment of Universal Mobile Telecommunications System (UMTS) Femto and Macro Long Term Evolution (LTE) systems. Prior to Cisco, Dr. Natarajan joined Motorola and was a Fellow of the Technical Staff. He developed the adaptive routing algorithms for Iridium, a Low Earth Orbit (LEO) satellite communication system. He subsequently pioneered and advocated All-IP Packet switching for mobile wireless networks and led the early customer demonstrations of 4G systems, including Voice over Internet Protocol (VoIP), Session Initiation Protocol (SIP), Mobile IP, and seamless inter-technology handoffs, such as Wi-Fi and Cellular Radio Access Network (RAN) through a sequence of customer trials. He led early research, standardization and pre-commercial implementations of 802.16e/ Worldwide Interoperability for Microwave Technology (WiMAX), as well as LTE, Frequency Division Duplex (FDD), and Time Division Duplex (TDD). Dr. Natarajan began his wireless career at IBM with fundamental contributions to Wireless Local Area Network (WLAN) architecture concepts and specifications of the baseline 802.11 standard that have been acknowledged by the Institute of Electrical and Electronics Engineers (IEEE) and was a Research Staff Member at IBM Thomas J. Watson Research Center in Yorktown Heights, NY.

Through much of his career, Dr. Natarajan has served as a trusted advisory consultant to a variety of customers across the globe. He has 35+ refereed technical publications, three Cisco Achievement Awards, Motorola Science Advisory Board Associate recognition, Global Standards Awards for Outstanding Performance, and 5 IBM Achievement Plateau awards. Dr. Natarajan has 38 issued U.S. patents, including several implemented in commercial wireless systems.

Dr. Natarajan earned his Bachelor of Technology from Indian Institute of Technology (Chennai), Master of Engineering with Distinction from Indian Institute of Science (Bangalore), and Ph.D. from Ohio State University, Columbus, OH. He is an IEEE Senior Member and a member of its communication society.

Dennis Roberson, President and CEO

Mr. Roberson is the Founder, President, Chief Executive Officer, and Member of Roberson and Associates, LLC and has over 40 years of industry experience. In parallel with this role, he served as a Research Professor in Computer Science at Illinois Institute of Technology where he was an active researcher in the wireless networking arena, a co-founder of IIT's Wireless Network and Communications Research Center (WiNCom), and a co-founder of the Intellectual Property Management and

Markets Program. His wireless research has focused on dynamic spectrum access networks, spectrum measurement systems and spectrum management, and wireless interference and its mitigation, all of which are important to the Roberson and Associates mission.

Previously, he served as Vice Provost for Research at Illinois Institute of Technology. Prior to IIT, Mr. Roberson was Executive Vice President and Chief Technology Officer at Motorola. He had an extensive corporate career, which included major business and technology responsibilities at IBM, Digital Equipment Corporation (DEC, now part of HPE), AT&T, and NCR. He has several issued and pending patents. He has been involved with a wide variety of technology, cultural, educational, and youth organizations, including service as Chair of the Federal Communications Commission Technical Advisory Council, and current membership on both the Commerce Spectrum Management Advisory Committee, the Board of the Marconi Society, and he Chairs the External Advisory Board for SpectrumX, the National Spectrum Research Center. Mr. Roberson also serves on the governing and/or advisory boards of several exciting technology-based companies. He is a frequent speaker at universities, companies, technical workshops, and conferences around the globe.

Mr. Roberson holds Bachelor of Science degrees in Electrical Engineering and in Physics from Washington State University and a Master of Science in Electrical Engineering from Stanford University.

