THE PAST, PRESENT, AND FUTURE OF COPPER ACCESS

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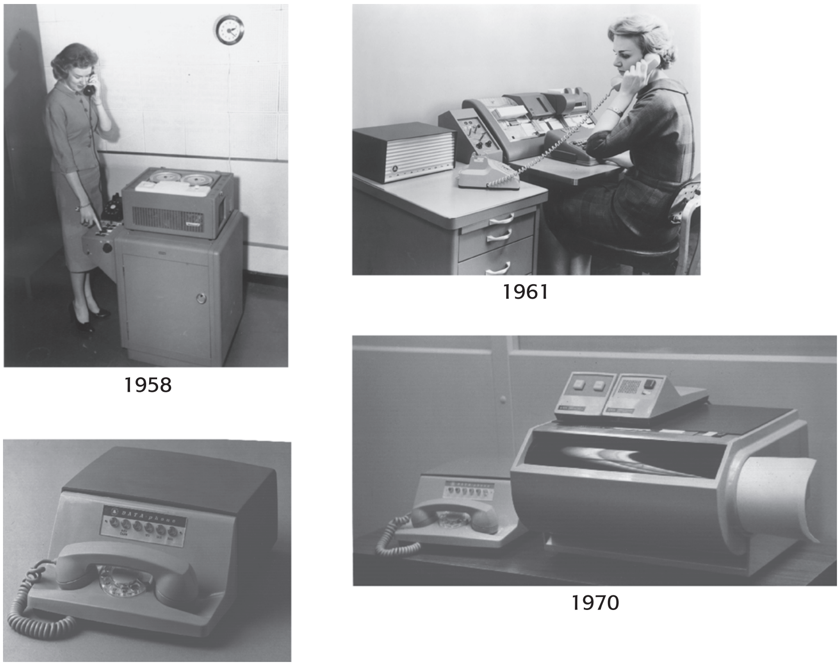
DIGITAL Subscriber Line technology has democratized broadband access, and over the past several decades, telecommunications providers have evolved from providing plain old telephone service (POTS) over a copper loop plant to providing broadband access and high-definition video over hybrid fiber-copper networks. After reviewing highlights of this evolution, this article focuses on three revolutionary copper technologies in different stages of development that will enable hybrid networks to continue to increase data rates over orders of magnitude for many years to come. The first of the three, vectoring, is a mature technology with massive ongoing rollout that provides end user speeds above 100 Mb/s across typical distances of 500 m. The second, G.fast, is the first ultrabroadband technology offering 1 Gb/s speeds, across typical distances of 100 m. It has recently gained approval in the standards bodies and is currently undergoing trials both in research labs and in the field by numerous telecom operators. Finally, we discuss Bell Labs' XG-FAST technology, now in proof of concept, which can deliver 10 Gb/s across a 30 meter copper drop cable. XG-FAST can leverage high speed copper to the premises to increase the number of homes-connected in a homes-passed fiber network.

Historic Overview: From Voice to Ultrabroadband

It has been almost 140 years since Alexander Graham Bell invented the telephone in 1876, but a considerable portion of wireline communication, especially in the "last mile" is still served via copper cables that were originally deployed to provide telephone service. In essence, a telephone converts an audible acoustical wave into a suitable analog electrical signal and transmits that signal along a pair of copper wires, while simultaneously converting the electrical signal originating from a distant telephone back into audible form.

From the beginning, telephone engineers encountered two challenges that are still fundamental today: attenuation and crosstalk. Electrical signals sent through wires attenuate, or become weaker, with distance. Like a deep ship's horn penetrating a foggy harbor, lower frequency signals carry further through wires than high frequency signals do. As a result, the maximum distance between a user's terminal and the nearest amplification point in the network depends strongly on the highest frequencies that need to be preserved. Fortunately for telephony, the frequency spectrum audible by humans extends only to 20 kHz. Moreover, the aspects of a voice signal most essential to good communication—the voiceband—can be limited to frequencies below 3.4 kHz. Thus, copper distribution networks can be wired to reach houses within several kilometers of a local exchange without intermediate amplification.

The earliest telephone systems were also plagued by crosstalk interference, a phenomenon in which a signal crosses from one telephone wire pair into another via electromagnetic coupling. Bell soon realized that the currents induced by electromagnetic interference (EMI) into the two transmission wires cancel out if the wires are twisted around each other, an observation that led to the invention of twisted pair



1958 1961 1966 1970

FIGURE 1. Early Bell System data products.

cable in 1881. As we will see, this technique provided sufficient protection against crosstalk until the introduction of VDSL2 technology over a century later.

1. Digital Voiceband Transmission

With the advent of digital computers in the 20th century, it became desirable to transfer data between remote machines. In 1958, Bell Labs developed the DataPhone voiceband modem, the first device allowing users to take advantage of the by then ubiquitous telephony network for machine-to-machine communication. Figure 1 shows an early DataPhone from 1958, and several subsequent iterations of this device. The DataPone was capable of modulating a 50 bit/s digital data stream onto a low-frequency analog signal, and conversely, demodulating such a data stream from a received analog signal. Other voiceband technologies, including document transmission via digital fax, followed.

