Chapter 2

Technical background

This chapter provides an overview of the technical domain in which the research was conducted. Relevant technical concepts and theory presented include the TCP/IP network layer stack, P2P and P2MP optical networks and the PON architecture.

2.1 Introduction

With the widespread use of technological advancements in the home, few have been as significant as the use of computers, assisting with autonomous tasks and allowing communication at a global level. As adoption rates of computers reached exponential levels, the importance of high performance communication systems have been ever increasing. To realise information transfer between computers, a *computer network*, or a collection of nodes interconnected by means of a communication system, is used.

The evolution of these communication systems, from simple local parallel links to global ultra-high bandwidth packet-switched optical fiber networks, necessitates increasingly advanced standardisation schemes and models to implement and integrate effectively.

2.2 The OSI model and TCP/IP

In an effort to categorise and standardise the functions of communication systems, the International Organisation for Standardisation (ISO) developed a layered framework known as the Open Systems Interconnection (OSI) model [18, 19]. This model allows inter-layer communication over a communication channel by implementing a seven layer stack, with each layer serving the layer above it and being served by the layer below. Through an abstraction process called encapsulation, each layer adds its own information to the data it received from the layer above it and passes it to the lower layers. These data transfers are known as Protocol Data Units (PDUs).

Each layer of the OSI model has a specific function necessary at each level of abstraction [20]:

- *Application layer*
  The application layer provides a link between user level applications and network resources and includes protocols to accomplish these specific tasks. Protocols such Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP) and File Transfer and Access Management Protocol (FTAM) are catered for web browsing and file transfers while the Simple Mail Transfer Protocol (SMTP) gives e-mail applications access to mail servers. Services encountered in the application layer are usually catered for a specific task inherent to the operation of an application.

- *Presentation layer*
  The presentation layer, also known as the syntax layer, provides a mapping layer between the application layer and lower layers. This includes mapping or translating differences in semantics and syntax from lower layers to a form that the application layer can understand. Security features such as encryption and decryption are also implemented in this protocol layer.

- *Session layer*

  This layer concerns itself with the management of all communicating processes through establishment, configuration and termination. Sessions are used to gracefully terminate connections as well as for connection recovery.

- *Transport layer*

  The transport layer allows higher layers to communicate in a network independent fashion, providing high level error control, flow control and segmentation. Five classes of transport level protocols are defined in the OSI model, ranging from class 0 with no error recovery to class 4 which ensure reliability through retransmission and error detection or correction. In the case of Transmission Control Protocol (TCP), this layer provides a reliable communication channel between users and handles retransmission and acknowledgement.

- *Network layer*

  The network layer is responsible for delivery of data between different networks. It provides logical node addressing and is used by routers to route packets to their respective destinations across networks over a number of hops.

- *Data-link layer*

  Whereas the network layer ensures inter-network data delivery, the data-link layer ensures intra-network data delivery through physical addressing. It processes data from higher layers into manageable data units called frames and provides flow control, access control and error detection or correction.

- *Physical layer*

  The physical layer provides the functions necessary to transmit the bit stream over a physical communication medium and is interface type specific. This layer is also responsible for line configuration in the form of synchronisation and electrical specifications. Transmission modes are also configured in the physical layer in the form of simplex (one-way), half-duplex (two-way non-simultaneous) and full-duplex (two-way simultaneous) operation.

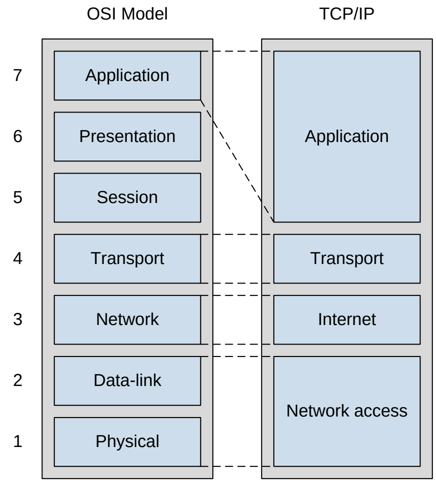


Figure 2.1: Similarities between the OSI model and TCP/IP

The Internet protocol suite, a result of research done by the Defense Advanced Research Projects Agency (DARPA) in the 1970s, is very similar to the OSI model in that it provides a layered stack of protocols. Due to the original protocol specification's inclusion of TCP and Internet Protocol (IP), the Internet protocol suite is also known as TCP/IP. Currently, the TCP/IP model and related protocols are maintained by the Internet Engineering Task Force (IETF) [21].

