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A DMT Transmission System for High-Speed Communication on Copper Wire Pairs

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Abstract: **In the context of future broadband multimedia services, a transmission system for high-speed communication on telephone copper wire pairs is presented. The experimental system is based on discrete multitone (DMT) modulation, which offers robustness against time dispersion and reasonable hardware complexity. The aim of the present work is to show the feasibility of broadband transmission (10–55 Mbit/s) on short copper cables (< 1000 m) in the existing local telephony network. Here, the implementation aspects and the hardware solutions are discussed. In particular, the implementation of a recent data-based frame synchronization method is described. The hardware constituting the experimental system is based on a fast Fourier transform (FFT) processor and programmable logic devices.**

1. INTRODUCTION

In this presentation we discuss the implementation of a communication system based on discrete multitone (DMT) modulation. This system is intended for asymmetrical broadband communication on short twisted-pair copper cables at data rates between 10 and 55 Mbit/s. The purpose is to demonstrate the feasibility of using the existing telephony access network for broadband communication, as opposed to, for example, investing in a fiber-to-the-home network solution. The first phase of the project concerns the downstream (from the network terminal to the subscriber) broadband transmission, posing the largest technical difficulties. For the purpose of rapid prototyping, the system is realized with mostly “off-the-shelf” hardware, involving no custom VLSI.

The project is a cooperation between Telia Research AB, Sweden and Luleå University of Technology, Sweden.

In parallel with the development of the demonstration system a feasibility study for VLSI implementation solutions will be performed. This investigation will also evaluate the development tools available to design and implement telecommunication systems all the way from algorithm to VLSI.

The presentation will proceed as follows. A background to the project is given in the next section. Section 3 provides a brief introduction to multicarrier modulation techniques. This is followed by a description of the hardware structure and especially the novel synchronization unit. Finally, we give some conclusions and summarize the paper.

2. PROJECT BACKGROUND AND MOTIVATION

There is today a public demand for multi-media services requiring broadband digital communication to the home, presently seldom provided. Ultimately, network solutions like fiber-to-the-home will provide the necessary bandwidth, but this requires very large and time-consuming infrastructure investments. In a short term perspective, say for the next 10 years, a viable way to offer broadband services to the customers is to use the existing twisted-pair copper cables of the telephony access network. The intended network solution is to have optical fiber to a telephone cabinet serving several homes (typically about 100 homes), with copper cable extensions no longer than 1000 meters.

For multi-media services like video-on-demand asymmetrical communication systems are preferable, see Fig. 1. Broadband access, here 10 – 55 Mbit/s, is then only provided in one direction, from the network terminal to the subscriber. In the up-stream link a narrowband channel, up to 2 Mbit/s, is available for customer data and system control signals.

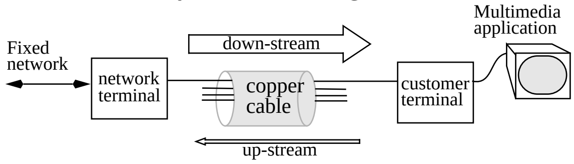

Figure 1: Basic organization of an asymmetric broadband communication system.

The capacity of the copper network is mainly limited by two factors. First, the attenuation of the copper pairs is an increasing function of frequency, which limits the useful transmission bandwidth. The attenuation also increases with the length of the cable. Secondly, the interference from transmission on neighboring pairs, so called cross-talk, act as colored additive noise. Cross-talk between pairs in the same cable is often the dominating source of interference in broadband communication on the copper network. One of the beneficial characteristics of the copper network is that it is largely stationary; its characteristics varies slowly.

The work surveyed in this paper uses DMT modulation, a modulation technique found to be well-suited for this type of channels [1, 3, 4, 5]. DMT modulation, a special case of multicarrier modulation, is briefly described in the following section.

3. MULTICARRIER MODULATION

Multicarrier modulation is ascribed two desirable properties particularly interesting for our application: implementability and flexibility. A problem often encountered when transmitting at high data rates over bandlimited channels is intersymbol interference, caused by the time dispersion of the channel. In a single carrier system this is often dealt with by an equalizer. An equalizer would, however, become prohibitively complex for communication on the copper network at our data rates. The time dispersion problem is intrinsically solved using multicarrier modulation.

