The Fourth Generation Broadband Concept

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ABSTRACT

Fixed-broadband access technology is evolving from exclusively copper-based solutions to hybrid fiber-copper architectures. This article presents the expected next step in the evolution of broadband systems, which we call the fourth-generation broadband concept. It identifies a technical, infrastructural, and economical niche and describes how the fiber-access network is extended and forked to feed a last and ultimate generation of DSL systems, shown to have gigabit potential. The underlying infrastructural concept is presented, economic aspects are described and discussed, and achievable data rates are calculated.

INTRODUCTION

The quality of life and modern economy depends more and more on the availability of ubiquitous low-cost broadband access. The demand on end-user data rates keeps increasing, which fuels the development and deployment of new systems. An analysis of this evolutionary process reveals that there is a gap — a missing, not foreseen system generation — to which we devote this article. The study presented in the following suggests labeling the missing generation as Generation 4.

Our classification of broadband systems into generations includes only broadband systems operating on the twisted-copper pairs of the public telephony network and optical fiber, namely, digital subscriber line (DSL) systems and fiber access systems. The future, as the present, certainly also will see other technologies such as coaxial-cable access systems (using cable-TV infrastructure) or fixed wireless access systems, but these are beyond the scope of this presentation.

In Fig. 1, the principle deployment history for broadband access equipment is illustrated. Note that the classification of systems as generations in Fig. 1 is introduced to define and emphasize a gap in the foreseen broadband evolution and is not a generally accepted terminology. The term broadband access equipment, for example, loosely denotes communications equipment that is intended for Internet access with a permanent connection, that is, post dial-up systems. During the last two decades, two generations of broadband access systems for telephone loops were deployed: Generation 1, which is mainly based on integrated services digital network (ISDN) [1], and Generation 2, which is mainly based on asymmetric DSL (ADSL) [2]. Both generations are characterized by systems deployed from the central office. Generation 1 marked the start of data communication beyond dial-up modems, whereas Generation 2 added a "real" transport network and user bandwidths that are comfortably greater than voiceband modems.

Today, we are seeing the launch of the third-generation broadband access system — the very-high-bit-rate DSL (VDSL) family [2] — that will provide customer data rates of up to 100 Mb/s. Whereas ADSL operates from the central office, often over cables that are several kilometers long, VDSL is designed to operate over shorter loops. Therefore, the VDSL equipment is normally placed in cabinets, resulting in a typical loop length that is below one kilometer. The backhaul solution, namely, the technology to bring data between the transport network and the cabinet, is almost exclusively based on optical fiber technology today. The transition from the second generation to the third generation thus implies an extension of the fiber network from the central offices to the cabinets. This is a first and fundamental step toward building a large-scale fiber-to-the-home (FTTH) infrastructure.

The fourth generation, presented and discussed here, is nothing more than the logical extension of the thinking behind Generation 3. The communication requirements of the future are assumed to require data rates an order of magnitude higher than Generation 3, that is, a step from around 100 Mb/s to around 1 Gb/s. To deliver these data rates using the in-place copper architecture requires even shorter loops. The key question is whether or not there exists a natural place to deploy the new transmission equipment in an economical fashion.

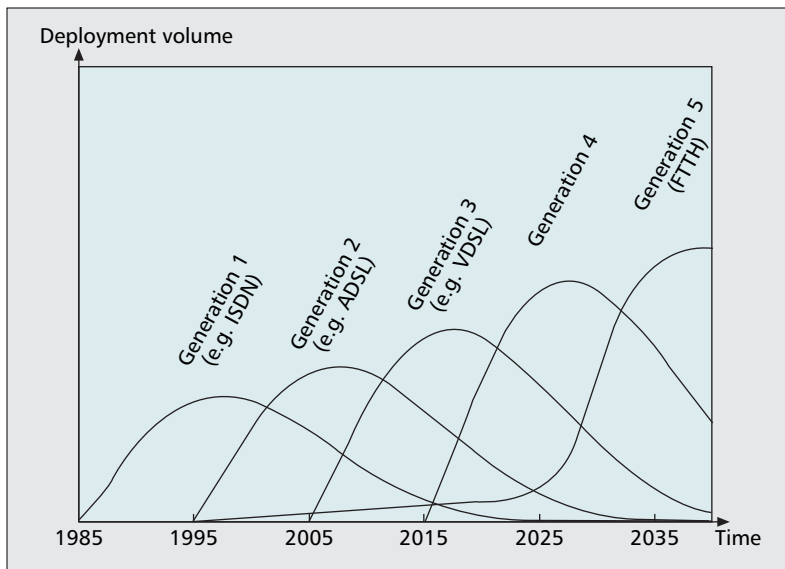With the fourth generation broadband con-

