Passive Optical Network (PON) Architectures and Applications

C.E. Holborow
P.P. Bohn
S.K. Das

AT&T Bell Laboratories

Abstract

Passive Optical Networks (PONs) have generated considerable interest for telephony applications, and this architecture has been claimed to be very suitable for distribution of video signals as well. The term PON covers an array of design variations (e.g. two fiber versus one fiber), and several trial networks have been built using different designs. This paper describes a number of current approaches to PON design, and typical parameters are given. The characteristics of a typical PON video delivery system are described in terms that allow network operators to evaluate the applicability of this technology to their networks.

1. Introduction

Optical fiber is an almost ideal transmission medium. It has huge bandwidth potential, it is almost inert, it is available in cables which are small, light, and easily handled compared to metallic cables, and it has very low transmission loss which does not vary significantly with temperature. Its major drawbacks are that splicing is more difficult than for copper cables and the cost of optoelectronic transducers is high. These drawbacks are steadily yielding to technological improvements.

Optical fiber transmission has been the technology of choice for long distance digital transmission for a decade, and is steadily becoming cost effective at shorter and shorter distances. In CATV networks, FM fiber optic supertrunk systems have been in use for many years, and AM fiber systems have supplanted coaxial trunking in most new and rebuild construction in the last two years.

In telephony applications, the long term goal is to take fiber all the way to the customer. This approach is usually called "fiber to the home" (FTTH). It will give the transmission benefits of fiber and the "future protection" provided by the bandwidth potential of fiber. However, it is not economically feasible at present. The cost of fiber optic systems makes it necessary for a number of customers to share each fiber network terminal. This approach is usually called "fiber to the curb" (FTTC).

One innovative approach to designing FTTH or FTTC networks is the use of Passive Optical Networks (PONs). This paper provides an introduction to PON technology. Section 2 summarizes the forces motivating the approach and some major network issues, and Section 3 describes some architectural variations that have been proposed for telephony applications. Section 4 discusses broadband PON architectural issues, and Section 5 summarizes the main points.

1.1 Terminology

A variety of terms for the two terminal types in a PON network appears in the literature. For readability, the discussion in this paper is written in FTTH terms, but it applies with obvious changes to FTTC networks as well. The term "exchange terminal" is used for the equipment that is located in the telephone exchange (or central office), and the term "customer terminal" is used for the equipment located at the customer site (or at the curb). "Downstream" is from the exchange to the customer, and "upstream" is from the customer to the exchange. In a CATV application, the exchange terminal would be at the head end.

In the literature, the exchange terminal is variously called Exchange Terminal (ET), Central Office Terminal (COT), Subscriber Loop Terminal (SLT), or Optical Line Terminal (OLT). The customer terminal is usually called Optical Network Unit (ONU), but other names such as Network Termination (NT) and Distant Terminal (DT) can be found.

2. Motivation and Issues

The PON approach to telephony access networks is an attempt to reduce costs by taking advantage of the following:

1. Most access network links are short (optical loss budget a few dB)
2. Low and medium rate (low power consumption) digital communication systems can accommodate loss budgets much greater than typical access networks.
3. Residential and small business access customers can be served by an average of less than 3 lines per customer. Even medium sized businesses only require a 24 line trunk to connect to a PBX. Low rate digital systems can easily serve tens of customers at this rate.
4. Cost savings can be realized by sharing the exchange transmitter laser over multiple customers.
5. Sharing feeder fibers is also possible if splitters are placed in the field close to the customers.
6. Sharing laser and feeder fiber over more than 20 customers means that network cost is dominated by the customer terminal, so higher splitting ratios yield only small extra savings.

