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A Scalable CWDM/TDM-PON network with future-proof elastic bandwidth

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Abstract - Among the passive optical network (PON) architectures two have prevailed: one is based on time division multiplexing (TDM) over a single wavelength channel and on a comprehensive timing protocol, and the other on coarse wavelength division multiplexing (CWDM). However, both proposals have orthogonal advantages and disadvantages. In this paper we describe a hierarchical CWDM/TDM passive optical network (PON). We demonstrate that the access network exhibits superior scalability, payload type transparency, and bandwidth elasticity allowing for bandwidth on demand, versatility, resiliency, provisionability, cost efficiency, protection and future-proofing features. We also demonstrate that this network can deliver to more than 16,000 end-users using simple and existing optical technology.

Keywords: - FTTH, CWDM access networks, PON, EPON

1 Introduction

Long haul and backbone optical networks evolved over the last two decades at an incredible speed leaving behind the access network. Thus, whereas long haul optical networks are able to transport Tbps aggregate traffic [1], access networks, also known as first/last mile, deliver few Mbps over very short loops and creating an unbalanced traffic flow from/to access points to the network or a bandwidth bottleneck [2].

Since its first deployment, optical technology has further advanced, new standards have been developed, new bandwidth-hungry services have emerged, and the deployment cost is on a decreasing path making fiber optic technology suitable for access networking. However, for optical technology to be effective and cost-efficient in access networks, additional challenges must be met such as robustness, deployability, reliability, simplicity, and specification tolerance. The first three are addressed with design and good engineering. The last two however are architecture and technology dependant. The technology that goes into the "first/last mile" is extremely cost-sensitive and it presents a challenge to system manufacturers as well as to network and service providers. Despite this, it has been determined that fiber is the only choice of medium that meets current and future bandwidth demands, so that it has been dubbed as "the next big thing".

Currently, there are several PON variants. The Ethernet PON (EPON) [3-5] capitalizes on the Ethernet protocol and data rates, the gigabit PON (GPON) [6] is a variant to meet gigabit rates and the broadband PON (BPON) to deliver broadband rates.

Among these PON architectures, there have been two that have prevailed. One is based on coarse wavelength division multiplexing (CWDM), the spectral grid of which is supported by ITU-T standards [7] and it was specifically defined for access network applications. PONs based on CWDM are known as CWDM-PON. The other optical access network is based on a single optical channel per direction and it is based on time division multiplexing and on 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) [2-4]. Notice that EPON adapts the Ethernet protocol at a data rate of 1 or 10 gigabit

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(GbE or 10GbE). Both architectures have advantages and disadvantages and each one attempts to resolve the disadvantages of the other.

In this paper we describe a hierarchical CWDM/TDM passive optical network (PON) with simple delay equalization. We call this hCT-PON access network. The hCT-PON access network is scalable to more than 16,000 end-users, is transparent to payload type, and it delivers an elastic bandwidth DS0 to Gbps. Moreover, the hCT-PON is future-proofed as it can adapt the CWDM or the DWDM ITU-T grid. Thus, considering cost of bandwidth unit per user, the cost-efficiency of the hCT-PON outperforms any proposed PON access network.

2 Hierarchical CWDM/TDM-PON

The proposed topology combines 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” or hCT-PON. As bandwidth needs increase, bandwidth exhaust is addressed by moving from the CWDM to the DWDM grid.

2.1 Downstream direction

At the OLT, sixteen (16) CWDM optical data channels and two supervisory channels are multiplexed and transmitted to the optical network demultiplexing unit (ONU-d), Figure 1. If the water-free single mode fiber is used, then all 18 CWDM channels are used in a fiber that exceeds 20 km. The next generation grid with 36 channels (10 nm separation) doubles the number of channels. For longer distances and more channels, sparse DWDM with 200 Ghz channel separation may be used. 16 of the 18 channels are allocated for data at OC-48 or OC-192. The remaining two channels are allocated for supervision, each at OC-3 or higher (OC-12 or 1GbE).