■ Figure 1. *A sketch of deployment volumes of broadband access techniques (number of new installations or upgrades per time unit). The time axis is based on historical data (up to present time), while the y-axis is no more than an illustration of trends.*

cept (4GBB), we present the "last" distribution point (DP) as a candidate from which broadband services could be delivered in a technically and economically feasible fashion. The copper plant is a star network, forking out into finer and finer segments (fewer and fewer lines running together) until eventually individual twisted pairs reach their respective user premises. The last DP can be found by following the lines from the users' homes and backwards into the network, where normally after 20 to 200 m you find a point in which a number of lines merge together and form a bundle. This is the most outward point at which a modem pack can be installed serving a number of customers, for example, 10 to 30. The last DP was considered as early as 1990, in the form of fiber-to-the building (FTTB) and fiber-to-the-curb (FTTC) discussions, but at the time it was not associated with a corresponding new generation of copper-access (DSL) equipment making full use of the greater bandwidth offered by the shorter loops. The earlier FTTB and FTTC discussions left few marks in the standardization processes and were essentially abandoned.[1] We believe that it may be time to develop the idea of moving to the last DP, but now dressed in modern technology and based on twenty years of experience from the development of the broadband market.

A natural question is, of course, how much this infrastructural quantum leap will cost, especially in comparison with installing optical fibers all the way out to the customer, that is, fiber-to-the home (FTTH). We return to this in the next section.

Figure 1 contains historical data for Generations 1 to 3 and predictions of the deployment timescale for the fourth and the fifth generation broadband. So far, the transition between any consecutive pair of earlier generations has taken about ten years. This suggests that the process that leads to the creation of a new generation broadband has a period of ten years, based on the lead time in standardization and product realization.

The supported data rate increases by roughly an order of magnitude from generation to generation. This also applies to the step from voiceband modems, which can be viewed as Generation 0 to Generation 1. The step to fourth generation broadband (4GBB), using the last DP and possibly, vectoring technology [3], will provide data rates on the order of 1 Gb/s, that is, 10 times the data rate of Generation 3 (e.g., VDSL2 with up to 100 Mb/s).

Applying the above argument to 20 years from now, the bandwidth demand by then should increase another order of magnitude to 10 Gb/s per household, serving as a view toward the technical specifications of Generation 5 — FTTH. According to the prediction in Fig. 1, the deployment volume of the fifth generation gradually will increase, exhibiting a peak around 2035.

HYBRID FIBER-COPPER-BASED BROADBAND ACCESS NETWORK

In most operational telecom networks, the topology of the access loop looks like the example network situation depicted in Fig. 2, where one primary cable connects the central office (CO) to various street cabinets (in the block labeled DP in CAB, meaning distribution point in cabinet), and from there, stepwise forking out to reach the users' premises.
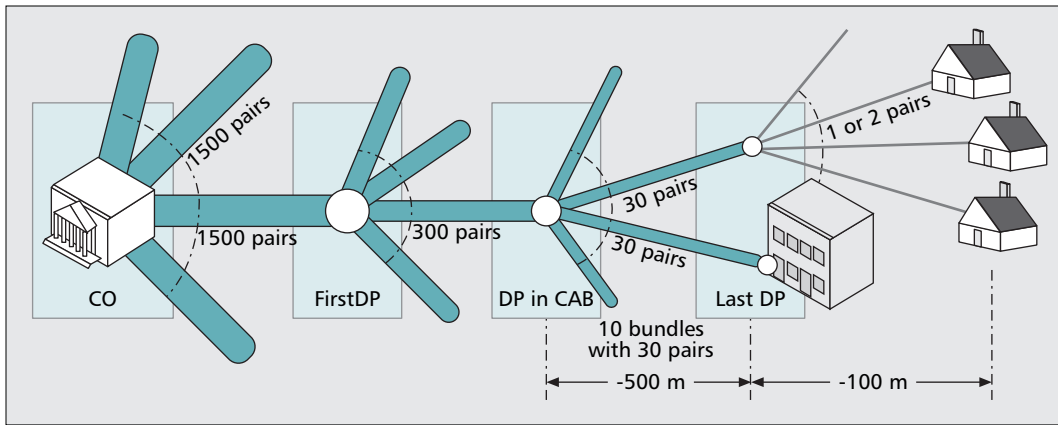
The average length of a copper pair, connecting the customer with the CO, ranges from 1.5 km to 3 km depending on country and area. This distance is the main obstacle to increasing the bandwidth from Generation 2 systems, where best-in-class is ADSL2+ — in practice, normally providing between 10 and 20 Mb/s to the higher bit rates offered by Generation 3 — today, VDSL2 provides up to 100 Mb/s per copper pair. By placing the transmission equipment in cabinets, it is possible to reduce the average length to less than 1 km (Fig. 2). Then, the cabinets typically are connected to the CO using optical fiber and to the users with VDSL2.

