XG-fast: the 5th generation broadband

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XG-FAST: The 5th Generation Broadband

Traditionally, copper network operators complement a fiber-to-the-home strategy with a hybrid fiber-copper deployment in which fiber is gradually brought closer to the consumer, and digital subscriber line technology is used for the remaining copper network. The authors propose the system concepts of XG-FAST, the 5th generation broadband (5GBB) technology capable of delivering a 10 Gb/s data rate over short copper pairs.

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Abstract

Traditionally, copper network operators complement a fiber-to-the-home (FTTH) strategy with a hybrid fiber-copper deployment in which fiber is gradually brought closer to the consumer, and digital subscriber line (DSL) technology is used for the remaining copper network. In this article we propose the system concepts of XG-FAST, the 5th generation broadband (5GBB) technology capable of delivering a 10 Gb/s data rate over short copper pairs. With a hardware proof-of-concept platform, it is demonstrated that multi-gigabit rates are achievable over typical drop lengths of up to 130 m, with net data rates exceeding 10 Gb/s on the shortest loops. The XG-FAST technology will make fiber-to-the-frontage (FTTF) deployments feasible, which avoids many of the hurdles accompanying a traditional FTTH roll-out. Single subscriber XG-FAST devices would be an integral component of FTTH deployments, and as such help accelerate a worldwide roll-out of FTTH services. Moreover, an FTTF XG-FAST network is able to provide a remotely managed infrastructure and a cost-effective multi-gigabit backhaul for future 5G wireless networks.

Introduction

About two decades ago, copper networks carried just a few kilobits per second. Today, digital subscriber line (DSL) technology offers rates exceeding 100 Mb/s over those same copper networks. Communication, computing, and storage capacity continue to increase significantly every year, and fixed access network technologies must provide ever higher data rates to support a wide variety of high-speed applications, such as video-on-demand, fast downloads, support for cloud-based applications, and transport and backhaul capabilities for wireless networks.

For copper networks, the achievable capacity is typically dominated by attenuation. Optical fiber technology has a much longer reach due to its inherent low attenuation, and is therefore ideal to transport high data rates over long distances. Current passive optical network (PON) technologies provide data rates up to 10 Gb/s, and the next-generation PON systems are expected to carry up to 40 Gb/s. However, a direct transition to full fiber-to-the-home (FTTH) connectivity is hampered by enormous capital expenditures and the very long roll-out time needed to build these networks. At the same time, nearly every household or residential building in developed countries is connected to the copper-based telephone network. Reusing these copper cables as a physical transport medium for broadband access networks has proven to be of great economical value. For this reason, the fiber connection has gradually been brought closer to the end-user, shortening the remaining copper loop to within a few hundred meters from the customer. This evolution has been accompanied by new generations of DSL technologies that leverage the higher capacity of these shorter copper loops.

For short and medium length copper loops, instead of attenuation, crosstalk across adjacent twisted pair cables proved to be the limiting factor to improve data rates. Vectored VDSL2 [1], the most recently deployed DSL technology, effectively suppresses crosstalk across adjacent copper lines in a cable. Using this technology, single line performance can be attained, making the loop length the limiting factor once again. This has led to the development of the fourth generation broadband (4GBB) technology, called "fast access to subscriber terminals," in short, G.fast, which was standardized in Dec. 2014 [2–4]. The target deployment scenarios for G.fast include multi-home deployments such as fiber-to-the-distribution-point (FTTdp) and fiber-to-the-building. The G.fast standard is optimized for copper loops up to 250 m with a 106 MHz bandwidth and a maximum aggregate data rate that approaches 1 Gb/s. Since the impact of crosstalk interference increases with frequency, vectoring has become mandatory in G.fast.

This article presents concepts for a fifth generation access technology, referred to as XG-FAST [5]. It aims to provide data rates up to 10 Gb/s to the end user over very short existing copper-based lines. Target deployment scenarios for XG-FAST include fiber-to-the-frontage (FTTF), where an optical network terminal (ONT) is installed near the boundary between public and private property to shorten the copper loop length while avoiding construction work on customer premises. Other deployment scenarios include home networks. Multi-gigabit data rates can also provide connectivity to 5G wireless networks, which, compared to 4G networks, should achieve 1,000 times the system capacity, 10 times the spectral efficiency, energy efficiency, and data rate (i.e. a peak data rate of 10 Gb/s for low mobility and a peak data rate of 1 Gb/s for high mobility) [6]. As such, XG-FAST then becomes synergistic with 5G wireless, where the XG-FAST drop into the home is extended with multi-gigabit 5G wireless technologies (the latest Wi-Fi 802.11ad standard already aims for maximum data rates of almost 7 Gb/s [7]). Although XG-FAST is presented here as a technology for twisted pair telephone cables, it can essentially be used with different cable types, including Ethernet cables, coaxial cables, and power lines.