The ONU-d consists of an optical wavelength demultiplexer (ODemux), SOA amplifiers, two splitters for the two supervisory channels, and 16 optical time division demultiplex network units (ONU-t). Each unit contains an optical switch which deflects packets in time slots to their corresponding fiber (the technology of this unit is the subject of another paper). The 18 channels are demultiplexed by the ODemux and each channel is amplified by an SOA. The shortest wavelength and the longest of the eighteen (18) channels are allocated for supervision. The sixteen (16) wavelengths from the ODemux are separated into group A and group B, each of 8 channels; each channel is connected with an ONU-t. The two supervisory channels are also separated, one for group A and the other for group B, and each channel is power split in 8 by an 1:8 splitter (not shown).

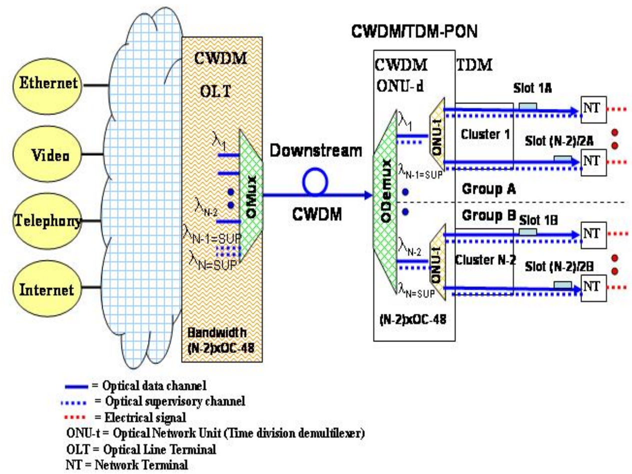

Figure 1: Architecture of the hCT-PON access network (downstream direction).

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). 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 unit (NT), where each NT serves one or more end-users. At the ONU-t, the deflection of packets in their corresponding time slots may be implemented with one of several optical technologies, (including optical switches or optical rings). The length of each fiber in the cluster is the same in order to eliminate group delay variations; this is easily accomplished by using length equalizing fibers. Each NT determines its own time slot and length from a reference clock and from supervisory messages. In addition, each NT receives one of the two supervisory channels that provides information regarding time reference (it is the same for all NTs in the same group), time slot location and length, payload type, testing, and more.

The point-to-multipoint topology assumes that NTs of the same group are sparsely located. When NTs are closely located, then this topology can be modified in a point to multipoint with an open ring physical topology, as shown in Figure 2. Notice that this is an advantage of our proposed network as a properly equipped ONU-d supports both topologies serving simultaneously sparse and dense NTs. However, in dense NTs, capital cost is shifted from the ONU-d's and the fiber plant to more complex NTs. NTs in this case recognize their own packet(s) in the optical stream [8] and mark the instance of their time slot, which must be known for time multiplexing packets in the upstream direction.

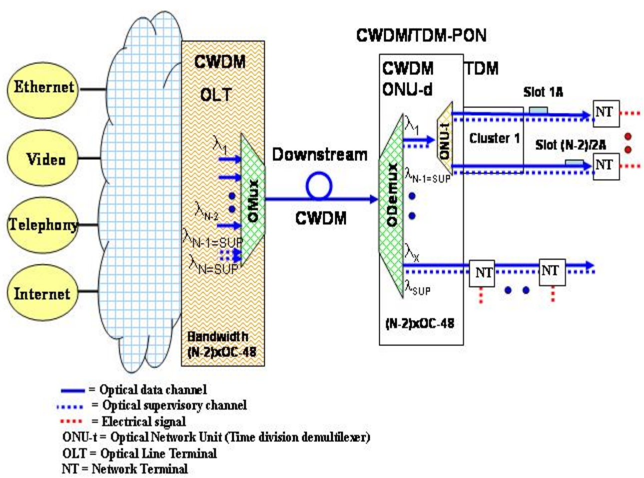

Figure 2: The hCT-PON supports simultaneously two different topologies (downstream direction).

2.2 Upstream direction

The upstream direction works as the downstream direction, Figure 3. 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).

