Towards Gigabit DSL (GDSL): Design of a CC/MC-CDMA modem

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***Abstract*— With the introduction of VDSL2 and the implementation of Fibre-to-the-Curb (FTTC), the theoretical limit of DSL technology is pushed even further than currently known ADSL technology. Current research is investigating the possibility of symmetric DSL at 1 Gbps (GDSL).**

This paper addresses the design and implementation of a complete complementary multi-carrier code-division multiple access (CC/MC-CDMA) transmitter / receiver pair.This fully functional modem combines the virtues of both orthogonal frequency division multiplexing (OFDM) and conventional code division multiple access (CDMA) to support many users simultaneously with higher spectral efficiencies than conventional CDMA systems and better noise tolerance than existing DSL solutions. By expanding the proposed system further, symmetric Gigabit DSL (GDSL) can be supported.

***Index Terms*— Gigabit DSL, OFDM, MC-CDMA, Complementary code**

I. INTRODUCTION

WITH the standardization of VDSL2 (G.993.2) and the existing implementation of Fibre-to-the-Curb (FTTC), the theoretical limit of DSL technologies are approaching 250 Mbps downstream (50 Mbps downstream up to 500m away from the DSLAM) [1]. ADSL in South Africa is approaching the 8 Mbps theoretical limit, while most countries are moving towards ADSL2+ (G.992.5), supporting 24 Mbps downstream and 1 Mbps upstream (increased to 3.5 Mbps when implementing Annex M). Still, this is not enough, especially after Vladimir Prodanovic [2] showed actual network usage graphs with more data being sent upstream than downstream, specifically as far as HDTV service providers are concerned.

Gigabit DSL services are technically feasible and tease the imagination of telephone company service providers. GDSL pushes the limit of 1 Gbps SYMMETRIC (both upstream and downstream). Such speeds well in excess of present DSL data rates necessitate a number of topological and signal-processing challenges. Fiber to within 300 meters of the subscriber is presumed, and even the fundamental practical data-carrying limits of 2-4 copper twisted pairs are being considered. This paper presents a possible technical solution for GDSL, providing better resilience to noise and mulit-user interference. Some background information is provided in Section II. The system is described in Section III. Section IV present some practical results that were obtained.

II. BACKGROUND

The advantages and success of multicarrier modulation (MCM) and CDMA techniques motivated many researchers to investigate the suitability of combining Multi-carrier modulation (MCM) with Code division multiple access (CDMA) for wideband multiple access communications [3]. The combination, known as Multicarrier CDMA (MC-CDMA) [4]–[6], allows one to benefit from the advantages of both schemes. Users are allowed to transmit on many available subchannels, thus obtaining the maximum benefit from multicarrier transmission. OFDM is robust to frequency-selective fading, but has the disadvantage of complex subcarrier synchronization and high sensitivity to frequency offset and non-linear amplification [6]. It is however crucial for Multicarrier transmission to have frequency non-selective fading over each subchannel. Signals can easily be transmitted and received using an IFFT / FFT, without increasing the complexity, and have the feature of high spectral efficiency due to minimally-dense carrier spacing [6]. Each user is assigned a CDMA code, which is used to differentiate between signals belonging to different users at the receiver. The combination of OFDM and CDMA has a major advantage of lowering the symbol rate in each subcarrier, providing quasi-synchronized transmission due to the longer symbol duration. MC-CDMA provides high-bandwidth efficiency, high capacity, low complexity implementation etc. [7]

The MC-CDMA transmitter spreads the original data over different subcarriers, using a given spreading code in the frequency domain. A fraction of the symbol, represented by a chip of the spreading code, is transmitted through a different subcarrier.

