Passive Optical Networks

in the Local Loop

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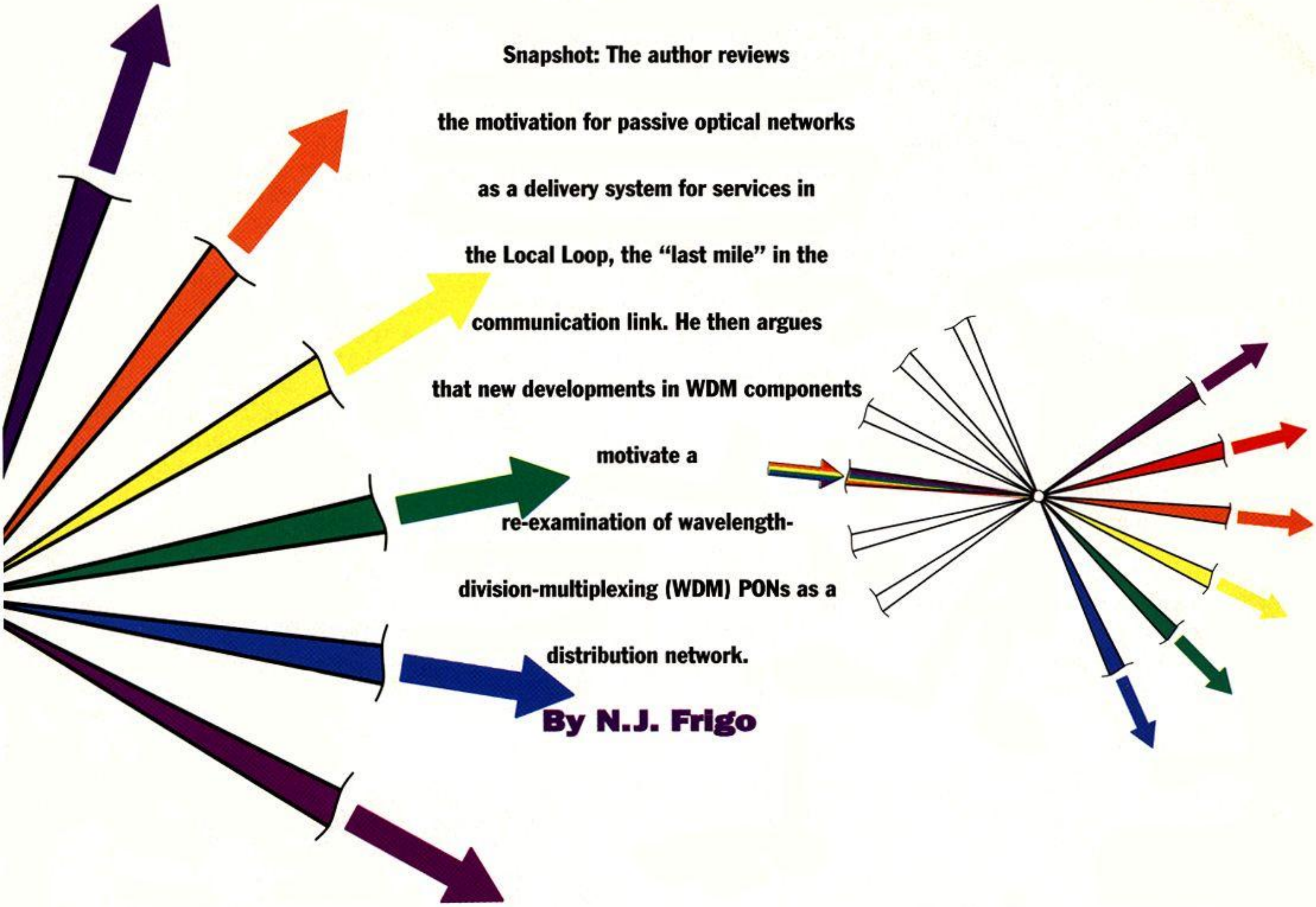

Snapshot: The author reviews the motivation for passive optical networks as a delivery system for services in the Local Loop, the "last mile" in the communication link. He then argues that new developments in WDM components motivate a re-examination of wavelength-division-multiplexing (WDM) PONs as a distribution network.