The 4GBB is the next logical step to shorten the loops, increase the bandwidth, and extend the optical-fiber access network. The transmission equipment then would be placed in the last DP, labeled as Last DP in Fig. 2, and typically connected to the CO with newly deployed fiber. The user still will be linked to the last DP by means of a copper pair.

The alternative to the concept of 4GBB described here is to deliver the fiber all the way out to every customer, that is, FTTH, or a fifth generation system, in our terminology. The problem with all deep-fiber strategies, and the reason why the technique is detained, is the cost of deploying the fiber.

According to the techno-economic investment evaluations in [4], the deployment of FTTH can be justified only in particularly dense urban areas, whereas the cost of deploying fiber to the last DP is moderate. As a rough estimation, using the example of Fig. 2, replacing the copper from the cabinet to the last DP will imply

[1] *It was recently pointed out by British Telecom researchers that technology developments soon will make it feasible to exploit the "last" DP to deliver broadband services, spawning the work presented here.*

■ Figure 2. *Access network topology and deployment scenario. This particular cable serves the outskirts of a small city in Sweden.*
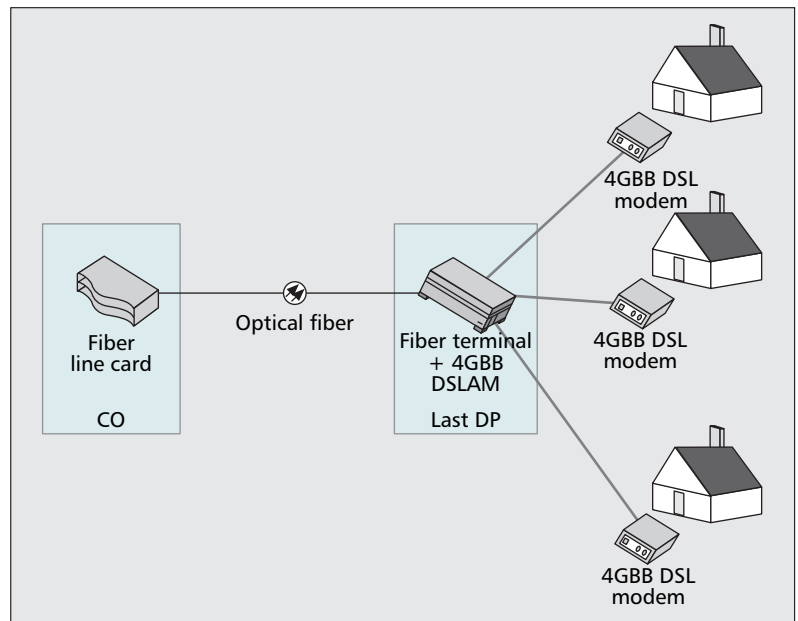
digging 5 km (500m × 10 bundles), whereas replacing the cabling from the last DP to each house will mean an additional 30 km/cabinet (100m × 30 × 10). If we consider the average cost for digging and ducting at €105,000/km, then the cost is €0.515 million for the fiber required for 4GBB, whereas an extra €3.15 million must be added to the cost for FTTH. This cost difference is the key realization that there is a niche for a 4GBB system.

THOUGHTS ON BACKHAUL SOLUTIONS

The connection between the 4GBB equipment and the CO can be realized in more ways than using optical fiber. Although this is not central to the 4GBB concept, it is a field of possible innovation.

If the 4GBB concept was to be deployed today, it is likely that a passive optical fiber network (PON) architecture (Fig. 3) would offer the most cost-effective solution. This solution could be reasonably "future proof" in that, without additional investments in fiber, the optical transmission equipment could be upgraded, for example, from gigabit-PON (G-PON) to 10G-PON, when such new technology becomes available.