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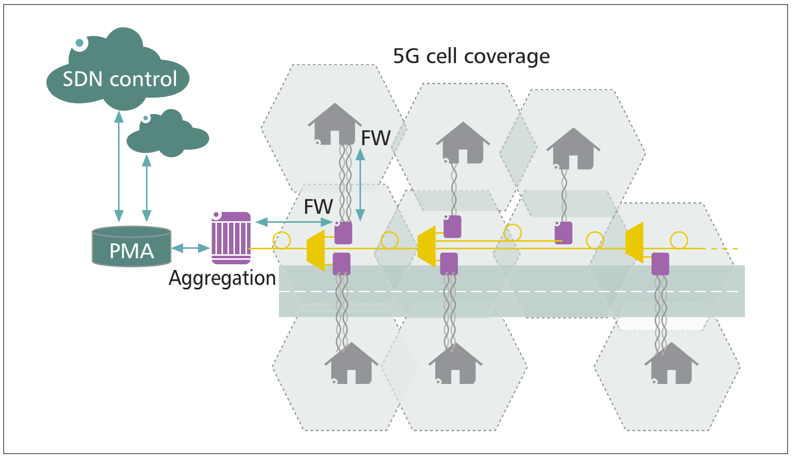

Figure 1. A homes-passed fiber network provides the basis for XG-FAST drops and dense 5G wireless access points. The persistent management agent (PMA) of G.fast is extended to XG-FAST and wireless. It provides the foundation of joint fixed-wireless SDN control as well as containing firmware (FW) for upgrade of network functions inside programmable universal remotes and customer premises equipment.

This article first discusses the role of XG-FAST in future mobile network architectures, which will require a centralized control of traffic referred to as software defined networking (SDN). The XG-FAST system concept is introduced next, and techniques are presented to improve performance. The viability of the XG-FAST technology is demonstrated with measurements performed on several short copper cables, and next steps are proposed to turn the XG-FAST technology concept into practice.

SDN-Controlled 5G Networks

Future 5G networks aim to support a wide variety of use cases, ranging from human-centric communication scenarios that demand high peak rates and low latency, and good connectivity when moving or in a crowd, to machine-oriented communication scenarios with many connected devices and an emphasis on low power consumption [8]. It is a common belief that a single radio access technology will not be able to satisfy all these different requirements simultaneously, and that the future 5G network will consist of a flexible combination of both existing and new radio concepts [8]. This means that 5G will have to be designed as a system rather than as a stand-alone technology.

One of the major 5G trends are small cell overlay networks [9]. This makes it possible to tackle the capacity challenge, and when combined with centralized control, this can be done in a power efficient way. The backhaul of these high capacity small cells must be realized by a high capacity backhaul technology. Often cited examples are mm waves, optical fiber and copper, depending on the targeted use case. We envisage XG-FAST to be a copper backhaul technology with multi-gigabit capacity and sub-ms latency. Low latency is essential for efficient mobile backhauling, and was also targeted for G.fast [3]. XG-FAST relies on a dense deployment of optically backhauled fixed access nodes, and hence is synergistic with the small cell deployment use case of dense urban areas. XG-FAST will consist of a homes-passed fiber network, where each home is connected over copper through XG-FAST, as illustrated in Fig. 1. Such a deployment provides an excellent basis for a 5G network with a low infrastructure deployment cost. Using XG-FAST for backhauling, indoor small cells can be provisioned at one or more locations within the home. In addition, outdoor small cells can be provisioned at the XG-FAST drop units in the street, directly multiplexing into the optical backhaul of XG-FAST. This requires adequate traffic management for the combined wireless and fixed traffic at the XG-FAST node.

Centralized Control

The centralized control plane that is desired for small cells [9] comes naturally with XG-FAST. A dense FTTF deployment requires an "install-and-forget" deployment model, where, after initial installation by a field technician, the access point is managed remotely. In reverse-powered G.fast, a persistent management agent (PMA) is maintained deeper in the network, such that the G.fast distribution point unit is virtually visible and manageable in the absence of reverse power. A PMA serves to provide virtualization of the network management function and can be extended to software defined control and management [10, 11]. A PMA thus becomes a cloud function that can be integrated with SDN control of the wireless access points for consistent management of the end-to-end link. The separation of the management and data plane is not a goal in itself, but follows from the reverse powering targeted for XG-FAST nodes. It enhances the benefits of SDN such as ease of service creation, firmware upgradeability, and facilitating control and diagnostics of a single network with multiple service providers through virtual or bitstream unbundling.

