A Broadband Scalable Hierarchical PON for Cost-efficient Fiber Access Networks

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Abstract - The traffic flow in long-haul dense wavelength division multiplexing fiber networks has surpassed by far the traffic deliverability from/to the access network thus creating what is known as "access bottleneck". This bottleneck was the result of two major factors, the inherent cost sensitivity of access networks that impedes deployment of new optical technology prior to cost maturity, and the lack of popularized new broadband services that would demand from the access network bandwidth higher than broadband that digital subscriber lines or cable could deliver. Nevertheless, the bandwidth landscape at the access is changing and it has been widely recognized that optical is the technology that can efficiently address the current and future bandwidth needs of the access network. In order to also meet low-cost objectives, it has been recognized that the optical technology should be mostly limited to passive culminating to a passive optical access network (PON). To date, two passive optical network proposals have prevailed. The time division multiplexing passive optical network (TDM-PON) uses a single optical channel and a complex timing protocol. The coarse wavelength division multiplexing PON (CWDM-PON) uses multiple optical channels with a complex wavelength management procedure. In this paper we describe the hierarchical CWDM/TDM-PON (hCT-PON). We show that the hCT-PON is scalable, , and it delivers synchronous and asynchronous bandwidth flexible from as low as DS0 to as high as Gbps. In addition, we show that the hCT-PON can serve more than 16,000 end-users thus reducing the cost per user.

Keywords: PON, Scalable PON, Broadband PON, Cost-Efficient PON,

1 Introduction

The success of the dense wavelength division multiplexing (DWDM) technology in the long-haul and backbone optical network is due mainly to advances in optical and photonic technology that enabled a transportable aggregate traffic in excess of one Tbps thus displacing copper [1]. Despite this, the access network did not follow in step the evolution of fiber network to offer an aggregate traffic commensurate with the DWDM network [2]. The main reasons can be summarized in cost-efficiency and in existing infrastructure. Access networks have an inverse proportional cost-efficiency profile with backbone and long-haul networks and thus optical access networks could not afford the advanced and costly photonic technology. Long-haul and backbone transports Tbps per fiber to millions end terminals and thus despite its high CAPEX and OPEX, the cost per Mbps-mile is low. Current access networks transport a fraction of Mbps per end terminal and they do not enjoy the same client density. As a consequence, the access network is cost-sensitive and it demands inexpensive technology with relaxed specifications and uncooled lasers to meet the cost-points of long haul. As an example, assume that in a long-haul application the cost of a laser transmitter modulated at 10 Gbps and for 100 km without amplification is (hypothetically) $40,000. Then, the cost per Gbps-km is only $40 and per Mbps-km is only 4 cents. Thus, if access networks should be cost competitive with long-haul, the laser transmitter should at about the same order, which is not. The second reason is the legacy loop plant infrastructure. This consists of twisted-pair (TP) copper wires designed to initially transport 4 Khz analog voice under 10 km, and later digital signals at 144 Kbps but at distances shorter than 6 km. With the rapid evolution of Internet, the demand for faster bit rates increased and sophisticated digital transmission technologies have been developed delivering Mbps but over shorter to distances. Thus, the end result has been an unbalanced traffic flow from/to access points to the optical communications network, and deservingly the access network has been dubbed “traffic bottleneck” of the last/first mile.

However, with recent advances in optical and photonic technology and the development of new standards, the cost structure of the access network has been improved, and a conscious decision was made to start deployment of fiber in the access network or passive optical network (PON), also known as fiber to the premises (FTTP), in anticipation of a rapidly growing bandwidth demand by end clients. However, which optical network architecture will be adopted at the FTTP is still in debate. Currently, there are two prevalent architectures for the passive optical network.

One optical access network is based on coarse wavelength division multiplexing (CWDM) based on a spectral grid supported by ITU-T standards, Table 1 [3]. The CWDM grid consists of 18 optical channels, each at a constant yet high data rate; this network is known as CWDM passive optical networks (CWDM-PON). This consists of passive optical and active photonic components with relaxed specifications to meet reliability, robustness and particularly cost requirements. However, although CWDM is able to deliver high data rate per channel, it cannot support a large base of subscribers in a flexible and scalable manner.