However, it could become an option to use the copper binder between the CO and the last DP as a backhaul solution (Fig. 4), thereby avoiding or postponing the cost of digging. With multiple-input multiple-output (MIMO) schemes [5] applied to cancel crosstalk and spatially correlated noise, our 30 pair binder could be converted to a 60 × 60 or 59 × 59 MIMO channel depending on whether or not the binder shield can be used. Such a copper backhaul solution could be suitable for shorter ranges, for example, supporting several Gb/s from the cabinet to the last DP [6]. This scheme then would be similar to the copper alternative (Cu)PON concept proposed by Cioffi *et al.* [7], in the sense that the copper is shared, but different in the sense that we use the shared DSL system only for the backhaul from the cabinet to the last DP. An interesting side effect of this solution is that the 4GBB equipment at the last DP could be powered on the same copper wires as used by the MIMO binder.
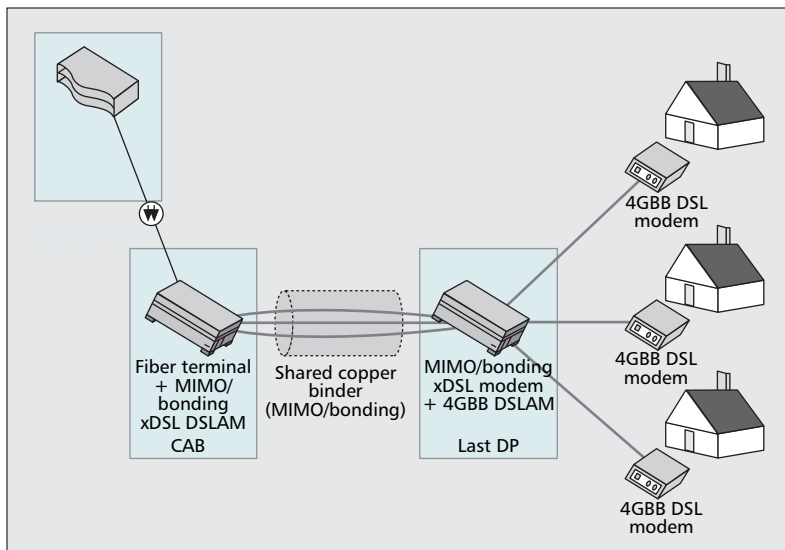

■ Figure 3. *Topology with fiber to the last DP.*

A THROUGHPUT PREDICTION

The previous section established the feasibility of the new 4GBB hybrid fiber-copper topology at an affordable cost of investment per customer. This section presents a projection of the achievable throughput connecting the last DP and the customer.

Electromagnetic compatibility of interacting equipment and services imposes major limitations for the achievable data rates. Data transmission over wires causes radiation and potentially disturbs nearby equipment. This undesirable effect is referred to as *egress* and limits the applicable transmit power spectral densities (PSDs). Reversely, cables, in particular aerial drop wires, pick up extrinsic disturbances (generated outside the cable), referred to as *ingress*. Lacking dedicated ingress and egress regulations, we derive realistic ingress levels and transmit PSD masks from ingress and egress limits defined in the existing international standard on radio interference [8], hereafter referred to

■ Figure 4. *Topology where a shared copper binder is used between cabinet and last distribution point.*

as CISPR-22.[2] Together with wideband cable models [9], these transmit PSDs, and the ingress levels provide the basis for throughput predictions.

REGULATORY AND LEGAL ASPECTS

Ingress and egress mechanisms, described in [10], can be roughly described as follows: transmission of data over a wire pair is performed by differential excitation of the pair (i.e., excitation of the circuit formed by the two wires of a pair). Due to the imperfection of the geometrical and consequently, also of the electrical, symmetry of each wire pair with respect to the earth, the differential signal causes a corresponding common-mode excitation of the wire pair (i.e., excitation of the circuit formed by the wire pair constituting a single conductor and earth). The pair of wires then acts as a transmit antenna and causes unwanted egress. The degree of symmetry (or asymmetry) causing the differential-mode to common-mode conversion, an important property of a wire pair or a cable, is referred to as *balance* and quantified by the ratio of the corresponding voltages or currents. Although the balance can reach values around 70 dB in the voiceband (i.e., in the kHz range), it decreases significantly with increasing frequency [5]. Extrapolating measurement results collected for frequencies up to 30 MHz, the conservative assumption that the balance decays linearly from 35 dB in the voiceband to 25 dB at 100MHz is adopted hereinafter.

