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Rainer Strobel
Intel Connected Home Division
Munich, Bayern
Germany

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Preface

The twisted pair access network is still the main technology for fixed Internet access, and even most of the wireless data traffic is offloaded via Wi-Fi and other wireless home networking technologies to the fixed access network. To satisfy the increasing demand for high bandwidth in the access network while keeping the deployment costs low, hybrid networks of fiber to the distribution point (FTTdp) are a promising technology and give an interesting field of innovation.

To achieve gigabit per second data rates on low-quality phone wires, significant improvements of the DSL technology are required. Besides higher data rates, low power consumption is another important requirement to enable the design of small distribution point units without local power supply. The G.fast technology is designed to address both, higher data rates and low power consumption.

This book covers three major fields of innovation, which are the basis for the G.fast technology: the characteristics of the twisted pair copper channel and MIMO channel modeling at the frequencies used for G.fast, physical layer optimization to achieve high data rates on twisted pair copper cable binders, and discontinuous operation to reduce power consumption.

The work on this dissertation started in 2011 at the time, when discussions in the ITU standardization on a next-generation DSL technology after VDSL2 Vectoring started. This gave the opportunity to work on the technology from the first pre-standardization investigations toward the availability of first products implementing the G.fast technology. It was my intention to cover implementation as well as research aspects in this work and to bring recent signal processing and communications research into practice.

I would like to thank Professor Wolfgang Utschick and the colleagues at the university for good discussions, ideas, and an inspiring environment. At the company, Intel, I would like to thank my colleagues for their support which allowed me to get insights into the "real world" of chip development and systems engineering for access networks. And I would like to thank my family and my friends for their support.

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Rainer Strobel

Contents

Acronyms

ADC	Analog-to-digital converter
ADSL	Asynchronous digital subscriber line
AFE	Analog front-end
ATIS	Alliance for Telecommunications Industry Solutions
AWGN	Additive white Gaussian noise
BER	Bit error rate
BS	Bit swap
BT	British Telecom
CA	Crosstalk avoidance
CDF	Cumulative density function
CE	Cyclic extension
CP	Cyclic prefix
CS	Cyclic suffix
CU	Coefficient update
DAC	Digital-to-analog converter
DC	Direct current
DF	Data frame
DFE	Digital front-end
DFT	Discrete Fourier transform
DMT	Discrete multi-tone
DO	Discontinuous operation
DOI	Discontinuous operation interval
DP	Distribution point
DPBO	Downstream power back-off
DPC	Dirty paper coding
DPU	Distribution point unit
DRA	Dynamic resource allocation
DSL	Digital subscriber line
DTAG	Deutsche Telekom
DTU	Data transmission unit

EL-FEXT	Equal length far-end cross talk
ETSI	European Telecommunication Standards Institute
FDD	Frequency-division duplexing
FEXT	Far-end cross talk
FFT	Fast Fourier transform
FRA	Fast rate adaptation
FTTB	Fiber to the building
FTTC	Fiber to the curb
FTTdp	Fiber to the distribution point
FTTH	Fiber to the home
FTU	Fast transceiver unit
FTU-O	FTU at the optical network side
FTU-R	FTU at the remote side
GPON	Gigabit passive optical network
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LD	Line driver
LMS	Least mean squares
LSB	Least significant bit
MIMO	Multiple input–multiple output
MISO	Multiple input–single output
MMSE	Minimum mean squared error
MSB	Most significant bit
MSE	Mean squared error
NEXT	Near-end cross talk
NOI	Normal operation interval
OSI	Open Systems Interconnection
PAM	Pulse amplitude modulation
PBO	Power back-off
PE	Polyethylene
PMD	Physical media dependent
PMS-TC	Physical media specific transmission convergence
PON	Passive optical network
PSD	Power spectral density
QAM	Quadrature amplitude modulation
RMC	Robust management channel
RPA	RMC parameter adjust
RS	Reed–Solomon code
SDSL	Synchronous digital subscriber line
SF	Sync frame
SHDSL	Synchronous high-speed digital subscriber line
SISO	Single input–single output
SNR	Signal-to-noise ratio
SRA	Seamless rate adaptation
SS	Sync symbol