The general idea behind multicarrier modulation is to divide one broadband channel into several narrowband channels, in our case 1024 channels, cf. Table 1. Instead of transmitting at a high data rate on a single channel, the data are transmitted simultaneously at low data rates on the many parallel channels. If the number of carriers is chosen large enough, the length of each symbol on the subcarriers will be much longer than the time dispersion of the channel: the frequency response seen on each narrowband channel will effectively be flat. The division of the channel into many subchannels also offers a flexibility in the number of simultaneous users and their respective data rates. A task such as multiplexing data from users with different data rates can, for instance, be accomplished easily by assigning each user different sets of subcarriers.

The present work uses a multicarrier technique called discrete multitone (DMT) modulation. DMT is closely related to orthogonal frequency division multiplexing (OFDM) which is used, e.g., in radio transmission [1]. Compared to OFDM, the DMT has an unequal number of bits transmitted on each carrier. The channel characteristics are measured in order to determine how the data should be distributed between the subcarriers. Carriers with high signal-to-noise-ratios (SNR) are assigned dense signaling constellations, e.g., 4096-QAM, while subcarriers with low SNR are assigned lower order constellations or perhaps even turned off. A table with the bit-loading factor for each subcarrier is returned to the transmitter via a control channel. Note that the channel, for practical purposes, is stationary when the media is twisted copper-pairs. This technique is called “bit-loading” and is a “water pouring” technique, a way to make effective use of the channel’s capacity. The system presented here uses between 0 and 12 bits/symbol on each subcarrier, cf. Table 1.

The subcarriers can be described as orthogonal and equally distant sinusoids used as basis functions to separate the data streams. This can be implemented using the fast Fourier transform (FFT) algorithm and efficient hardware realizations of the FFT algorithm can be achieved either by using FFT-processors or dedicated hardware.

However, to keep the orthogonality between the subcarriers and avoid inter-carrier interference a cyclic extension of the symbol packet, hereinafter referred to as the cyclic prefix, is necessary, see Fig. 2. The cyclic prefix, a repeated part of the symbol packet, also introduces some robustness against imperfect timing of the sampling in the receiver. As we will see in the sequel, it is also exploited in the synchronization algorithm whose implementation is described in Section 4.1.

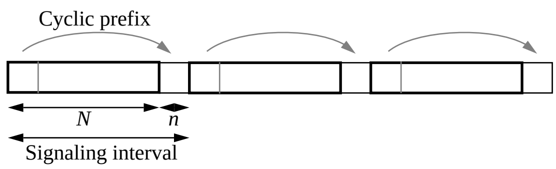

Figure 2: Structure of DMT with cyclic prefix. The signaling interval is divided into a DMT symbol (N samples) and a guard space (n samples). The guard space is filled with a cyclic extension of the data samples.

Parameters	Typical values
Sampling rate	13.3 MHz
Total number of carriers (FFT length)	$N = 1024$
Used number of carriers <corresponding bandwidth>	768 <10 MHz>
Guard space (cyclic prefix)	$n = 128$ samples
Bit-loading factors (bits/symbol)	0–12
Typical uncoded data rates for 100–1000 m cable (15 dBm signal power, bit-error-rate of 10^{-7})	10–55 Mbit/s

Table 1: System specification.

4. HARDWARE STRUCTURE

Our goal is to build an experimental hardware platform for testing of different aspects of DMT and for demonstrations of the technique by its applications. This presentation will focus on the receiver as it is the most complex part of the modem. The basic operations of the transmitter are encoding and mapping of the symbols using the bit-loading algorithm, followed by an inverse-FFT.

An overview of the receiver is shown in Fig. 3. The receiver consists of 8 VME boards in one VME case and of one separate analog interface. One of these boards is a Sparc workstation which initializes and controls the receiver. The receiver front-end consists of the analog interface and three Catalina Research Inc. VME boards: one ADC board and two boards containing the FFT processor and buffers (marked FFT in Fig. 3). The remaining functions are implemented on four in-house designed VME boards using FPGAs, one Plessey 16×16 bit complex multiplier, and dual-port memories.

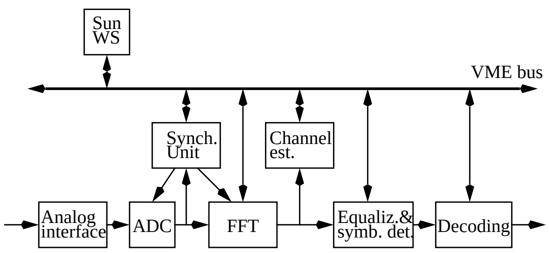

Figure 3: Receiver overview. The main dataflow is found in the lower part of the figure.