Table 1. The CWDM wavelengths grid

Wavelength	Frequency	Wavelength	Frequency
1271	232.6	1451	206.5
1291	230.1	1471	203.6
1311	227.7	1491	200.9
1331	225.1	1511	198.2
1351	221.8	1531	195.6
1371	218.5	1551	193.1
1391	215.4	1571	190.7
1411	217.3	1591	188.2
1431	209.3	1611	185.9

The other optical access network has a single optical channel at very high data rate and it is based on a time division multiplexing scheme with flexible time slots controlled by an elaborate timing protocol to effectively multiplex subscriber data in the time domain. This network is known as time division multiplexing-Ethernet passive optical network (TDM-EPON) [4-6].

A third optical technology that will not be addressed in this paper is optical ring metropolitan access network; this is the subject of another study. In addition, it should be mentioned that PON variants are the EPON that adapts the Ethernet protocol at a data rate of 1 or 10 gigabit (GbE or 10GbE) and others that are beyond the purpose of this paper.

In this paper we describe a hierarchical CWDM/TDM passive optical network (hCT-PON). We demonstrate that hCT-PON is scalable, it is topology-friendly, it delivers synchronous and asynchronous payload types, it supports elastic services from DS0 to Gbps, and it supports a scalable customer base that may reach 16,000 end-users. We also discuss bandwidth elasticity, versatility, resiliency and cost-efficiency of the hCT-PON access network. It will become evident that, considering cost per bandwidth-mile or cost per user, the cost-efficiency of the hCT-PON outperforms any previous PON access network.

2 CWDM-PON and TDM-EPON networks

The increasing demand in bandwidth has reached the access network, which for a decade has become the bottleneck to large Metro and backbone networks. Recently, the fiber to the premises (FTTP) has been identified to be the network that is able to deliver gigabits per second to premises and enterprise alike. As a consequence, besides the optical Metro ring topology, various fiber-based PON access network topologies have been architected with two contenders, CWDM-PON and TDM-EPON.

PON networks were intended to use directly modulated uncooled lasers of the vertical cavity surface emitting lasers (VCSEL) or high-speed light emitting lasers (LEDs), the light of which is coupled onto multimode fiber (MMF) or single mode fiber (SMF) in order to take advantage of the CWDM grid of 18 optical channels specified by ITU-T standards over the low-loss optical spectrum (1260 nm-1621 nm) of water-free fiber. The CWDM channel separation is 20 nm (compare with 0.39 nm or 50 Ghz for DWDM). Thus, PON uses passive components with relaxed specification (filters with 13 nm trapezoidal bandwidth, passive optical mux/demux), and semiconductor optical amplifiers (SOA) at the head-end, if amplification is needed. Traffic flow in PON is expected to be asymmetric; the downstream traffic can be much higher than the upstream.

The CWDM-PON architecture entails two basic units, the optical network termination unit (ONU) at the subscriber side and the optical line terminating unit (OLT) at the network side, Figure 1. At the OLT, 18 optical channels are coupled onto a single fiber, which are demultiplexed at the ONU where the various payloads are distributed to the network terminal (NT) located at the premises (residential, enterprise, or base-stations).

In the upstream direction, the reverse operation takes place, although in this case traffic may be asymmetric.

The protocol used in the current version is the next generation SONET/SDH [7] which encapsulates and transports all existing protocols, Internet, Ethernet, Fiber Channel, FICON, telephony, video, and others and therefore it is a good fit in CWDM PONs. At the ONU, each service is separated and it is transmitted to the subscriber.