These points suggest an architecture which has a single "low rate" transmitter (say 20-40 Mb/s line rate) broadcasting to 20 or more customer terminals, with each customer using only part of the total bandwidth. The signal travels on a single feeder fiber to a point near the customers, where it is split and routed down separate fibers to each customer terminal (see Figure 1). Clearly, this a point-to-multipoint transmission architecture, which is logically, but not physically, the same as that used in the present CATV network. The classical telephony architecture is a point-to-point structure. The PON equipment design is optimized where possible to reduce the cost of the customer terminal.

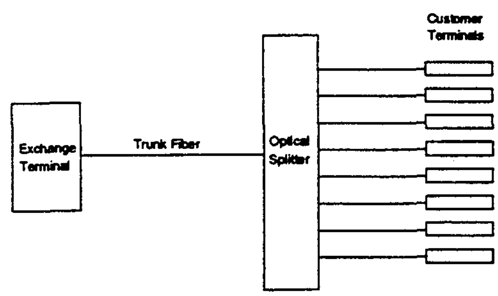

Figure 1. PON Architecture

Many major issues must be addressed to complete the design of a fully functional network:

- The discussion above addresses only the downstream (exchange-to-customer) link. The upstream (customer-to-exchange) link must also be implemented at low cost. The upstream fiber network is assumed to be the same topology (and in some cases the same network) as the downstream network. The loss budgets in the two directions are the same and only a single exchange receiver is needed.

Sharing upstream bandwidth is more complicated than sharing downstream bandwidth, because customer terminal transmissions must be timed to avoid collisions.

- Privacy: signals must be secured, and customer terminals must be monitored and controlled to ensure that data for one customer is very difficult for another person to intercept.
- Operations and maintenance: the whole network must not be taken out of service to add a new customer or to service a faulty customer terminal. This and other operational issues require careful design of control software and operational procedures.
- On-line bandwidth allocation: since customer service requirements change, it must be possible to change the bandwidth allocated to a customer without interrupting service to other customers.
- Power savings: to conserve power, customer terminals must have a "sleep" mode which they enter when there is no active traffic for them. (This is important for telephony services, where battery backup at the customer terminal is usual.)
- Fiber breaks: how do you locate a fiber break between splitter and customer terminal without interrupting service on the network? Ideally, one would prefer to do this from the exchange terminal. This may be feasible using a wave division multiplexer (WDM) to separate optical time domain reflectometer (OTDR) signals from traffic signals on the network. The OTDR dynamic range must be high to cope with the splitter loss. The OTDR display will show superimposed traces because each customer line will generate a separate reflection. If the fault cannot be seen among the superimposed traces, fault location must be done from the customer end. If service personnel do not have access to the customer end, it is necessary to work from the splitter by opening up a splice.
- Measures must be taken to prevent a faulty customer terminal transmitter from jamming the network with continuous transmission. The obvious requirement is global and addressable commands which instruct all (or one) customer terminal(s) to stop transmitting, and redundant transmitter disabling circuitry in the customer terminal.

3. PON Architectures

A wide variety of PON architecture implementations have been suggested, and several trial systems have been demonstrated using very different techniques. The main choices (which are interrelated) to be made are:

1. How many fibers should go to each customer?
2. What line protocols should be used to share downstream and upstream bandwidth?
3. What wavelengths should be used for downstream and upstream transmission for narrowband and broadband service?

These questions are probably best understood by enumerating possible answers. While the discussion this far has centered on narrowband (NB) telephony service, any viable architecture must also be capable of carrying broadband (BB) broadcast CATV service. It is desirable that normal AM CATV should be possible, for the same reasons that AM is used in CATV coaxial distribution.

3.1 Number of Fibers

Some possible answers to question 1 are:

1. Two fibers: one fiber for each direction, wave division multiplex (WDM) NB and BB downstream.

The broadband signal will suffer loss due to the WDM, but this is only a small part of the loss budget. Isolation of the customer BB receiver from the NB signal must be excellent to prevent degradation of BB performance.

