Ultra-broadband access enabled by fiber optics

(Invited Paper)

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The advent of low loss optical fiber has consistently led us to the ultra-broadband era, where bandwidths exceeding 1 Gb/s are commonplace. This Review reviews the early history of fiber access, pointing out some of the lasting design choices and signature features of fiber access. The progress of the various passive optical network technologies is also reviewed, and some views regarding the future trends of fiber in the access.

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Broadband access services are increasingly important for everyday life. Nearly every existing activity has been improved by networking to some extent, and new goods and services that are enabled by broadband networking emerge every day. Therefore, it is key that technology provide an efficient, cost effective, and universally available access to the worldwide network.

While there are many media that can play a role, single mode optical fiber stands alone as the ultimate solution to the broadband access problem. Fiber combines high bandwidth (≫1 Tb/s) with low loss (≪1 dB/km), and given the present optoelectronic technology fiber to the home (FTTH) can easily provide access to >10 Gb/s over a distance of >20 km. Such capabilities certainly meet the long term needs of the human users of the network. While machine to machine communication could grow to higher levels, it is also true that machines do not need to be located at people's homes. Therefore, it is safe to assume that single mode fiber will be the end-state of the fixed access network.

This Review will review the early history of FTTH networks to highlight some of the key choices that were made; choices that we continue to live with today. It will also briefly review the evolution of mainstream passive optical network (PON) technologies. Lastly, it will mention some new techniques that are the focus of future research.

As soon as low loss fiber was developed, the telephone network operators began to consider how to deploy this in their access networks. Of course, fiber was a natural fit for long-haul, metro, and even access feeder networks; and it quickly took a leading role there. However, in access it faced the combined challenges of relatively high costs and low revenues. The average tariff rates from residential access are quite low, and they tend to be fixed (not dependent on traffic volume). Meanwhile, the cost of optoelectronics, the fiber itself, and their installation were all high compared to the legacy media. So, various architectures were considered, as shown in Fig. 1.

The first was the simple replacement of the home run copper wires with fibers. This passive single star topology is simple and future-proof (since every customer has their own fiber), but it is very expensive. The amount of fiber is very high, and each home requires two transceivers (one on either end). For that reason, home run fiber has never been widely deployed.

The second architecture considered using an access multiplexer or remote terminal (RT) out in the field. This active double star topology is similar to the digital loop carrier systems that were in use for telephone service. This system helps by reducing the amount of fiber being used, since it multiplexes the signals on fewer fibers. Unfortunately, it does nothing to help the amount of optoelectronic transceivers, and ever worse it requires power supplies in the remote location. Thus, this architecture has seen relatively small use in practical networks.

The third architecture uses passive optical splitters to perform the multiplexing at the remote node. This passive double star topology achieves the reduction of fiber of the active double star, and what's more it reduces the optoelectronics to approximately one per user[1]. Since the splitter is simply a directional coupler, it does not require electrical power. For these many benefits, the PON architecture has been the favored approach in over 90% of all FTTH networks today, and PON has become synonymous with optical access all over the world.

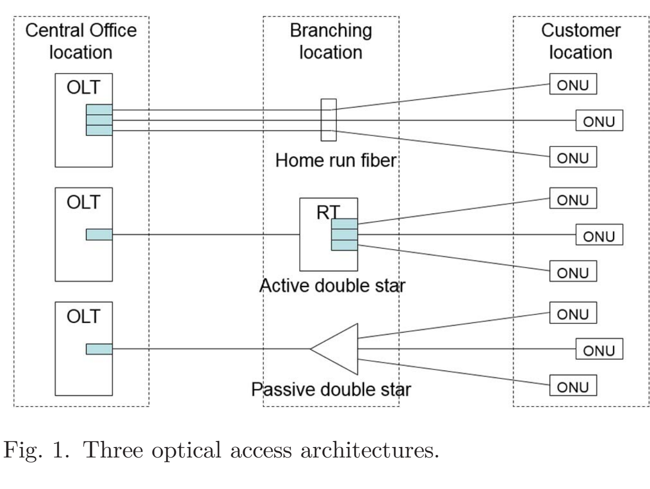

Fig. 1. Three optical access architectures.

