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Research Report

Signal Processing for Network Access Technologies: An Overview

Giovanni Cherubini

IBM Research Division
Zurich Research Laboratory
8803 Rüschlikon
Switzerland

IBM Research Division
Almaden · T.J. Watson · Tokyo · Zurich

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Giovanni Cherubini

IBM Research Division, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland

Abstract

Signal processing techniques that are at the core of state-of-the-art network access technologies are discussed. Emphasis is placed on recent developments in access technologies for the public telephone network, local-area networks, and cable TV/community antenna TV wide-area networks.

1 Introduction

Network access technologies will allow subscribers of wired and wireless networks to approach, over bi-directional transmission links that exhibit sufficient capacity in both directions of transmission, services offered by various providers, e.g., telephony, Internet access at local-area-network speeds, broadcast and on-demand educational and entertainment television, and telecommuting. Unshielded twisted-pair (UTP) cables originally deployed in the customer service area for analog 4 kHz bandwidth connections to the local telephone office, intra-building local-area network (LAN) UTP cable plants, as well as coaxial cables currently employed by cable TV/community antenna TV (CATV) networks to distribute analog TV signals represent the existing infrastructure for the development of copper-based access technologies. Broadband wireless access systems are also gaining wide acceptance as a means to provide communications services [1]. For example, digital-enhanced cordless telecommunications (DECT) and personal access communications systems (PACS) are emerging as access technologies for the wireless local loop that can support end-user mobility as well [2]. Wireless LANs are considered for extending or replacing wired LANs in environments where mobility and portability are key requirements. The multichannel multipoint distribution service (MMDS) and the local multipoint distribution service (LMDS) are proposed as *wireless cable* networks that can offer the required bi-directional transmission capabilities to subscribers in areas with a favorable terrain structure. Hybrid structures, where downstream transmission from the provider to a subscriber and upstream transmission in the opposite direction are achieved over different media, are also being considered, e.g., direct broadcast satellite (DBS) delivery of data services combined with upstream transmission links over the public switched telephone network (PSTN).

The session on signal processing of the 9th Tyrrhenian International Workshop on Digital Communications focuses on modulation techniques, and algorithms for receiver synchronization and data detection that can be applied to wide-band wireless transmission. The papers presented in this session constitute an eminent survey of signal-processing techniques for transmission over MMDS and LMDS links. This paper attempts to give the reader an overview of the state of the art in copper-cable network access technologies as well, and is organized as follows. In Section 2, digital transmission in the customer service area of the public telephone network is addressed. Trellis precoding techniques for transmission over channels with intersymbol interference (ISI) are also discussed. In Section 3, high-speed data transmission over UTP cables in the local-area network environment is considered. The features of the most advanced transceiver technology to date, defined for 100 Mbit/s Fast Ethernet transmission over two pairs of voice-grade cabling, are illustrated. Finally, the technical challenges posed by the design of cable modems for hybrid-fiber-coax (HFC) CATV networks are outlined in Section 4.

2 Digital transmission over twisted-pair cables in the customer service area

The state of the art in modem technology for the PSTN is represented by the V.34 Standard of the International Telecommunications Union–Telecommunications Standardization Sector (ITU-T). Trellis-enhanced precoding for trellis-coded transmission over ISI channels, as employed in V.34 modems, allows coding and shaping gains to be achieved with a minimal transmit power penalty for arbitrary signal constellations, provided the ISI channels are linearly invertible. With this technique, reliable communications at data rates up to 33.6 kbit/s over telephone channels can be achieved.

The assumption of an analog end-to-end connection for voiceband modems does not lead to an accurate model for the majority of telephone channels encountered today. In fact, the network itself is essentially digital, transporting voice or data at a rate of 64 kbit/s. If modem servers employed by service providers are connected digitally to the PSTN, there is only one analog local loop between the subscriber and the rest of the network. Modems designed for this refined channel model are usually referred to as *PCM modems*. PCM modems will be capable of transmission at rates between 40 and 56 kbit/s over channels with frequencies in the range from 0 Hz to $\sim$4 kHz.

UTP subscriber cables in the customer service area also represent a cost-effective alternative to optical fibers for high-speed data transmission links over distances up to 6000 m. Although optical fibers have better transmission characteristics, a low-cost and reliable transmission link using UTP cables is preferable in many subscriber line applications due to the large number of existing cable plants [3].