Because voiceband data transmission systems used the same low-frequency band as telephony (voice communication), they had the drawback that voice service was unavailable when the modem was in use. For this reason, in many places it became common practice to install two phone lines for each customer—one for dedicated voice service, and another for a fax machine or early dial-up data access. We will later describe how coordinated transmission across these two pairs per customer is one of the features exploited by Bell Labs' XG-FAST concept to achieve a 10× increase in data transmission over the state of the art.

By the late 1970s, emerging concepts such as quadrature amplitude modulation (QAM) and echo cancellation increased modem speeds to 9.6 kilobits per second. Then, in 1982, Gottfried Ungerboeck at the IBM Zurich Research Laboratory demonstrated that it was possible to increase the data rate by a factor of two for a given bit error ratio (BER) by applying Trellis Coded Modulation (TCM), a scheme in which forward error correction with a convolutional parity check is applied on mapped symbols rather than on a bitstream [1]. Building on TCM and other innovations, the International Telecommunications Union (ITU) V.34 standard enabled data rates above 30 kilobits per second. The subsequent ITU V.90 standard leveraged analog-to-digital conversion at the local exchange to further boost rates to 56 kilobits per second. At this stage, fundamental Shannon limits showed that the data-carrying capacity of the voiceband channel had been almost fully exploited.

2. Broadband Internet Access

The rise of the World Wide Web in 1989 kicked off a continuous increase in data traffic that has presented challenges and opportunities for telecom networks and their operators ever since. To overcome the fundamental limitations of the voiceband channel, Asymmetric Digital Subscriber Line (ADSL) technologies extended the signaling to higher frequencies—up to 1.1 MHz in ADSL1 and ADSL2, and up to 2.2 MHz in ADSL2plus. Standardized in 2003, ADSL2plus is one of the most widely used broadband technologies in use today [2]. Each ADSL access node is located in a central office (CO) building which can serve an area within a 5 kilometer radius. Most versions of ADSL use the technique of Frequency Division Duplexing (FDD), allowing voice service, downstream data communication, and upstream data communication to operate simultaneously and independently, using distinct frequency bands. Increasing the transmission bandwidth by two to three orders of magnitude beyond the voiceband posed an enormous challenge for the task of equalization, that is, compensating for signal distortion. This challenge was met by introducing Discrete Multi Tone (DMT) transmission, in which each wide-frequency band is subdivided into many narrow frequency channels (called carriers), efficiently allowing equalization and transmission parameters to be individually optimized on a per-carrier basis. In ADSL, the carrier spacing is 4.3125 kHz.

3. Fiber Optics and Fiber-to-the-Cabinet

The invention of optical fiber communication launched a whole new world in data communication—initially for long-haul applications, and subsequently in access networks. The information-carrying capacity of optical fiber is orders of magnitude higher than that of copper wire, since attenuation can be as low as 0.2 dB per kilometer, across infrared bands wide enough to carry signals with frequencies measured in terahertz. Other advantages of optical fiber include low power consumption, relatively low maintenance, and lack of external interference.

Given that the raw capacity of the optical fiber channel is virtually unlimited in access scenarios, the key design problem has always been to find cost-effective ways to deliver the desired data rates to users. One approach is fiber-to-the-home (FTTH) architecture, which debuted in 1986 in Hunter's Creek, Florida, with a system that delivered TV service to a community of 250 residents. FTTH today is usually based on a passive optical network (PON) where fiber is deployed in a tree structure, with an aggregate data capacity measured in gigabits per second shared among dozens of users. The key obstacle to universal FTTH service has been the significant construction costs associated with deploying a new network infrastructure. For this reason, most FTTH deployments are sited in greenfield conditions, strategic venues, or otherwise easily-accessible locations. A notable exception is Japan, where passive optical networks (PONs) have provided FTTH with end user speeds of 10 Mb/s since 1999, and where the number of FTTH subscribers has surpassed the number of DSL subscribers since 2008 [3]. In the U.S., early adopter Verizon launched FiOS FTTH services in 2005, and one decade later, FiOS has approximately 6.5 million subscribers with 16 million homes passed [4].

Fiber-to-the-cabinet (FTTC) architecture evolved in parallel with FTTH as a way to take advantage of fiber's disruptive capacity while still leveraging the copper distribution network. In this approach, an operator's DSL equipment is deployed much closer to the subscriber premises, in small outdoor cabinets. New fiber infrastructure is built to connect the cabinet to the service provider network, while existing copper infrastructure connects the cabinet to the subscriber. Here, a relatively modest investment in fiber infrastructure shortens the copper access distance for a large number of users, greatly increasing potential data rates by reducing attenuation and allowing transmission at higher frequencies. The Very High Speed Digital Subscriber Line (VDSL2) standard was introduced in 2006 to exploit the spectrum opened up by FTTC, defining multiple upstream and downstream bands that extend to 17.7 MHz or to 30 MHz. Vectored VDSL2, discussed further below, was introduced in 2010 to boost VDSL2 rates via crosstalk cancellation.