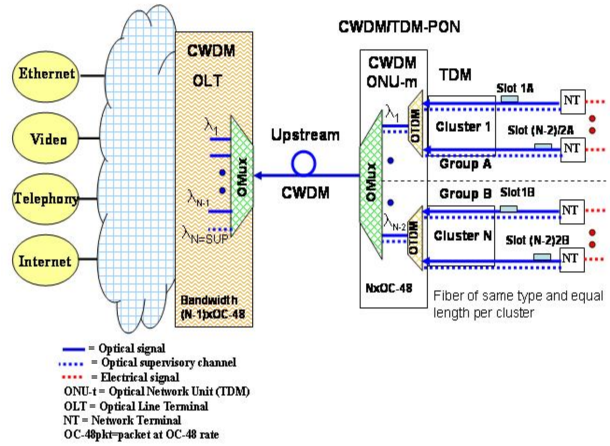

Figure 3: Architecture of the hCT-PON access network (upstream direction).

In the upstream direction, each OTDM time multiplexes packets from their cluster and transmits them to the optical multiplexer (OMux). The OTDM in this case is simple and it consists of a coupler to perform the time division multiplexing and also wavelength division multiplexing for the data channel and the supervisory channel. The OMux time division multiplexes messages from the two groups onto the two supervisory channels, and it couples all 18 CWDM channels onto the fiber. The latter is received by the OLT's optical demultiplexer unit (ODemux).

As in the downstream direction, so in the upstream the hCT-PON supports multiple topologies, two of which are shown in Figure 4. The NTs for each case have different design complexity commensurate with that in the downstream direction.

In order to use the 18 channels defined in CWDM, water free fiber must be used. The hCT-PON may also adapt the DWDM grid with relaxed specifications (200 Ghz channel separation) in which case 40 channels in the C-band over standard single mode fiber may be used. Furthermore, if the C and L bands are jointly used, then the number of channels is doubled to 80. That is, the hCT-PON is not limited by the WDM grid (CWDM or DWDM); the only limitation in this case is cost and maturity of technology, which is expected to improve over time.

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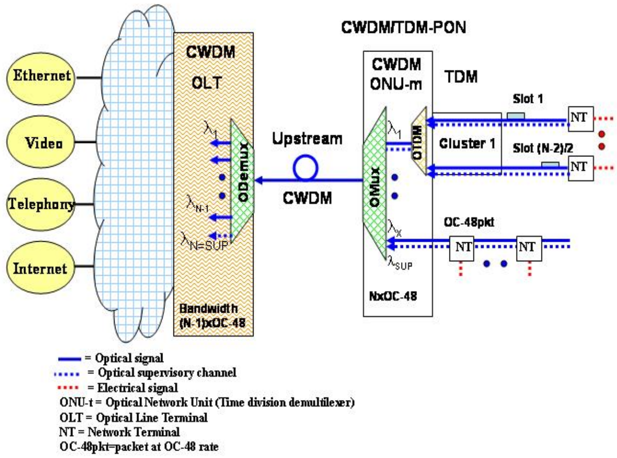

Figure 4: The hCT-PON supports simultaneously two different topologies (upstream direction).

2.3 Path delay-differential equalization

In the downstream direction, although each wavelength arrives at each ONU-t with a small phase difference, it does not affect the transmission method because the outputs from the ONU-t are coupled onto a fiber-cluster with each fiber having equal length to equalize for differential delay within the cluster. This engineering rule, equal length and same fiber type within a cluster, substantially simplifies inventory and logistics of the fiber plant while it maintains flexibility and network scalability. Hardware design, protocol complexity, maintenance and provisioning are also simplified.

3 Bandwidth elasticity and management

3.1 Data channels

Let us assume a modulation rate of OC-48 per data optical channel. For most CWDM applications, OC-48 (2.5 Gbps) is considered cost-efficient because uncooled lasers and optical components with relaxed specifications may be used. For bandwidth scalability and elasticity we have chosen a minimal time slot granularity of 125 nsec, Figure 5. Thus, 2.5 Gbps bandwidth is subdivided in small amounts 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 very fast internet/ethernet, voice, and video. For specific applications that require more bandwidth, more than one time slot per NT 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 (64 Kbps) and/or ISDN rates (144 Kbps).