High bit-rate digital subscriber line (HDSL) offers a solution for bi-directional transmission at 1.544 Mbit/s (T1 rate) over two pairs and distances up to 4500 m in a customer service area. More recently, single-line DSL (SDSL) was introduced to provide full-duplex transmission at T1 rate over a single pair. Asymmetric digital subscriber line (ADSL) architectures have been proposed to transmit video-on-demand signals via subscriber loops. For example, ADSL-3 is designed for the downstream transmission of four compressed 1.5 Mbit/s video signals in addition to a full-duplex 384 kbit/s data signal, a 16 kbit/s control signal, and analog telephone service over distances up to 3600 m [4]. Very high-rate ADSL (VDSL) is regarded as the next-generation system for fiber-to-the-curb (FTTC) architectures [5], with data rates up to 51.84 Mbit/s (SONET OC-1/STS-1 rate) downstream and up to 2.3 Mbit/s upstream, over distances up to a few hundred meters.

Various baseband and passband modulation techniques are being considered for symmetric and asymmetric high-rate transmission over UTP cables in the customer service area. Among them, 2B1Q quaternary baseband modulation has been selected by the American National Standards Institute (ANSI) as the standard modulation scheme for HDSL, and Discrete Multitone (DMT) modulation has been selected by ANSI as the standard for ADSL. For a comparison of rates achievable over an ISI channel with additive white Gaussian noise (AWGN) by DMT modulation and Quadrature Amplitude Modulation (QAM) techniques, which are presently competing to prevail in the ADSL environment, the reader is referred to [6].

As mentioned above, reliable transmission with high spectral efficiency over the telephone channel can be achieved by techniques combining trellis coding [7] and precoding. To briefly discuss trellis precoding techniques, let us consider the response of a discrete-time ISI channel with AWGN expressed by $h(D) = 1 + h_1 D + h_2 D^2 \ldots$, and assume that $h(D)$ is known at the transmitter. Let $\mathcal{A} \subset \Lambda_0 + \lambda$ be a finite set of modulation symbols into which information is encoded, where Λ_0 denotes the lattice underlying $\mathcal{A}$, and λ is a given, possibly non-zero offset value. In general, the aim of precoding is to determine a sequence of transmit signals $x(D) = u(D)/h(D)$ such that in the absence of noise at the channel output an apparently ISI-free symbol sequence $u(D)$ with elements in $\Lambda_0 + \lambda$ is received. To achieve this with constrained channel inputs, the elements of $u(D)$ must be allowed to occur in a set larger than $\mathcal{A}$. In the case of systems that employ trellis coding, the sequence $u(D)$ must be a valid code sequence.

With Tomlinson–Harashima (TH) precoding [8, 9], memoryless modulo operations are performed in the transmitter and receiver to reduce transmit signals and decoded received symbols to a fundamental region containing $\mathcal{A}$, provided a *power-efficient modulo extension* exists for this region. For a system that employs trellis coding, straightforward application of TH precoding requires that the power-efficient modulo extension remains valid for all subsets of $\mathcal{A}$ obtained by set partitioning [10]. This limitation on the permissible shapes of signal sets was overcome by *flexible precoding* [11], where a precoder adds to a sequence $a(D)$ of transmit symbols in $\mathcal{A}$ the smallest *dither* signals for which at the channel output a uniquely decodable symbol sequence $u(D)$ is obtained. For inverse precoding at the receiver, linear channel inversion is required. Combining flexible precoding with trellis coding, however, results in a transmit power penalty that can be significantly larger than that of TH precoding. This penalty was reduced to the same value as in TH precoding by *trellis-enhanced precoding* [12], which consists of a combination of flexible precoding with a technique known as feedback TCM encoding.

The presence of spectral nulls in the channel frequency response represents a problem for the application of trellis-enhanced precoding because in this case the filter realizing the inverse channel characteristic at the receiver may induce unlimited error propagation. The essential properties of trellis-enhanced precoding can be retained and error propagation at the inverse precoder completely avoided, provided that a power-efficient modulo extension valid for the signal set $\mathcal{A}$ exists. This is achieved by a technique called *trellis-augmented precoding* [13], which combines the concept of feedback TCM encoding with TH precoding.

