Fiber-to-the-Home: 1977–2007

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Invited Paper

***Abstract*—Fiber has been envisioned for delivering broadband services to the residential customer for over 30 years, yet it has only recently entered the mainstream. Currently, fiber-to-the-home (FTTH) is being installed in many countries at remarkable rates (even though it still constitutes only a fraction of all broadband lines in most countries). Other lightwave transmission technologies have progressed far faster. What has held FTTH up for so long? What improvements along the way have occurred? What recent changes have made it successful? This article follows the progress in moving fiber toward the home and major architectural changes that have reduced costs while increasing capabilities to meet today's needs.**

***Index Terms*—Broadband, broadband passive optical network (BPON), ethernet-based passive optical network (EPON), Full Service Access Network (FSAN), fiber-to-the-home (FTTH), fiber-to-the-premises (FTTP), Gigabit passive optical network (GPON), optical communications, passive optical network (PON).**

I. Introduction

FIBER-TO-THE-HOME (FTTH, or fiber-to-the-premises, FTTP) is currently experiencing double-digit growth [1] (or higher[1]) in Europe, several Asian countries, and the United States as residential customers seek faster connections for broadband services. This thirst for speed has exceeded even recent predictions, driven partly by the downloading or streaming of more and more video content over the Web, the unanticipated success of high-definition television, and the growing popularity of exchanging photographic, video, and audio content. New uses favoring greater bandwidth appear continually, and many service providers are planning networks capable of 50 Mb/s, 100 Mb/s, or higher, per customer. With essentially unlimited bandwidth potential, it is clear why, for so many years, FTTH has been called the "end game" for broadband access.

Most broadband customers today rely on networks comprised of ordinary telephone wire driven to very high bit rates using the latest digital subscriber line (DSL) technology, or optical fiber delivering services to a neighborhood optical-to-electrical (O-E) conversion cabinet beyond which shorter lengths of either dedicated twisted copper pairs carrying DSL (fiber to the node, or FTTN) or shared coaxial cable (hybrid fiber-coax, or HFC) complete the connection to the home. DSL was developed by the telephone industry in the 1980s building on the concepts of ISDN (Integrated Services Digital Network) augmented by digital signal processing for overcoming wireline impairments. Most DSL is asymmetric in bit rate, with the higher rate downstream toward the customer and bit rates set by many factors: the specific type of DSL employed, the length of copper wire over which service is delivered, and limits imposed by the service provider for marketing or technical reasons. The highest-speed version of DSL (very-high-speed DSL 2nd Generation, labeled VDSL2, defined by the international standard ITU-T G.993.2) can attain 100 Mb/s symmetric transmission over about 500 m and reduced rates over longer distances.

HFC was developed about the same time by the cable-television (CaTV) industry to leverage the low loss of fiber for reducing the number of series-connected amplifiers in a traditional tree-and-branch coaxial-cable subscriber network. A typical system today delivers 750 MHz shared among about 500 customers per O-E node.

Both DSL and HFC have gone through several phases of evolution, including standardization, and typically deliver up to 25 Mb/s downstream to each customer and lower rates in the return (upstream) direction. HFC systems are on the verge of new enhancements that can increase speeds in both directions to > 100 Mb/s by bonding multiple channels in both the downstream and upstream directions. For example, the ~ 40 Mb/s payloads of four separate 6 MHz channels each carrying 256-QAM (quadrature amplitude modulated) digital signals can be logically combined via bonding to deliver ~ 160 Mb/s aggregate downstream bandwidth.

End-to-end fiber, however, can easily meet such performance levels, on a per-customer basis, while still offering the capability to evolve in the future to far higher speeds without fundamental changes. This "future proof" characteristic of FTTH, as well as the many other advantages of fiber technology, have been widely recognized since the concept was first promoted over 30 years ago. During the early years after low-loss fiber and continuously operable room-temperature semiconductor lasers were first demonstrated (both in 1970), lightwave-based systems were proposed and prototyped for nearly every telecom and datacom application which was previously the domain of copper or microwaves: short data links, intra- and inter-building video links, cable-television trunks and feeders, satellite entrance links, short- and long-haul telephone trunks, transoceanic submarine cables, and FTTH. Yet all but FTTH became experiments followed quickly by field-trials, then products which subsequently went through several generations of performance enhancements and cost reductions. Furthermore, all except FTTH have become nearly

Manuscript received January 31, 2008; revised March 12, 2008.

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Digital Object Identifier 10.1109/JLT.2008.923601

[1]According to an October 2007 study by the Fiber to the Home Council and the Telecommunications Industry Association [2], the most recent annual growth rate for FTTH connections in the United States was 112%, September 2006 to September 2007.

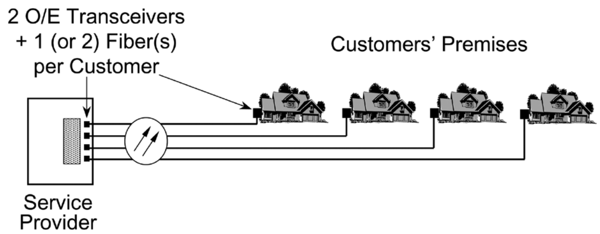

Fig. 1. Point-to-point FTTH, using dedicated O-E interfaces both at the service provider's and each customer's premises.

ubiquitous, replacing the copper-/microwave-/satellite-based networks that preceded them. What has made the road to FTTH so bumpy, and what recent developments are responsible for its recent successes?

II. Early Trials and Issues

Indeed, FTTH was first installed in a trial for 168 customers in 1977 in Higashi-Ikoma near Nara, Japan, [3] delivering interactive video services for purposes such as education and community-oriented services, video-on-demand programming, and security and telecommunications services. During the early to mid-1980s, numerous other trials were spread out across Europe (notably Biarritz, France [4], Milton-Keynes in England [5], and BIGFON in Berlin [6]), North America (notably Elie, Manatoba in Canada [7]), Japan [8] and elsewhere [9], [10]. All were technical successes, and, by the late 1980s, several of the leading telephone carriers were poised to begin adding FTTH to their network evolution plans. But several problematic areas left doubt in many people's minds, mostly those responsible for financial decisions at a time when the future of telephone service as a regulated utility was in serious question. Specifically, these issues were high costs; electrical powering; uncertain service demands (and the associated costs and revenues for these services); competing technologies that were becoming available; what to do with the old copper network already in place; and a number of regulatory issues, particularly in the United States.