By combining the physical and data-link layers of the OSI model into a single layer known as the network access layer, the four layer TCP/IP stack can be constructed as indicated in figure 2.1. The presentation and session layers of the OSI model are not included in this stack and their functions are distributed among the application and transport layers of TCP/IP.

2.3 Physical/Network access layer

Looking more closely at the physical layer in the OSI model or the network access layer of TCP/IP as defined above, it is clear that these layers deal with the physical interconnects between interfaces in a network. These interconnects can be categorised into three main categories: metallic wire, optic-fiber and wireless.

Even though all these interconnects rely on the same principle of electromagnetic wave propagation, the medium in which these waves propagate differs for each - electric signals in copper or aluminium for metallic mediums, light pulses through glass or plastic for optic-fiber and radio or microwaves through free-space*for wireless [20]. The scope of the research in this dissertation is limited to optic fiber communication mediums.

2.3.1 Fiber networks

An optic-fiber based network (henceforth referred to as fiber network) can be defined as a network where nodes are interconnected by guided cables known as optic-fibers. These optic-fiber networks transfer information by modulating a light source, guiding this modulated light through a cable containing a transparent core of glass or polymer and then detecting it at the receiving end. Depending on the width and composition of the core and the light coherence, light is transferred through the optic-fiber through the use of total internal reflection in either single-mode or multimode.

When the light source consists of multiple beams travelling through a thicker core, the fiber is called a multimode fiber, while a highly focused beam through a thin core is known as a single-mode fiber. Multimode fibers are cheaper to produce and the transmission equipment are easier to design, but has a higher level of distortion due to scattering and large reflection angles. Single-mode fibers are more expensive, but due to the coherent light source and thin core, has a reflection angle close to 90°, resulting in an almost horizontal beam propagating through the fiber and low distortion [20]. The differences between single- and multimode fibers are illustrated in figure 2.2.

Even though optic fibers have a much longer reach than metallic cables, distance is still limited due to power loss in the form of heat and reflected light. Optic fibers also suffer from attenuation known as Channel Insertion Loss (CIL) due to connections, splices and optical equipment such as splitters, multiplexers and filters. The total allowable

Free-space in this sense refers to the *medium* and not the generality of interference-free space widely used to approximate radio wave propagation attenuation or loss that can be tolerated on an optic fiber link without detection errors is known as the optical power budget and is usually a figure given in decibels (dB), calculable as:

$$\text{Total loss (dB)} = 10\log_{10}\frac{P_T}{P_R} \tag{2.1}$$

where P_T is the power transmitted at one end of the transmission line and P_R is the power received at the other end [22]. It can then be inferred that with higher power budgets, longer reaches and more CIL can be tolerated. Current optical transceiver technology allows for low reach budgets from 20 dB using multimode fibers to long reach budgets of up to 29 dB with singlemode fibers and high power optics.

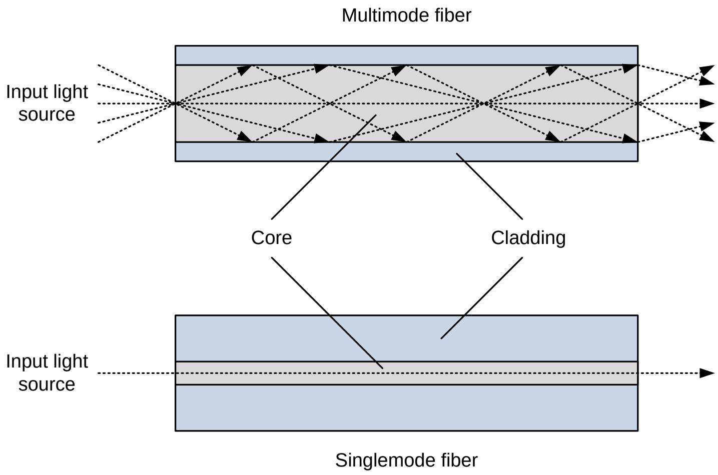


Figure 2.2: Single- and multimode fibers

With the increasing tendency to implement fiber networks, fiber has moved from strictly backbone or core network to last mile deployment. This is mostly due to technology and standard advances which results in reduced fiber deployment cost and easier integration with the rest of the network. This measure of fiber penetration from the exchange to last mile deployment is referred to as Fiber-to-the-x (FTTx).