Conversely to egress, a time-varying electromagnetic field in the vicinity of a wire pair causes a common-mode excitation of both wires with respect to earth. The wire pair simply acts like a receive antenna. The balance, which is a reciprocal property, determines the amount of resulting differential-mode ingress caused by common-mode to differential-mode conversion.

As a principal assumption, [10] suggests that an electromagnetic field with electric field-strength *x* volt/m causes an induced worst-case common-mode voltage of *x* volt — an observa-

tion that is based mainly on experience gained through measurements both in the laboratory and in the field. Independent theoretical and experimental work [11, 12] supports this observation to an extent large enough to warrant application for throughput predictions.

Egress — For the frequency range 0–30 MHz, the invoked egress limits orientate themselves on the standardized VDSL band plans, adopting the transmit PSD limit of –60 dBm/Hz. The standard CISPR-22 suggests a quasi-peak limit for radiation caused by an electric appliance measured at a distance of 10 m. The limit, which is specified in terms of electric field strength, is 30 dBµV/m measured in any band of 9 kHz width in the frequency range 30–230 MHz. A transmit PSD below –63 dBm/Hz ensures that this limit is on average not violated, assuming a balance of 30 dB.

It is pointed out in [10] that radiated emission with a field strength as low as 0 dBµV/m might be detected by and thus cause disturbance for radio receivers. Consequently, it is reasonable to assume a transmit PSD that decays linearly with frequency from –60 dBm/Hz at 30 MHz to a value at 100 MHz that ensures a field strength below 12 dBµV/m, which is the level caused by today's modems in the amateur radio bands. Standardized band plans limit the PSD within these bands to –80 dBm/Hz. The impact of these bands on the throughput analysis is insignificant and thus neglected. Figure 5 depicts the resulting transmit PSD mask (dashed-dotted line) and the corresponding receive PSDs (solid lines) for different loop lengths.

Ingress — Reversely of the egress mechanism, the wires pick up radiation caused by devices operating in close vicinity. Assuming that these devices operate at the radiation limits suggested by the CISPR-22 standard, the resulting ingress PSD[3] is roughly –133 dBm/Hz for a balance of 30 dB, which is a level comparable to background noise. Apart from the radiation-induced interference, there is disturbance caused by conducted common-mode interference. Assuming that the wire pair obeys the limits suggested by CISPR-22, the resulting ingress PSD[4] is roughly –90 dBm/Hz for a balance of 30 dB. Instead of an ingress level of –133 dBm/Hz, which corresponds to an ingress-free environment and is a rather unrealistic scenario, –110 dBm/Hz is assumed to characterize the situation of *moderate* ingress. A level of –90 dBm/Hz, on the other hand, characterizes *strong* ingress and appears to be a rather pessimistic assumption. Although radio interference is an issue for currently deployed DSL systems that operate mainly at frequencies below 10 MHz, ingress levels observed in the field are far below the worst-case CISPR-22 level mentioned previously. To summarize: the two levels should embrace ingress levels encountered in practice and serve as a basis for throughput predictions.

In a far-end cross-talk (FEXT)-free environment, a background-noise PSD of –130 dBm/Hz is, though conservative, a widely accepted value for frequencies up to 30 MHz. Aiming at assumptions that can be referred to as realistic

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[2] *Comité international spécial des perturbations radioélectriques.*

[3] *An electric field strength of 47 dBµV/m causes a differential-mode voltage of 7.08 µV (balance 30 dB), which corresponds to a PSD of roughly –133 dBm/Hz in 100 Ohm over a measurement bandwidth of 9 kHz.*

[4] *A conducted common-mode voltage of 90 dBµV causes a differential-mode voltage of 1 mV (balance 30 dB), which corresponds to a PSD of roughly –90 dBm/Hz in 100 ohm over a measurement bandwidth of 9 kHz.*

to conservative, a linear transition (in log domain) from the background-noise level at lower frequencies to the CISPR-22 ingress level at higher frequencies is assumed in the range from 10 MHz to 30 MHz. The resulting noise PSD for a FEXT-free environment is shown in Fig. 5 (dotted line).

As discussed in the previous section, the cable segments at the customer end of the access network exhibit short lengths and a low number of pairs. Consequently, it is reasonable to assume that the number of expected crosstalkers is low. Apart from the FEXT-free case, a scenario with both ingress and one equal-length FEXT disturber is considered.