The capacity of MC-CDMA is limited by Multiple Access Interference (MAI), as in Direct-sequence CDMA (DS-CDMA), and carrier frequency dispersion-induced Interchannel Interference (ICI). Performance and robustness to frequency offset can then be gained at the price of an increase in computational complexity and bandwidth efficiency. To achieve high performance, channel-dependent multiuser detection is needed [3]. However, relative to DS-CDMA, MC-CDMA have the following distinctive advantages:

- Synchronization: Block synchronization can be achieved

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and maintained in MC-CDMA due to long chip/symbol duration. This is instrumental to multi-user detection

- Loading: With information being transmitted in parallel narrowband streams, it is convenient to employ adaptive loading techniques (DMT Waterfilling) to distribute transmission power efficiently based on subchannel signal-to-interference noise ratio (SINR) to achieve optimum efficiency.

III. SYSTEM DESCRIPTION

A fully operational Discrete Multitone (DMT)-based transmitter/receiver pair was designed and implemented on FPGA. The block diagram of the basic CC/MC-CDMA transmitter is shown in Fig. 1.

The user's data is split into a number of parallel subchannels. The number of subchannels are allocated according to the Complete Complementary (CC) sequence length that is used, the number of pilot tones, the bandwidth used etc. Based on the signal-to-noise profile of the channel, a specific modulation scheme is used on each subchannel. Bits are grouped accordingly and represented by a symbol, containing a real and imaginary part. Based on the spreading code length, a block of subchannels are CC-code spreaded. The technique used can not be explained further (patent pending). It can be mentioned that ideally, a CDMA designer would like to have a code with perfect autocorrelation and zero cross-correlation. Through manipulation of the CC codes, we obtained these properties. Under these conditions, a CC-spreaded sequence can be cyclically shifted by n chips relative to the other sequences. Normally CDMA systems can only obtain a spectral efficiency of $1/L$ bits/s/Hz, where L is the sequence length. Using this CC-spreading technique, we obtain a spectral efficiency of 1 symbol/s/Hz (b/s/Hz efficiency will depend on the modulation scheme used for each subchannel). For our proposed system, we used 16-QAM modulation for all subchannels, thus providing us with 4 bits/s/Hz. This can however be increased to 32768-QAM (15 bits/s/Hz). Each symbol is respectively multiplied by the cyclically shifted CC spreading code. All CC-spreaded symbols are added to create a complex CC/MC-CDMA signal in the frequency domain. An IFFT and DAC are used to transpose this signal to the time domain and put the signal on the channel.

The effect of multi-user interference is simulated by adding other users' signals to the transmitted CC/MC-CDMA signal in an Additive White Gaussian Noise (AWGN) channel. In conventional ADSL, ADSL2+ etc. systems, the design is based on a chosen bit error rate (BER) of 10^{-7}. The data rate decreases as the noise in the system (mainly due from AWGN noise, line attenuation, other users etc.) increase. In our system a data rate was first chosen and the BER then determined, for a number of interference scenarios. In a wire line channel, signals from other twisted pairs couple into the desired twisted pair. The interference is called Near-End Crosstalk (NEXT).

The resistance R, capacitance C, inductance L and conductance G of a copper line, at a specified frequency f are determined by:

$$R(f) = \sqrt[4]{r_{oc}^4 + a_c \cdot f^2} \tag{1}$$

where r_{oc} is the copper DC resistance and a_c is a constant characterizing the increase of resistance with frequency in the "skin effect",

$$L(f) = \frac{l_0 + l_\infty \left(\frac{f}{f_m}\right)^b}{1 + \left(\frac{f}{f_m}\right)^b} \tag{2}$$

where l_0 and l_∞ are the low-frequency and high-frequency inductance respectively, and b is a parameter chosen to characterize the transition between low and high frequencies in the measured inductance values,

$$C(f) = c_\infty + c_0 \cdot f^{-c_e} \tag{3}$$

where c_∞ is the "contact" capacitance and c_0 and c_e are constants chosen to fit the measurements, and

$$G(f) = g_0 \cdot f^{+g_e} \tag{4}$$

where g_0 and g_e are constants chosen to fit the measurements.

Values for the different constants for different wire types are summarized in Table I for ADSL.

The characteristic impedance Z_o and the propagation constant γ of the twisted-pair, at a specific frequency f is expressed as [8], [9]:

$$Z_o = \sqrt{\frac{R + j\omega.L}{G + j\omega.C}} \tag{5}$$

$$\gamma = \sqrt{(R + j\omega.L)\,(G + j\omega.C)} \tag{6}$$

where $\omega = 2\pi f$.