4. Ultra-Broadband Access in Hybrid Fiber-Copper Networks

To provide nationwide rollout of broadband services while gradually transitioning to an FTTH network, telephone network operators are leveraging hybrid fiber-copper architectures collectively dubbed FTTx. FTTx solutions include fiber-to-the-cabinet (FTTC) with vectored VDSL2, fiber-to-the-distribution point (FTTdp) with G.fast, and fiber-to-the-frontage (FTTF) with XG-FAST (Figure 2). Shortening the copper loop with each subsequent technology innovation releases ever more spectrum (Figure 3), but also presents new challenges for deployment. Outside, access nodes may be deployed in small cabinets, on telephone poles, wall-mounted, or underground in manholes;

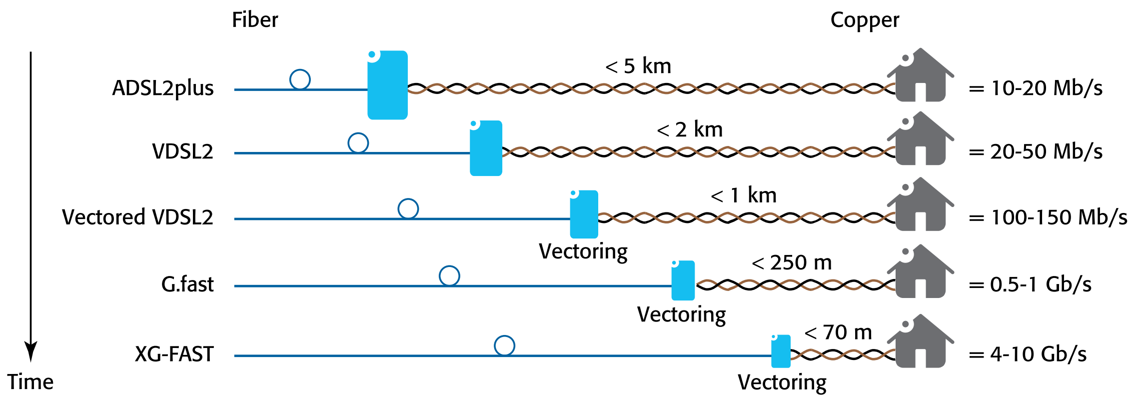


FIGURE 2. **Hybrid fiber-copper access network: The introduction of copper technologies goes hand in hand with a gradually deeper fiber deployment. The rates provided are typical data rates.**

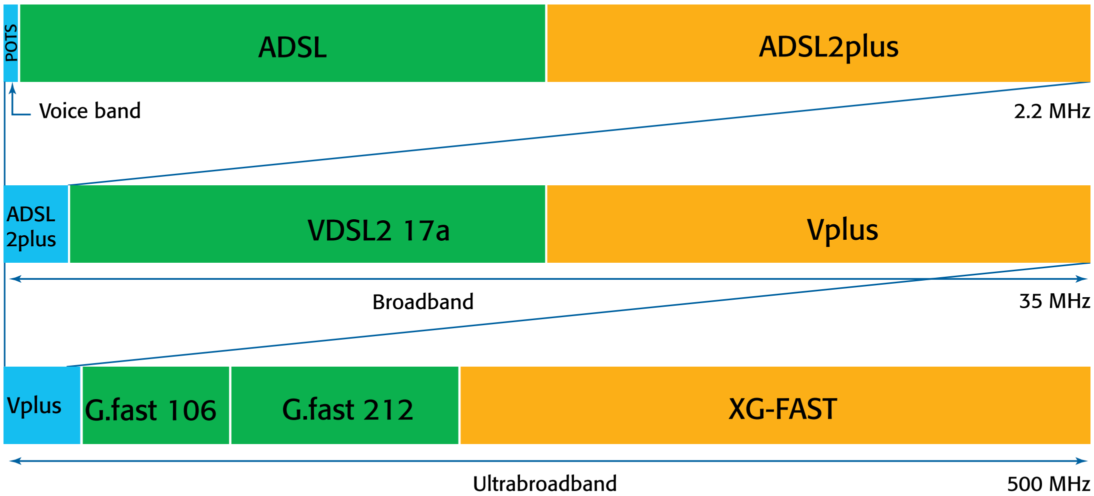


FIGURE 3. **Illustration of the progressively larger spectral bands used for data communication over twisted copper pairs, beginning with voiceband modems, and culminating with XG-FAST.**

in apartment buildings, nodes may be deployed in the basement or near manipulation points on each floor. An economically optimized network may include several different FTTx elements simultaneously, for example using FTTH for individual homes next to an apartment building served by FTTdp.

Table I provides an overview of the copper access technologies we have discussed, beginning with the DataPhone in 1958. The table also includes G.fast, an emerging ultrabroadband technology delivering speeds up to 1 Gb/s over some tens of meters and optimized for loops shorter than 250 m, and XG-FAST, a Bell Labs proof of concept technology delivering 10 Gb/s over tens of meters. In the sections that follow, we will provide more detail on three copper technologies of particular interest today: vectored VDSL2, G.fast, and XG-FAST.