B. Historical Accuracy of nbn Predictions

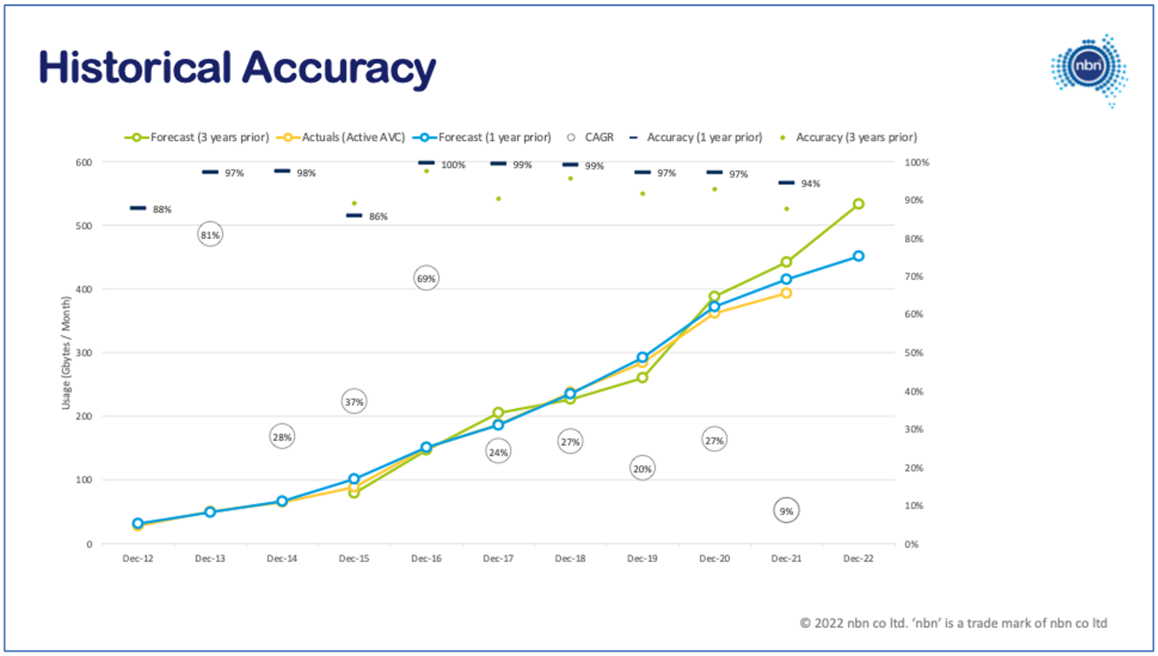

Figure 25. Historical Accuracy of nbn Predictions

C. NBN NETWORK OVERVIEW

The nbn network is a large-scale national network spanning Australia. This appendix is a high-level glimpse of the logical and physical aspects of the network. A more complete description of the network is beyond the scope of this report. At a logical level, the following diagram shows various nodes and links in the network.

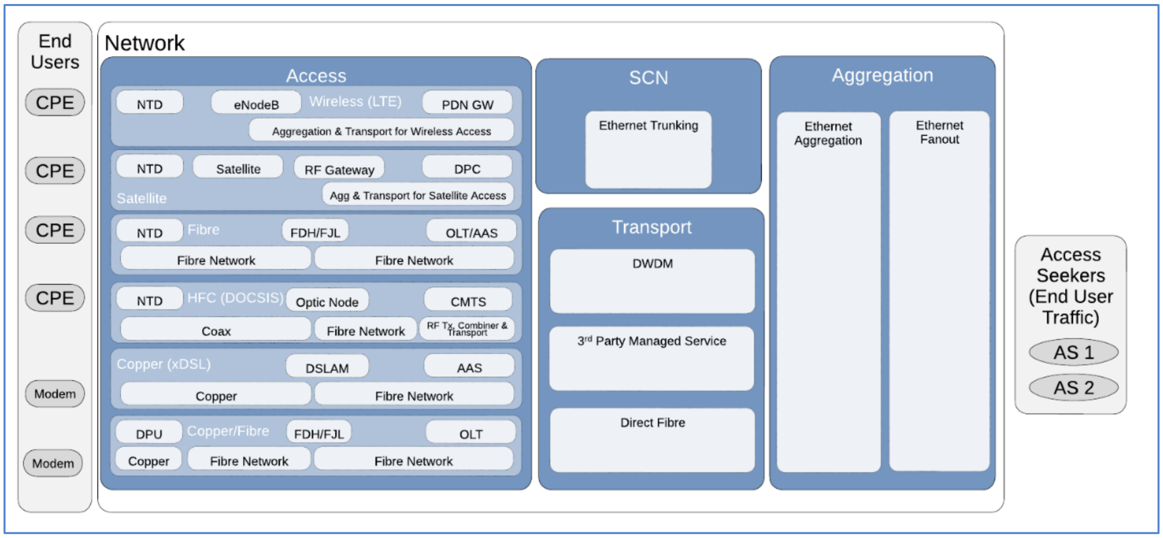

Figure 26. nbn Network Nodes and Links

Links are SCN, Transport (DWDM, 3rd part Manages Services and Direct Fibre) whether they be 1G, 10G Ethernet or 10G , 40G AND 100G DWDM wavelengths. Also, connectivity 10G and 100G ethernet fibre links are also between Ethernet Aggregation Switches (NODES) (EAS's) and Ethernet Fanout Switches (NODES) (EFS's).

Nodes are EAS, EFS, CMTS, AAS, DSLAM, eNodeB, RF Gateways, OLT. These devices have backhauls / links.

POP / Aggregation points in the entire diagram above of which there are 121 of them around all of Australia.

A detailed Point of Interconnect (**POI**) diagram that is deployed in the nbn network is shown below.