The insertion loss function of the twisted-pair loop with source impedance Z_s and terminal impedance Z_t is [8], [10]:

$$H_{ins}(f) = \frac{Z_s + Z_t}{A.Z_t + B + C.Z_s.Z_t + D.Z_s} \tag{7}$$

The attenuation through the cable [dB] is expressed as [10]:

$$L_{dB}(f) = 10.log_{10} \mid H_{ins}(f) \mid^2 \tag{8}$$

The PSD of Near-end crosstalk (NEXT) noise, for the line under consideration, can be expressed as:

$$\begin{aligned} &PSD_{NEXT} = PSD_{Disturber} \cdot x_n \cdot f^{1.5} \\ &x_n = 8.814 \cdot 10^{-14} \cdot \left(\tfrac{n}{49}\right)^{0.6}, \;\; n < 50, \;\; 0 \leq f < \infty \end{aligned} \tag{9}$$

where n is the number of disturbers, and f is the frequency [Hz].

Far-end crosstalk (FEXT) is dependent on the characteristics of the line. The original signal at the transmitter will be attenuated due to the inherent propagation loss of the line. In a real network, FEXT is not just a function of the crosstalk in the cable, but also of the cable topology [11], i.e.

$$\begin{aligned} &PSD_{FEXT} = PSD_{Disturber} \cdot x_n \cdot d \cdot \mid H_{ins}(f) \mid^2 \cdot f^2 \\ &x_n = 2.6247 \cdot 10^{-16} \cdot \left(\tfrac{n}{49}\right)^{0.6}, \;\; n < 50, \;\; 0 \leq f < \infty \end{aligned} \tag{10}$$

where n is the number of disturbers, d is the length of the disturbing line [km], $H_{ins}(f)$ is the insertion loss for the line under consideration, $\mid \cdot \mid^2$ is the modulus-squared function, and f is the frequency [Hz].