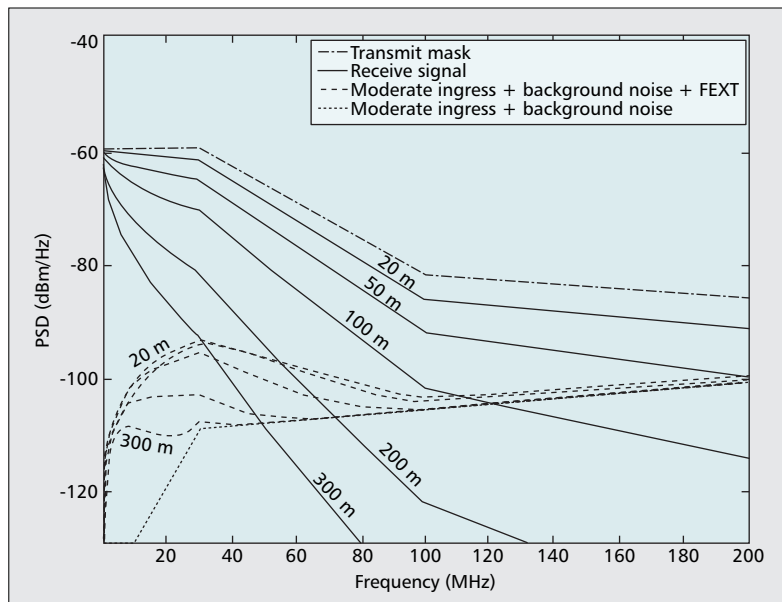### PHYSICAL-LAYER TECHNIQUES ON THE LAST DROP

In the following, we briefly survey technology options for the link between the last DP and the customer. In general, the cables bridging this gap are short. Consequently, the exploitable bandwidth by far exceeds the 30 MHz-range used today by VDSL2.

MIMO Signaling — In many (if not most) countries, there are cables with two twisted pairs connecting the last DP with the customers' premises. Thus, apart from bandwidth, there also is the "spatial dimension" that can be exploited.

MIMO techniques applied to wireline transmission, in combination with multicarrier modulation, diagonalize the spatial channel on a per-subcarrier basis. Each spatial subchannel is described by a matrix. Diagonalization eliminates the off-diagonal elements, which model the FEXT coupling, and thus turns the FEXT-limited channel into a background-noise limited channel. FEXT caused by neighboring lines that are not part of the MIMO system remains and can be handled using the technique discussed next.

Dynamic Spectrum Management (Type Level 3/Vectoring) — Whereas MIMO techniques require collocation of wire pairs on both sides of the cable, the most advanced form of dynamic spectrum management (DSM), referred to as level-3 DSM or vectoring [3], requires collocation of wire pairs on only one of the two sides. In cases where MIMO techniques are not applicable, vectoring techniques potentially eliminate FEXT by pre-coding and interference cancellation in downstream and upstream direction, respectively.

Split-Pair/Common-Mode Signaling — Recent research suggests abandoning the twisted-pair concept and adopting a multi-conductor view: instead of using the K differential modes of a K-pair cable, $2K - 1$ independent transmission modes can be exploited using so-called split-pair modes [13]. Together with FEXT-eliminating techniques, split-pair signaling can yield throughput gains proportional to the ratio of exploited modes. Clearly, the ingress/egress issue is critical because split pairs are not twisted. However, cable shields could mitigate the problem.