The analog interface includes a line transformer, a gain control, and a VCXO to adjust the impedance, level, and sampling frequency. A quadrature modulator is used to demodulate the incoming signal. After a low-pass filter the quadrature baseband signals are sent to the two analog/digital converters (ADC). The signal is sampled at 13.3 MHz with a resolution of 12 bits for each channel. A synchronization unit is operating directly on the sampled signals and generates a frame clock for the control of the FFT buffers and also a control signal for the VCXO. One of the novel aspects of our DMT system is the design of the synchronization unit, which will be further discussed below.

After sampling and buffering, a complex 1024 FFT is performed by the customized set of Catalina Research [2] VME cards containing SHARP processors. The customization basically consists of interfaces to our synchronization unit. A complex 1024 FFT, taking 65.48µs, is performed for each frame. A buffering is performed after the FFT and data is sent to the next card as 16 + 16 bit complex numbers at 13.3 MHz.

A separate card will perform a channel estimation on the output from the FFT. Periodically transmitted frames with known data are used to estimate the channel properties. This is then used to compute a bit-loading mask for each symbol, information subsequently sent to the transmitter through the up-stream channel.

In the next step (and card) in the dataflow the symbol detection is performed. This includes a simple pre-equalization followed by a symbol demapping unit. This demapping is computed according to the bit-loading mask for each symbol. The last board performs block decoding on the detected bit-stream. The data is then ready for customer applications.

4.1 Synchronization

We will here present the foundational ideas of the synchronization method proposed in [7] and also a simplified version with both improved performance and substantially lower hardware complexity. We will, furthermore, describe how it has been implemented in our experimental system.

Characteristic of the synchronization method is that it does not need any known data. Most other methods of synchronization use some form of pilot tones [6]. The basic idea is to use the property that data is repeated, in form of the cyclic prefix, in most multicarrier systems.

The basic method, cf. Fig. 4, is based on performing a continuous cross-correlation between the conjugate of the sampled input signal and the non-conjugated signal delayed by N samples. The implicit multiplication catches the correlation between the parts of the signal interval which are repeated and gives a positive contribution to the cross-correlation. Samples outside the repeated part are un-correlated and give a zero-mean contribution. The output of the multiplier is here filtered by a moving average filter with the window length n (the length of the cyclic prefix). The absolute value of the filter output will then act as input to a peak detector device, feeding a phase locked loop (PLL), which in turn produces the frame clock and a control signal for the VCXO generating the sampling clock.

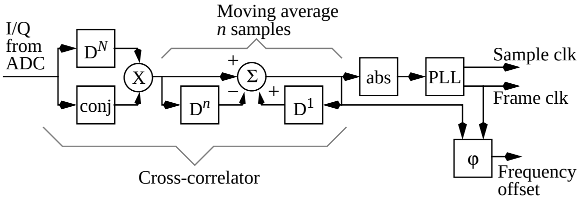

Figure 4: Synchronization unit principal overview. The notation D^{α} indicates a delay of α samples, "conj" and "abs" indicate the calculation of the complex conjugate and the complex absolute value, respectively.

A frequency offset in the input signal due to separate transmitter and receiver local oscillators, can easily be calculated by measuring the phase where the cross-correlation signal has its maximum, i.e., once per signaling interval. The phase shift of the cross-correlation is directly proportional to the frequency offset ω multiplied by the symbol length *N*. This feature is not used in our system, but would be relevant in a radio based systems.

The presented non-data aided synchronization method can be applied on most existing multi-carrier systems since the use of cyclic prefixes is a dominating design rule.

The straight-forward way of using a pure cross-correlator, as in Fig. 4, has been shown to be disadvantageous in our case [7]. A simplified synchronization scheme has been implemented by quantizing the complex input signal to only the sign bits. This non-linear operation increases the performance and, as an attractive side effect, dramatically reduces the hardware complexity. The multiplication operation can now be realized using a few gates in a programmable logic device and the delay-lines needed (RAM cells) are reduced from a word length of, for example, 24 bits to only 2 bits.