By far, the biggest issue was cost. FTTH trials were very successful technically, but at per-subscriber costs far higher than any previous trial or existing service. Whereas the goal for residential telephone service was commonly quoted as U.S. \$1000 per subscriber and as low as about U.S. \$600 [11], [12] for cable-TV service, costs for the early FTTH trials ranged from many thousands of U.S. dollars (at best) to as high as the order of U.S. \$100 000. This was partly due to the high cost of the new technologies at the time combined with prototypical quantities, and partly due to the fact that each home had a simple point-to-point (P2P) connection to the service provider, requiring one or possibly two dedicated fibers, each with two dedicated optical transceivers, as in Fig. 1. The shaded box behind the O-E transceivers indicates whatever backend circuitry is needed to multiplex the transmitted data or retime and demultiplex the received data.

In contrast, in other applications at the time, the cost of the fiber (with appropriate O-E interfaces) was shared across multiple customers, possibly even hundreds. Also, lightwave technology had not yet established itself as one that would be characterized by a strong learning curve, following a predictable path to much lower manufacturing costs as production quantities rose. Finally, switched video services were fundamental to the service mix envisioned at the time, yet analog video transmission was marginal and expensive, and digital video was very expensive. (DVDs remained a decade or more in the future.)

Another roadblock was electrical powering. In many places, particularly the United States, the assurance of reliable, uninterruptible electrical powering of the home interface was a fairly important issue, one with no good solution on the horizon.[2] Cellular service as a possible backup was not yet common, consumer-grade uninterruptible power supplies (UPSs) were not yet being manufactured, and there were many questions—mostly cost, maintenance, and environmental—concerning the use of batteries supplied by the service provider.

As big a question as costs (on one side of the ledger) was what services customers really wanted and would pay for (on the other side of the ledger). A business case was difficult to develop without monthly revenues larger than what was easy to imagine at the time. Today's Web-based services and HDTV were barely on the horizon. Possible operational cost savings attributable to FTTH systems, now commonly recognized, were just being assessed.

Adding uncertainty to deciding how to proceed was the appearance of several capable broadband platforms, each of which was claimed by its promoters to be the least expensive yet still provide more-than-adequate bandwidth for new services. These included HFC, DSL, fixed wireless, and several versions of fiber to the curb (FTTC). The 1990s saw several companies test one, and then abandon it for another, none of which involved FTTH.

At the time major telephone companies in the United States were deciding whether or not to begin implementing FTTH, their undepreciated investment in their copper local-distribution networks exceeded \$40B, [13], [14] the depreciation of which is a large source of construction funds for replacing the old copper. The Federal Communications Commission prescribed a 27-year depreciation for this copper, the longest (and therefore lowest depreciation rate) of all countries considering building broadband networks. During the 1990s, most of the large companies received permission from regulators to accelerate this depreciation, so by the late 1990s, 27 years had been reduced to an average of 13. Some companies eventually wrote off their old copper. Nevertheless, these negotiations and decisions added to the delay in getting started.

There were also complex regulatory issues which stood in the way. These were related to whether and at what price telephone companies would be required to lease bandwidth in their new broadband networks to competitors, under what conditions telephone companies could obtain local franchises to deliver video, and whether Internet access should be treated as a telecommunications service subject to telephony regulation or a data service. These will not be addressed further, but suffice it to say that these were largely resolved, at least from the perspective in the United States [15].

III. Cost Reduction

While high costs impeded direct replacement of the copper subscriber network with fiber, many visionaries recognized the

[2]It was widely believed to be a "requirement" rather than an "objective" (as it was) to provide telephone service—one of those services always considered to be part of the FTTH service suite—with 99.99% ("four nines") availability, so-called "lifeline" service.

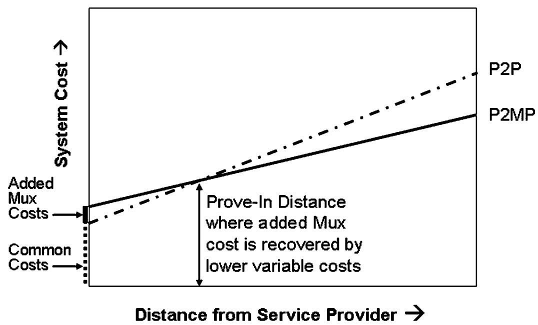

Fig. 2. The cost of a multiplexed point-to-multipoint digital-loop-carrier system versus a point-to-point system as a function of distance to the customer. Beyond a prove-in distance, savings are attributable to the lower cost of the smaller, shared cable.

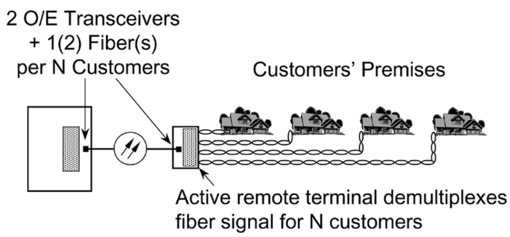

Fig. 3. Point-to-multipoint FTTC system with an an active remote unit located close to 4 to 16 homes, typically.

importance of at least installing fiber as far possible toward residences as soon as possible.

The telephone industry first accomplished this by modifying "digital loop carrier" (DLC), so that fiber replaced metallic feeder cable to remote multiplexer cabinets in new installations. In this point-to-multipoint (P2MP) system, telephone circuits for 96 customers are multiplexed at the telephone central office (CO) and demultiplexed at the remote terminal for subsequent delivery to the customer over regular twisted copper pairs for up to 12 000 ft ($\sim$ 3.7 km) [16], [17]. The added cost of multiplexing and O-E equipment was paid back beyond a prove-in distance by reducing the number (and variable cost) of cables between the CO and the neighborhood cabinet, as seen in Fig. 2.

Since most new growth (and new telephone lines) occurs at the perimeters of communities, such systems usually met their cost objective quickly. As the costs dropped, the prove-in distance became shorter until it was soon comparable with the lengths served by the derived copper lines. One can see how these DLC systems were the forerunner of today's FTTN broadband systems. The key differences are the use of much higher bit rates on the feeder delivering services to the node and the use of advanced versions of DSL driving shorter lengths of copper cable, from $\leq$ 1000 to $\leq$ 5000 ft depending on the bit rate desired, to deliver the services to the customer.