By N.J. Frigo

When we place or receive a telephone call, we enter the periphery of a vast switched network that allows trillions of possible connection paths; we are served in our local area, the last mile, by a central office (CO) that supports one or several exchanges (*i.e.,* the three-digit prefix in a seven-digit telephone number) of up to 10,000 subscribers each.

The CO service can be modeled[1] as in Figure 1 (see next page). Communications channels between the CO and subscribers are supported either directly in a single star or by remote nodes (RNs) in a double star. The double star configuration is preferred for all but the shortest links because instead of requiring a link from the CO to each subscriber, the calls for a group of subscribers can be multiplexed and sent on a single "feeder" link to the RN, where they are electronically demultiplexed and distributed on individual "distribution" lines.

In traditional networks with copper twisted pairs, this reduction of feeder pairs yields an increasing economic advantage with increasing link length and subscriber density. The savings in transmission costs, however, must be balanced by the costs of installing, powering, and maintaining the RN electronics.

Until recent times, the economic advantages and disadvantages were readily calculable. The universal telephone service has a fixed information rate of 64 kb/sec per line whether used for voice, fax, or data modem transmission. More than a decade ago, however, network planners began to worry about provisioning the newer services that are now starting to appear.

Early Fiber-in-the-Loop (FITL) trials successively replaced feeder and distribution lines with fiber optics, but political difficulties with utilities commissions [and early recognition that Fiber-to-the-Home (FTTH) was too expensive] motivated Fiber-to-the-Curb (FTTC) architectures that shared expensive optics and electronics over several subscribers.[2] Even so, the costs of the RN remained high in the proposed networks as did the recognition that the RN could be a bottleneck for future services, especially with diverse line rates and service acceptances. This posed a problem: once the RNs were installed for today's services, could there be any assurance that their capacity (*e.g.,* throughput or maximum

"Routing" property of the waveguide grating router (WGR). The WGR splits light entering an input port into its spectral components on a set of output ports (left drawing). The same spectral components entering an *adjacent* input port (right drawing) exit on adjacent output ports. Note that the violet component has "wrapped around" from the bottom port (left) to the top port (right). (See text and Fig. 3 for more details.)

rate) would not quickly become obsolete? In short, would they be vulnerable to an explosive growth in service demands such as we have witnessed with the newly popular Web Browsers? The challenge could be cast as "How do we design a distribution network that can be installed as inexpensively as the current copper plant, yet be "future proof" against unknown information loads from unimagined services."

Passive optical networks (PONs) were proposed in the late 1980s as a solution to this challenge, in which optical fiber replaces copper twisted pair and the RNs become optical splitters instead of electronic demultiplexers (see Fig. 1). Then, between the CO and the individual living units there would be only passive optical components, which gave rise to the "PON" appellation. The fiber was to be terminated at an "optical network unit" (ONU), comprising a transceiver to perform the electrical/optical (E/O) and optical/electrical (O/E) conversions necessary to link the CO to the subscribers. As they had for FITL, cost estimates quickly prompted the idea of sharing an ONU among several subscribers, albeit at the expense of the passive attribute. In this paper, we will avoid the FTTH/FTTC issues and concentrate on the architectures themselves: For editorial convenience we will assume an FTTH architecture in which each ONU serves a single living unit.

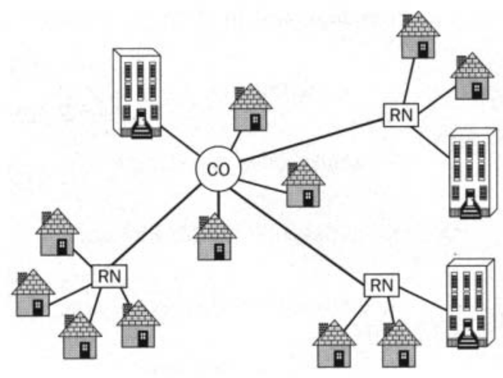

Figure 1. Telephony distribution architecture. Central office (CO) serves subscribers directly and with multiplexed traffic through remote nodes (RN). In current systems, the RN contains electronic demultiplexers.

PON background

An early, and still popular, architecture was proposed as "Telephony over PON" or "TPON" by British Telecom Research Lab (BTRL) as a strategy to install fiber as quickly as possible.[3] It is based on using a passive power splitter (PS) or coupler (such as a 1 × N star coupler) as the RN. Chief among the advantages of this approach is the availability and maturity of the necessary components, although ongoing research is still yielding performance improvements and cost reductions.