As the fiber termination point moves closer to the user premises as illustrated in figure 2.3, the network arrangements are referred to as FTTN, FTTC, FTTB and finally FTTH.

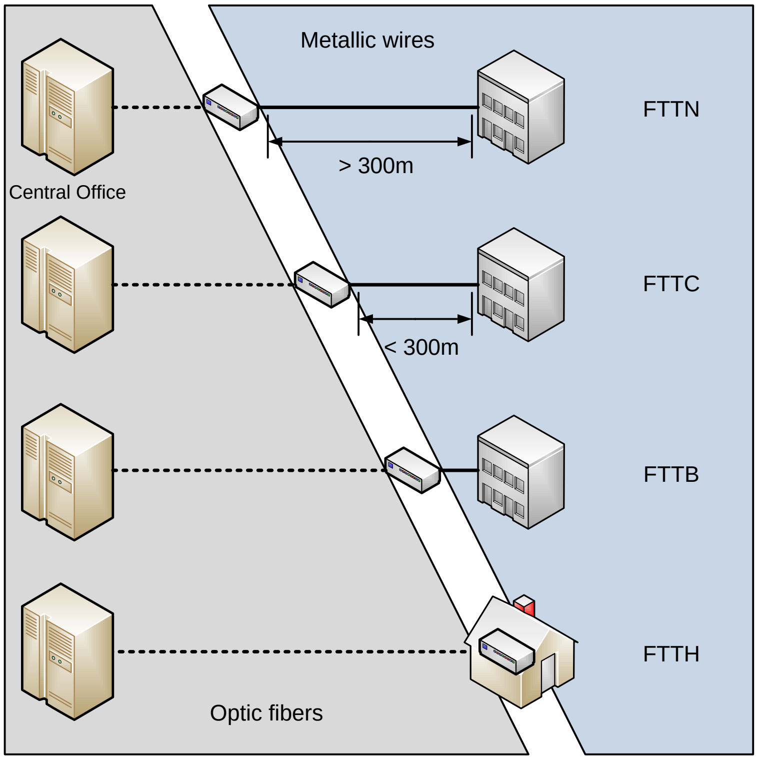
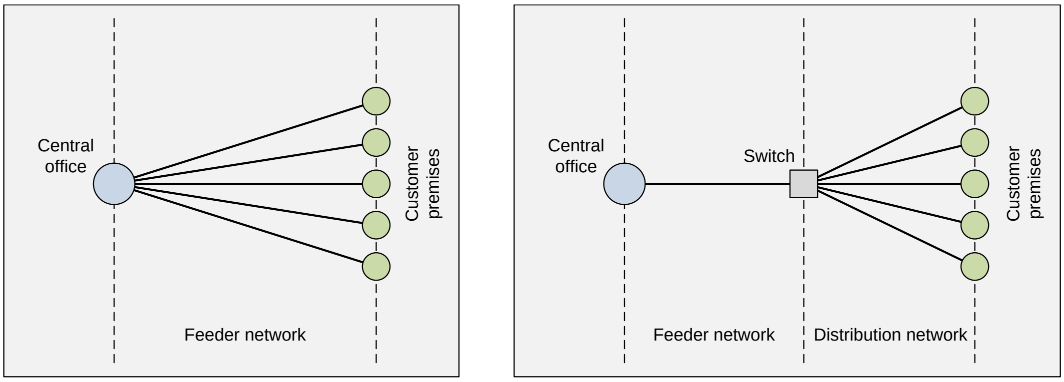


Figure 2.3: Fiber penetration for different FTTx architectures from backbone to last mile deployment

Fiber networks are typically categorised as either P2P or P2MP. With P2P solutions, the subscriber links directly to the CO or exchange with a dedicated feeder fiber, while P2MP solutions share a single fiber across multiple subscribers as illustrated in figure 2.4. Even though dedicated fibers provide the best future proofing in terms of bandwidth, it comes at a prohibitive cost when large numbers of subscribers are involved. Depending on the length of the fiber loop, a dedicated infrastructure can be up to 100 percent more expensive [1] than a shared solution and therefore most SPs opt for a shared infrastructure.