The next step in moving fiber closer to the customer was "fiber to the curb," where a smaller, powered, curbside cabinet demultiplexed the fiber feeder signal and served fewer homes, usually 4–16 such as in Fig. 3.

Because high bandwidth could readily be moved close to the subscriber, it was easy to provide ISDN data service if the customer needed it. Later systems were upgraded to DSL for higher speeds over the copper. And some products also added HFC-like overlays using a separate feeder fiber to deliver video services to the curbside unit, beyond which short lengths ($<$ 500 ft or $\sim$ 150 m) of coax were placed alongside the telephone twisted pairs to reach the customer. FTTC first proved in for new construction in the early 1990s, then for rehabilitation of existing lines about 2000.

Meanwhile, progress was continuing on technologies key to FTTH, accelerating the next stages toward its commercial realization. For example, work was first done to substitute inexpensive light-emitting diodes for expensive lasers (at that time) and using single-mode fiber [18]–[20]. Extremely low-cost 780-nm lasers had been developed for compact disc players, and their packaging and alignment optics provided guidance for early low-cost 1300-nm "loop lasers" [21]. Subsequently, R&D was carried out on loop lasers which could achieve $<$ U.S. \$50 prices, and also be highly reliable and stable over a wide range of temperatures [22]–[25]. Also in the mid-1990s, development was underway on MPEG-2 digital video chips capable of decompressing both high-quality video and Dolby Digital audio for the DVD players about to be introduced. Previously, compressed high-quality video was usually transmitted at 45 Mb/s, but now inexpensive 10-Mb/s video was appearing which could easily be adapted to FTTH. The growing consumer market for reliable sealed-lead-acid batteries for uninterruptible power supplies for personal computers and home security systems led to lower costs and more user-friendly replacements. Finally, as production volumes rose sharply, single-mode fiber was establishing an aggressive learning curve, about the same as VLSI (very-large-scale integration) semiconductor chips which became remarkably inexpensive at mass-market volumes.[3]

But one of the major steps toward reducing costs was to redesign the network to move from a dedicated P2P architecture requiring two transmitters, two receivers, and one (or possibly two) dedicated fibers for each customer to a P2MP network like FTTC capable of sharing fibers and key components.

A. *Passive Optical Networks*

It was recognized in the 1980s that, because of the ease of splitting and combining optical signals using small, passive optical multiport devices, it would be possible to achieve the cost-sharing $1 \rightarrow N$ topology such as fiber-to-the-cabinet (or curb) passively. This is highly desirable because it:

- Eliminates the need for active optoelectronic and electronic devices located in a cabinet in the harsh outside environment.
- Eliminates the need for power-conversion equipment and backup batteries in the same location and environment.
- Eliminates possible hazards as might exist with high-energy-density standby batteries.
- Eliminates the possibility of noise from power converters, or from backup generators that might be required during extended power outages.
- Eliminates issues of electromagnetic interference (EMI) or electromagnetic compatibility (EMC), or hazards that might be related to copper conductors.

[3]Optical fiber's Learning Curve rate was about 75%, comparable with the historical rate of 74% demonstrated by calculator chips and close to 68% for DRAM chips. This percentage is defined as the fraction C_2/C_1 of the production cost C_1 at cumulative volume V_1 to which a product falls when the cumulative production volume doubles, to $V_2 = 2V_1$. For example, see [26].

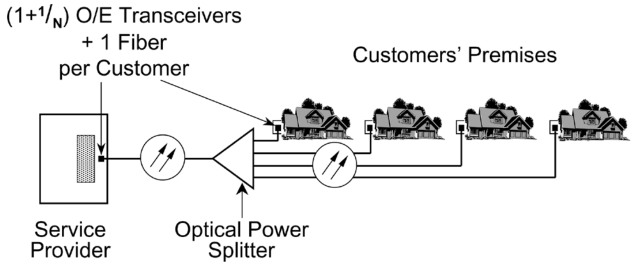

Fig. 4. Point-to-multipoint passive optical network.

- Eliminates the ongoing utility costs associated with the power consumption of an active interface, which can become substantial.
- Eliminates the need for any type of environmental control which might otherwise be needed.

Furthermore:

- Elimination of the powered O-E and associated equipment significantly reduces the failure rate of the node and associated repair costs.
- No bandwidth-dependent technology is inserted at the branch point in the fiber path, substantially increasing the options for future upgrades.

In a simple power-splitting passive optical network (PON), traffic for the N customers is electrically multiplexed and optically transmitted from a single laser over a single fiber to a remote $1 \rightarrow N$ power splitter, as in Fig. 4. Note that a single O-E transceiver at the service provider is shared by N subscribers. In the earliest PONs reported, the synchronous transfer mode (STM), the asynchronous transfer mode (ATM), and subcarrier frequency-division multiplexing (subcarrier FDM or SCM) were all demonstrated for multiplexing subscriber traffic [27]–[29].

At the power splitter, commonly a planar lightwave circuit (PLC), downstream light is equally divided among its N tributaries and upstream light is combined, both experiencing an attenuation equal to 10logN (plus excess losses). Each customer, receiving the same multiplexed signal, processes framing and/or header information after detection to select only that customer's intended traffic (i.e., a broadcast-and-select network). Security techniques in the downstream protocol such as encryption prevent eavesdropping on signals intended for other customers.[4]

One should keep in mind that the total downstream bandwidth is also shared. The service provider can choose to allocate the total bandwidth equally across all N tributaries (or even less for a lower price), or to manage the bandwidth in ways that can permanently assign different rates to some customers or temporarily allow higher rates. A related issue is that, in order to upgrade the PON sometime in the future to a higher bit rate, all of the customers' O-E interfaces must be changed at the same time.

The upstream direction is much more interesting. First is the question of whether to reuse the downstream fiber (single-fiber or 1-F solution) or simply install a second, parallel fiber network (two-fiber or 2-F solution) [31]. This was debated for several years even for the P2P FTTH networks. The technical simplicity of the 2-F solution is appealing, but there are added costs of the extra fiber and extra fiber appearances at the service-provider terminations, the higher maintenance costs of a two-fiber path to each customer, and extra testing expenses to assure the two fibers are always connected properly.