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.

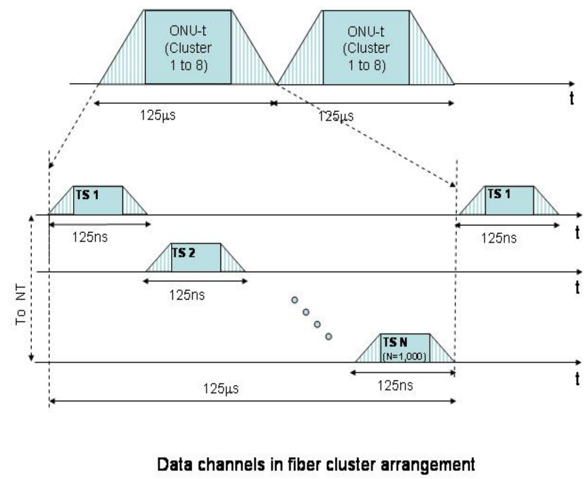

Figure 5: Time Division Demultiplexing of an optical data channel for a cluster of NTs

3.2 Supervisory channel

In the downstream direction, time division multiplexed supervisory messages for each NT are contiguously concatenated. Because all NTs have been divided in two groups each containing half the data channels, each supervisory channel addresses half of the NTs in the network. For 1000 NTs per data channel, each supervisory channel has an address space of 8,000 NTs (the potential address space is 2^{16}).

If we assume that two messages per second per NT are sufficient, then, 16,000 messages per second are carried by each supervisory channel. Now, a cluster of NTs is addressed within 1/16 of a second or 62.5 msec. Thusly, a cluster is addressed twice per second, and each of the 8,000 NTs in a cluster is addressed with a 7 µsec time slot. 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. In the future, messages may expand to 72 octets with 4 μsec margin. Moreover, the guard bands are set to zero or to a fixed pattern such as 01010101. The structure of the supervisory (or control) messages consists of a header, a data field and a CRC trailer.

In the upstream direction, 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. Then, all messages from all 8 OTDMs are time division multiplexed at the OMux and coupled onto one of the two supervisory channels. Each of the 62.5 msec intervals has guard bands at each side to relax specifications and avoid collisions.

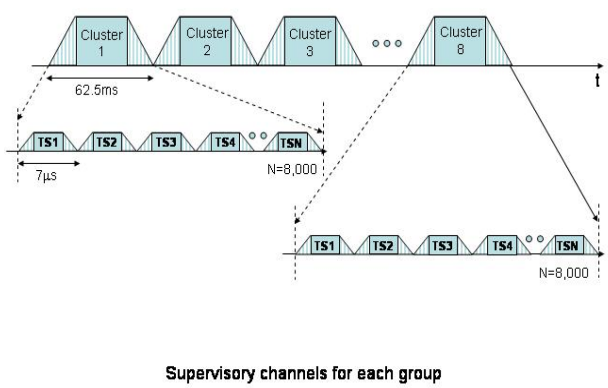

Figure 6: Time Division Multiplexing of a supervisory channel per eight clusters of NTs

4 Bandwidth elasticity and cost-efficiency

In the downstream direction, 16 optical channels transport an aggregate bandwidth of 16x2.5 = 40 Gbps. Each optical channel may serve up to 1,000 NTs, and a hCT-PON a total of 16,000 NTs; each NT delivers to the end users the equivalent of 2.5 Mbps. 2.5 Mbps is sufficient for both high speed data and synchronous payloads (DS1 or E11). Consequently, each DS1 or E11 may be further demultiplexed to offer DS0 or other fractional DS1/E11 services such as DSL and ISDN. For applications that demand very high bandwidth, concatenating *k* time slots (*k*=1 to 1000), *k*x2.5 Mbps may be transported, thus demonstrating the bandwidth elasticity of the network.