3 High-speed data transmission over UTP cables in a LAN environment

High-speed transmission over an intra-building copper plant is currently being studied by several standardization bodies, which reflects the interest of the industry in systems that allow the upgrading of local-area networks with already deployed UTP cabling. For example, the ATM Forum and the Study Group 13 of the ITU-T consider transmission at rates up to 155.52 Mbit/s and beyond for the ATM user-network interface. The task force 1000BASE-T of the IEEE 802.3 working group is currently investigating transmission at 1 Gbit/s over four pairs of data-grade cabling for switched Ethernet LANs.

UTP cables were classified by EIA/TIA depending on their transmission characteristics. Category 3 (UTP-3) cables are also referred to as voice-grade cables, and category 4 and 5 cables (UTP-4 and UTP-5) correspond to data-grade cables. UTP-3 cables exhibit higher signal attenuation and, more importantly, substantially greater near-end crosstalk (NEXT) coupling between individual pairs than do UTP-4 and UTP-5 cables. For LAN applications, the length of a transmission link is limited to 100 m. Existing intra-building wiring systems use cable bundles, usually 4 or 25 pairs, and signals may traverse line discontinuities caused by connectors. For data transmission over UTP-3 cables, to achieve best performance and to meet limits on emitted radiation, signal bandwidth must be confined to frequencies not exceeding 30 MHz. Furthermore, sophisticated signal processing techniques are needed. The new 100BASE-T2 standard for 100 Mbit/s fast Ethernet transmission over two pairs of UTP-3 cabling represents in this respect a quantum step in LAN transceiver technology [14]. The 100BASE-T2 standard was developed to enable users of the mature 10BASE-T Ethernet LAN technology to upgrade their networks from 10 to 100 Mbit/s performance while retaining an existing voice-grade or data-grade cabling infrastructure.

For 100BASE-T2, a *dual-duplex* baseband transmission concept is adopted. Bi-directional 100 Mbit/s transmission over two pairs is accomplished by full-duplex transmission of 50 Mbit/s streams over each of two pairs at a modulation rate of 25 MBaud. The lower modulation rate and/or spectral efficiency required per pair for achieving the 100 Mbit/s aggregate rate constitutes an advantage over mono-duplex transmission, where one pair would be used to transmit only in one direction and the other pair to transmit only in the reverse direction. Dual-duplex transmission requires two transmitters and two receivers at each end of a link, as well as separation of the simultaneously transmitted and received signals on each pair. Sufficient separation cannot be accomplished by analog hybrid circuits only. In dual-duplex transceivers it is therefore necessary to suppress echoes returning from the hybrids and impedance discontinuities in the cable, as well as self-NEXT, by adaptive digital echo and NEXT cancellation. Adaptive digital equalizers with fractional-T spaced taps are employed to compensate for signal distortion. Although a dual-duplex scheme might appear to require higher implementation complexity than a mono-duplex scheme, it turns out that the two schemes are equivalent in terms of the number of multiply-and-add operations per second needed to perform the various filtering operations.

If signals with spectral components that occupy a bandwidth that is larger than the minimum Nyquist bandwidth are transmitted, received signals exhibit spectral redundancy that can be exploited to suppress alien NEXT by adaptive digital equalization with fractional-T spaced taps. To illustrate the principle of alien NEXT suppression, let us consider a dual-duplex transmission system where transmit signals exhibit 100% excess bandwidth, and where an adaptive decision-feedback equalizer (DFE) structure is employed at the receiver to obtain estimates of the pairs of symbols (A_n^r, B_n^r) transmitted by the remote transceiver, as shown in Figure 1. Perfect echo and self-NEXT cancellation prior to symbol detection is assumed. Note that, if signal attenuation and disturbances increase with frequency, as is the case for transmission over UTP cables, a DFE receiver provides significantly higher noise immunity compared to that achieved by a receiver with linear forward equalization only.