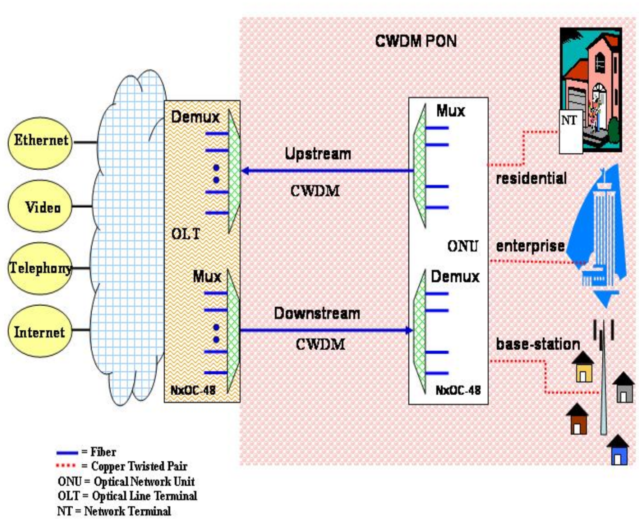

Figure 1. Architecture of the CWDM-PON access network

The TDM-PON network uses a different approach. The OLT time multiplexes Ethernet packets and transmits them in the downstream direction; this technology is optimized for variable length Ethernet packets. At some point in the downstream direction the optical power is divided by a 1:N optical splitter, where according to [4] N is between 4 and 64. Each prong of the splitter is terminated at an ONU, which has a unique address. The ONU reads the destination address of each packet and it selects the ones that match its address, which also sends to the end user network terminating unit, Figure 2. However, the upstream direction requires careful synchronization because packets arriving at each ONU need to be rate adapted and time division multiplexed due to lack of collision detection and avoidance. Thus, each ONU is assigned a time slot (not necessarily of the same duration) in which packets are transmitted to the splitter in the upstream direction; this clearly requires synchronization with a reference clock, which in the optical regime is not easy. The ONU may be dynamically provisioned with control packets to adjust the time slot duration based on need and service priority allowing for dynamic bandwidth allocation, but this is a more elaborate scheme [5]. In order to accommodate many users, this technology proposes a single channel at a data rate of 10 Gbps. However, because this data rate is sensitive to dispersion and differential propagation delay due to unequal fiber distances between splitter and ONU, inter-packet guard-bands must be included decreasing bandwidth efficiency. The TDM-PON proposes one wavelength for the downstream and another for the upstream direction and thus the single fiber is in a bidirectional duplex mode. Finally, as the user database increases and as the bandwidth demand increases, this technology may experience congestion.

3 Hierarchical CWDM/TDM-PON

The proposed topology uses CWDM in a point-to-point topology between OLT and ONU, an optical tree topology at the ONU, and an optical TDM in a point-to-multipoint topology between ONU and NTs. We call this network “hierarchical CWDM/TDM-PON” access network (hCT-PON). For simplicity of description, we describe the downstream and the upstream directions of the network separately.

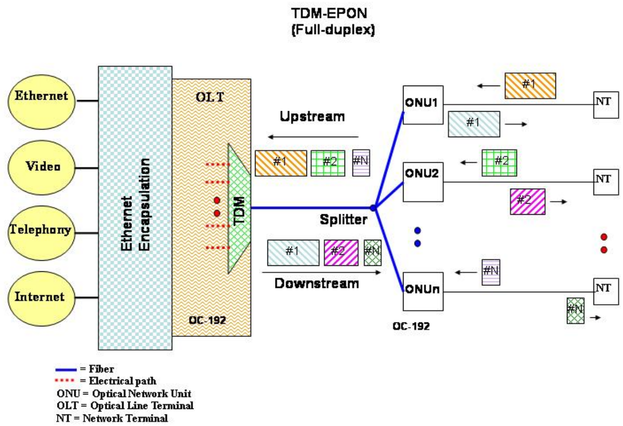

Figure 2. Architecture of the TDM-EPON access network (adapted from [4])

3.1 Downstream direction

At the OLT, 16 CWDM optical data channels and two supervisory channels are multiplexed and transmitted through fiber to the optical network demultiplexing unit (ONU-d), Figure 3. This entails the point-to-point topology. For longer distances and for more channels, sparse DWDM may be also be used with 200 or 100 Ghz channel separation, although DWDM trades channels and aggregate bandwidth with cost. With CWDM, 16 of the 18 channels are allocated for data at OC-48 rate each (although OC-192 may also be possible). The remaining two channels are allocated for supervision, each at OC-3.

The ONU-d consists of an optical wavelength demultiplexer (ODemux), SOA amplifiers, two splitters for the two supervisory channels, and 16 optical time division demultiplexing network units (ONU-t); each unit contains an optical switch which deflects packets in time slots to their associated fiber. The 18 channels (wavelengths) are demultiplexed by the ODemux and each channel is amplified by an SOA. 16 client data bearing wavelengths from the ODemux are separated in two groups (group A and group B) each of 8 channels, and each channel is connected with an ONU-t. The two supervisory channels also are separated, one for group A and the other for group B, and each channel is power split by an 1:8 splitter (not shown).

One of the 16 data outputs from the optical demultiplexer and a supervisory channel from the splitter are routed to an optical time division demultiplexing network unit (ONU-t).