For communication between the PMA and the fixed access node, the industry selected the NETCONF protocol, which provides a means for exchanging configuration information using the data modeling language YANG. The high data rate and low latency of XG-FAST itself facilitates cloudification of 5G control and data plane functions. End users cannot, or will not, deal with in-home Wi-Fi or 5G access point management. Centralized configuration and management is necessary to avoid misconfigurations and conflicting settings of neighboring cells. A further step entails virtualizing layer 2 and layer 3 of fixed and wireless technologies, such as authorization and forwarding rules.

By taking the 5G system design into consideration for XG-FAST, one could imagine a node containing universal hardware components, which are programmable to act as either a fixed or a wireless resource. Centralized control can then be exploited even more efficiently to decrease power consumption. For example, during the day (more mobile users) more resources can be assigned to 5G outdoor wireless access points, while in the evening (more users inside homes) more resources can be assigned to the fixed processing, benefiting the in-home wireless access point capacity.

Given the massive number of required devices for an FTTF deployment, they will have to be as

Technology	Cable type	Duplexing	Modulation	RF bandwidth	Aggregate data rate (US+DS)
G.fast	TP	TDD	DMT (up to 4096-QAM)	104 MHz	1 Gb/s (1 pair)
G.hn	TP, PL, coax	TDD	DMT (up to 4096-QAM)	100 MHz	1 Gb/s (1 pair)
1000/10G BASE-T	TP CAT5/CAT6	Full duplex	PAM-5/PAM-16	≈ 80 MHz/400 MHz	2 Gb/s/20 Gb/s (four pairs)
XG-FAST	TP, coax	Full duplex/TDD	DMT (up to 32768-QAM)	500 MHz	10 Gb/s (one/two pairs)

Table 1. Overview of some relevant gigabit copper access technologies for twisted pair. US: upstream; DS: downstream; TDD: time-division duplexing; DMT: discrete multi-tone; PAM: pulse-amplitude modulation.

Given the massive number of required devices for an FTTF deployment, they will have to be as low-cost and low-power as possible to be viable. Besides centralized control, XG-FAST devices can therefore benefit from centralizing part of their physical layer data functionality.

low-cost and low-power as possible to be viable. Besides centralized control, XG-FAST devices can therefore benefit from centralizing part of their physical layer data functionality. Moreover, in that central aggregation node the centralized functionality can be virtualized to facilitate management and increase flexibility. For downstream traffic, one option could be to centralize some functionality up to the frequency domain, consisting of framing, forward error correction (FEC), and constellation mapping. This keeps the fiber link digital (upholding the compatibility with FTTH), while not blowing up the required fiber capacity.

Copper Broadband

In access networks, existing copper infrastructure mainly consists of twisted pair (TP) and coaxial cabling. Power lines (PL) can also be exploited, especially for in-home distribution. Table 1 highlights several technologies that have been developed for these cable types and which can achieve data rates of at least 1 Gb/s.

The Ethernet technologies 1000 BASE-T and 10G BASE-T are P2P technologies that provide a symmetric data rate of 1 Gb/s and 10 Gb/s, respectively. The physical layer design of these technologies requires a specific cable type (minimum CAT5 or CAT6) containing four twisted pairs, which essentially makes them unsuitable for deployment in copper access networks. The copper access network has mostly been built prior to the advent of the Internet and Ethernet, using telephony-grade cabling with a variable number of pairs available per home. The data rate for XG-FAST will be matched to the cable quality. This flexibility is a crucial advantage in brown field deployments that reuse an existing copper infrastructure.

The other technologies in Table 1 do allow operation on legacy copper access infrastructure. The home network standard G.hn is a P2MP technology specified to achieve data rates up to 1 Gb/s, and can operate over twisted pair, coaxial cable, and power lines [12]. It uses DMT modulation over 100 MHz of baseband or passband spectrum, and low density parity check (LDPC) coding for forward error correction. Similarly, G.fast uses DMT modulation over a 104 MHz block of spectrum, ranging from 2.2 MHz to 106 MHz, to avoid spectral overlap with legacy ADSL technologies. The current version of the standard is optimized for loops shorter than 250 m and uses time division duplexing (TDD) to duplex upstream and downstream traffic. The FEC is Reed Solomon (RS) combined with trellis coded modulation (TCM). Unlike G.hn, G.fast has a carrier-grade management protocol. Despite the similarity of their physical layer, G.fast outperforms G.hn in access networks thanks to crosstalk cancellation and increased framing efficiency.