The forward equalizer sections of the DFE operate on pairs of $T/2$-spaced input signals $(y_{A,k}, y_{B,k})$. Because the signals exhibit 100% excess bandwidth, the superposition of spectral input-signal components at frequencies f and $f - 1/T$, for $0 < f < 1/2T$, in the T-sampled equalizer output signals can mitigate the effects of synchronous interference [15] and asynchronous disturbances [14]. Interference suppression achieved by superposition of spectral signal components can be regarded as a frequency diversity technique. Inclusion of the op-

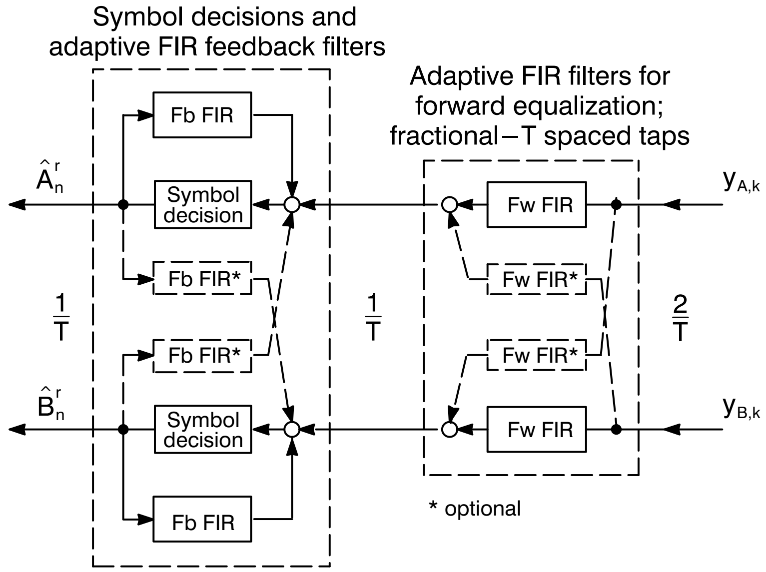

Figure 1: DFE with cross-coupling filters for interference suppression in dual-duplex systems.

tional cross-coupling forward and backward filters shown in Figure 1 significantly enhances the capability of suppressing alien crosstalk [14]. This corresponds to adding space diversity at the expense of higher implementation complexity. For dual-duplex transmission, this structure permits the complete suppression of the alien-NEXT interferences stemming from another dual-duplex transceiver operating in the same four-pair cable at identical clock rate. Alternatively, interference from a single asynchronous source can also be eliminated.

4 HFC CATV systems

The HFC CATV wide-area network is a point-to-multipoint, tree and branch access network in the downstream direction, with downstream frequencies in the 54–750 MHz bandwidth, and a multipoint-to-point, bus access network in the upstream direction, with upstream frequencies in the 5–42 MHz bandwidth. The downstream transmission originates from a head-end node, and is broadcast to all subscriber nodes located at the tips of the branches in the tree and branch network. An upstream transmission originates from a subscriber node and reaches the head-end node through a multipoint-to-point access network where the access medium is shared by all subscribers that communicate with the head-end. The IEEE 802.14 working group is presently chartered with creating physical (PHY) layer and medium access control (MAC) layer specifications for the HFC CATV systems.

In the downstream direction, continuous broadcast operation simplifies the modem design. Moreover, in existing cable plants, large values of the signal-to-noise ratio are supposed to be available for downstream transmission. Therefore typical data rates of 30–45 Mbit/s per 6 MHz channel can be achieved without sophisticated modulation and coding techniques, with spectral efficiencies of 6–8 bits/s/Hz.

In the upstream direction, PHY and MAC layers pose significant technical challenges. Because the upstream channel is accessed by multiple users, an elaborate MAC protocol is required. The upstream modems must have burst synchronization as well as equalization capability. Algorithms that can be applied for rapid training of an upstream modem receiver employing an equalizer with fractional-T spaced taps are described in [16]. Burst and impulse noises inherent in the upstream cable plant and, more importantly, narrow-band interference signals, which are called *ingress noise* and are due to in-home appliances and HF-radio interference, accumulate on the return path to the head end. The time-varying noise power spectral density suggests that an upstream modem must have the inherent capability of frequency agile transmission with various modulation rates and spectral efficiencies. For upstream transmission, the IEEE 802.14 working group examines frequency agile multi-mode (FAMM) modems, which include the above mentioned transmission capabilities, with modulation rates up to 5.120 MBaud and spectral efficiencies of 2–4 bits/s/Hz. Simple forms of trellis-coded modulation are also being considered to provide greater noise immunity.

5 Conclusion

With state-of-the-art modem technology it is possible to achieve reliable data transmission over existing UTP cables and coaxial cables at much higher rates than originally thought feasible. The competition between the various wired, wireless, and hybrid access technologies to gain acceptance as the most attractive solution for the *last mile* problem remains open. As a result, signal processing for network access technologies will continue to be a topic of interest from many perspectives.

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