Of course, the passive splitter has no intelligence, and simply broadcasts the downstream signal to all endpoints, and combines the upstream signals from all endpoints. In order to make the system work, the PON needs to have a carefully designed system of hardware at either end. The optical line terminal (OLT) at the central location acts as the master, and it controls all the optical network units (ONUs) such that only one ONU is transmitting at any one time. The upstream is therefore operating in a time division multiple access (TDMA) mode.

The widespread deployment of PONs makes its basic fiber infrastructure the common thread uniting all the PON systems devised so far. While operators are willing to replace the end equipment from time to time, the fiber plant itself should never be changed out.

The PON architecture has gone through many generations of systems: ATM-PON, Broadband-PON[2], Gigabit-PON[3], and Ten Gigabit-PON[4,5] (and their Ethernet variants EPON and 10GEPON[6]), see Fig. 2. Each system represents speed increase (typically 4×); but all of these use the same TDMA system, using WDM to combine the two directions of transmission over a single fiber splitter-based PON. One of the notable aspects of these PON systems is that the upgrade of PON does not require changes to the fiber network infrastructure: all of the systems have the same reach and power budget, and the bandwidth of the fiber is far wider than any access system could use. In all likelihood, the PONs being deployed today will be in the field for a very long time. This has also motivated the coexistence capability of all these systems: it is possible to operate 3 generations of PON system on a single PON.

The most recent major system to be developed is the NG-PON2 system[7,8]. NG-PON2 was a significant change from the previous system in that it used multi-wavelength operation to reach total bandwidths of 40 Gb/s or higher, as shown in Fig. 3. This raises interesting crosstalk issues, as the system must keep the ONU transmissions apart in wavelength as well as time. This requires the ONU transmitter to be very spectrally pure and well controlled, with minimal energy in other channels, and of course the ONUs need to be tunable to select the desired channel. While these optical capabilities are not so difficult, they are

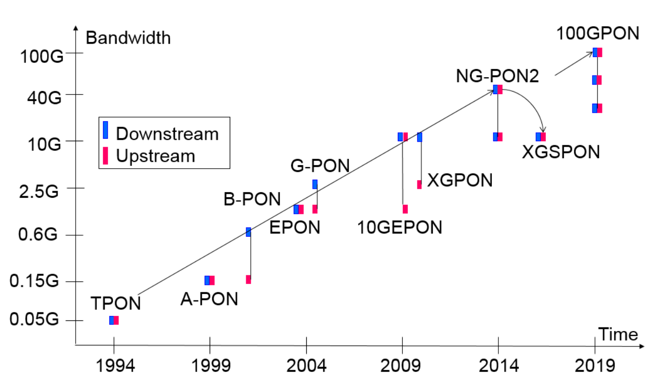

Fig. 2. Evolution of fiber access systems over time.

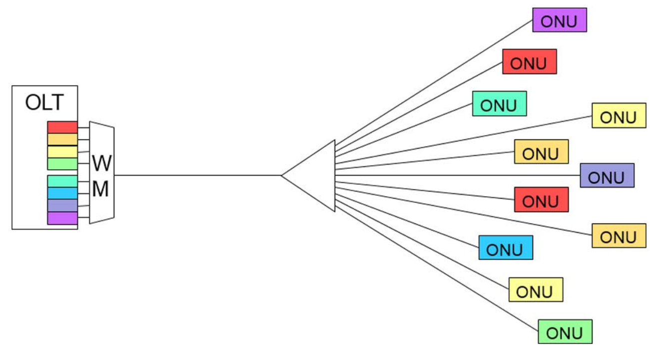

Fig. 3. NG-PON2 system architecture.

new to access, and currently they are fairly expensive. Cost reduction will happen, but it will take time. Some operators are not willing to wait, as they have Gigabit rate PONs that they would like to upgrade. This helped to motivate the latest ITU PON standard, XGS-PON, the symmetrical version of XG-PON.

Currently, there are projects starting within both IEEE and ITU to consider transmission at 25 Gb/s per wavelength. This could be used to create a single channel 25G-PON, or even a multi-channel 50G or 100G-PON. Whether these efforts become successful depends on the development of cost-effective optics and/or digital signal processors that can support 25G operation. This is currently still a technical risk, but many are working to find solutions. Perhaps in five years these might be ready for incorporation into the existing single- and multi-channel PON systems.