XG-FAST further expands the signal bandwidth to 500 MHz, making it possible to increase the achievable data rate over the shortest loops. In the next Section, we propose synergistic system concepts for XG-FAST that make it possible to increase its spectral efficiency compared to G.fast, such as adaptive modulation, MIMO vectoring in combination with bonding and phantom mode transmission, and full duplex transmission.

XG-FAST System Concepts

Powering

Because of the sheer number and distributed nature of XG-FAST devices in an FTTF deployment scenario, the devices will preferably be powered by the customer premises equipment (CPE), a scenario known as "reverse powering." As the XG-FAST device is tailored for a single user, reverse powering becomes easier compared to multi-user distribution point units. The shorter loop lengths also reduce the loss of the reverse power provided over that loop. This should simplify the reverse powering requirements compared to G.fast.

Bandwidth

The biggest contributor to the data rate increase will be the expansion of the signal bandwidth, enabled by shortening the copper loops through increasing fiber penetration. The 70 m operator cable in the proof-of-concept later uses less than 400 MHz, while the 30 m cable is able to exploit a bandwidth larger than 500 MHz. Based on these cable measurements and modeling, a signal bandwidth of the order of 500 MHz is considered to be a good choice for XG-FAST [5].

Modulation

Current xDSL technologies use discrete multitone (DMT) modulation, which divides the frequency spectrum into equally spaced parallel channels or "tones" that are independent due to orthogonality. The bit-loading per tone can be separately adjusted for each tone. DMT modulation for XG-FAST is a logical choice, in order to be able to exploit the full potential of every copper loop (whatever its quality) with a finely-tuned bit-loading on every tone.

XG-FAST will allow for simultaneous upstream and downstream on the same frequency (full duplex), doubling the spectral efficiency compared to currently used time or frequency division duplexing schemes.

Adaptive Modulation and Coding

Transients in wideband interference originating from external sources have an impact over a large part of the signal bandwidth. To accommodate such noise transients, the gap to capacity is typically artificially increased by adjusting the signal-to-noise-ratio margin (SNRM). This is essentially a proactive capacity reduction mechanism that ensures quality of service in case of an unexpected increase in wideband noise. A typical SNRM value used in practice is 6 dB, corresponding to a spectral efficiency loss of 2 bit/s/Hz. A modulation technique called transmitter controlled adaptive modulation (TxCAM) makes it possible to reduce this loss in spectral efficiency [13]. TxCAM is a hierarchically-layered modulation scheme in which the transmitter can autonomously adapt the data rate by turning off layers in case of a sudden noise increase. This autonomy mitigates the need for a lengthy command-and-response procedure to negotiate a change between transmitter and receiver to do a data rate adaptation. With TxCAM, the line can be operated without a SNRM and hence increase the spectral efficiency by up to 2 bit/s/Hz. Regarding forward error correction, TxCAM is unsuited for use with coded modulation such as the TCM currently used in G.fast. So although a shift from TCM to low density parity check (LDPC) coding on the merits of coding gain alone may not be worthwhile [14], the use of TxCAM would be synergetic with LDPC coding as a forward error correction scheme.

Bonding

In many places, customer sites have been equipped with two copper pairs, one for dedicated voice service and another for fax or early dial-up data access. This can be exploited by XG-FAST, which has the benefit of being a single subscriber device and allows each customer to be served with an optimized technology.

These pairs can be bonded together, meaning that the two physical layer data streams are multiplexed to provide a single pipe to the user. When vectoring is used, the achievable data rate gain is proportional to the number of channels.

Phantom Mode Transmission

Two available twisted pairs can also be used as two "virtual" wires to create a third "virtual" pair, called the phantom mode. This concept is well known and was already considered at the end of the 19th century. The differential signal of the phantom mode is the difference between the common mode signals on both twisted pairs. The channel characteristics of the phantom mode are typically worse than those of the twisted pairs because its two "wires" are essentially two different twisted pairs, resulting in unbalances. Due to the large crosstalk interference generated by phantom channels, it is essential to use vectoring to yield a data rate gain that is worth the hardware effort.

The three data streams associated with the three modes can again be bonded together, potentially providing a threefold increase in data rate compared to a single twisted pair. Further on, we will experimentally demonstrate the feasibility of using phantom mode transmission at the high frequencies targeted for XG-FAST.