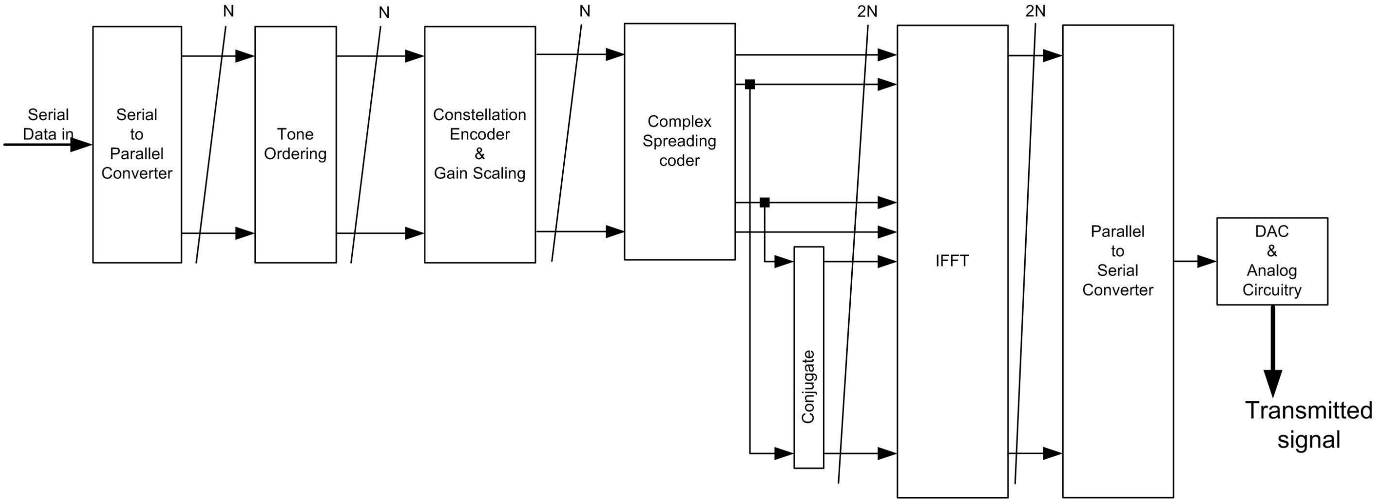

Fig. 1. Basic MC-CDMA transmitter structure

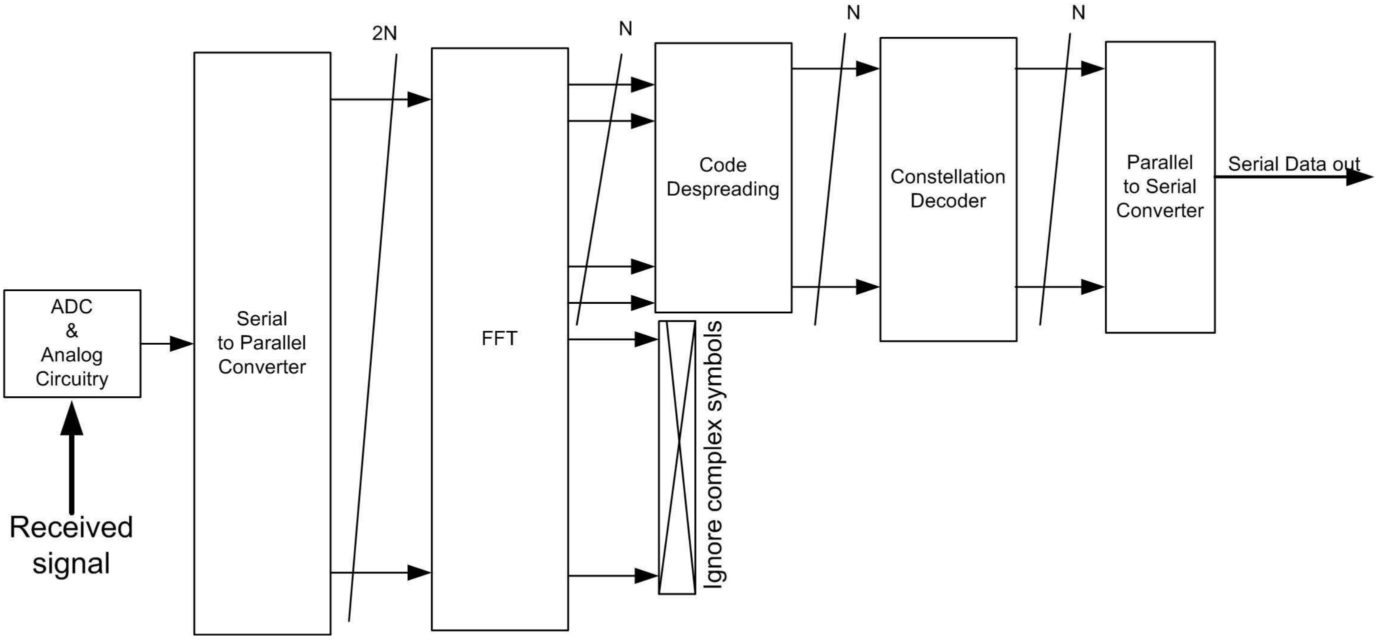

Fig. 2. Basic MC-CDMA receiver structure

TABLE I
CABLE PARAMETERS FOR 0.4MM (26AWG) WIRE

roc (kΩ)	**ac**	**l**$_o$ (mH)	**l**$_\infty$ (mH)	**f**$_m$ (MHz)	**b**	**C (nF/km)**
0.2800	0.0969	0.5873	0.4260	0.7459	1.3850	49

Galli *et al.* [12] explained that ”the telecommunications industry has characterized crosstalk in terms of power sums. For a given pair in a binder group, the power-sum NEXT is formed from the sum of the pair-to-pair NEXT coupling powers of the other pairs in the binder group to this given pair. For a typical 25-pair binder group in a 1000-ft (approx. 300m) long PIC cable, the 25 power sums are shown in Fig. 3. Two things should be noted here. The first is that the power sum is usually displayed as a power sum ’loss’, and the lower the loss the higher the NEXT coupling. The second is that the NEXT power-sum loss is approximately linear with frequency on the log-log scale.” Thus, to simplify the simulation, worst NEXT levels were defined, like e.g. -20dB. This in simple terms mean that the interfering signals are 20dB weaker than the desired signal. In a GDSL system however, the frequency-selective attenuation of the system will need to be taken into consideration, but will not be considered in this paper.