SU	Signal update
TCM	Trellis coded modulation
TDD	Time-division duplexing
TDMA	Time-division multiple access
THP	Tomlinson–Harashima precoding
TIGA	Transmitter-initiated gain adjustment
TOT	Tone ordering table
TPS-TC	Transport protocol specific transmission convergence
UPBO	Upstream power back-off
VDSL	Very high-speed digital subscriber line
VDSL2	Very high-speed digital subscriber line 2
VF	Velocity factor
W-MMSE	Weighted minimum mean squared error

Chapter 1
Introduction to Fast Digital Access and FTTdp Networks

Broadband Internet access is an integral part of modern life. More and more private activities and work tasks depend on Internet services. This causes the demand for higher data rates in the Internet access network. While wireless broadband experiences an immense growth within the last years, the main portion of Internet data traffic is still transported over the fixed access network. Even most of the wireless data traffic is transported to the subscribers via the fixed Internet access network and locally distributed by a wireless local area network.

To satisfy the increasing demands, the fixed broadband access network is continuously improved by introduction of more advanced data transmission technologies and by changing the network architecture to bring high speed fiber connections closer to the subscribers. The three main transmission media used for fixed broadband access are twisted pair copper wires if the telephony network, coaxial cables and fiber connections of the gigabit passive optical network (GPON).

Copper-based access is by far the most widely used broadband technology among them because of the wide availability of the fixed telephony network [1]. Due to the long evolution of the copper-based access network, there is a variety of coexisting technologies. Figure 1.1 gives an overview on the mix of technologies and network topologies.

The first generation of digital subscriber line technologies is based on ADSL (asynchronous digital subscriber line [2]) and SDSL (synchronous digital subscriber line [3]) transmission technologies. They achieve data rates in the range of 10s of Mbits/s and support a twisted pair line length of several kilometers. ADSL and SDSL are served from a central office, a network node that supplies several thousand subscribers.

To improve data rates and service quality, new network nodes, the street cabinets, and a new transmission technology, VDSL2 (very high speed digital subscriber line 2 [4]), has been introduced. The VDSL2 service achieves 100 Mbit/s data rate and

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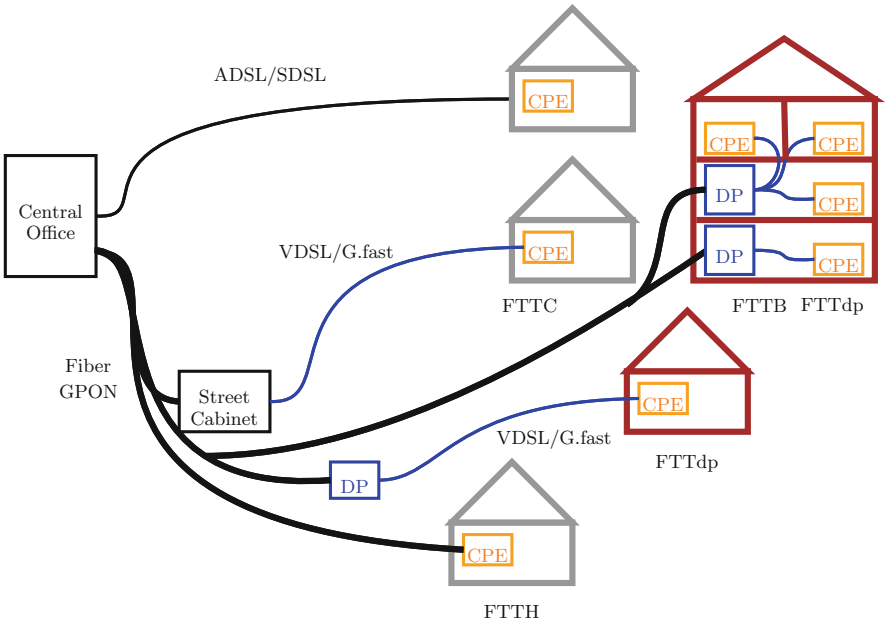