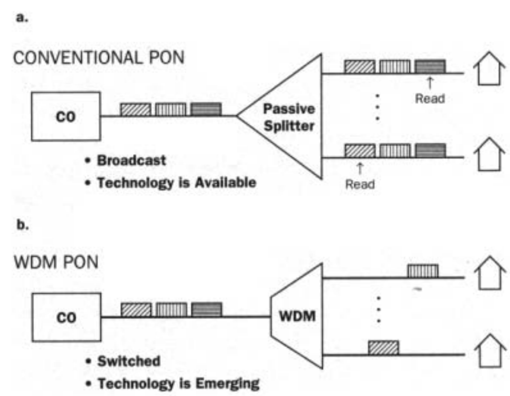

Figure 2. Broadcast and switched PONs. In broadcast PON, all subscribers receive a common signal and decode only their packets. In WDM PON, only packets intended for subscriber reach him.

Since each of the N outputs of the PS are on an equal footing, each ONU in a broadcast PON receives a replica of the same signal. A time-division multiplexed (TDM) protocol is established to permit each subscriber to read his, and only his, packets (see Fig. 2a). Such PONs are variously called broadcast PONs since the CO broadcasts a common signal to all ONUs, or point-to-multipoint PONs. Traffic in the upstream direction (*i.e.*, from the ONU to the CO) is coordinated with a time-division multiple access (TDMA) strategy: All ONUs receive clock information in the downstream broadcast and instructions for allowed transmit times. Although a variety of strategies for upstream coordination have been proposed, there are several characteristics that all broadcast PONs share. The passive splitting implies that the vast majority of optical power intended for a given ONU will, in fact, go to other ONUs. A consequence of this is that there is an N-fold power budget penalty due to the optical splitting. Additionally, the fact that N subscribers share the downstream laser imposes another N-fold power budget penalty since the bits would be that much shorter in duration. (To be sure, this also implies an N-fold reduction in laser cost per ONU !)

These penalties (as well as privacy and network integrity issues) seriously limit the ultimate performance of the broadcast PON, raising the "future proof" question of how upgrades are to be implemented. Even in the earliest discussions, wavelength-division multiplexing (discussed below) was proposed as the upgrade strategy. However, performance limitations, the indeterminate upgrade path, and cost of optical amplifiers has conspired to limit widespread acceptance of broadcast PONs in competitive loop markets. Its justification of rapid fiber installation has been insufficient to induce widespread commercial U.S. deployment.

Concerns about privacy (*e.g.*, all subscribers have access to all downstream messages) and network integrity (any subscriber can corrupt an entire node by violating the upstream TDMA protocol) prompted proposals by several Bellcore groups to use wavelength-division multiplexing (WDM) PONs instead of broadcast PONs.[4] In these networks, a WDM device at the RN directs downstream light to unique output ports as a function of optical wavelength, permitting the equivalent of switched (or point-to-point) communication (see Fig. 2b) while still sharing a fiber feeder. Similarly, upstream light can be multiplexed in the same way. The advantages of WDM PONs were clear. WDM, by directing light to one (and only one) subscriber removed the N-fold broadcasting penalty at the same time that it removed the privacy and network integrity concerns.

Similarly, a WDM at the CO could multiplex N sources, one for each wavelength channel. While this removes the N-fold sharing penalty, it imposes a cost penalty. Cost has been the major disadvantage of this network; technical risks, such as channel crosstalk and wavelength alignment, have not been addressed.

Thus the original PON proposals as Loop architectures ran into both ends of a stiff cost/performance tradeoff. Broadcast PONs were cost effective, but had unclear future performance potential, while WDM PONs had excellent performance potential but were unlikely to meet the stringent cost targets for universal service local access architectures. Recent progress in WDM component development has made that tradeoff appear less forbidding.