Crosstalk Cancellation in VDSL2

Although VDSL2 was initially considered to be a straightforward extension of ADSL to higher frequencies (an increase from 2 MHz to 17 MHz or higher), the picture changed significantly when the extent of crosstalk interference became clear. While crosstalk has modest impact on ADSL, it was discovered to be a limiting factor for VDSL2 data rates. In most twisted pair cables, the strength of crosstalk interference relative to the "useful" signal is observed to increase quadratically with frequency [5]. Thus for example, in a cable where the useful signal is 3600 times stronger than the crosstalk at 2 MHz (ADSLplus), it might be only 400 times stronger at 6 MHz, and only 100 times stronger at 12 MHz. Although the crosstalk is much weaker than the signal in each case, and hence could aptly be called "cross-whispering," it is

TABLE I. Overview of the Most Relevant Copper Access Technologies

		Standard approved	Service area radius	Max DS rate bit/s**	Max US rate bit/s**	Bandwidth	Duplexing	Modulation	#Carriers	ATP dBm*
1G	Bell 101	1958	>10 km	0.1 k	0.1 k	2.3 kHz	FDD	FSK	1	
voiceband	V.32	1984	>10 km	9.6 k	9.6 k	3.0 kHz	FD	QAM	1	-15
	V.34	1994	>10 km	28.8 k	28.8 k	3.7 kHz	FD	QAM	1	-15
	V.90	1998	>10 km	56 k	33.6 k	4.0 kHz	FD	QAM	1	-15
2G	ADSL	1999	5 km	8.0 M	1.0 M	1.1 MHz	FDD	DMT	256	19.9
Broadband	ADSL2plus	2003	5 km	24 M	1.3 M	2.2 MHz	FDD	DMT	512	19.9
3G	VDSL2 17a	2006	2 km	100 M		17.7 MHz	FDD	DMT	4096	14.5
Broadband	VDSL2 17a vectored	2010	1 km	150 M		17.7 MHz	FDD	DMT	4096	14.5
	Vplus	expected 2015	500 m	350 M		35 MHz	FDD	DMT	8192	14.5
4G	G.fast 106	2014	250 m	1.0 G		106 MHz	TDD	DMT	2048	4.0
Ultra-Broadband	G.fast 212	expected 2016	150 m	2.0 G		212 MHz	TDD	DMT	4096	
5G	XG-FAST single pair	expected 2020	70 m	4.0 G		500 MHz		DMT		-2.0
Ultra-Broadband	XG-FAST two pairs	expected 2020	70 m	10 G		500 MHz		DMT		-2.0

*For voiceband modems, expressed in dBm0

** From 3GBB onwards, expressed in aggregate rate (down+up)

ATP (Aggregate Transmit Power); BB (Broadband); DMT (Discrete Multitone); DS (Downstream); FD (Full Duplex); FDD (Frequency Division Duplexing); FSK (Frequency Shift Keying); G (Generation); TDD (Time Division Duplexing); US (Upstream); QAM (Quadrature Amplitude Modulation)

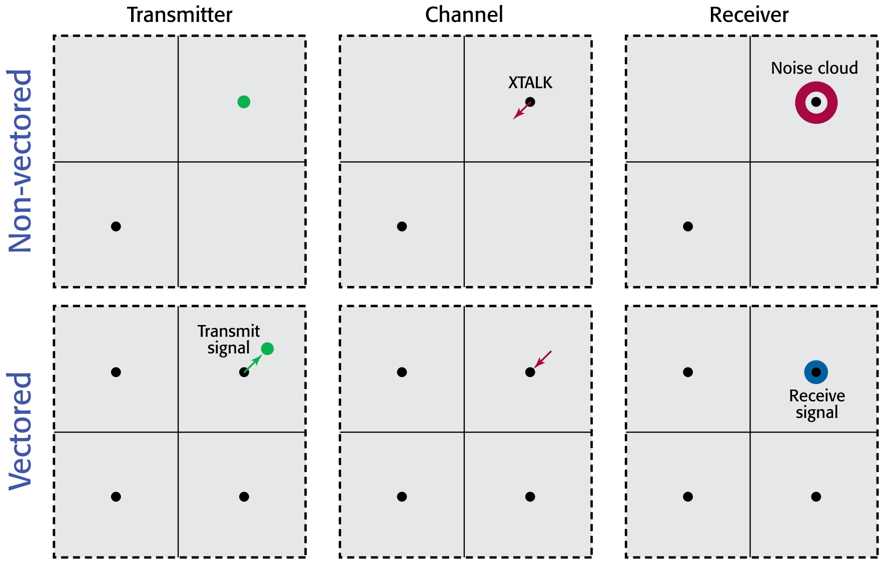


FIGURE 4. **Frequency domain representation of a single carrier in downstream non-vectored (top) and vectored (bottom) mode on the transmitter (left), channel (middle) and receiver (right).**

nevertheless strong enough to reduce attainable data rates by as much as 50% for VDSL2. Vectored VDSL uses a computationally intensive precompensation technique to suppress crosstalk, boosting data rates.

Figure 4 illustrates the effect of crosstalk and vectoring. The frequency domain representation shows the in-phase and quadrature components of a quadrature amplitude modulation (QAM) symbol on a single carrier. The black dots represent the constellation diagram, and the number of black dots represent the capacity of the carrier. For example, a constellation with 4 dots can convey up to two data bits, while a constellation with 2 dots can only carry a single bit of data. In non-vectored mode, the constellation point that results from the mapping of bits in the transmit buffer is sent directly on the link. The channel will add crosstalk. As a result, the received signal comprises the intended constellation point plus the interference. This interference reduces signal-to-noise-ratio (SNR), forcing the transmitter to send a constellation pattern with fewer distinct points, reducing the number of data bits that can be conveyed in a symbol. In vectored mode, a precompensation signal is added that cancels-out the crosstalk added by the channel [6–8]. As a result, interference at the receiver is mitigated, enhancing the SNR, and allowing transmission of denser constellation patterns that convey more data bits.