Fig. 1.1 Overview over copper access network topologies and technologies

works on loops shorter than 1000 m. A fiber connection is used to connect the street cabinets with the central office. The street cabinets serve several hundred subscribers. The network topology is called fiber to the curb (FTTC). With the introduction of crosstalk cancelation for VDSL2, 100 Mbit/s DSL services achieve much longer reach.

The next generation network topology is called fiber to the distribution point (FTTdp). The distribution point (DP) is a network node, which has typically a distance below 100 m to the subscriber. At the DP, cable bundles contain a small number of twisted pairs, connecting e.g., 16 or 24 subscribers. The fiber runs to the DP, where a distribution point unit (DPU) is placed. It is supplied with power over the twisted pairs from the subscriber side, as there is typically no local power supply at the distribution point.

Sometimes, FTTdp networks are named fiber to the building (FTTB) in case that the distribution point is inside a building or even fiber to the home (FTTH) when the distribution point serves only a single household.

The transmission technology to be used to transport the data from the fiber link over the remaining distance of twisted pair copper wires is G.fast, as standardized by the ITU [5, 6]. Target data rates are 1 Gbit/s or even 2 Gbit/s on very short loops [7].

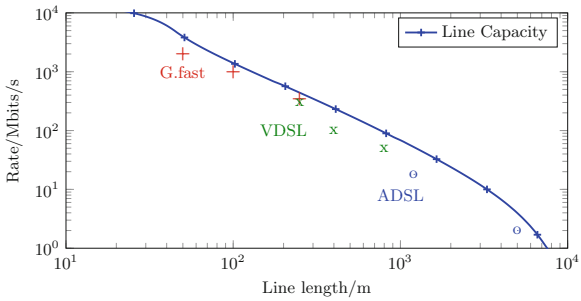

Fig. 1.2 The capacity of a single twisted pair as a function of line length

The general tendency of copper access technologies is shown Fig. 1.2.[1] The required data rates increase continuously, while the copper access network follows this demand by shortening the length of the copper wires between optical network unit and subscriber. More recent technologies allow higher rates at shorter line length by using a wider spectrum. Past technologies like ADSL or VDSL as well as the current G.fast systems are optimized to achieve optimal performance at their target line length, which is for G.fast around 100 m achieving up to 400 m.

This work focuses on the FTTdp network and the corresponding physical layer technology, G.fast. The key requirements of G.fast FTTdp are

- deployment flexibility,
- low power consumption,
- high data rates and low latency.

The flexibility of deployment is achieved by the reverse power feeding architecture where no local power supply is needed at the DPU. The DPU shall be very small, does not require active cooling and can be placed in a water-proof outdoor housing. This leads to the requirement of low power consumption to allow passive cooling and reverse power feeding.

Finally, the technology must be capable to transport high data rates at low latency to give a fiber-like broadband experience while keeping the advantages of a copper technology like customer self install and high quality of service.

1.1 Transmission Technologies

The technology of choice for the FTTdp network is standardized in the ITU-T G.9700 [6] and ITU-T G.9701 [5] standards also known as G.fast.Besides G.fast, there are various legacy technologies deployed. A new technology introduced in the access network must prove to be compatible with the legacy technologies.

[1] Capacity is calculated for a single twisted pair line of cable type CAD55 [5]. The aggregate transmit power is limited to 20 dBm, the background noise is at −140 dBm/Hz and the bandwidth is infinite

Pointing to Fig. 1.1, there are legacy technologies such as VDSL2 [4], ASDL and SDSL deployed. Passive optical networks (PON) or coaxial cable networks may also coexist with the copper network as an alternative Internet access technology.