Recent WDM component advances

Perhaps the most favorable WDM development in recent years has been the rapid progress in waveguide grating routers. There are three salient properties of this component. Early research demonstrated the concept of patterning waveguides lithographically onto substrates to achieve the optical performance of a diffraction grating.[5] This enables the WDM property of splitting light as a function of wavelength (*e.g.*, $f_1 - f_8$ entering input port 1 and exiting ports 1–8 in Fig. 3), and is the defining characteristic of WDM devices. The second property is a generalization of the WDM property to $N \times N$ devices in a particular manner. Not only do each of the N inputs possess the WDM property, but there is a cyclical relationship between the input port numbers, the output port numbers, and the optical channel number. We call this the routing property;[6] it can be expressed, for example, as f_1 exiting output port j if introduced on input port j (see f_1 on ports 1 and 5 in Fig. 3). Similarly, f_2 entering input port 5 would exit port 6, and so forth. The third property, periodicity, is illustrated by f_9 wrapping around to port 1 in Figure 3. That is, higher channels, instead of being dropped by the WGR, are overlayed on lower channels. An analog of this property is a diffraction grating for which the second diffraction order overlaps the first order, instead of being greatly displaced.

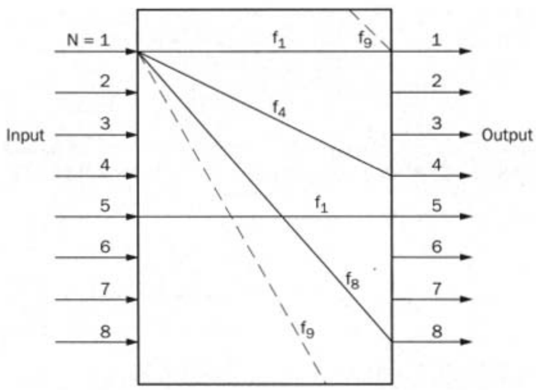

Figure 3. Waveguide grating router. Possesses WDM property (input #1 to output #1–#8 for f_1 to f_8), routing property (*e.g.*, f_1 on input #5 to output #5), and "periodicity property" (input #1 to output #1 for f_9). Increased functionality enables new architectural advantages.

These remarkable properties[7] enable signficant PON architectural improvements. First, the periodicity property permits efficient use of sources whose spectral width greatly exceeds the free spectral range (*e.g.*, the period f_9–f_1 in Fig. 3) of the WGR. This so-called spectral slicing[8] derives its name from the sieve action performed by a WDM device under illumination by an optical broadband source such as an LED: its spectrum is sliced into the output ports. The periodicity property harvests the light that would have spilled over the limits of a conventional WDM with the same spectral range. Second, the periodicity property permits the WGR to be used in both 1.3 μm and 1.5 μm windows. There are changes in the channel spacing, and so on, but this does not seriously affect the efficiency of spectral slicing. Third, the routing property eliminates wavelength collisions by permitting different fibers to use the same wavelength. Consider the upstream signals in Figure 2. To reach the CO, upstream light from an ONU must be in the same channel as the downstream light it receives. System performance degrades when the two wavelengths are close enough to beat at a frequency near or below the signal bandwidth. The routing property allows frequency re-use on different ports, so that f_1, for example, connects input-side ports 1 and 5 to output ports 1 and 5, while f_2 connects the same input-side ports to output ports 2 and 6, for instance. Fourth, the periodicity property permits the use of intermediate WDM (IWDM) to segregate services for instance by using f_1 and f_9 to supply two different services to the user on port 1. IWDM is intermediate between the dense WDM of the channel spacings (1 ≈ 1 nm) and coarse WDM such as 1.3 μm/1.5 μm.

Of course, one needs optical sources to carry information on the channels set by the WGR. In WDM sources as well there has been dramatic progress in three categories. First, for tunable lasers (lasers that emit at one wavelength at a time, but that wavelength can be chosen from a known set), there have been great strides in developing wide tuning ranges using a variety of methods, such as multisection DBRs,[9] split-cavity Y lasers,[10] and vernier-type tuning with sampled[11] or super structure gratings.[12] Second, integrated arrays of DBR[13] or DFB[14] lasers whose outputs are combined in a passive splitter, have been demonstrated. These hold the potential of providing low-cost N-laser devices. Third, shared intracavity lasers such as the MAGIC laser[15] and the waveguide grating router laser[16] have demonstrated accurate channel spacing that is determined by macroscopic patterns. Currently these classes of lasers are generally available only in small quantities, but there is active research in all three areas around the globe.