A vectored DSL system requires two components, shown in Figure 5, which are not found in previous DSL systems: a *vector control entity* (VCE) that determines a suitable compensation matrix, and a *vector processor* (VP) at the access node that performs matrix-vector multiplication in real time.

1. The vector control entity provides the intelligence of the vectored system. It gathers raw information from the receivers about the physical interaction between the twisted pairs and processes the information to determine a suitable compensation matrix, where the element in the row i and column j pertains to the amount of compensation needed on victim i to protect from crosstalk of disturber j. The raw information generally includes frequency domain samples or slicer error samples [9], though SNR reports can also be used [10].
2. The term vectoring comes from the operation of the vector processor (VP). For downstream transmission, the VP takes complex values representing the desired signal for each user, forms them into a vector, and multiplies this vector by the pre-compensation matrix to obtain a vector of pre-compensated signals for transmission. In the upstream direction, the VP similarly takes complex received values from each user, forms them into a vector, and multiplies this vector by a post-compensation matrix to obtain a vector of post-compensated signals for demodulation. These operations are performed in real time, for every carrier in every transmitted symbol. The VP resides in the access node.

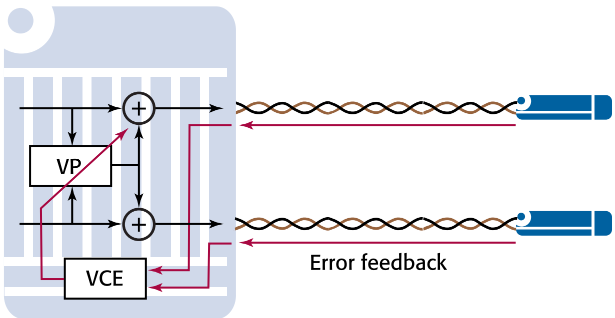


FIGURE 5. **The vector control entry (VCE) processes error feedback from the customer premises equipment to obtain vector processing (VP) coefficients.**

G.vector is a supplement to VDSL2 that adds features to facilitate vectoring. Crosstalk estimation is supported through transmission of probe sequences and the corresponding collection of error feedback. Seamless initialization is supported by the addition of vectoring-specific initialization procedures [6].

1. Zero-Touch Migration from VDSL2 to Vectored VDSL2

Introducing vectored VDSL2 into a legacy (non-vectored) VDSL2 access network is not without complication. Legacy VDSL2 customer premises equipment (CPE) does not support probe sequences, which means that there is no ability to estimate the crosstalk that the legacy line generates into the neighboring vectored lines. As a result, both the legacy channels and the vectored channels experience crosstalk and neither receives full cancellation gain. Depending on make and model, a legacy CPE may be firmware-upgradeable to a vector-friendly mode which can coexist in a vectored group without impacting the vectored lines. However, not all models can support an upgrade, and even in those that do, an attempted upgrade may fail. The prospect of replacing all legacy CPE with vectored CPE is logistically challenging, and the cost is not easily justified for legacy users satisfied with non-vectored rates. Zero-touch vectoring can offer a solution. Zero-touch algorithms manipulate transmit signals on legacy lines such that all crosstalk channels can be estimated without impacting legacy CPE [9]. As a result, an operator can retain legacy CPE while providing vectored CPE only to end users who require vectored performance. The advent of zero-touch vectoring means that a neighborhood-wide data rate is no longer dependent on the willingness or ability of every single household to replace the CPE.

2. Vplus in a Dense Cabinet Deployment

Vectored VDSL2 and zero-touch installations have been commercially available since 2011, and massive rollouts are underway to deliver 100 Mb/s services. While to date, vectoring has mostly been applied using the 17 MHz VDSL2 profile (17a), in principle it could also be applied to the 30 MHz VDSL2 profile (30a) optimized for relatively short length. However, because these profiles were originally defined without vectoring in mind, they use different carrier spacings and symbol rates, meaning that vectoring would not be effective if 17a and 30a profiles are deployed in the same network. Vplus is a proposal to avoid this incompatibility by accessing 35 MHz spectrum using the same carrier spacing and symbol rate as 17a. Vplus fills a gap in deployment options by providing enhanced services from the cabinet over copper loops of less than 500 meters.

Ultrabroadband Hybrid Fiber Copper Networks

G.fast marks the beginning of ultrabroadband, the first copper access technology to provide up to one gigabit per second transmission over twisted pairs [11]. G.fast is intended to be used in an FTTdp architecture, i.e., with loop lengths below 250 m. The shorter loop lengths provide for an increase in spectrum, initially to 106 MHz and then to 212 MHz in a future phase. The shorter loop length also implies that more distribution point units (DPUs) will be needed to cover the same service footprint. To accommodate the rollout of additional equipment, DPU installation must be done swiftly and with as few hands-on service visits as possible. Rapid deployment can be facilitated in two ways. Leveraging customer premises equipment to power the DPU via the copper cable (reverse powering) can reduce dependency on electrical utility providers and relax the need for building permits. Next, providing equipment that end-users can install themselves can reduce the need to schedule appointments for visits from service technicians. A robust and adaptive modulation scheme is key enabler for self-installation. Ideally, G.fast systems should be designed for “install and forget” operation—once installed, there should be no need to physically revisit the distribution point for further manipulation. Zero-touch management applications include remote management through a persistent management agent that remains available even when the CPE is inactive and the DPU is unpowered. It should also support the remote switching of users to different services.