Two-Sided Signal Coordination

Crosstalk cancellation techniques remain essential in XG-FAST when multiple pairs are being used by a single user. In VDSL2 and G.fast, crosstalk cancellation is achieved by signal coordination solely at the access node, which is a multiple-input-single-output (MISO) scheme. Since XG-FAST is primarily a single-user technology, it is now possible to achieve signal coordination in both the transmitter and the receiver, creating opportunities for new precoder and equalization schemes. It allows the use of better performing multiple-input-multiple-output (MIMO) schemes, which was not possible in previous DSL generations.

In G.fast, a linear gain-scaled precoder has been introduced to address the fact that crosstalk can be as large or larger than the direct channel, and non-linear precoders are being studied [2]. With two-sided coordination, the power penalty due to linear or non-linear precoding can be removed by exploiting the eigenmodes of the channel with singular value decomposition (SVD). In this scheme, both precoder and postcoder matrices are unitary matrices. Precoding at the transmitter rotates the signal vector without increasing the transmit power, and postcoding at the receiver rotates the received signal vector without noise enhancement. These operations diagonalize the channel, decomposing it into separate virtual sub-channels (the eigenmodes of the channel). The SVD transmission scheme can be interpreted as the coherent combination of the signals so as to achieve improved SNR. Variants for the precoder and equalizer matrices can be obtained based on singular value decomposition that take a minimum mean-square error criterion, rather than zero-forcing, or that take noise covariance into account.

Although XG-FAST is primarily a single-user technology, it does not preclude coordination at the central side among multiple bonded vectoring groups. In that case, zero-forcing may be applied across groups, while maintaining the above precoder and postcoder structure [15].

Full Duplex Transmission

In multi-user DSL deployments, simultaneous upstream and downstream communication on identical frequencies is made impossible by near-end crosstalk at the customer side of the network. When used as a single-subscriber technology, XG-FAST will have no NEXT between CPEs, hence allowing for simultaneous upstream and downstream on the same frequency, which we will refer to as full duplex, doubling the spectral efficiency compared to currently used time or frequency division duplexing schemes.

It requires an analog hybrid at the transceivers that attenuates the transmit signal to the level of or below that of the received signal, not to substantially increase the required dynamic range of the analog-to-digital converter. The residual echo signal is further removed digitally using vectoring techniques. Note that compared to TDD, full duplex transmission also allows a reduced latency and framing overhead.

Proof of Concept

In this section, we demonstrate the potential of XG-FAST with a hardware proof-of-concept platform. It incorporates the system concepts mentioned above: increased bandwidth, two-sided coordinated vectoring, bonding and phantom mode, and full duplex transmission. We also operate the system at an SNRM of 0 dB, which emulates the benefit of using TxCAM. The purpose of this demonstration is to show the raw potential of XG-FAST. It is not meant to be a fully optimized platform.

A 500 MHz baseband spectrum is used for the DMT signal, and forward error correction is provided using a (255, 239) Reed Solomon code. We show results for two duplexing schemes: TDD as in G.fast, and full duplex. The vectoring matrices are calculated based on channel data measured by transmitting a pilot sequence of 16 DMT symbols. The short length of the copper loops allows the use of a short cyclic extension (CE), which was never longer than 1.2 μs. The framing overhead is 6.25 percent for TDD, as in G.fast, and 3.47 percent for full duplex. The transmit power was never larger than 5 dBm per direction. The performance was measured on CAT5e cables (AWG-24 or 0.51 mm diameter) of length 30 m to 120 m, and on telephone cables provided by a European operator (0.6 mm copper diameter) of length 30 m to 130 m.

Figure 2 shows the aggregate (sum of upstream and downstream) net data rate (NDR) that was achieved on the different cables. The squares correspond to the CAT5e cables, and the stars correspond to the operator cables. The solid (blue) lines show the NDR over two pairs using bonding, phantom mode, and TDD; the dashed (orange) lines show the rate over a single pair using full duplex; the dotted (green) lines show the rate achieved over a single pair using TDD.

Using a single pair, an aggregate NDR of 5 Gb/s and 4.5 Gb/s is achieved on the shortest 30 m CAT5e and operator cable. Up to 70 m operator cable and 120 m CAT5e cable, it is possible to achieve an aggregate NDR exceeding 2 Gb/s, allowing for 1 Gb/s symmetric, which is an important milestone for data communication over a single telephone line.

Still using a single pair, but operating in full duplex instead of TDD, the aggregate NDR can be almost doubled to 9.7 Gb/s (CAT5e) and 8.8 Gb/s (operator cable) on the shortest loops. The reach of symmetric gigabit service is also greatly increased to 130 m, achieving a 2.5 Gb/s aggregate rate on operator cabling. The ratio of the full duplex rate over twice the TDD rate ranges from 83 percent to 98 percent for the different cables. Further improvements are expected by improving the analog front end of the transceivers.