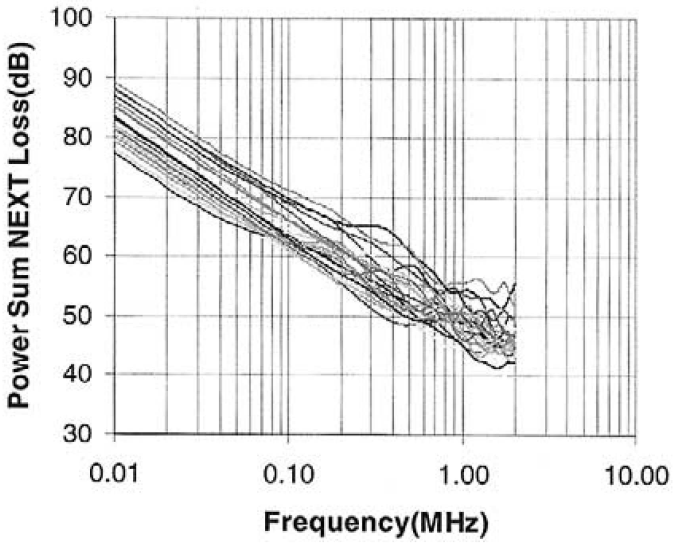

Fig. 3. Power sum NEXT loss (measured) for a 300m 25-pair PIC cable [12]

The block diagram of the basic CC/MC-CDMA receiver is shown in Fig. 2. The received signal is converted back to the frequency domain by using the ADC and the FFT module. Each of the symbols for each of the subchannels are recovered by correlating it with the corresponding cyclic-shifted version of the CC spreading code for that subchannel. Because of zero cross-correlation, symbols are recovered nearly perfectly. The length of the spreading sequences used, provides a processing-gain equal to L in the system. This can be used to support a larger amount of users or allow more noise in the system. Lastly, the symbols are converted back to bits, based on the modulation scheme used in each subchannel.

IV. RESULTS

We implemented the system in a 1 MHz bandwidth, using 16-QAM modulation over all 64 subchannels. Fig. 4 shows the obtained power spectral density (PSD) of the system. The system obtained a throughput of 4 Mbps. The system was also simulated for 3 NEXT loss levels (10dB, 20dB and 40dB) as shown in Fig. 5 to Fig. 7. For the case of 10dB NEXT (Fig.