G.fast marks the beginning of ultrabroadband.

1. Managing Strong Crosstalk

Since G.fast is designed for shorter loop lengths than VDSL2, the number of users terminating at a G.fast access node will be smaller than the number covered by a typical VDSL2 node. While the reduced number reduces the complexity of vectoring operations, other aspects of the channel make vectoring more challenging. Indeed, if crosstalk at VDSL2 frequencies can be considered “whispering,” then crosstalk at G.fast in many topologies is more akin to “shouting.” At G.fast transmission frequencies, crosstalk energy can exceed the direct signal energy in the channel. This means that the energy required for the precompensation signal in the downstream is no longer negligible compared to the energy of the user signal. The transmitted signal is the sum of the user signal and the precompensation signal, and its power must be lower than a pre-defined power spectral density (PSD) mask. Figure 6 depicts two methods to control vectored signal power in a “cross-shouting” environment. Using linear gain-scaled precoding, the power of the user signal is reduced to accommodate the power of the precompensation signal. Since the transmit signals are a linear combination of user signals, the problem is distributed over the user

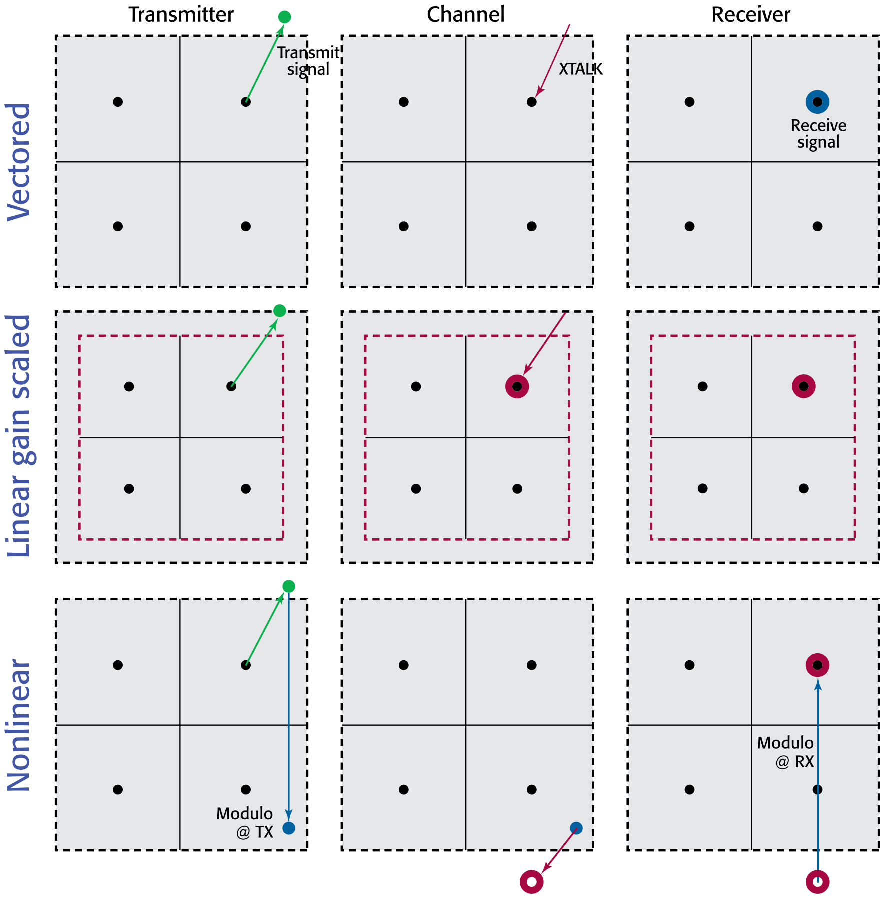


FIGURE 6. **To ensure downstream power spectral density constraints, G.fast defines linear gain scaled precoding (middle) and nonlinear precoding (bottom).**

base and many degrees of freedom exist to meet the PSD constraint. Column norm scaling [12] offers a simple yet fair class of solution mechanisms. Linear gain-scaled precoding is supported by the first version of G.fast, which has been approved at ITU as G.9701. The second method is called nonlinear precoding. Tomlinson-Harashima Precoding (THP) [8] is a well-known nonlinear precoding technique in which a nonlinear modulo operation is applied to the sequentially processed signals. The modulo operation ensures that the PSD constraint is met. Because nonlinear precoding does not require the aggressive gain scaling incurred by linear precoding in high crosstalk, it can achieve higher data rates. Support for nonlinear precoding is under consideration for a future amendment of the G.fast standard.

2. Gigabits to the Masses

A true FTTH access network architecture is said to be available when optical fiber crosses onto a subscriber's land lot boundary (building frontage) and then terminates either inside the building or no more than two meters from an external wall of the building [13]. Make no mistake, migrating from FTTx to FTTH—bringing fiber to every street (homes passed) and adding an optical drop cable from every home passed directly to the individual premises (homes connected)—remains a hurdle. In comparison, a homes-passed network is a fairly straightforward extension of an FTTdp network.