Bidirectional sharing of a single fiber can be accomplished in many ways [32]. Methods that use nominally the same wavelength in both directions include the insertion of directionally sensitive devices (couplers, circulators) at each end, or the use of different noninterfering modulation formats in the two directions, or even half-duplex signaling including time-compression multiplexing. Probably the most straightforward approach, however, is simply to use different wavelengths for downstream and upstream communication plus an inexpensive wavelength-division-multiplexing device at each end. As the costs of long-wavelength lasers and detectors for both the 1.3- and 1.5-μm low-loss windows fell, the usual 1-F approach became the use of 1.5 μm downstream and 1.3 μm upstream. Single-fiber wavelength-division-multiplexed (WDM) solutions have prevailed leading to the development of inexpensive, stable, reliable, low-loss/low-reflection 1.3/1.5-μm diplexers integrated with optical transceivers, and more recently, triplexers to allow a second downstream wavelength in the 1.5-μm window (to be discussed below).

The second upstream question is unique to PONs in, being a multiaccess network, how to deal with collisions. Since passively combining optical signals provides no capabilities for buffering and retiming, signals from different tributaries can experience collisions. Therefore, a multiaccess protocol is required to prevent collisions (most desirable) or mediate their effects (e.g., retransmission, not as desirable).

The two types of PONs that have changed the landscape and led to the recent growth in FTTH are designs which emerged from two important activities; the Full Service Access Network (FSAN) initiative and the Ethernet in the First Mile (EFM) initiative.

B. Full-Service-Access-Network Initiative

Recognizing that products sharing a common design available from multiple suppliers and acceptable to several large network providers would lead to large production volumes, thus cost reductions, seven major telecom providers from Europe and Japan began meeting with ten international manufacturers in June 1995. Their objective was to agree on a common broadband platform that each provider could use to deliver a wide range of voice, video and data services. Prior to this, there had been a number of manufacturer-specific products developed without standardization, which had hindered the decision-making process. The first public forum describing this effort was held in June 1996, following which other service providers and suppliers joined this effort toward what might lead to FTTH standards. Eventually, the number of service providers participating in FSAN rose to 15 and the number of suppliers to 36, and they currently remain active on advanced topics.[5] Following committee-level meetings on various facets of the design where needs, expectations, and manufacturing

[4]Normally, encryption is used only for the downstream signal. It was recently demonstrated, however, that even weak reflections of upstream optical signals within the passive splitter (now a combiner) can occur and be transmitted back downstream to all customers [30].

[5]See http://www.fsanweb.org.

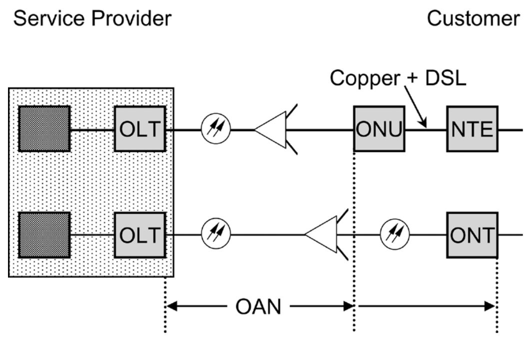

Fig. 5. FSAN APON nomenclature for termination of the optical access network away from the customer, to be completed with copper twisted-pair carrying DSL (upper) and for termination at the customer's premises (FTTH) (lower).

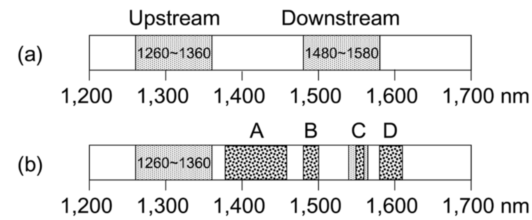

Fig. 6. Original spectrum allocation for APON (a) and subsequent allocation for BPON providing wavelengths for enhancements and other future uses (b).

capabilities are discussed, a design emerged which defined standard nomenclature and wavelengths, used ATM to multiplex downstream and upstream traffic, defined a protocol to prevent collisions arising from passive multiplexing, etc. ATM-based PONs, or APONs, took advantage of ATMs short, fixed-length (53-byte) packet format agreed to within the telecommunications industry in the late 1980s for accommodating video and data as flexibly as traditional voice traffic. FSAN also dealt with cost issues by carefully roadmapping the technologies to understand how the latter would need to evolve. Critical costs still needed to fall by 5X or more as volumes rose from prototypical quantities to full production quantities (annual production ~ 1 M units) [33], [34].

A word about FSAN nomenclature, which is now common for most PONs (see Fig. 5): The service provider's interface between the backbone network and a PON is called an OLT, or Optical Line Termination. Equipment behind the OLT (dark boxes in the figure) can include switches, servers, and routers connecting to the core network.)

For fiber-to-the-cabinet or fiber-to-the-curb, the remote unit is called an ONU, or Optical Network Unit, as indicated in the top of Fig. 5. The termination of the DSL copper pair from the ONU to the residence is called the NTE, or Network Termination Equipment (end or edge of the network, as it were) which also provides some protection functions, for example from transients and other electrical faults that copper might conduct to customer's premises. When the fiber terminates at the premises (FTTH), as in the lower part of the figure, the active unit at the home is called an ONT, or Optical Network Termination (again, the end or edge of the network). The all-optical portion of the network is the OAN, or Optical Access Network.

The results of the FSAN activities (specifically, the Optical Access Networks Group of FSAN) are submitted to appropriate standards bodies for consideration, usually ITU, the International Telecommunication Union. Previous submissions for PONs have subsequently become ITU-T G.983.x and 984.x international standards.

The G.983 standards describe an APON which utilizes ATM for multiplexing digital traffic but also sets aside a wavelength region for adding conventional broadcast video signals. The broadcast overlay is subcarrier multiplexed and, therefore, can deliver either analog (NTSC, PAL, or SECAM) or digital (e.g., n-QAM or n-VSB) video. Some parameters include:

- $1 \rightarrow N$ PON ($N = 16$ or 32) applicable with:
  - — Fiber to the Home (or Business)
  - — Fiber to the Curb (or Business) utilizing DSL for the final connections
  - — Fiber to the Cabinet utilizing DSL for the final connections
  - — Fiber to the Exchange (essentially a feeder for multiple, small service-provider facilities much larger than a cabinet).
- Maximum of 20 km of standard single-mode fiber (ITU-T G.652).
- Downstream/upstream bit rates of 155/155 Mb/s or 622/155 Mb/s, shared among the N customers.
- 1.5 μm downstream and 1.3 μm upstream using a single fiber. (Subsequently enhanced—see BPON below.)
- Three classes (A, B, and C) of optical path losses (20, 25, and 30 dB max.) associated with corresponding transmitter optical power levels and receiver sensitivities. This allows cost optimization for more- or less-demanding applications; e.g., installations with less splitting and/or shorter fiber paths (Class A) have specifications for lower-power transmitters and less-sensitive receivers to reduce costs.
- ATM signaling both down and upstream using a unique FSAN frame structure [35].
- A "ranging" protocol to determine the total length of each customer's optical path through the splitter so that precise timing could be established to prevent upstream collisions.
- Since the PON is a multicast network, privacy and security are assured by "churning" each customer's switched traffic in accordance with a frequently updated user-generated key sent back to the service provider.
- Other protocol details to allocate bandwidth according to need, discover new terminations as they are added, etc.