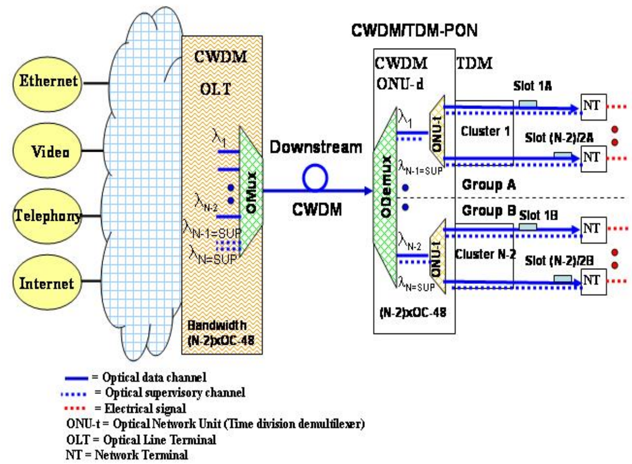

Figure 3. Architecture of the Hierarchical CWDM/TDM-PON access network (downstream direction).

The ONU-t time demultiplexes packets of equal length and each demultiplexed packet is routed to a fiber in a cluster of fibers; each fiber in the cluster connects the ONU-t with a network terminating units (NT), where each NT serves one or more end-users. Each fiber in the cluster may have the same length to eliminate group delay variations. This engineering rule substantially simplifies inventory and logistics of the fiber plant, while it maintains flexibility and network expandability, and it simplifies hardware design, protocol complexity, maintenance and provisioning. Finally, each NT determines its own time slot and length from a reference clock and from supervisory messages.

3.2 Upstream direction

The upstream direction works as the downstream direction, Figure 4. In this case, each NT receives traffic from the end-user, it packetizes it and it transmits each packet within its allotted time slot. Each NT does the same with supervisory messages, which now are time multiplexed onto the supervisory channel. Since the data channel and the supervisory channel are on different wavelengths, the NT wavelength multiplexes the two and couples onto the fiber in the direction to optical time division multiplexing unit (OTDM).

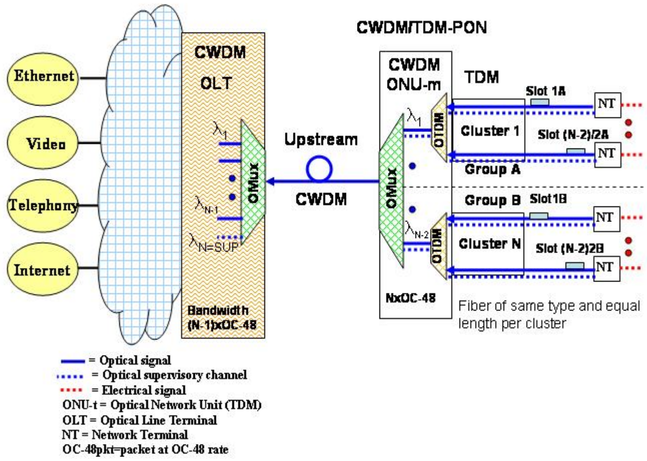

Figure 4. Architecture of the Hierarchical CWDM/TDM-PON access network (upstream direction).

4 Bandwidth allocation

For simplicity of description, assume a modulation rate of OC-48 (2.5 Gbps) per data optical channel; with current technology and demand, for most CWDM applications OC-48 is a pragmatic and cost-efficient data rate because uncooled lasers and optical components with relaxed specifications may be employed. SONET/SDH and the next-generation SONET/SDH specify frames transmitted in 125 μsec. Therefore, for bandwidth scalability we have chosen a minimal time slot granularity of 125/1000 or 125 nsec, Figure 5. Thus, 2.5 Gbps bandwidth are subdivided in small increments of 2.5 Mbps, each delivered in the downstream direction to 1,000 NTs; for many access applications, 2.5 Mbps is sufficient bandwidth for fast-internet/ethernet, voice, compressed video, and more. For specific applications that require more bandwidth, more than one time slot is allocated and for applications requiring less bandwidth, the 2.5 Mbps may be scaled down to 1.5 or 2 Mbps to emulate DS1 or E11 rates, which may be further demultiplexed to individual DS0 and/or ISDN rates. In the upstream direction, each NT receives packet data from end devices and it transmits them in their corresponding time slot. The OTDM time multiplexes data from NTs without optical buffering onto a single channel and sends them to the OMux.