1.1.1 SDSL

Synchronous digital subscriber line (SDSL, SHDSL [3]) technologies are based on single-carrier baseband modulation. They use pulse amplitude modulation (M-PAM) with different constellation sizes. Synchronous DSL transceivers send upstream and downstream signals synchronously, meaning with the same symbol rate at the same time and frequency (full duplex transmission). The full duplex scheme uses the channel more efficient than time or frequency duplexing, because it is not required to allocate separate frequencies or time for each transmission direction.

At each receiver, the near-end transmit signal is canceled out by echo cancelation. SDSL transceivers introduced forward error correction using trellis coding [8]. Tomlinson precoding [9] for pre-distortion of the channel introduced to compensate the channel distortion. SDSL technology is widely used for business applications, where symmetric services with equal upstream and downstream rates are needed.

Private users usually require high downstream and lower upstream data rates and therefore use an asynchronous DSL service.

1.1.2 ADSL/VDSL

Asynchronous DSL (ADSL) and Very High Speed DSL 2 (VDSL2) use DMT multicarrier modulation. Uplink and downlink signals use different frequencies (frequency division duplexing, FDD). Upstream and downstream frequency bands are fixed in band plans which are part of the corresponding standards (ADSL [2], VDSL2 [4]). There are several profiles available, which allow different upstream/downstream ratios.

VDSL2 supports data rates around 100 Mbit/s using frequencies up to 17.6 MHz. A VDSL2 extension called G.vector [10] defines protocols for crosstalk cancelation. Forward error correction is done with a specific type of trellis code, the 4D Wei code [11], which is combined with an outer Reed-Solomon [12] code.

1.1.3 G.fast

The G.fast standard also uses DMT modulation. Linear crosstalk cancelation is a mandatory part of the G.fast specification. In contrast to VDSL2, G.fast uses time division duplexing (TDD) to separate upstream and downstream transmission. TDD

requires the synchronization of all lines in a binder such that upstream and downstream time slots are aligned. But the synchronization is anyway required for crosstalk cancelation.

In terms of power consumption, TDD has advantages, because the transmitter can be switched off during the receive phase and vice versa. Low power consumption is very important for G.fast, because it is designed to be used in a small form-factor DPU allowing power supply by reverse power feeding.

1.1.4 Coexistence

The different access technologies coexist with each other. This is mainly implemented by a spectral separation of the services. VDSL uses a wider spectrum than ADSL and G.fast a wider spectrum than VDSL. In that sense, it is possible to exclude the legacy spectrum from the used frequency bands.

In case that the frequency bands of two technologies overlap, the legacy service is protected with specific spectral constraints. VDSL supports protection of ADSL with a method called downstream power back-off (DPBO) and upstream power back-off (UPBO). UPBO is also applied in VDSL deployments without crosstalk cancelation to protect the upstream signals of longer loops.

1.2 Reference Model

Communication systems are modeled in a layer model, e.g. the OSI ISO model [13]. Referring to the 7-layer OSI-ISO model, the G.fast standard defines a physical layer (layer 1) point-to-point protocol as well as the interface to the layer 2 (data link layer [13]).

The G.fast physical layer is divided into three sub-layers as shown in Fig. 1.3, the transport protocol specific transmission convergence (TPS-TC) sublayer, the physical media specific transmission convergence sublayer (PMS-TC) and the physical media dependent (PMD) sublayer. There are interfaces between the sub-layers as well as the interface to the higher layer and to the physical media.

The TPS-TC sublayer converts the packet based traffic of the higher layer into data transmission units (DTUs). The defined functionality includes the insertion of the overhead channel (the eoc overhead channel [5]) as well as buffering and traffic management towards the higher layer (Layer 2). The interface towards the higher layer is called γ interface and the interface to the PMS-TC sub-layer is the α interface.

The PMS-TC sublayer performs Reed-Solomon coding on the DTUs. At this point, physical layer retransmission buffers are handled. Each DTU contains redundancy information that is used to check whether the DTU has been received correctly. In case of a decoding error, a retransmission of the corresponding data is requested.