An early enhancement was to reserve wavelengths from 1550 to 1560 nm for adding an optional downstream signal to deliver broadcast video. It is, of course, the same band that the CaTV industry uses to transport subcarrier-multiplexed video because 1550 nm is easily amplified using erbium-doped fiber amplifiers, and the SCM signals, once detected, are compatible with ordinary set-top boxes and tuners. This wavelength option and others were defined in ITU-T G.983.3. Fig. 6(a) shows the original spectral allocations, and Fig. 6(b) the enhancements. In Fig. 6(b), band C can be allocated for the video-distribution option (1550–1560 nm) or other downstream digital service (1539–1565 nm) including dense wavelength-division-multiplexed (DWDM) services based on the ITU grid frequencies as specified in ITU-T G.959.1. Band B, used for regular ATM downstream transmission, was reduced to 1480–1500 nm, and two other new bands A (approximately 1380–1460 nm plus guard bands) and D (within the conventional optical transmission L or "long" band from 1570–1610 nm) were reserved for future use. To emphasize that these new capabilities exceeded those of a simple APON, FSAN redesignated it as a "Broadband PON" or BPON.

There was significant interest within the group in moving to higher speeds and also incorporating Ethernet, particularly Gigabit Ethernet. A second set of proposals resulted in ITU standards G.984.x. These Gigabit PON (GPON) standards build on the set of G.983.x and add new capabilities, some of which are:

- Extensions of splitting ratios to 1:64 and 1:128.
- Extensions to 2.488 Gb/s in both directions.
- Extended logical reach of 60 km
- Higher privacy and security through use of the Advanced Encryption Standard (AES) algorithm.
- A bandwidth-efficient new GPON Transmission Convergence 125-μs frame structure at Layer 2 within which ATM cells and new GPON Encapsulation Method (GEM) frames can both be combined. Then, within the GEM frames, synchronous telephony services (T1/E1 and DS-0) and data services such as Ethernet can be efficiently multiplexed [36], [37].

Both BPON and GPON systems are currently being installed by numerous operators.

C. Ethernet-in-the-First-Mile Initiative

Ethernet, the variable-length packet-transport technology introduced in the early 1980s and now fundamental to data communications and local-area networks, is the network from which nearly all Internet traffic originates [38]. Thus, as data traffic has become as significant as voice traffic on backbone networks, Ethernet has become competitive with synchronous STM and ATM transmission formats. Equally important, Ethernet has established a remarkable track record for continual price reductions with time and with each new generation of Ethernet, usually characterized as being 10X faster than the preceding generation. It is also ubiquitous in home computer networks and is the networking interface now built into all personal computers (PCs). As a result, there is great interest in using Ethernet for local access between homes and service providers. Analogous to the FSAN effort, the EFM group met in November 2000 and subsequently became a task force of the IEEE 802.3 (Ethernet) standards committee, IEEE 802.3ah. Over 200 delegates from about 80 companies participated.

Working similarly as FSAN, the EFM group developed a new access network offering several topologies for transporting Ethernet. A ranging protocol was defined that works much like FSAN ranging, determining the path length to each network termination so that passive multiplexing of the upstream signals can be achieved without collisions. These proposals were incorporated into a standard, IEEE 802.3ah—2004, which included a PON FTTH solution as well as networks utilizing P2P fiber and copper.

The group adopted nomenclature similar to that used in ITU-T G.983.1 to help avoid confusion, and were guided by some of the FSAN decisions regarding fiber, fiber lengths, wavelengths, and splitting. Some of the key parameters include:

- $1 \rightarrow N$ PON ($N \geq 16$) principally for use with Fiber to the Home (or Business).
- Point-to-point fiber.
- Point-to-multipoint fiber.
- Point-to-point DSL.
- Length ≥ 10 km of standard single-mode fiber (ITU-T G.652) at 1.25 Gb/s.
- Downstream/upstream: 1 Gb/s Gigabit Ethernet interface,[6] shared among the N customers.
- 1490 nm downstream and 1310 nm upstream, with wavelength ranges the same as ITU-T G.983.3.
- Bit-error-rate $\leq 10^{-12}$ with forward error correction optional.
- Ethernet frame structure in both directions, with modified headers.
- GATE-REPORT full-duplex protocol with ranging to establish timing.
- Other protocol details to discover and authenticate new terminations as they are added.
- No specified security but allowance for; e.g., encryption, to be a supplier-added feature.

Ethernet-based PONs (EPONs or GEPONs as they are also called since most utilize Gigabit Ethernet) are currently being installed worldwide, and are especially favored in Asia.

D. Further Comments on Power-Splitting PONs

For power-splitting PONs, there are two additional advantages not yet mentioned—one related to traffic management and one to topological flexibility. In the emerging market for broadband, there is a wide range of bandwidth usage among different customers, by type of household and services, and by time of day. There are also uncertainties related to churn. The ability to reassign bandwidth dynamically in a shared network like a PON is an advantage here. Through dynamic bandwidth assignment (DBA), one customer can be temporarily granted greater bandwidth than average if other customers on the network are utilizing less than average. Furthermore, since traffic, especially Web-browsing traffic, is often bursty, some of the multiplexed channels can operate with higher apparent bandwidth than the shared bit rate would suggest by using statistical multiplexing. Here a shared channel is divided into variable bit-rate channels which adapt to the instantaneous needs of the customers [39]. Improvements in bandwidth utilization by factors of 4X to 6X are commonly observed, and greater improvements are seen when Web browsing predominates.