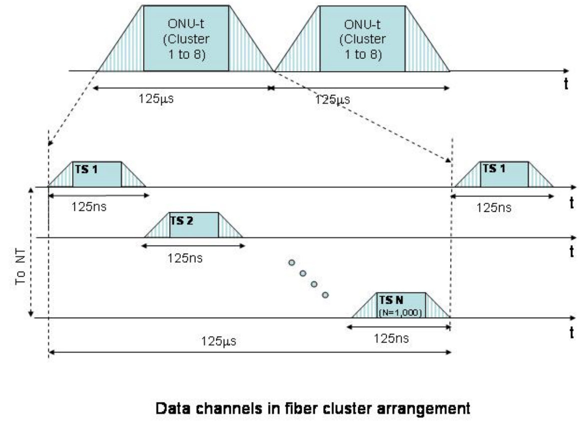

Figure 5. Time Division Demultiplexing of one optical data channel for a cluster of NTs

5 Supervisory Channel and control

Downstream, TDM supervisory messages for each NT are contiguously concatenated. NTs have been partitioned in two groups, and each supervisory channel addresses half of the NTs. At 1000 NTs per data channel, each supervisory channel addresses 8,000 NTs. At OC-3 (155 Mbps) and for 36 octets per message, approximately a 2 μsec window per NT is centered within the 7 μsec window leaving 5 μsec for margin and for future-proofing, Figure 6; messages may expand to 72 octets with 4 μsec margin. Guardbands may be set to zero or to a fixed pattern such as 01010101. Supervisory messages consists of a header, a data field and a CRC trailer.

Upstream, each NT transmits a 36-octet message back to OTDM, where all messages of a NT cluster are time division multiplexed in their corresponding 62.5 msec slot. Then, all messages from all 8 OTDMs are time division multiplexed at the OMux and coupled onto one of the two supervisory channels. Each 62.5 msec interval has a short guard band at each side to relax specifications and avoid collisions.

6 Bandwidth elasticity and cost-efficiency

Downstream, 16 optical channels transport an aggregate bandwidth of 40 Gbps. Each optical channel may serve up to 1,000 NTs, or a total of 16,000 NTs; at minimum, each NT delivers to each end-user 2.5 Mbps. DS1s or E11s may be further demultiplexed to offer DS0 or DSL and ISDN. For applications that demand very high bandwidth, multiple time slots may be assigned to a NT. Concatenating k time slots (k=1 to 1000), kx2.5 Mbps may be transported, demonstrating the bandwidth elasticity of the network.

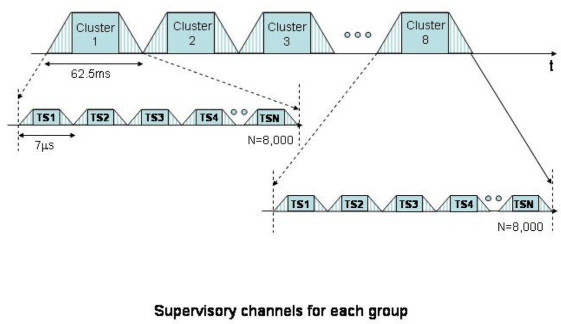

Figure 6. TDM for one optical supervisory channel per eight clusters of NTs

The distribution of 1,000 fibers per cluster may seem a very large number; in practice, this number is expected to be smaller. In addition, a combination of cluster and open loop topology may be used to meet needs cost-efficiently. If a smaller network is needed, then the network may be initially partially equipped and grow as needed. That is, the network is scaleable as necessary from basic rate to ultra-broadband.

The network described so far delivers bandwidth in 2.5 Mbps increments. However, Ethernet traffic is packetized and although the bit rate may be high (100MbE, 1GbE), the continuous equivalent rate is much lower due to the non-contiguity of data-bearing packets. As such, Ethernet traffic may be delivered to/from NT after it has been smoothed out, segmented and rate adjusted. At the NT, Ethernet packet size and rate is restored. A similar process may also be used for Internet and other data traffic. Thus, the proposed network may deliver all types of traffic in increments of 2.5 Mbps to meet current and future applications.

7 Conclusion

We have presented a versatile and scalable passive optical network. The network has a hierarchical topology that uses a hybrid CWDM/TDM-PON (hCT-PON) approach to optimize scalability, elasticity and cost-effectiveness of the network architecture.

This network uses 16 optical channels for data and two for supervision. At a data rate of OC-48 per optical channel, an aggregate 16x2.5 Gbps=40 Gbps is achieved. The network is able to deliver any type of client data, synchronous or asynchronous. Because each Gbps data corresponds to 15 million DS0s (simultaneous uncompressed conversations) or more than 500 compressed simultaneous video channels, we believe that such aggregation in the access network is more than adequate to meet all current and future needs for both residential and enterprise clients. However, the hCT-PON access network is not architected around the OC-48 rate but it is flexible and it can be engineered at lower (OC-12) and at higher (OC-192) rates to meet specific needs.

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