The wordlength reduction to two bits enables us to average over several frames before the moving average filter in order to further increase the performance [7]. This second filter averages over L = 7 frames and operates directly on the output of the multiplier. The new hardware structure is shown in Fig. 5. A look-up table ROM is used for the computation of the absolute value of the output of the averaging filter. The absolute value of the filter output typically forms a triangular-shaped signal which has the periodicity of the frame rate, see Fig. 6.

The implementation of the synchronization function is based on programmable gate arrays and dual-port RAMs.

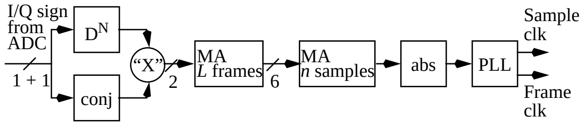

Figure 5: Sign-based synchronization solution. The reduction in word-length allows an additional moving average (MA) filter (averaging over *L* frames) to be added, which further improves the performance.

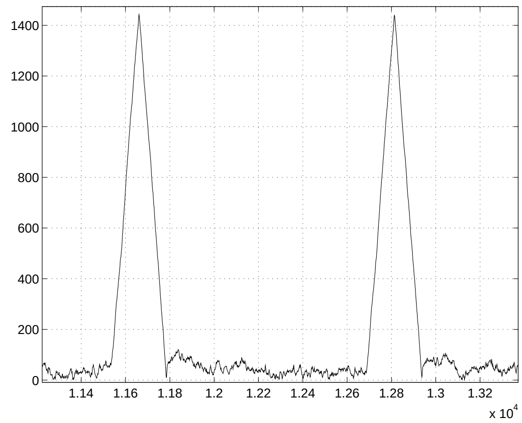

Figure 6: The absolute value of the filtered cross-correlation sequence.

The demand for detailed synchronization leads to long settling times, even up to 30s. This, and the difficulty to accurately model the actual components and the actual channel has made it hard to simulate and fully evaluate the synchronization method using computer simulations. With our experimental system we intend to evaluate the performance of this method, both stand alone and combined with a pilot tone.

5. CONCLUSION

In this paper we describe the implementation of an experimental broadband communication system for telephone copper wire pairs. This system is intended to demonstrate the feasibility of using the telephone copper access network for future multimedia applications, for example, services like video-on-demand.

The experimental system is based on discrete multitone modulation (DMT), which is a multicarrier modulation technique. Using DMT, we achieve a considerable system flexibility, and capacities between 10 and 55 Mbit/s, depending on the channel characteristics. The implementation of the system is described in this paper and is relatively straightforward.

The synchronization is crucial for reaching high capacities when using DMT. In particular, we describe in some detail the implementation of a recently introduced synchronization method.

ACKNOWLEDGEMENT

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REFERENCES

[1] Bingham, J. A. C., “Multicarrier modulation for data transmission: an idea whose time has to come,” *IEEE Communications Magazine*, vol. 28, no. 5, pp. 5-14, 1990.

[2] Catalina Research Inc., “Digital Signal Processors,” CRi, 1321 Aeroplaza Drive, Colorado Springs, CO 80916-2247, USA, 1995.

[3] Chow, J. S., J. C. Tu and J. M. Cioffi, “A discrete multitone transceiver system for HDSL applications,” *IEEE Journal on Selected Areas in Communications*, vol. 9, no. 6, pp. 895-908, 1991.

[4] Chow, P. S., N. Al-Dhahir, J. M. Cioffi and J. A. C. Bingham, “A multicarrier E1-HDSL transceiver system with coded modulation,” *European Transactions on Telecommunications and Related Technologies*, vol. 4, no. 3, pp. 257-266, 1993.

[5] Ruiz, A., J. M. Cioffi and S. Kasturia, “Discrete multiple tone modulation with coset coding for the spectrally shaped channel,” *IEEE Transactions on Communications*, vol. 40, no. 6, pp. 1012-1029, 1992.

[6] Sari, H., G. Karam and I. Jeanclaude, “Transmission techniques for digital terrestrial TV broadcasting,” *IEEE Communications Magazine*, pp. 100-109, 1995.

[7] van de Beek, J.-J., M. Sandell, M. Isaksson and P. O. Börjesson, “Low-complexity frame synchronization in OFDM systems,” in *International Conference on Universal Personal Communication (ICUPC'95)*, Tokyo, Japan, 1995.