When using TDD on two twisted pairs while exploiting bonding and phantom mode transmission, the aggregate NDR exceeds 10 Gb/s on a 30 m operator cable and a 50 m CAT5e cable. Note that the two pair measurements currently had to be performed with an inferior analog front end compared to the single pair measurements, yielding a downward bias in data rates. Compared to a single line rate with the same analog front end (not shown), bonding and phantom mode combined provide a gain between 2.6 and 2.8 for all cables, except for the 0.6 mm operator cable of 70 m, which yields a combined gain as high as 3.2 due to the MIMO benefits of vectoring with two-sided coordination.

The operator cables of 70 m and 130 m are only able to use 400 MHz and 250 MHz of signal bandwidth, respectively, due to the increasing channel loss with increasing length. Expanding the spectrum beyond 500 MHz yields modest improvements on the shortest cables. For example, expanding the bandwidth to 650 MHz and 800 MHz on the 30 m operator cable, respectively, allows a modest 400 Mb/s and 500 Mb/s rate increase per direction on top of the 4.5 Gb/s that is achieved over 500 MHz.

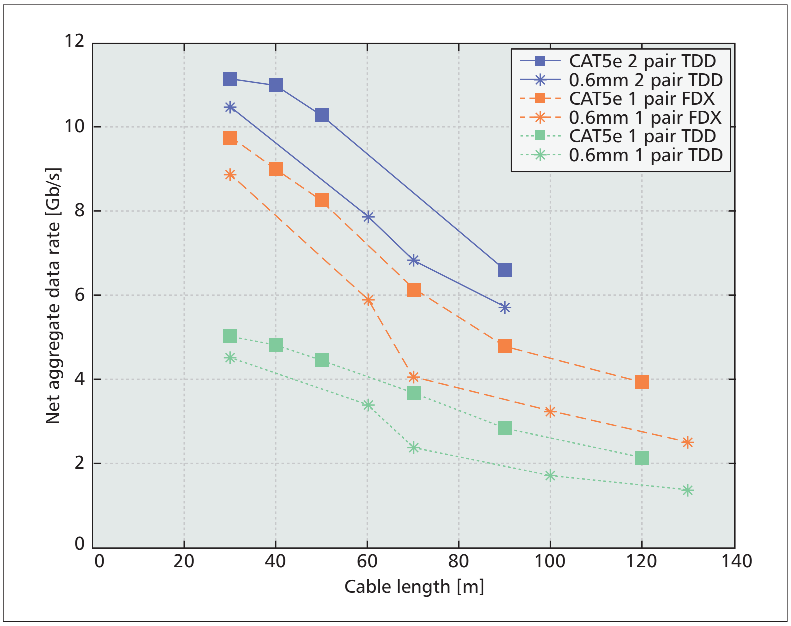

Figure 2. Rate-reach curve for CAT5e cables and 0.6 mm cables provided by a European operator on one and two twisted pairs with the proof-of-concept hardware platform.

We also performed measurements on a coaxial cable of RG6 type, which is a typical drop cable used in hybrid fiber-coaxial networks. The superior channel characteristics compared to twisted pair cabling make it possible to extend the reach of XG-FAST. An NDR of 5.38 Gb/s was achieved on a 20 m long RG6 cable using TDD and a transmit power of 3 dBm. Increasing the length of the RG6 cable to 100 m only reduced the NDR to 5.25 Gb/s using a transmit power of 7 dBm, indicating a nearly flat rate-reach curve for loop lengths up to at least 100 m.

Conclusion

In this article, we introduced the basic concepts of XG-FAST, a novel multi-gigabit transmission technology capable of transmitting more than 10 Gb/s over short copper pairs. One of the possible deployment scenarios for XG-FAST is FTTF (ONT-outside-the-home), in which XG-FAST is used as the next-generation DSL technology succeeding G.fast. The performance will depend on the cable quality and will gracefully degrade with increasing copper loop length, which is desired in brown field deployments that reuse an existing copper infrastructure.

We experimentally demonstrated an aggregate net data rate exceeding 8.8 Gb/s and 2.5 Gb/s over a single pair of, respectively, a 30 m and 130 m 0.6 mm twisted pair telephone cable from a European operator, using full duplex transmission and a signal bandwidth of 500 MHz. Using two pairs and time division duplexing instead of full duplex, we

The hybrid fiber-copper network with XG-FAST provides an ideal basis for dense deployment of 5G small cells. With uniform SDN control across fixed and wireless and the virtualization of functions within the access points, a single universal and programmable access point comes within reach.

demonstrated a 10 Gb/s rate using bonding and phantom mode transmission for loops up to 30 m.