Once a communication channel is set up by a WDM, and light of the correct wavelength is sent to an ONU, another wrinkle is possible: By reflecting that light or returning it to the RN, one is assured of being at the correct wavelength. Thus, a modulator can also be considered to be a source. Recently, silicon micromechanical switch (actually a first-order FP filter operated in reflection) has operated error free at 1.5 Mb/sec. Its simple fabrication and surface-normal design presage very low costs.[17] For higher speed applications a Y-branch switch has been demonstrated.[18]

Recent WDM PON architectures

An example of an architecture that has been enabled by the recent component progress is RITE-Net,[19] an initial entry of which is shown in Figure 4. As usual, the WDM device (in this case a WGR) sets the wavelength channels. The source can be any of the multiwavelength sources, but a potentially inexpensive source is a tunable DBR:[9] it has a single drive circuit and achieves a reasonably high output power. The routing property of the WGR permits a portion of the downstream light to be used as a carrier for upstream information. Thus at the ONU, a receiver decodes downstream information, but a portion of the downstream light is either transmitted (upper ONU) or reflected (lower ONU) back to the CO with upstream information impressed by overmodulating the downstream light. Separating upstream and downstream signals with two fibers eliminates impairments caused by scattering in the fiber, which has been shown to degrade link performance.[20] Additionally, the routing property obviates both the need for an optical source at the ONU and for registering its wavelength: the downstream light is recycled for the upstream signal. In addition to enjoying the traditional WDM advantages (privacy, network integrity, upgrade potential), this architecture permits low-cost, low-power ONUs to be deployed. Also, since it is controlled by the CO, no upstream light from an ONU can interfere with that from another ONU, even when a single laser is shared for all upstream and downstream channels. Thus, a high quality-of-service channel for a neighborhood business, for example, cannot be degraded by a neighbor's low-quality ONU.

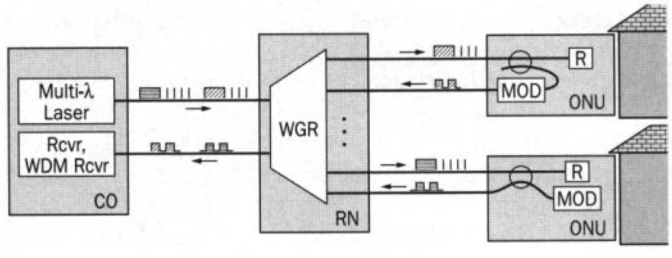

Figure 4. RITE-Net architecture. WGR routing property permits an optical loopback. This eliminates the optical source at the ONU and avoids optical beat interference.

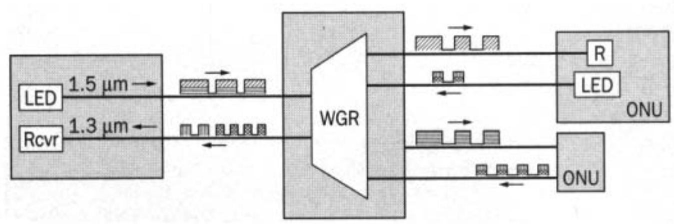

Figure 5. Bi-directional spectral slicing architecture. WGR periodicity property permits WGR to act as power splitter. This enables low-cost PON with WDM infrastructure.

Another architecture, LAR-Net,[21] has been proposed to avoid the use of a modulator, since commercial models are not yet available. In this architecture, the periodicity property of the WGR is exploited to use efficient spectral slicing of an LED source at the ONU to carry upstream traffic. Separating the upstream and downstream traffic with coarse (1.3 µm/1.5 µm) WDM permits a single fiber to be used, trading off fiber plant for a WDM in the ONU.[21] The downstream channels are carried by a multiwavelength laser, and thus are capable of high capacity. As in the RITE Net architecture, the upstream traffic rate will be sometimes lower due to a reduced power budget, and it can be sorted at the CO by a WDM receiver, if desired.

A third architecture exploits the spectral slicing in both directions of a bi-directional spectral slicing PON.[22] In this case, operation is similar to that of a broadcast PON: spectral slicing mimics the power-splitting PONs, putting equal powers on each output (see Fig. 5). It shares all the broadcast performance limitations and they are exacerbated by lower LED power. However in this case, in contrast to the conventional PON, the upgrade path is clear: the PON may start life as a broadcast PON, but the fiber infrastructure (including the WGR) for a high performance WDM PON is already installed. That is, in initial deployments the WDM infrastructure is used merely as a broadcast PON. However, when a broadband upgrade to the network is needed, it can be converted rapidly to a high performance WDM PON.