Installing the final optical drop is logistically one of the most challenging steps to full fiber deployment since it involves manipulation on privately-owned lots which may include digging up driveways or other hardscaped surfaces, drilling through an external wall, and installing new in-home cabling, often in a less-than-aesthetic overlay manner. A fiber-to-the-frontage architecture avoids this step by retaining the existing copper drop cable, which is typically less than 30 meters long. With this motivation in mind, Bell Labs recently demonstrated XG-FAST, a proof of concept technology that can deliver 10 Gb/s over a 30 meter copper drop [14]. An FTTF architecture coupled with XG-FAST copper technology—which can be deployed using zero-touch and self-installation protocols—has the potential to convert the homes passed by a fiber network to homes connected, without a technician ever setting foot on a private lot, while delivering multiple Gb/s services on a par with current or planned fiber services such as Google Fiber's 1 Gb/s symmetric service. With XG-FAST in combination with a homes-passed fiber network, there is no immediate need to bring fiber into the home.

Besides expanding spectrum to 500 MHz, XG-FAST leverages a number of key technology concepts including bonding, phantom mode, multiple-input multiple-output (MIMO) transmission, adaptive modulation, and reverse powering.

- Bonding: In the final drop from the frontage into the home, as noted earlier, two twisted copper pairs are often available as a result of historical installation of multiple phone lines. These two pairs can be bonded together, meaning that two physical layer data streams are merged to provide a single pipe with double the offered data rate. To a lesser extent, bonding is also applicable to fiber-to-the-cabinet installations, though the two pairs may not always be connected from the cabinet to the frontage.
- Phantom mode: Cable quality permitting, the presence of two pairs can in fact allow us to address three transmission modes at the physical layer: the two differential modes (one for each pair) and a so-called phantom mode built-up as a differential signal between the common modes of the two pairs [14]. The three data streams associated with the three modes can be bonded together to increase the data rate even further.

XG-Fast exploits the spatial dimension beyond a single pair.

- MIMO transmission: Other than in multiple dwelling units and in some other outlier circumstances, the copper loops serving different users in FTTF deployments will be physically separated, with negligible crosstalk coupling between users. On the other hand, very strong coupling can be expected between the two or three transmission modes serving a single user via bonding. In such circumstances, XG-FAST can leverage two-sided, point-to-point MIMO techniques to maximize channel capacity, in contrast to multi-user, single-sided signal coordination appropriate for VDSL and G.fast vectoring. By using pre- and post-coders based on the singular value decomposition of the channel matrix, data is effectively modulated onto independent "eigen-modes" of the channel rather than on the physical differential modes described above. Because the pre- and post-coders are energy-preserving unitary matrices, the full capacity of the channel can be exploited without the gain scaling penalty associated with single-sided coordination.
- Adaptive modulation: Transmitter Controlled Adaptive Modulation (TCAM) is a hierarchical modulation scheme which, in a dynamic environment, provides up to a 2 bit/s/Hz increase in spectral efficiency compared to conventional schemes [15]. This innovation is discussed further in connection with quality of service (QoS) below.

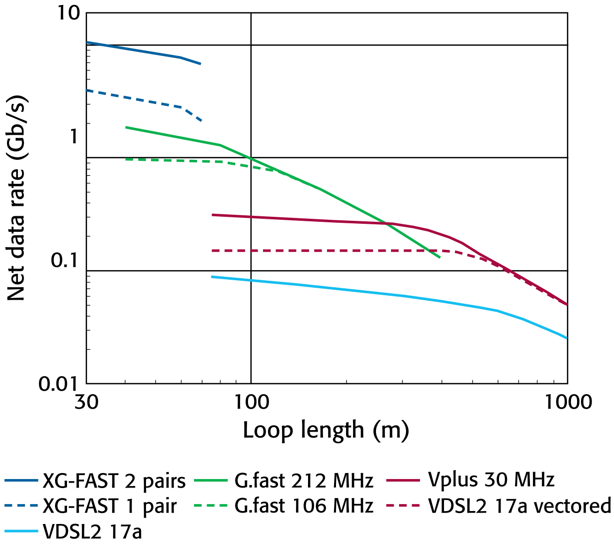


FIGURE 7. **By bringing fiber closer to the end users, the net data rate over the copper drop increases exponentially with copper technology generation. The data points are indicative, and may not be applicable to all cable types.**

Figure 7 shows a rate-reach curve obtained by a prototype XG-FAST system exploiting a 500 MHz spectrum over a 0.6 mm gauge twisted pair drop cable. The results demonstrate the improvement of exploiting the spatial dimension (bonding, phantom mode, and MIMO) beyond a single pair.

3. Carrier Grade Quality of Service

Quality of service requirements for copper technologies, imposed to support the deployment of high-definition television (HDTV) services already require telecom carriers to limit error events to less than one every four hours on average [16]. This is achieved through a combination of error correction coding and other error protection methods. For example, in a static noise environment (which can be modeled through additive white Gaussian noise), a Reed-Solomon (RS) outer code may be combined with a Trellis Coded Modulation (TCM) inner code to provide performance as close as 3.45 dB to Shannon capacity limits (cf. signal processing path in Figure 8). More complex coding schemes such as Low Density Parity Check (LDPC) codes can potentially improve performance by 0.5 dB to 2 dB in a static noise environment [17, 18].