As the previous section shows, the main drive for optical access networking is to increase capacity. However, every trend has a limit, and it seems that access may be reaching its limit. This begs the question of what will be the hot topics for optical access research. We would suggest that there will be a shift away from speed towards the capabilities of loss budget, cost reduction, application flexibility, and software integration.

To increase the loss capability of PON systems, the most direct method is to develop higher power transmitters and more sensitive receivers. In the conventional sense, there are some small enhancements (a few dB) to be had by improving the device design and packaging precision. For example, photodetectors are limited by the associated pre-amplifier. If the amplifier has higher gain, then greater sensitivity can be achieved. Of course, higher gain also comes with a risk of electronic instability, so it is not so easy to implement. Another example is optical packaging technology. Most conventionally packaged lasers couple less than half their laser output into the fiber. Alignment stability and accuracy are part of this, but a bigger factor is mode mismatch. Either aspherical optical elements or improved laser chip designs may help.

Another interesting possibility is few-mode fiber. It is a well-known fact that in the downstream direction the power is divided amongst all the endpoints due to conservation of energy, and this represents an unavoidable loss in the power budget. In the upstream, there is a similar loss due to conservation of brightness, but this loss is somewhat avoidable. If the upstream side of the splitter has multiple modes, then each mode can catch some of the light. Early work on this concept involved the so-called mode coupled receiver, where several upstream fibers were coupled into a single detector with a large enough area to capture all the light[9,10]. This was experimentally demonstrated, but it has the drawback that active optoelectronics are needed at the branching point. Later work moved to employ few-mode fibers to carry the combined light over the feeder part of the network. This design keeps the remote branching point completely passive, and using a specially engineered few mode fiber, the combined signals can be received using conventional detectors[11]. A drawback of this is the necessity for deployment of a new fiber type, which is generally not encouraged for access networks.

The most fundamental requirement for any access network is to be low cost, both in the initial start-up phase as well as the built-out phase. The conventional methods to getting to lower cost have to do with raising volumes to the point where entire manufacturing lines can be occupied with a single standardized component type. The existing PON technologies have already achieved this, and so further methods need to be explored.

One method that has been discussed widely for many years is optical integration. The most recent incarnation of this is silicon photonics. While the technical capability of the integrated optics has steadily gotten better, there is still some way to go to meet the performance of discrete components. A more fundamental problem has to do with the applicability of integration technology. For designs that have a high complexity and a high parts count, then integration makes a lot of sense, as it will reduce size and cost in a direct way. However, in optical access the most critical optical module (the ONU transceiver) has only three optical elements (a laser, a detector, and a diplexing filter). Such a simple device really makes no sense to integrate. What's more, silicon photonics cannot integrate the optical source monolithically, so the hope of a single chip ONU is not attainable. Even III-V optoelectronics chips have a significant issue in that the wavelength bands used in optical access are far apart in wavelength, making it difficult to make a single device that is optically active for both transmit and receive. Therefore, we do not hold out much hope for optical integration technologies in access.

A more promising scheme to achieve lower cost would be to exploit the statistical nature of loss budgets. The current design practice for optical access is the worst-case method. The link is engineered so that even if every single component is at its worst possible value, the link will still work. This is obviously over-engineered, but it also gives the operators the simplicity of design that they would like. The statistical design method works to operate the network closer to the mean optical performance level. This can be accomplished in access networks by making the active equipment adaptive to the link conditions. The simplest adaptation is speed: for bad links the bit rate could be reduced, and for good links the bit rate could be raised[12]. The overall capacity is maintained while reducing the significant (>3 dB) worst-case margin can be recovered.

The classic use of PON technology is FTTH, and any new system should maintain this focus so that it achieves high volumes for its key components. That said, the deployed FTTH network quickly becomes the largest part of an operator's fiber network. This huge resource must be leveraged to the maximum extent possible, so that its profitability is increased. The most direct way to do this is to add additional applications and users onto the network. There are several major categories of emerging application to be considered, such as business services and wireless fronthaul.