Finally, we mention that there is a potential drive to provide CATV service over telephony networks; cable and telephone providers may wish to compete in the other's market. In this case, an inexpensive method for delivering CATV is necessary. An example was shown recently.[23] Robust quadrature phase-shift keying (QPSK) signals from a commercial satellite service were delivered over a broadcast PON. Since we have argued that the bi-directional spectral slicing PON is the functional equivalent of a broadcast PON, it should be possible to implement cost effective digital CATV service over even the most inexpensive WDM PON implementation.

Discussion

We have shown that recent advances in WDM component technology are laying the groundwork for low-cost components in the near future, a necessary condition for a large scale WDM PON deployment. However, while current research effort is promising and commercial components are becoming available, there are *no* low-cost WDM PON components available today. In the Local Loop, low cost is not merely a desirable attribute, but the dominant necessity. Competing architectures have strong selling points as well. Hybrid fiber-coax (HFC), switched digital video (SDV), and wireless architectures clearly are less expensive to implement since they minimize laying fiber optic lines, permit extensive sharing, and use more mature components. While the WDM PON is arguably more future-proof than these other alternatives, network planners must wrestle with the need to predict how future-proof the network needs to be (*i.e.*, how resilient it must be to accomodate dramatic usage changes such as the recent popularity of the World Wide Web). Furthermore, new regulatory proposals complicate the financial risks assumed in introducing a new network. Potential network providers must weigh the economic consequences of expected "take rates" in a competitive environment. It is costly to provide a network capable of supplying diverse services at low expected subscription rates.

The promise of WDM PON architectures is great: they can be introduced at a low level, can exploit low-cost technology as it becomes available, and can be upgraded to very high performance levels as needed. In the end, however, a business decision must be made. Can the network supply the highest broadband performance that will be demanded by some users at the lowest cost that will be tolerated by more conventional users? We argue that both sides of this equation are changing rapidly, and that for scenarios in which there is heavy and diverse traffic, WDM PONs may well prove to be the most effective distribution network.

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Glossary

Broadcast Network: A network in which a group of subscribers receive the same communication signal, but decode only the logical channel corresponding to their communication link.

CO: Central Office. Location from which telephone calls for an Exchange are sent, received, and switched.

DBR: Distributed Bragg Reflector Laser. A laser in which a wave-length selective periodic perturbation at one end of the laser preferentially reflects a given wavelength of light, making the laser preferentially operate at that wavelength.

DFB: Distributed Feedback Laser. A laser in which a wavelength selective periodic perturbation throughout the laser makes the laser preferentially operate at that wavelength.

Distribution Link: Communication link between Remote Node and a terminal serving a subscriber.

Feeder Link: Communication link between a Central Office and a Remote Node that carries multiplexed traffic.

FAITH: Fiber-Almost-into-the-Home. A joke symbolizing the difficulty of obtaining an FTTH system that is cost-effective.

FITL: Fiber-in-the-Loop. The use of fiber optic feeder and distribution links instead of their copper-based counterparts. FTTC and FTTH are examples.

HFC: Hybrid Fiber Coax. A mixed network in which feeder fiber carries both switched and broadcast information to a Remote Node, where it is processed and delivered to terminals over coaxial cable.

ONU: Optical Network Unit. A device that terminates an optical Distribution Link and establishes a conventional link with a subscriber (FTTH) or subscribers (FTTC).

PON: Passive Optical Network. A FITL network in which there are no electrical devices between a Central Office and an Optical Network Unit. There is some debate about whether FTTC should be considered to be a PON, because its ONU is not passive.

SDV: Switched Digital Video. A network delivering switched services (currently with a modem over copper wires) while simultaneously delivering CATV service over a separate network.

Spectral Slicing: The technique of sending a broadband optical signal to a WDM device to establish an optical connection between two points by using a portion of the broadband optical signal's spectrum.

Switched network: A network in which a each subscriber has information directed (switched) to him alone.

TDMA: Time-Division Multiple Access. The use of pre-determined permissible time slots to allow a number of users to access a common communication medium.

WGR: Waveguide Grating Router. A WDM device that operates as a diffraction grating by use of patterned waveguides on a substrate. It has features that augment the conventional WDM devices. Also called array waveguide grating.