2. Two fibers: one for NB (bidirectional), one for BB (one way).

   There is a choice here with the NB on one bidirectional fiber. The line can be full duplex using a WDM or directional couplers, or half duplex allowing only one end to transmit at a time. If a WDM is used, the isolation must be high enough to prevent the transmitter from interfering with the collocated receiver. If directional couplers are used, the optical reflections must be kept low so that near end cross talk does not interfere with reception. If the optical loss budget is high and the network generates optical reflections, it is possible for the level of the reflected transmitted signal to be comparable to the signal received from the far end [1]. Using a half duplex approach, where the exchange terminal transmits a long burst and then each of the active customer terminals transmits a short reply burst, eliminates most concerns about optical reflections on the NB fiber, but roughly halves the data transfer rate possible for a given line rate.

3. One fiber: bidirectional with WDM of NB and BB to customer.

   Use of one fiber is clearly more economic, but it is also more complicated since it involves both WDM of the downstream signals and bidirectional use of the fiber. In addition to the points mentioned above, at the customer terminal the isolation between the upstream transmitter and the downstream broadband receiver must be excellent. However, all of this is within the capability of existing optics technology.

3.2 Line Protocol

Downstream traffic must be multiplexed into a single bitstream. The bandwidth allocated to each customer must be changeable on-line to cope with changing customer needs. To best utilize the system capacity, it is highly desirable that bandwidth unused by one customer be available for allocation to other customers. The protocol also must address many operational details such as bringing a new customer terminal into service, verifying that a new terminal is authorized to be on the network, as well as detecting and isolating faults.

The upstream traffic must be time division multiplexed in such a way that the bursts from the customer terminals do not collide at the exchange receiver. This is accomplished by measuring the range to each customer terminal and giving each terminal a delay time to wait after it receives the end of the exchange transmission before commencing its transmission. The range measurement requires a guard interval in the return path time allocation so that a new terminal of unknown range can be brought into service. Guard intervals may also be needed between transmissions from the customer terminals.

Various degrees of interleave of the customer terminal transmissions have been proposed, from bit interleaving to full burst interleaving. Longer transmissions reduce the number of guard intervals, so there is less dead time (or more data for a given line rate).

Bit interleaving requires very accurate ranging: to within a small fraction of a bit if guard intervals are to be avoided altogether. This is necessary because so many guard intervals would be needed that data throughput would be too low. It also requires control of the customer transmitter laser power by the exchange terminal, together with an advanced exchange receiver, because consecutive bits from different customer transmitters will not be the same amplitude but must be nearly so in order to be received without error.

Burst interleaving requires fast clock acquisition by the exchange receiver, but is otherwise more robust. However, it is less efficient in terms of data rate for a given line rate.

Another tradeoff to be made is in the choice of frame length, where one frame is one complete cycle of transmissions by the exchange and all customer terminals. A short frame reduces the delay through the network. However, a short frame also reduces the efficiency of transmission, because the proportional loss of bandwidth due to network overhead and guard times is higher. The loss of efficiency may require a higher data rate.

3.3 Wavelength Choice and WDM

To keep costs low, an uncooled laser must be used in the customer terminal and both the line protocol and wavelength choice must allow for this.

For telephony applications, the normal wavelength for narrowband data is the 1300 nm window. This is a reflection of the maturity (and low cost) of devices at this wavelength. For the exchange laser, the choice is arbitrary, and the 1550 nm window could serve as well, particularly since dispersion on the short links will have no effect on digital signals but may have major impact on AM wide band signals.

Since the customer terminal transmitter cost is a major item in the network cost, 1300 nm uncooled lasers are preferred for this function.

Wave division multiplexing is possible to allow simultaneous use of both windows. At present, dense WDM using several closely placed transmitters in the same window is not economic, but this possibility remains open for future use.