Business services largely amount to providing large symmetric bandwidth pipes to businesses that are operating their own enterprise networks. There are two possible service paradigms. Some users wish to have completely contention-less bandwidth; that is, something akin to a direct dark fiber connection. This can be provided via wavelength overlay, such that the high capacity customer is given their very own wavelength. Such a system is defined as part of the NG-PON2 system. The challenge of this is to devise a network that aggregates enough overlay users to make itself commercially viable. Other users want to have dynamic access to very high bandwidth services, sometimes up to 100 Gb/s. The technology in play for this is wavelength bonding, where the user's data flows can be spread over several channels to achieve a higher rate. Such a system is being developed in the 100GEPON project.

Wireless fronthaul is an interesting emerging application. This system works by carrying minimally processed signal samples from the remote antennas to the central location. The centralization of processing enables better coordination of multiple antenna sites, and potentially cost and power savings on the processing. However, the bandwidths involved for front haul are very large, and the latency and jitter requirements are daunting. At present, there is a gap between the transport supply that access networks can provide and the transport demands that 'classic' front haul need. There are several ways to address this gap. On the supply side, more efficient front haul systems have been proposed, that use quasi-analog transmission, as well as transport systems that have built in flexible bandwidth allocation to adapt to the changing traffic patterns of the wireless system[13]. On the demand side, the functional split of the front haul system is being reconsidered. By moving some of the low-level computational functions back to the remote antenna, the transport requirements can be lowered[14]. All of this is an active area of research, and the final answer is not obvious.

Beyond the basic data transport capabilities of the network, there are various management and other features that define the services on the PON. The conventional PON system would support any added features in the

OLT equipment, leaving the ONU to be as simple as possible. The OLT would be managed as the gateway to the access network, and then the OLT would manage its subtending ONUs via a local management system (in the ITU systems, the ONU management and control interface (OMCI))[15]. This current arrangement works well, and the entire gamut of conventional access services is supported. However, there are a few issues with this arrangement, such as the speed of new service introduction and the interoperability of ONUs and OLTs.

Conventional access services are relatively simple transport-centric constructs. They generally involve establishing a virtual connection between the user's termination and the network service gateway, as well as the configuring the user profile on the user's equipment. In future, many operators hope to have more complex service offerings where the user themselves can request or dynamically provision services of different types. One example service would be a scheduled high capacity private virtual network between all the locations of a small business. This could be used to perform data backups or database synchronizations at high speed but when the network is relatively idle. One of the key enablers of new services is the opening of the management interfaces to the OLT PON equipment. The hope is that the operators or other third parties can write their own software applications to develop new services, and not have to wait for the usual requirements-standards-implementation-deployment cycle. The open interfaces to the OLT are likely to be Netconf/YANG based, as this is commonly accepted as the next generation of management and programming interface. There is work in several standards groups to define the basic framework for this[16].

Current OLT-ONU interoperability is supported based on the standards relevant for the particular system in question, and there are many cases of deployed systems where multiple vendors' ONUs operate on another vendor's OLT. That said, there are issues with the current scheme. For one, the PON cannot be called "plug-and-play". The ONU-OLT interoperability needs to be confirmed via testing, and in many cases some small remedial software coding must be done to resolve outstanding issues. For another, any interoperating system is described by four separate deliverable items (the OLT and ONU hardware and software). If any of these four items change due to a new release, then the interoperability must be reconfirmed. This is operationally unwieldy. The opening of the ONU management interfaces could potentially solve these problems by logically separating the management functions from the physical equipment[17]. In one simple model, each vendor would be responsible for the software of his own equipment, and provide management interfaces to higher layer controllers. Then, the operator (or third party) would be responsible for system integration and controller software. While this gives the operator much more detailed control, this control comes with much greater development responsibility. The evolution of this new world of disintegrated software systems is still unsettled.

The progress of optical access systems has a long history, spanning a few decades and several orders of magnitude of bandwidth capacity. The linear evolution of systems towards higher speed continues today, but may be leveling out at the 100 Gb/s level. Future work will turn towards other system enhancements such as PON convergence, optical capability enhancement, and service and software flexibility. In this way, PON systems will continue to grow to serve the entire world, providing cost effective broadband to everyone.

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