2.3.2 Shared fiber networks

Dividing P2MP fiber networks into passive and active infrastructures, we are left with PON and Active Ethernet (AE) type implementations respectively. AE networks use electrical splitters to split packets from the feeder fiber to a number of ONUs down the



A) Point-to-point (P2P) network   B) Point-to-multipoint (P2MP) network

Figure 2.4: Point-to-point (P2P) network vs point-to-multipoint (P2MP) networks

line while Passive Optical Networks (PONs) use passive splitters to accomplish the same task. Passive components are usually preferred due to the ease of infrastructure upgrades, the splitters being agnostic to the transmission rate and multiplexing techniques used on the line. Furthermore, along with lower unit costs, passive splitters do not require power to be routed to the outside plant which reduces operational costs [1].

2.4 Passive Optical Networks (PONs)

Of the standard PON types, the GPON standard, which is based on APON, and the EPON standard, which is a derivation of the existing Institute of Electrical and Electronics Engineers (IEEE) 802.3 standard, are most notable.

Both GPON and EPON have a similar physical layer structure, consisting of an OLT at an exchange or CO, serving a number of passive optical splitters, which in turn distributes the signals to a number of ONUs. Each ONU then has a specified number of service ports depending on the customer requirements. This results in a tree structure as depicted in figure 2.5, with a single fiber from the CO serving several dozens (up to 128 in the case of GPON [1]) of ONUs.

Multi-hierarchy networks are also possible, with a split signal from a passive splitter going through a second passive splitter before reaching the customer premises, although optical loss on the splitters usually makes these PONs impractical. Therefore multi-hierarchy networks are not considered in this research.

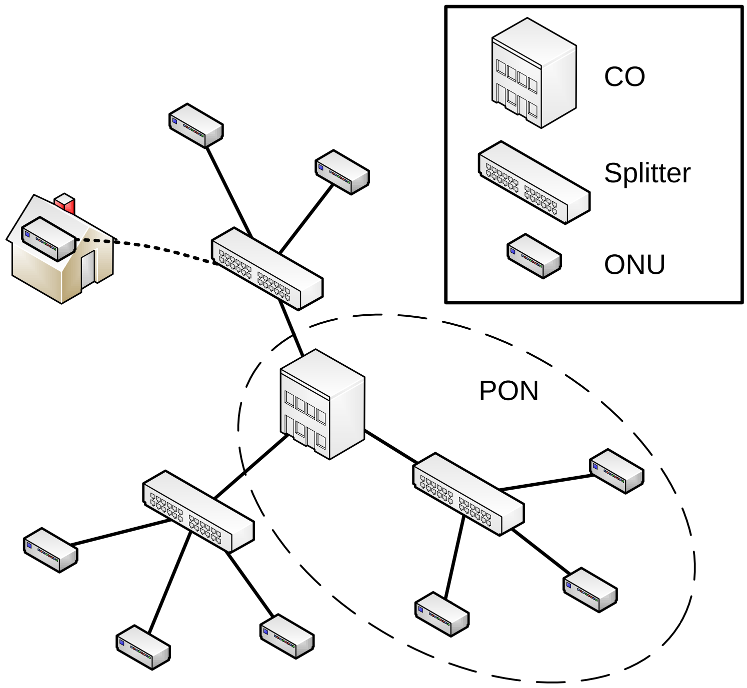


Figure 2.5: Basic passive optical network topology

2.4.1 IEEE 802.3ah / 802.3av

What began as a call from the IEEE for a research group known as Ethernet in the First Mile (EFM), culminated in the formation of the P802.3ah task force. After a three year charter, the task force ratified the Ethernet over point-to-multipoint standard known as the IEEE 802.3ah [7].