■ **Figure 5.** *Transmit and receive power spectral densities (PSDs): The uppermost line (dashed-dotted) is the transmit PSD mask, followed by receive PSDs (solid lines) for loop lengths 20 m, 50 m, 100 m, 200m, and 300m (AWG24/0.5 mm). Transmission is impaired by moderate ingress (–110 dBm/Hz), FEXT from one equal-length crosstalker, and background noise (–130 dBm/Hz).*
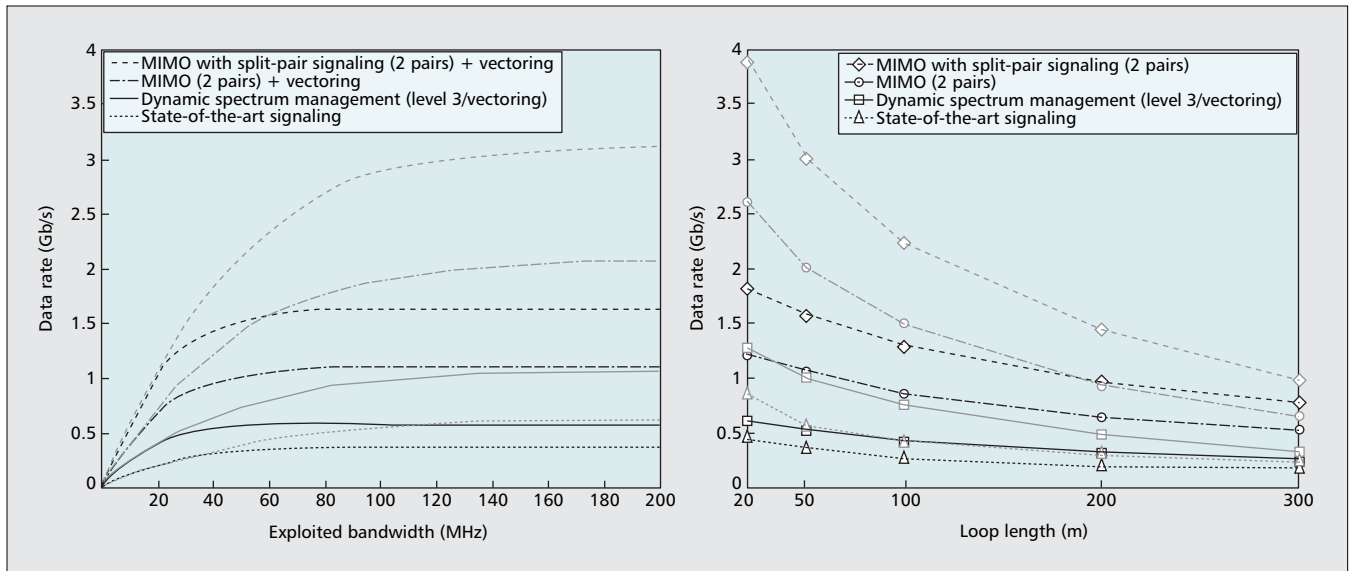
THROUGHPUT LIMITS

After the constraints in the form of transmit PSD, ingress PSD, and background-noise level are found, the computation of the achievable data rate is straightforward [2]. A signal-to-noise ratio gap of 9.5 dB is assumed, which yields the throughput achieved with uncoded quadrature amplitude modulation (QAM) transmission at a bit error rate of 10^{-7}, from which state-of-the-art channel coding would reduce the bit error rate to low enough levels for all common services. The results presented in the following represent aggregate downstream and upstream data rates.

The following technology options for the link from the last DP to the customer are compared:
• State-of-the-art (differential-mode) signaling over one twisted pair (existing solution)
• State-of-the-art signaling over one twisted pair in combination with vectoring
• State-of-the-art MIMO signaling over two twisted pairs in combination with vectoring
• Split-pair MIMO signaling over two twisted pairs in combination with vectoring

The achievable data rate versus exploited bandwidth is depicted in Fig. 6 (left plot) for a 50-m drop-wire. In general, the data rate increases rapidly with frequency for low frequencies and flattens out for high frequencies. Exploiting the bandwidth up to frequencies where the data rate flattens out, yields the throughput versus loop length depicted in Fig. 6 (right plot). Exploiting the available bandwidth with state-of-the-art signaling is not sufficient to approach the Gb/s-limit. Very short loops in combination with vectoring, however, support data rates around 1 Gb/s. MIMO techniques and signaling via split-pair modes exceed the

■ **Figure 6.** *Left: Throughput over a 50m drop-wire vs. exploited bandwidth for different technology options and both strong ingress (–90 dBm/Hz, black lines) and moderate ingress (–110 dBm/Hz, gray lines); right: throughput vs. loop length.*

Gb/s-limit in the presence of strong ingress and boost the throughput to several Gb/s in the presence of moderate ingress.

CONCLUSIONS

In many countries, more than one third of the population regularly uses the Internet. In addition to the tremendous residential usage, the market for small- and medium-size enterprises is growing. The capacity within the backbone networks is virtually unlimited (at least in the sense that it is economically feasible to upgrade it to match virtually any need), leaving the transmission bottlenecks located within the first mile. The development of broadband services markets worldwide is thus dependent on having access networks that live up to the vision of the future society. In this area, a key enabler for the development of society, few new concepts have been presented. Notable exceptions are the work of Cioffi [7, 13], to which the 4GBB concept presented in this article is a natural complement.