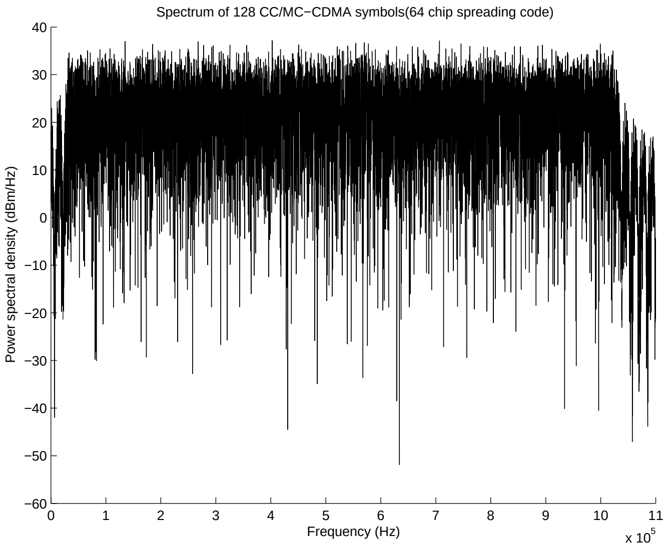

Fig. 4. Power spectral density of the CC/MC-CDMA modem

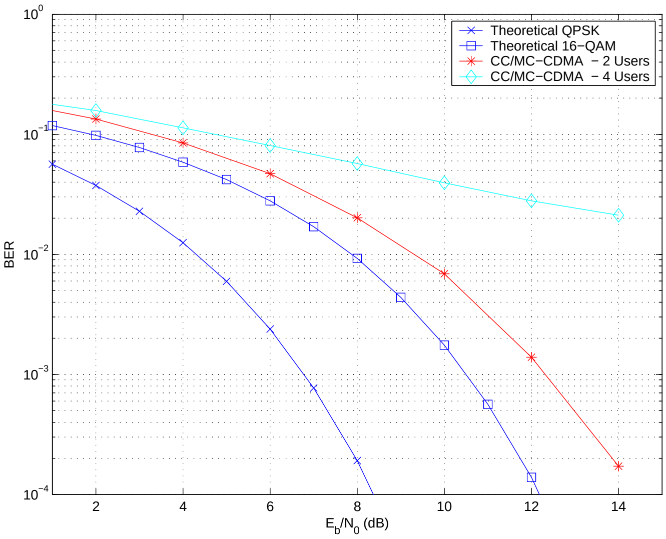

Fig. 5. BER performance for a 10dB NEXT level, compared to theoretical QPSK and 16-QAM

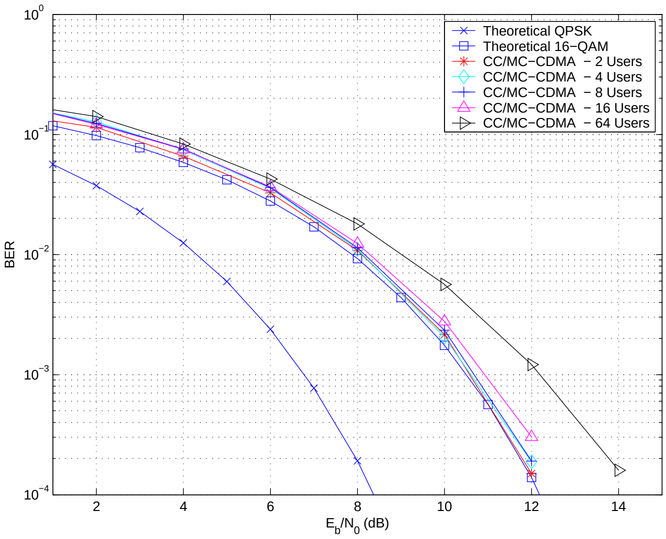

Fig. 6. BER performance for a 20dB NEXT level, compared to theoretical QPSK and 16-QAM

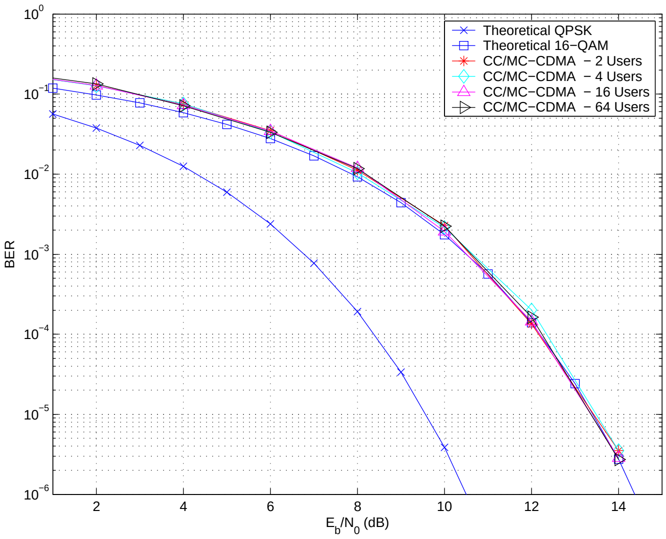

Fig. 7. BER performance for a 40dB NEXT level, compared to theoretical QPSK and 16-QAM

5), it is clear that the system is not capable of supporting many users, showing degradation in the performance for two users (1 interfering user) and totally unacceptable performance for 4 users. For the case of 20dB NEXT (Fig. 6), the system shows good performance up to 16 users and gradually worsens towards 64 users. When considering the 40dB case, the system virtually provides the same performance irrespective of the number of interfering users.