SMALL POI:

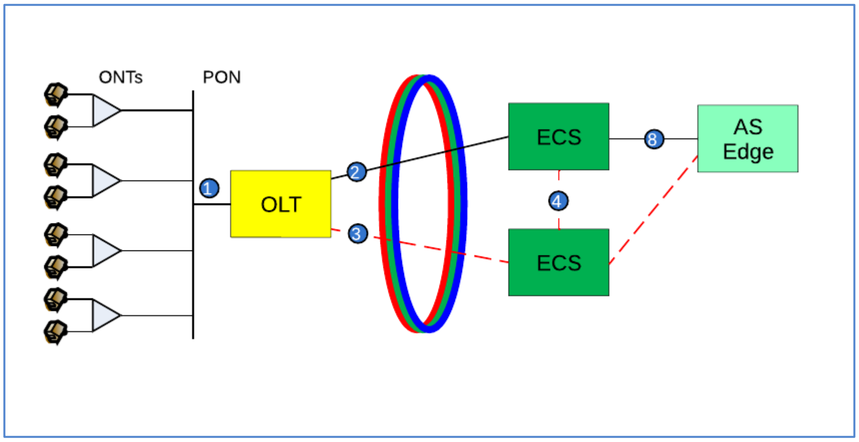

Figure 27. Small POI Diagram

Links Description

1 PON with 2.4Gbps downstream and 1.2GBps upstream capacity

2 Primary backhaul link (OLT is an example but could be CMTS or AAS) up to 4 x 10Gbps links

3 Redundant backhaul link up to 4 x 10GBps links

4 Inter Chassis links up to 18 x 10GBps

8 RSP interconnect (1G or 10G links)

Medium POI:

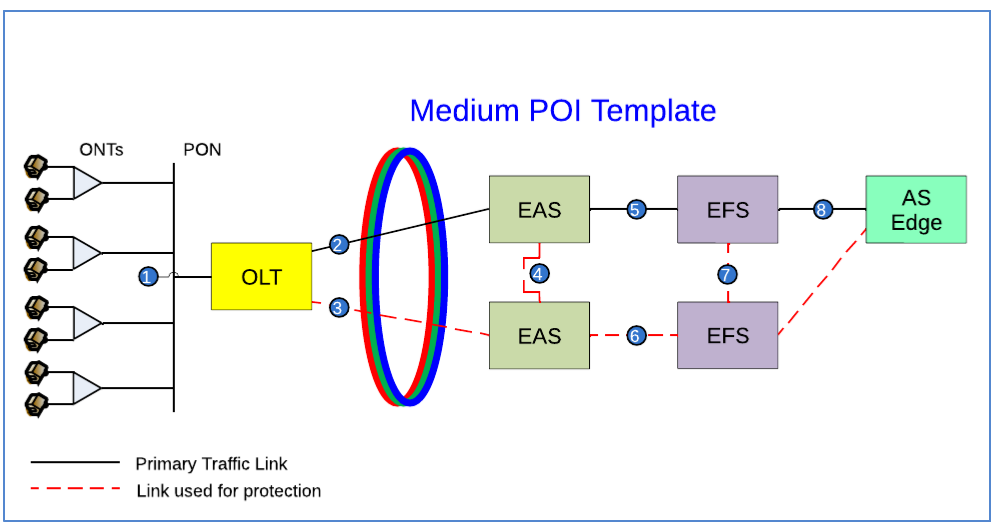

Figure 28. Medium POI Diagram

Links	Description
1	PON with 2.4Gbps downstream and 1.2GBps upstream capacity
2	Primary backhaul link (OLT is an example but could be CMTS or AAS) upto 4 x 10Gbps links
3	Redundant backhaul link upto 4 x 10Gbps links
4	Inter Chassis redundant EAS links upto 18 x 10Gbps
5	Primary Inter Chassis EAS to EFS links upto 18 x 10Gbps
6	Secondary Inter Chassis EAS to EFS links upto 18 x 10Gbps
7	Inter Chassis redundant EFS links upto 18 x 10Gbps
8	RSP interconnect (1G or 10G links)

Large POIs:

Large POIs look like medium POIs with addition EAS EFS ladders.

D. Table of Abbreviations

4K	Video resolution of about 4,000 pixels
8K	Video resolution of about 8.000 pixels
A-EV	Autonomous Electric Vehicle
ATM	Asynchronous transfer mode
CTIA	Cellular Telecommunications and Internet Association
ETEM	End-User throughput estimation model
EV	Electric Vehicle
FCC	USA Federal Communication Commission
FRB	Flat Rate Billing
GDP	Gross Domestic Product
GoS	Grade of Service
ICE	Internal combustion engine
IFTF	Institute for the Future
ITU	International Telecommunications Union
LAN	Local area network
LDM	Link Dimensioning Model
MBS	Megabits per second
MTM	Multi-technology Mix
NAB	National Association of Broadcasters (USA)
NCTA	Internet and Television Association
PEST	Political, economic, social, and technology
POI	Point of interest
TaaS	Transportation as a Service
Tbps	Terabits per second
TDM	Temporal Distribution Model
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol Internet Protocol
UBB	Usage based billing
WAN	Wide Area Network

E. ACKNOWLEDGEMENT

The authors wish to express their gratitude to the modeling team at nbn. The nbn team has developed and executed a world class model that has proven to be accurate over multiple years. This paper would not have been possible without their frank and open cooperation. We hope that the team can grow so that the hard-earned knowledge can be maintained.