Today, broadband strategies beyond VDSL2 are based on telecom operators eventually deploying FTTH to meet future bandwidth demands. Although fiber offers the greatest potential as an access medium, deployment is hampered by prohibitively large investment costs. While remedies for this are sought, copper still has an important role to play, with the 4GBB system as a candidate for bridging the gap between today's VDSL2 and FTTH. New fiber-copper-based systems that carry a partial investment in extending the fiber network manage a smooth migration from legacy networks to an all-fiber-optic network of the future.

Taking advantage of last distribution points close to the customer, exploiting the available bandwidth, and employing advanced signal processing techniques provides data rates on the order of Gb/s to the customer.

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BIOGRAPHIES

PER ÖDLING received his Ph.D. in Signal Processing in 1995 from Luleå University of Technology, Sweden. In 2000, he was awarded the Docent degree from Lund Institute of Technology, and in 2003 he was appointed Full Professor there. From 1995, he was an Assistant Professor at Luleå University of Technology, serving as Vice Head of the Division of Signal Processing. In parallel, he consulted for Telia AB and ST-Microelectronics, developing an OFDM-based proposal for the standardization of UMTS/IMT-2000 and VDSL for standardization in ITU, ETSI, and ANSI. Accepting

a position as Key Researcher at the Telecommunications Research Center, Vienna in 1999, he left the arctic north for historic Vienna. There, he spent three years advising graduate students and industry. He also consulted for the Austrian Telecommunications Regulatory Authority on the unbundling of the local loop. He is, since 2003, a Professor at Lund Institute of Technology, stationed at Ericsson AB, Stockholm. For two years he served as an Associate Editor for the IEEE Transactions on Vehicular Technology. From August 2008 he is, part time, the secretary of the Industrial Research Committee of the Royal Swedish Academy of Engineering Sciences. He has published more than fifty journal and conference papers, thirty-five standardization contributions, and a dozen patents.

THOMAS MAGESACHER received his Ph.D. degree in Signal Processing in 2006 from Lund University, Sweden. He spent the year 2007 as post-doctoral fellow at the Electrical Engineering Department, Stanford University, USA. He has five years of professional experience in the semiconductor industry working on the design and implementation of communication algorithms and he has been involved in several startup ventures. He serves as an editor of the ELSEVIER International Journal on Electronics and Communications. Currently, he is an assistant professor at Lund University funded by the Swedish Research Council. His research interests include information processing, multi-conductor channel modeling, and applied optimization theory.

STEFAN HÖST received his Ph.D. in information theory in 2000 from Lund University, Sweden. Since February 2000 he has a position as Associate Professor at the department of Electrical and Information Technology at Lund University. His research interests covers modulation techniques, DSL-technologies, error correcting codes and signal processing.

PER OLA BÖRJESSON received his Ph.D. degree in telecommunication theory in 1980 from Lund University, Lund, Sweden. In 1983, he received the degree of Docent in telecommunication theory. Between 1988 and 1998, he was Professor of signal processing at Luleå University of Technology. Since 1998, he is Professor of signal processing at Lund University. Currently he is researching loop qualification and Orthogonal Frequency Division Multiplexing (OFDM) or Discrete Multitone (DMT) Modulation at Ericsson DSL-lab. His primary research interest lies in high-performance communication systems, in particular, high-data-rate wireless and twisted-pair systems. He emphasizes the interaction between models and real systems, from the creation of application-oriented models based on system knowledge to the implementation and evaluation of algorithms. He has filed about 10 patents and has published more than 50 original refereed scientific papers and conference papers, among them highly cited works concerning synchronization and channel estimation for OFDM systems.

MIGUEL BERG received a Lic. Eng. in 1999 and a Ph.D. in wireless communication systems in 2002 from the Royal Institute of Technology in Stockholm, Sweden. Currently he is working as a team leader for research on DSL line testing and copper plant management at Ericsson Research. He is actively involved in a number of research projects in the area of broadband access and has published a number of scientific papers, patents, and standardization contributions.

Enrique Areizaga is the Broadband Networks manager at Robotiker-tecnalia. He is responsible for directing and leading the company's business in the broadband markets. He supervises the Robotiker's strategic cooperation with carriers around the world and leads several projects with leading carriers defining future broadband access solutions. He received his M.Sc. degree in Physics in 1989 from the Basque Country University, Spain. He spent the year 1989 as grant holder at the Dr. Neher Laboratories (currently TNO) in The Netherlands. He has more than 20 years of professional experience in the telecommunications industry. He has collaborated as reviewer and evaluator in several national and international programs, and has coauthored more than 20 conference papers.