As potential future work, the combination of full duplex transmission and multi-pair bonding and vectoring will be able to achieve aggregate rates exceeding 20 Gb/s, which is 10 Gb/s symmetric, on only two pairs. As a reference, 10GBASE-T delivers an aggregate data rate of 20 Gb/s over four pairs of CAT6 cable up to 55 m long. Other future work includes the exploration of vectoring schemes in a multi-user setting with multiple pairs per user (e.g. apartment buildings), and channel characterization of the installed copper plant for the high frequency range of 500 MHz considered for XG-FAST.

The hybrid fiber-copper network with XG-FAST provides an ideal basis for dense deployment of 5G small cells. With uniform SDN control across fixed and wireless and the virtualization of functions within the access points, a single universal and programmable access point comes within reach. The XG-FAST technology would complement fiber and next-generation 5G wireless technologies and be a further evolution of the G.fast technology. FTTF XG-FAST deployments will naturally allow the existing copper plant to serve both future wireline access and backhaul for 5G mobile technologies that are specified to operate at multi-gigabit data rates.

The fourth generation DSL technology, G.fast (G.9701), was recently standardized at ITU-T in December 2014. Ongoing efforts are focused on amendments for low-power modes and an updated band plan up to 212 MHz. Standardization of XG-FAST is beneficial, even though it is a single-user technology. The standardization of the physical layer helps grow the market for operators, leading to more cost-effective chip sets due to economies of scale. The physical layer of XG-FAST could leverage the consented ITU-T G.fast standard, requiring an updated band plan covering frequencies up to 500 MHz, or give rise to a new standard allowing for novel concepts to be included (e.g. adaptive modulation, multiple pairs, phantom mode, two-sided vectoring, full duplex). Special attention to transmit PSD limitations by the ITU Terrestrial and Radio groups will be required given the larger bandwidths used for signaling.

References

[1] Self-FEXT Cancellation (Vectoring) for Use with VDSL2 Transceivers, ITU-T Recommendation G.993.5, Apr. 2010.

[2] M. Timmers ***et al.***, "G.fast: Evolving the Copper Access Network," *IEEE Commun. Mag.*, vol. 51, no. 8, Aug. 2013, pp. 74–79.

[3] ***Fast Access to Subscriber Terminals (FAST) — Physical Layer Specification***, ITU-T Recommendation G.9701, Dec. 2014.

[4] P. Ödling ***et al.***, "The Fourth Generation Broadband Concept," ***IEEE Commun. Mag.***, vol. 47, no. 1, Jan. 2009, pp. 63–69.

[5] W. Coomans ***et al.***, "XG-FAST: Towards 10 Gb/s Copper Access," ***Proc. IEEE Global Commun. Conf. 3rd IEEE Wksp. Telecommunication Standards: From Research to Standards***, Austin, TX, Dec. 2014, pp. 630–35.

[6] C.-X. Wang ***et al.***, "Cellular Architecture and Key Technologies for 5G Wireless Communication Networks," ***IEEE Commun. Mag.***, vol. 52, no. 2, Feb. 2014, pp. 122–30.

[7] ***Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications — Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band***, IEEE Std. 802.11ad, Dec. 2012.

[8] A. Osseiran ***et al.***, "Scenarios for 5G Mobile and Wireless Communications: The Vision of the METIS Project," ***IEEE Commun. Mag.***, vol. 52, no. 5, May 2014, pp. 26–35.

[9] V. Jungnickel ***et al.***, "The Role of Small Cells, Coordinated Multipoint, and Massive MIMO in 5G," *IEEE Commun. Mag.*, vol. 52, no. 5, May 2014, pp. 44–51.

[10] B. Kozicki ***et al.***, "Software-Defined Networks and Network Functions Virtualization in Wireline Access Networks," *Proc. IEEE Global Commun. Conf. 3rd IEEE Wksp. Telecommunication Standards: From Research to Standards*, Austin, TX, Dec. 2014, pp. 595–600.

[11] K. J. Kerpez ***et al.***, "Software-Defined Access Networks," ***IEEE Commun. Mag.***, vol. 52, no. 9, Sept. 2014, pp. 152–59.

[12] Unified High-Speed Wireline-Based Home Networking Transceivers — System Architecture and Physical Layer Specification, ITU-T Recommendation G.9960, Dec. 2011.

[13] M. Timmers ***et al.***, "Transmitter-Controlled Adaptive Modulation: Concepts and Results," *Bell Labs Tech. J.*, vol. 18, no. 1, 2013, pp. 153–69.