The distribution of 1,000 fibers per cluster may be challenging, if all end-users do not require more than DS1 or E11 service. As bandwidth becomes commodity, and as bandwidth per NT increases, the number of NTs in the cluster decreases and so does the number of fibers. Despite this, 1,000 NTs per optical channel demonstrates an access network able to deliver multi-services with elastic bandwidth to a very large number of end devices. If a smaller network is needed, then the network can be partially equipped; in such case, not all 16 optical data channels are used, not both groups, not all clusters, not both supervisory channels, not all fibers per cluster, and not all time slots are populated. That is, the network is scaled as needed to deliver bandwidth from basic rate to ultra-broadband in order to meet end-user needs.

In the upstream direction, the bandwidth elasticity is similarly demonstrated. NTs deliver 2.5 Mbps or multiple of it. NTs may also be used as aggregation points for DS0, DSL and ISDN services. If in the upstream direction certain clusters are expected to transport a fraction of OC-48 per optical channel, the transmitters in this cluster may be further relaxed to transmit at a lower bitrate such as OC-12 or even OC-3. In this case, the time slot arrangement remains the same and time slots are scaled accordingly (four times for OC-12 and twelve times for OC-3). This possible arrangement of asymmetric traffic further relaxes specifications and lowers the overall network cost.

5 Future-proofing

The hCT-PON described so far was based on the CWDM grid with 16 data channels and 2 supervisory channels. As client density increases, as bandwidth demand increases, and as component cost decreases the hCT-PON may be reengineered on a sparse DWDM grid with 200 Ghz channel spacing. In this case, for the C-band only the number of optical channels is more than double since now 40 channels are available. Moreover, if the C and L band are utilized, the number of channels available is 80. The same may be achieved in the C-band if 100 Ghz channel spacing is selected. That is, the hCT-PON is not limited by its architecture but on the contrary allows for scalability and new technology retrofit to provide new services to an increasing client base.

6 Conclusion

We presented a resilient and scalable passive optical network for access, the hCT-PON. This network has a hierarchical tolerant topology that uses a CWDM standard applicable to a tree and open ring topology. The hCT-PON may also utilize a sparse DWDM grid with 200 Ghz channel spacing.

Based on the CWDM grid, the hCT-PON 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) or higher (OC-192) rates to meet specific needs. Similarly, the hCT-PON may be engineered based on the DWDM grid in which case the number of end devices and/or bandwidth deliverability doubles or quadruples.

References

1. S.V. Kartalopoulos, *DWDM Networks, Devices, and Technology,* IEEE Press/Wiley, 2003.
2. S.V. Kartalopoulos, "Consumer Communications in the Next Generation Access Network," *Proceeding of the IEEE CCNC 2004 Conference*, Las Vegas, Jan. 5-8, 2004, pp. 273 – 278.
3. G. Kramer, and G. Pesavento, "Ethernet Passive Optical Network (EPON): Building a Next Generation Optical Access Network," *IEEE Communications Mag*., vol. 40, pp. 66-73, Feb. 2002.
4. G. Kramer, B. Mukherjee, and G. Pesavento, "IPACT: A Dynamic Protocol for an Ethernet PON (EPON)", *IEEE Communications Mag*., vol. 40, pp. 74-80, Feb. 2002.
5. M. McGarry, M. Maier, and M. Reisslein, "Ethernet PONs: A Survey of Dynamic Bandwidth Algorithms," *IEEE Communications Mag*., vol. 42, pp. S8-S15, Aug. 2004.
6. J.D. Angelopoulos et al., "Efficient Transport of Packets with QoS in an FSAN-Aligned GPON", IEEE Communications Mag., vol. 42, no. 2, Feb 2004, pp. 92-98.
7. ITU-T recommendation G.694.2, "*Spectral grids for WDM applications: CWDM Wavelength grid*", 6/2002
8. S.V. Kartalopoulos, "Optical pattern detector and digital-to-analog converter for optical communications systems"**,** *SPIE Optical Engineering*, vol. 43, no. 9, pp. 2150-2155, Sept 2004.