V. CONCLUSION AND FURTHER WORK

When considering the measured NEXT power sums or ”loss” of Fig. 3 the worst NEXT level in this 1MHz band is less than 40dB, which leads us to the conclusion that our proposed system will perform well. The proposed system shows some promising results in terms of multi-user interference mitigation, due to the added processing gain, while still maintaining the high-spectral efficiency needed to obtain a high data rate in a limited bandwidth. Future work will extend the CC scheme to 512 subchannel bands, with 30-60 of these bands implemented in parallel. Ultimately, the GDSL system will utilize a bandwidth of 60-120 MHz on a single pair, or 30-60 MHz on two pairs. Stanford University /Bar-Han University suggested some configurations in which GDSL would be feasible on lengths of 150-300m of 4 twisted pairs. Basically the full binder capacity of 4 drop wires are examined with 6dB of margin and the usual 4dB of coding gain to find that rates that exceed 1Gbps are possible in a DSL of 300m or less, by using sophisticated full-binder-vectoring methods to exploit crosstalk [13].

REFERENCES

[1] “”Gigabit DSL next?”.” *http://blogs.pcworld.co.nz/pcworld/techsploder/2006/10/gigabit_dsl_next.html/* (Last visit: 4 March, 2007).

[2] “”Gigabit DSL next?”.” *http://www.isp-planet.com/cplanet /tech/2004/prime_letter_040622_2_need_speed.html/* (Last visit: 25 June, 2007).

[3] H. Lui, *Signal Processing Applications in CDMA Communications*. Artech House Publisers, Boston, London, 2000. ISBN 1-58053-042-7.

[4] N. Yee and J. P. Linnartz, “BER of multicarrier CDMA in an indoor Rician fading channel,” in *Proc. ACSSC ’93*, (Volume 1), pp. 426–430, Pacific Grove, CA, USA, November 1993.

[5] K. Fazel and L. Papke, “On the performance of convolutionally-coded CDMA/OFDM for mobile communication systems,” in *Proc. PIMRC ’93*, pp. 468–472, Yokohama, Japan, September 1993.

[6] S. Hara and R. Prasad, “Overview of multicarrier CDMA,” *IEEE Commun. Mag.*, vol. 35, no. 2, pp. 126–133, December 1997.

[7] P. Švač, “Variable Two-Shift Complete Complementary Code,” in *Proc. EUROCON 2005*, pp. 482–485, 21-24 November 2005.

[8] T. Starr, J. M. Cioffi, and P. J. Silverman, *Understanding Digital Subscriber Line Technology*. Prentice Hall Communications Engineering and Emerging Technologies Series, Prentice Hall, New York, 1999. ISBN 0-13-780545-4.

[9] J. J. Werner, “The HDSL Environment,” *IEEE JSAC*, vol. 9, no. 6, pp. 785–800, August 1991.

[10] W. Y. Chen, *DSL: Simulation Techniques and Standards Development for Digital Subscriber Line Systems*. MacMillan Technology Series 1998, Indianapolis, 1998. ISBN 0-57-870017-5.

[11] J. W. Cook, R. H. Kirkby, M. G. Booth, K. T. Foster, D. E. A. Clarke, and G. Young, “The noise and crosstalk environment for ADSL and VDSL systems,” *IEEE Comm. Mag.*, vol. 37, no. 5, pp. 73–78, May 1999.

[12] S. Galli, C. Valenti, and K. J. Kerpez, “A Frequency-Domain Approach to Crosstalk Identification in xDSL Systems,” *IEEE JSAC*, vol. 19, no. 8, pp. 1497–1506, August 2001.

[13] “”GDSL (Gigabit DSL)”.” *http://www.eng.biu.ac.il /∼leshema/standard%20contributions/3E144871-GDSL_final.pdf/* (Last visit: 12 April, 2007).

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