The other advantage is a PON's topological flexibility, in that splitters can be placed anywhere along the optical path. For example, in a rural area, a $1 \rightarrow N$ splitter can be located far from the OLT near a cluster of homes, so the shared path is longer for lower fiber cost, a "fiber-lean" configuration. A $1 \rightarrow 16$ example is shown in Fig. 7(a).

Alternatively, in an urban area where distances to customers are generally short, the single $1 \rightarrow 16$ splitter can be located at the OLT so that all fiber paths are P2P, a "fiber-rich" configuration, as in Fig. 7(b). Although we have sacrificed the fiber-

[6]Note that the transmission line rate of Gigabit Ethernet is 1.25 Gb/s, also referred to above. This arises from the 8b/10b coding (a 10-bit symbol encodes 8 bits of data) that is used with NRZ signaling to maintain DC balance at the receiver and decision circuit.

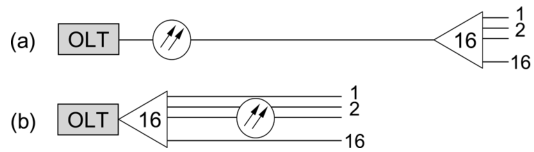

Fig. 7. Splitter location at two extremes of distance from the Optical Line Termination: Far from the OLT resulting in maximum fiber sharing (a) and close to or at the OLT for minimum fiber sharing resulting in a fiber-rich network (b). Customers (not shown) would be located at the numbered ends of the fibers.

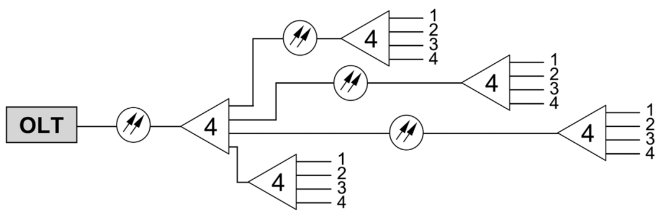

Fig. 8. Multiple smaller splitters are used instead of one to achieve topological flexibility in reaching customers (not shown).

sharing advantage of a PON, there are other benefits. First, there is still only one O-E interface at the OLT rather than 16. Second, upgrades of individual customers are now simplified if a few need P2P FTTH, for example. A fiber need only be moved from a splitter port to a nearby dedicated transceiver. Third, the bandwidth-management features of a PON remain available.

Finally, a $1 \rightarrow N$ (e.g., $1 \rightarrow 16$ here) splitter can be configured from multiple splitters (e.g., four $1 \rightarrow 4$ splitters here, all fed by a fifth $1 \rightarrow 4$ splitter). The four splitters connected to customers can be located at various distances and directions from the fifth splitter to map into clusters of homes as in Fig. 8, resulting in shorter tributary fiber lengths. This arrangement, and another consisting of four $1 \rightarrow 8$ splitters constituting a $1 \rightarrow 32$ PON, are actually common implementations. Other combinations of splitters are possible.

E. Wavelength-Multiplexed PONs

Another important PON can be constructed using N discrete wavelengths to serve N customers, still sharing a single fiber to a splitting point as in the basic power-splitting PON of Fig. 4. At the splitting point, however, each customer's wavelength is separated at a WDM device instead of a power splitter. This can be done for a few wavelengths (e.g., four) using low-cost coarse WDM (CWDM) technologies, or for many wavelengths (e.g., 16–32) using more-expensive DWDM.

For DWDM, the key challenge has been the high costs of dedicated single-wavelength light sources at the OLT and ONT, with the added inventory issue of many wavelength-specific light sources for field servicing of the ONTs. There are also issues of cost and temperature stability of DWDM devices of which two are generally necessary: one at the usual splitter location and one at the OLT. Much innovative R&D has been done over the past 15 years to minimize the cost issues in order to take advantage of several important advantages of WDM-PONs, which include:

- *Bandwidth* A WDM-PON provides a dedicated channel to each subscriber, allowing almost any realistic bit rate or signaling format to be used, now or as a later upgrade.
- *Security* Dedicated downstream and upstream channels eliminate security issues, again simplifying the protocol.
- *Protocol* Dedicated downstream and upstream channels eliminate the need for a collision-avoidance protocol.
- *Power Budget* The 10 logN term in the power budget is replaced by the few dB of the WDM devices, increasing the budget by approximately 9–12 dB for 16–32 customers.
- *Growth* Now or in the future, an N-channel WDM-PON can be expanded to NXM customers by installing an M-channel PON on each tributary. This can also be applied to less than all N tributaries.

Most research has focused on eliminating or minimizing the need for wavelength-specific light sources, ranging from the use of spectrally sliced superluminescent LEDs [40], [41] to injection-locked devices [42], [43] to the simple amplification and reuse of the incoming light (optical loopback) [44]. The latest successes in making "colorless ONUs" utilize reflective semiconductor optical amplifiers (RSOAs) at the ONT [45]–[47]. Further discussion of these techniques and other topics such as temperature-stable array-waveguide (AWG) devices for the passive devices is beyond the scope of this paper, so the reader is referred to excellent review articles [48]–[50].

The current situation with WDM-PONs is that significant cost-reducing advances have been made so that products are becoming available in response to growing interest, and trials are underway. The greatest interest presently seems to be in Korea but other service providers acknowledge they are following the developments with interest and see WDM-PONs as a likely next-generation PON.

What bears watching closely with WDM-PONs is, since they are very close to a P2P FTTH system except for the shared fiber between the OLT and DWDM device, what are the tradeoffs or disadvantages of simply installing a P2P system to avoid the added DWDM costs?

F. P2P and Other FTTH

Point-to-multipoint PON architectures have achieved wide attention partly due to the 20–35% capital-expense reductions often cited [51] due to fiber and OLT sharing, and to the promise of low-maintenance passive outside plant. However, there is growing interest in P2P FTTH solutions, and P2MP FTTH systems which either employ O-E-O conversion partway to the customers ("Active Ethernet") or use subcarrier modulation (RFoG, or "radio frequency over glass").

The EFM Initiative supports P2P FTTH, as does the FTTH Council, particularly for multidwelling units (MDUs) such as apartment buildings, and small-office/home-office (SOHO) applications. In these cases, because of the physical collocation of multiple customers in apartments and small offices, there is the immediate opportunity for aggregation (and thus cost sharing) of these customers' traffic at an Ethernet switch located on the premises. The switch serves each separate customer within the building via CAT5 or CAT5e inside wiring. Such an MDU and small-office application are shown in Fig. 9, in addition to FTTH for a data-intensive home-office customer.