[14] J. Neckebroek ***et al.***, "Comparison of Error-Control Schemes for High-Rate Communication over Short DSL Loops Affected by Impulsive Noise," *Proc. IEEE Int. Commun. Conf.*, Budapest, Hungary, June 2013, pp. 4014–19.

[15] R. B. Moraes ***et al.***, "DMT MIMO IC Rate Maximization in DSL with Combined Signal and Spectrum Coordination," *IEEE Trans. Signal Proc.*, vol. 61, no. 7, July 2013, pp. 1756–69.

Biographies

Werner Coomans (werner.coomans@alcatel-lucent.com) has been an access technology researcher at Bell Labs since 2013. His research focuses on next-generation fixed access technologies over copper. Prior to joining Bell Labs he obtained master and Ph.D. degrees in engineering sciences, with a focus on semiconductor lasers, from the Vrije Universiteit Brussel (VUB).

Rodrigo B. Moraes [S'08, M'14] obtained the bachelor degree at the UFPA, Belém, Brazil, in 2005, the M.Sc. degree at the Pontifical Catholic University, Rio de Janeiro, Brazil, in 2009, and the Ph.D. degree in 2014 at the KU Leuven, Belgium, all in electrical engineering. Since 2014 he has been a research engineer at Bell Labs, Alcatel-Lucent, in Antwerp, Belgium. He has received best paper awards at IEEE ICC (2013) and IEEE Globecom (2014).

Koen Hooghe received an electrotechnical engineering degree from the University of Ghent. He is a hardware expert with Bell Labs Access Node Technology and has participated in the development of access systems and core routers as a hardware designer, project lead, and systems architect. He has been involved in research for next-generation access nodes at the physical layer, packet processing, systems architecture, and energy efficiency improvements. He contributed to the ETSI Environmental Engineering standards group.

Alex Duque received a BSEE degree from Lehigh University and an MSEE degree from Worcester Polytechnic Institute. He began his career designing communication satellite hardware for Lockheed-Martin Corporation. He then designed cell phone modem ASICs for Lucent Technologies. In 1998 he shifted from the Consumer Products Division into various research groups within Bell Laboratories, where he continues to develop ASIC and FPGA designs both for research projects and for Alcatel-Lucent products.

Joe Galaro joined Bell Labs in 1990, after spending 10 years with Lockheed Electronics working on DSP, ASIC, and hardware design for aircraft, satellite, and shipboard systems. In his tenure at the labs he developed various technologies providing higher bandwidth data transmission. These technologies have included dial-up modems, ISDN, cable modem CMTS, DSL, HD IBOC radio, XGPON, and XG-FAST. He provides significant hardware design experience (circuit design, FPGA, and ASIC) as well as system architecture insights.

Michael Timmers is a technology strategist in the Fixed Networks Division of Alcatel-Lucent turning ideas into reality by closely engaging with research, development, and customers. Previously, he researched and prototyped the latest DSL advancements in Bell Labs Access Research Domain in Antwerp, Belgium. He received an M.S. in engineering from Katholieke Universiteit Leuven in 2005, and a Ph.D. with a dissertation on cognitive radio in 2009 at the Interuniversitary MicroElectronics Center (IMEC) in Belgium.

Adriaan J. van Wijngaarden [S'87, M'98, SM'03] is a research scientist at Bell Laboratories, Murray Hill. He has been deeply engaged in theoretical and application-driven research in communications, information theory, coding, and algorithmic optimization, and provided key contributions to optical transport and access networks. He has more than 75 publications and 65 patents. He is a co-recipient of the Bell Labs President's Award (2011) and a best paper award (Globecom, 2014).

Mamoun Guenach (guenach@gmail.com) has been a research scientist at Bell Labs, Alcatel-Lucent, since 2006. He received the degree of engineer in electronics and communications from the Ecole Mohamadia d'Ingénieurs in Morocco. Following that, he moved to the faculty of applied sciences at the Université Catholique de Louvain (UCL) Belgium, where he received an M.Sc. degree in electricity and a Ph.D. degree in applied sciences. Since 2015 he has been a part-time visiting professor at Ghent University.

Jochen Maes (jochen.maes@alcatel-lucent.com) [SM'11] joined Bell Labs in 2006, where he continuously shifts the limits of copper. He holds an M.Sc. in physics and a Ph.D. in science. He heads the Copper Access team within the Fixed Networks program, focused on leveraging legacy infrastructure through innovations in systems and transceiver design. He contributes to several ITU standards. His work has received Broadband Infovision Awards (2010, 2014) and the Bell Labs President's Award (2011).