However, copper access systems must also deal with non-stationary impairments such as impulsive noise (IN) and transient wideband or narrowband interferers [19]. Impulsive noise consists of energy pulses with durations ranging from microseconds to milliseconds, which originate mainly from the electrical grid and which can repeat

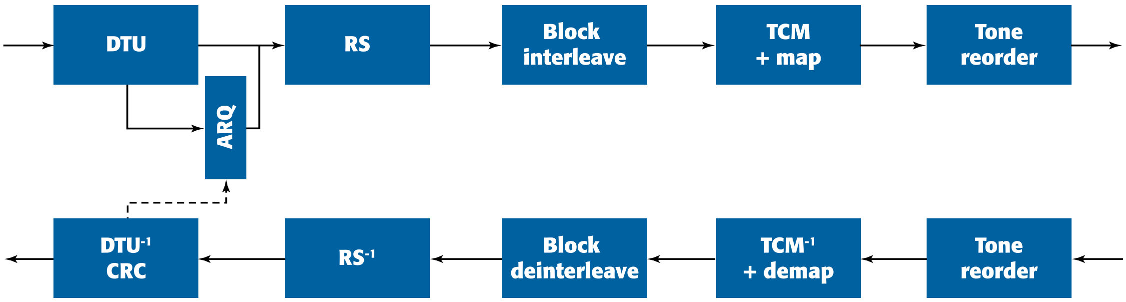


FIGURE 8. Building blocks relevant to error protection mechanisms, as used in the data paths of VDSL2 (with G.inp) and G.fast.

at cycle frequencies of 100 Hz or 120 Hz. IN is typically modeled through a Markov process. Due to the short duration of the pulses, IN has wideband frequency components. The main safeguards against IN in current copper access systems are a block interleaver between the inner and outer code, and an automatic repeat request (ARQ) retransmission scheme. The interference from narrowband radio frequency ingress (RFI) fluctuates over time due to changes in ambient conditions, often on a daily cycle. Narrowband interference is normally dealt with through tone-reordering, a form of frequency interleaving.

These error protection mechanisms in the data path can be complemented by adapting the coding and modulation parameters. For example, if narrowband interference persists, a bit-swap or seamless rate adaptation will reduce bit loading on the affected carriers, freeing-up error correction resources for interference coming down the pike. Transients in wideband interference, originating from telecommunication systems and other sources, affect a large fraction of carriers. To accommodate such transients, the capacity gap can be artificially increased by adjusting the signal-to-noise-ratio margin (SNRM). The SNRM is essentially a proactive capacity reduction mechanism that ensures QoS in case of an unexpected increase in wideband noise. A typical SNRM value used in practice is 6 dB, corresponding to a loss of spectral efficiency of 2 bits/s/Hz, which is about 20% of the spectral efficiency averaged over carriers in a typical VDSL scenario. Dynamic Line Management (DLM) is a technique that automatically optimizes the SNRM, among many other parameters, to the conditions on each line. Another technique, the Fast Rate Adaptation (FRA) mechanism defined in G.fast, is designed to quickly reduce the data rate in the event of a sudden noise increase. FRA can make a reduced SNRM more palatable, since the penalty incurred when noise exceeds the margin is only a temporary sharp rate reduction, rather than a session re-initialization. Carrying this concept yet further, Transmitter Controlled Adaptive Modulation (TCAM) is proposed as a way to reduce SNRM to a minimum through fine-grained, robust rate adaptation. TCAM is a hierarchically-layered modulation scheme in which the transmitter can adapt data rate by turning layers off autonomously when necessary. This autonomy mitigates the need for a lengthy command-and-response procedure to negotiate a change with the receiver, which thus increases adjustment speed. With TCAM, the line can be operated without an SNRM and hence with up to 2 bit/s/Hz greater spectral efficiency. TCAM has not been adopted in current standards, but is a candidate for new standards such as XG-FAST.

Figure 8 provides an illustration of the relevant building blocks for error protection used in the data paths for VDSL2 (with G.inp) and G.fast.

Quality of service can be further assured through automated network management. A network analyzer performs the tasks of upgrade and activation (network analysis), troubleshooting (diagnosis), and proactive optimization through Dynamic Line Management (DLM). Network analysis provides a prediction of how well a service will run statistically across the network as well as on each individual line. As such, a service provider wishing to introduce a new service level or technology can assess several options and select the service best suited for its network. Loop diagnosis, typically triggered upon customer request, provides help desk operators with a step-by-step work flow and provides experts in the Network Operations Center with in-depth analysis. Dynamic Line Management automates network configuration by monitoring QoS metrics, predicting performance, and selecting an individualized profile for each user. In a hybrid fiber-copper network, a network analyzer is ideally able to provide these functions for all variants of copper and optical technology in use in the network. The network analyzer also has a role in a bitstream unbundling environment where multiple service providers may provide separate services at the data layer over a common physical infrastructure.

Conclusions

We provided an overview of several generations of copper access technologies, from voiceband to ultrabroadband. We observe a continued trend of leveraging the copper loop to speed up introduction of high-rate services in a hybrid fiber-copper network. A wide scale deployment of VDSL2 vectoring, a 100+ Mb/s technology, is ongoing. At the same time, the recently approved G.fast standard is being trialed in the lab and operators are preparing field trials. With XG-FAST, a 10 Gb/s technology in the prototype stage, copper continues to satisfy growing demands in data rate. With these technologies, copper provides competitive options for evolving the hybrid fiber-copper access network.

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