In an MDU or small office, the ONT would be located in some common area such as a basement or data closet. Several immediate benefits can be identified:

- The outside network remains passive.

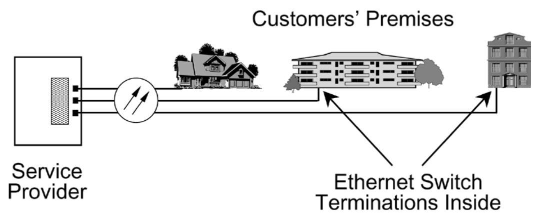

Fig. 9. Point-to-point FTTH/FTTP application where equipment and fiber sharing are accomplished using Ethernet switches which aggregate traffic at apartment and small-office buildings. This is also often designated FTTB (Building).

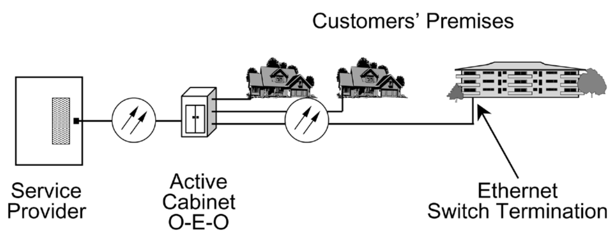

Fig. 10. Point-to-multipoint Active Ethernet. The active cabinet contains an Ethernet switch to select downstream traffic for each customer or group of customers, and aggregate upstream traffic. On the customer-side of the cabinet, signals are converted via optical transceivers for transmission over fiber to each customer premises.

- Since $1 \rightarrow N$ sharing occurs separately from the optical path, the optical power budget is unaffected by the number of customers, thus the range can be greater in the absence of the 10logN splitter loss, or independent of splitter location.
- There is no need for a ranging protocol.
- The switch buffers each customer's traffic, so each customer experiences a full-rate interface (usually 100 Mb/s or 1 Gb/s) and improved throughput, in the same sense as with an Ethernet switched local area network (LAN).
- Security issues are minimized since the switch allows only the traffic destined for each customer to be sent over the assigned inside wiring.
- Upgrades are easier, because they can be done on a switch-by-switch basis.

Even without this MDU/SOHO consideration, a case can be made for P2P FTTH in densely populated areas located relatively close to the service provider. Here, the fiber portion of the total cost may be small, and continues to decrease with time so that later build-outs will cost even less. Such an up-front investment looks attractive because of the added flexibility for future upgrades as well as the maturity of the technology [52].

Fiber-to-the-cabinet or fiber-to-the-node usually denotes service beyond the cabinet or node which is delivered by copper or coaxial cable, However, a new product is becoming established which delivers FTTH (or FTTP) via a P2MP topology but over an active outside-plant network. For some but not necessarily all of the P2P Ethernet-bearing fibers of Fig. 9, active cabinets are added containing Ethernet switches to aggregate traffic from several homes or buildings, as in Fig. 10.

All the advantages just mentioned still apply except the first—the outside network associated with these fibers is no longer passive. As described by their manufacturers, however, such products are assumed to be installed along with P2P customers so that the total number of active cabinets to be powered and maintained is minimized. So-called "Active Ethernet" systems are available from several suppliers, and a vigorous debate is underway regarding comparisons with both GPONs and EPONs.

The third system, RFoG, is a P2MP PON system which is related to HFC. RFoG extends the same optical signals used in a hybrid fiber-coax system to the customers' premises. As mentioned briefly in the Introduction, HFC is one of the major network architectures delivering broadband services to homes today, particularly in the United States [53], [54].

In HFC, single-mode fibers transport downstream video and downstream and upstream data between a CaTV headend (or distribution hub) and a remote node located close to customers. At HFC remote nodes the downstream optical signal, which is subcarrier-modulated with a lineup of many AM-VSB analog-video and QAM digital signals in 6-MHz subcarrier channels (in North America), is converted to an electrical signal, amplified, and delivered to customers via a tapped coaxial-cable feeder network. Upstream data from customers is returned using QAM or QPSK (quadrature phase-shift keying) in the 5–42 MHz frequency band of the feeder cable. At the node, this is combined with upstream signals from other coaxial-cable tributaries the node may serve and transmitted optically back to the distribution hub or headend.

An RFoG system substitutes a passive optical splitter for the active electronics at the node and continues with an optical signal to each customer. The customer termination performs the $O \rightarrow E$ conversion as well as an $E \rightarrow O$ conversion of upstream data. Since the upstream signals are multiplexed onto unique subcarrier frequencies, there are no collisions to be prevented, thus no additional protocols are needed. The Society of Cable Television Engineers (SCTE) is beginning work to standardize RFoG, and pre-standard products are emerging.

G. Operations Cost Reductions

As discussed above, costs of the technologies required for FTTH have been falling continually as production volumes increase, both for FTTH or other transmission products. Costs of once-expensive components related to video, or batteries for standby power have fallen as volumes increased for other consumer applications. The PON architectures have helped greatly through their elimination of outside-plant powering equipment and their cost-sharing aspects, promising savings in capital expenses (CAPEX) over those of P2P networks. Such systems have been noted as having installed costs as low as about U.S. \$1350 per subscriber [15], [55], but this is strongly a function of where and how the system is installed. Nevertheless, it has been recognized that costs approaching these values have been reached by various network providers.[7]

[7]The lowest costs cited often assume all homes to which the service could be available (i.e., passed by the fiber feeder) are also customers, and reflect the expenses associated with buying and installing the technology. In many cases, however, some homes remain under construction, or are constructed but not yet occupied, or are customers of a competing service provider, or do not want the service—none of which is technology-related. In these cases, the "take rate" is not 100% and the "cost/subscriber" is higher, equal to the cost/home-passed divided by the take rate + the cost to connect a subscriber. The effect of take rate on FTTH cost and profitability has been examined [56], and current take rates for different FTTH service providers and changes with time have been presented [2].