The IEEE 802.3ah or EPON deals only with the network access layer, providing bidirectional fiber links on the 1490 nm and 1310 nm wavelengths for down- and upload respectively at 1 Gb/s data rates. An additional 1550 nm wavelength is reserved for future use, either for analog services or digital expansion. EPON provides a link budget of 24 dB with a minimum split ratio of 1:16, although 29 dB power budget capable components can provide split ratios of up to 1:64 [1].

With strong roots in Ethernet, EPON has the same MAC layer and the same packet format as 802.3 devices, resulting in easy interoperability between 802.3 standards. EPON packets are not encapsulated before transmission over the fiber, rather using the same 802.3 Ethernet frames placed on the medium with standard Interpacket Gaps (IPGs). To distinguish packets for delivery to each ONU, the Ethernet preamble is modified to include a Logical Link ID (LLID), with an ONU having the ability to be registered as either a single physical or multiple virtual ONUs for different services including video, Voice-over-IP (VOIP) and standard data [1].

To further increase the transfer speed of EPON, the P802.3av task force was established, ratifying a 10 Gb/s standard known as IEEE 802.3av in 2009 [23]. Known as 10G-EPON or XEPON, the standard allows for symmetrical 10 Gb/s as well as asymmetrical links with 1 Gb/s and 10 Gb/s up- and downstream rates respectively. By using a different wavelength for the downstream link (1577 nm) and an overlapping wavelength for the upstream link (1270 nm), both 1G-EPON and 10G-EPON can coexist on the same outside plant when the upstream channels are separated with Time Division Multiplexing (TDM), allowing for an incremental and seamless service upgrade.

2.4.2 ITU-T G.984 / G.987

Following the Full Service Access Network (FSAN) consortium in 2001, the International Telecommunication Union - Telecommunication Standardisation Sector (ITU-T) ratified four standards on GPON, including the basic physical architecture [3], the Physical Medium Dependent (PMD) layer [4], the Transmission Convergence (TC) layer and GPON management [6]. These standards, along with their respective amendments, describe GPON functionality at the physical and data-link layers of the OSI model.

While EPON uses variable sized frames as used in Ethernet, GPON uses fixed-size, 125 μs frames to transfer data, resembling transmissions as specified in Asynchronous Transfer Mode (ATM). Using the same wavelengths as EPON at 28 dB power budgets but with downstream and upstream rates of 2.488 Gb/s and 1.244 Gb/s respectively, GPON provides not only faster transmission speeds, but due to its ATM origins, also the ability to run synchronous services over the network. This allows SPs to run legacy services over the same GPON architecture, facilitating easier and more cost effective adoption.

Due to GPON's synchronous ability, distance constraints are implemented to avoid synchronisation issues, with the standard specifying total reach of up to 60 km and differential distances between ONUs of up to 20 km. The standard also allows split ratios of up to 1:128, although practical applications will usually see lower ratios being used due to the limited optical power budget [1].

Finally, in keeping up with increases in bandwidth as seen in 10G-EPON, an upgraded 10 Gb/s version of GPON, G.987, also known as 10G-PON or XG-PON, was ratified by the ITU-T in 2010 [24–26]. Like with 10G-EPON, two specifications are given; an asymmetrical version known as XG-PON1 with speeds of 2.5 Gb/s and 10 Gb/s up- and downstream rates respectively and a 10 Gb/s symmetrical version known as XG-PON2. Once again, the 1577 nm and 1270 nm wavelengths are used for down- and upstream connections respectively, due to their low chromatic dispersive nature.

2.5 Conclusion

In this chapter, the technical concepts relating to the research were outlined. Firstly, an overview of the OSI model and Internet Protocol Suite was given and similarities were discussed. After elaborating on the physical layer of the OSI model, fiber networks were introduced. Then P2MP or shared fiber networks, and in particular PONs, were detailed, focussing on both EPON and GPON. Finally, the concepts of FTTx and fiber penetration were outlined. In the following chapter, we will look at modelling as a concept as well as techniques for solving mathematical models.