3.4 Typical Narrowband PON Parameters

Typical parameter ranges for narrowband PONs are:

- Range: up to 10 km (6 miles)
- Splitting ratio: 8, 16, or 32
- Number of 64 kb/s channels: 150-400
- Optical loss budget: 20-30 dB
- Optical line rate: 20-40 Mb/s

4. Broadband PON Design

The optical loss budgets above are suitable for FM or digital CATV transmission systems. The application of these two technologies to PONs is straightforward but use of either of them today would make a customer terminal expensive and provide insufficient channels for a broadcast CATV service. The advent of compressed digital television will make digital CATV delivery on PONs much more attractive.

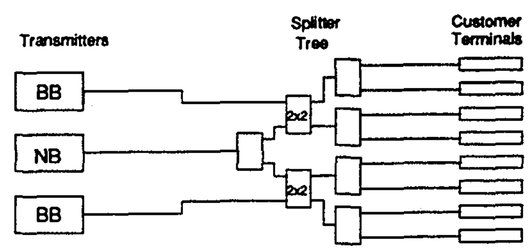

Figure 2. Use of 2x2 couplers to allow different NB and BB splitting ratios

Typical PON loss budgets are far beyond the reach of AM technology using DFB laser transmitters. Lower splitting ratios must be used for broadband distribution with these systems. This is easily achieved if the splitting tree uses 2x2 couplers, with multiple AM systems feeding into the splitting tree at lower splitting ratios than the NB transmitter (see Figure 2).

The need for multiple transmitters and "trunk" fibers increases the cost of the system. The high cost of broadband distribution is fundamental to the use of AM fiber optic systems: such systems require high receiver power levels compared with digital or FM systems.

For a carrier-to-noise ratio of 48 dB at the customer terminal, a typical AM system must have a received optical power of about -7 dBm. (Receiver noise current 6 pA/sqrt(Hz) and 4% optical modulation index assumed.) A typical DFB transmitter operates at 6 dBm, so the optical loss budget of the system is 13 dB. If 6 dB is allocated for connectors, fiber loss, and splice loss, the splitter loss can be 7 dB, which allows a four-way split.

The only option to support higher splitting ratios with AM systems is to increase the transmitter power. This suggests consideration of externally modulated systems or optical amplifiers. These technologies have not been widely deployed to date, and there are some limitations on how they can be used.

External modulation systems currently operate only in the 1300 nm band. They use a narrow line source laser, and stimulated Brillouin scattering (SBS) limits optical power in the trunk fibers to less than 15 dBm for a short fiber and less than 12 dBm for a longer fiber (see Figure 3) [2,3]. Higher power transmitters can be used, but the optical signal must be split at the exchange to keep the level in the multiple trunk fibers below the SBS threshold.

Available optical amplifiers operate in the 1550 nm band. On standard fiber, dispersion will cause excessive second order distortion unless compensation is used [4]. While optical amplifier repeaters could be used in the outside plant, the network would no longer be passive.

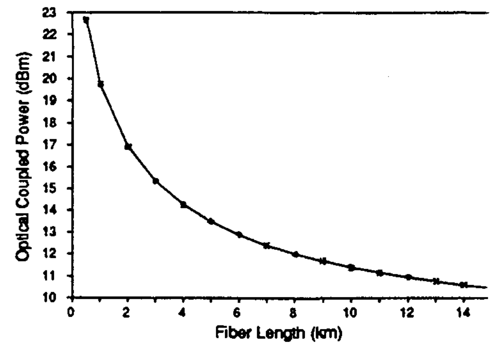

Figure 3. SBS Threshold for CW Laser vs Leng

5. Summary

This paper has described the motivat for and typical characteristics of Pass Optical Networks for telephony services. also examined the delivery of CATV serv on networks of this type.

While the optical power demanded AM fiber optic transmission of CATV sigr makes it uneconomic to consider PON serv to the customer, some current applications AM fiber systems in CATV trunking can regarded as PONs, with the terminat points being the optical nodes wh conversion to coaxial distribution takes pla The current splitting ratios are limited by power available from the transmitter to val much lower than those used in dig telephony PONs.

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