In addition to CAPEX, ongoing expenses of operating these systems (OPEX) are equally important. Obviously, the elimination of the 24-7 cost of utility-provided power is one of several ongoing operational expenses that can play a role in a business case, especially when considered over several years. There are many other on-going expenses related to supervision and testing, maintenance, service changes, etc. which is called OAM&P (operations, administration, maintenance and provisioning) expenses [57], [58]. The annual OAM&P expenses can be several hundred U.S. dollars per-line (which varies widely by service provider and location). When considered over a period of years during which the system is in-service, maintained, subjected to service and customer changes, and powered, the net of these expenses can be as significant as initial capital expenses. The analysis is performed using life-cycle costing and discounted cash-flow analysis.

It has been recognized for many years that large operations cost savings related to broadband delivery are possible through the use of fiber, especially PONs, and moving intelligence to the customer's premises [59]–[63]. Some examples of important savings include:

- *Remote Testing* utilizing test capabilities and network intelligence located at the premises, for more accurate isolation and analysis of problems. Savings of 25–30% versus the lack of this capability.
- *Accurate Dispatch* of maintenance personnel based on remote testing eliminates the need for second dispatches in some cases. Savings of 20–60%.
- *Service Activation* is simplified since no physical work is needed and often the customer can self-activate new services. Savings of 30–65%.
- *Disconnect/Reconnect* or customer churn is simplified, again because this requires no physical work. Savings of 35–50%.

These have been discussed in more detail in the references cited, and in more detail elsewhere. In a Bernstein-Telcordia study [64], the following operations savings are identified and described in detail for FTTH:

- *Customer Service Orders and Troubleshooting*: Savings of 48%.
- *Central Office Operations*: Savings of 87%.
- *Outside Plant Operations*: Savings of 81%.
- *Network Operations*: Savings of 31%.

This study also quantifies the annual OAM&P savings for three areas in the United States, the average of which is $151/yr. When considered in a life-cycle sense, over 10 years of service this discounts to about U.S. $1000 depending on the discount rate assumed, and slightly more if inflation is considered.

Not to be omitted are the electrical power savings. There is an analysis for estimating the life-cycle cost of power, including backup, floor space, environmental conditioning, and maintenance known as "capital worth of a watt" [65]. Based on this reference and updated for today's prices, inflation rates and a 10-year period, one watt of electrical power dissipated continuously for 10 years at a central office costs approximately $17. At a remote terminal such as a fiber node, this expense may increase approximately by a factor of 2X [66]. Therefore, if we assume VDSL2 serving homes directly from a central office is replaced by a PON and that 3.5W is saved [67], then the equivalent capital worth of this power is about $60. If the VDSL2 is delivered from a fiber node where the power is more expensive to provide, this rises to above $100. Obviously these expenses are 10% or less of the other operational savings over the same 10-year period, but nevertheless must be included in a business case for broadband.

It is worth noting the following interesting observation from the Yano Research Institute regarding the Japanese experience with FTTH: " …PON systems exhibited the most remarkable growth among various (Japanese)… markets due to their contribution in lowering the cost of service providers [68]."

IV. Services and Revenues

The services picture has changed through the years that FTTH has been considered for broadband access. Only 20 years ago, the key services for FTTH or for an advanced two-way cable TV system were thought to be cable TV (about 35 channels), basic telephone service, video telephony, and videotex. Videotex was a two-way, interactive, standardized, screen-based service for information retrieval or messaging. More-advanced services included enhanced telephone services (e.g., remote meter reading, home security, data services associated with ISDN) and other video applications (video on demand, home shopping, distance learning). Monthly revenues derived from these services were usually thought to be about U.S. $60, perhaps rising as high as U.S. $90 with the advanced aspects included and there was little or no experience at the time with residential voice, video, and data all being provided by the telephone company.

Today's services reflect the enormous progress in consumer electronics over the last 20 years, the emergence of Web-based services, and customers' demands for entertainment, interactivity, "social" networking, and—most recently for video—image size and quality. Looking ahead, then, we can see a network capable of delivering several simultaneous channels of video and digital music, Internet access at up to 20 or 30 Mb/s (especially desirable now that more than half of all Internet users report watching online video weekly [69]), and telephone service (with Voice Over Internet Protocol becoming common). Video service is usually marketed as delivering over 100 channels, or hundreds of channels, including digital tiers with surround sound, a lineup of high-definition TV channels, pay-per-view, time-shifting DVR (digital video recorder) features, etc. We have, of course, just described today's widely available "triple-play" offering with established monthly pricing of U.S. $100 on the low end to over U.S. $200 on the high end. Triple-play packages are successfully marketed and provided by both cable-television and telephone companies, both of which are now thought of as telecommunications companies. With the high-bandwidth Internet connection, it is easy to include essentially any of the advanced services once envisioned for FTTH. Home security (without cellular backup) remains an open issue at this time, however, because it is believed that the reliability of a Voice over Internet Protocol (VoIP) interface is not yet equal to a "landline" telephone connection.

V. Summary

Many roadblocks have been encountered slowing the progress toward FTTH since it was first proposed. Gradually, but especially since the mid 1990s, each of these barriers has been overcome. Highly versatile passive optical networks resulting from the FSAN and EFM initiatives have played a notable role in reducing both the initial capital expenses to build as well as the ongoing costs to operate FTTH.

Optoelectronic devices especially for access applications have been developed, and other lightwave technologies as well as fiber have continued to become less expensive as they have been produced in large quantities for other applications. As a result, the cost of FTTH has fallen sufficiently to make a compelling business case for its installation. In North America, there are about 10M homes passed by FTTH, although only about 2M lines (slightly more than 2% of homes) are in-service [2]. In Hong Kong, South Korea and Japan, however, FTTH serves approximately a ten-fold higher percentage of homes, moving it well into the mainstream [70], [71].

Interestingly, there are many entities other than large telephone service providers installing FTTH. Examples include utility companies (particularly in Europe), municipalities, independent local-exchange carriers, competitive carriers, and even real-estate developers. There is growing interest within the cable television industry as well.

Other positive developments include customer excitement over fiber and rising demand for FTTH. It has been observed that the presence of a FTTH connection can add value of U.S. $4000–15 000 to the selling price of a home [72].

Financial and regulatory issues have mostly been resolved during the last decade, and promised operational savings are now being realized. For example, Verizon, one of three regional telecommunications operators in the United States, reports that their FTTH installations have reduced outside-plant trouble reports by 80% [73].

It would appear that, as momentum builds, FTTH has begun an irreversible drive finally to replace copper pairs and coaxial cable for access to the emerging broadband network, enabling whatever new services are added to today's already-capable service menu.

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