# Towards Gigabit DSL (GDSL): System Feasibility Study

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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 ADSL2+ technology. Current research is investigating the possibility of symmetric DSL at 1 Gbps (GDSL).**

**This paper follows on a SATNAC 2007 paper and addresses a study on the feasibility of a complete complementary multi-carrier code-division multiple access (CC/MC-CDMA) transceiver system. 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. We also determine the capacity of the CC-MC-CDMA system.**

***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]. ADSL2+ (G.992.5) in South Africa is approaching the 8 Mbps product offering limit, while most countries are moving towards ADSL2+, supporting 24 Mbps downstream and 1 Mbps upstream (increased to 3.5 Mbps upstream when implementing Annex M). Still, this is not enough, 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). Although Gigabit Passive Optical Networks (GPONs) and Wave Division Multiplexing (WDM)-based PONs are viable last-mile solutions, these are not necessarily cost-effective solutions, especially in an existing network scenario. GDSL is a last-mile solution where the last 300m or less of the subscriber line consists of copper. This paper investigates (from SATNAC '07) the feasibility of a GDSL system, based on its bit-error rate (BER) and NEXT/FEXT analysis. The capacity of the system is also determined. Some background information is provided in Section II. The system is described in Section III, followed by the Design of the system in Section IV. Section V present some practical results that were obtained.

## II. BACKGROUND

The advantages and success of multi-carrier 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 [2]. The combination, known as Multi-carrier CDMA (MC-CDMA) [3]–[5], 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 multi-carrier 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 [5]. It is however crucial for Multi-carrier 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 [5]. 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 sub-carrier, providing quasi-synchronized transmission due to the longer symbol duration. MC-CDMA provides high-bandwidth efficiency, high capacity, low complexity implementation etc. [6].

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 Inter-Channel 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 [2]. However, relative to DS-CDMA, MC-CDMA have the following distinctive advantages:

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- Synchronization: Block synchronization can be achieved 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

The block diagram of the basic CC/MC-CDMA transmitter is shown in Fig. 1.

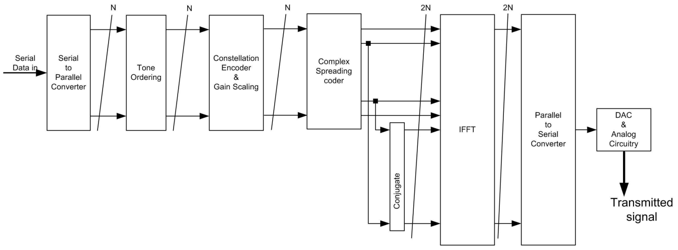

Fig. 1. Basic MC-CDMA transmitter structure

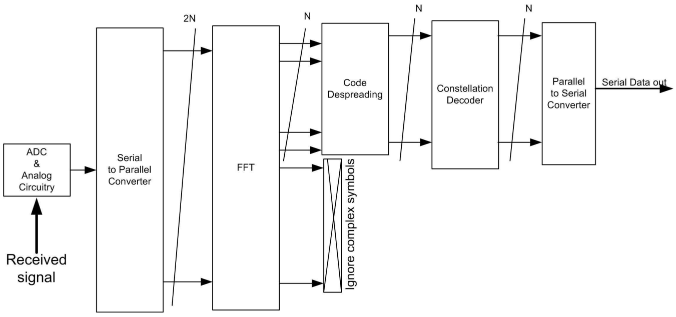

Fig. 2. Basic MC-CDMA receiver structure

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). The system can support up 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 send it out 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) environment. 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 the development of a GDSL system, the data rate is known (1 Gbps), while the rest of the system should be designed around this limit. In a wire line channel, signals from other twisted pairs couple into the desired twisted pair. The interference is called Near-End Crosstalk (NEXT). Also, the intererence from transmitters on the other end of the channel (called Far-end Crosstalk (FEXT)) also interferes, but is much smaller than 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 $l_\infty$ 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 $c_\infty$ 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 0.5mm (24 AWG) copper wire is summarized in Table I.

The characteristic impedance $Z_o$ and the propagation constant $\gamma$ 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 $\omega = 2\pi f$.

TABLE I
CABLE PARAMETERS FOR 0.5MM (24AWG) WIRE

| **roc** (kΩ) | **ac** | **l**$_o$ (mH) | **l**$_\infty$ (mH) | **f**$_m$ (MHz) | **b** | **C (nF/km)** |
|---|---|---|---|---|---|---|
| 0.1740 | 0.0530 | 0.6173 | 0.4789 | 0.5538 | 1.1530 | 50 |

The insertion loss function of a 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 is expressed as [10], as shown in Fig. 3:

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

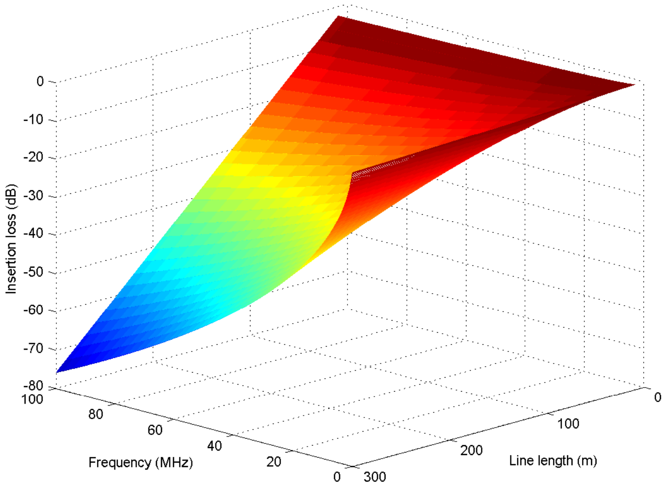

Fig. 3. Insertion loss (dB) vs. Line length (m) and Frequency (MHz) for 0.5mm (24 AWG) copper wire

The PSD of Near-end crosstalk (NEXT) noise (Fig. 4), can be expressed as:

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

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 (of a disturber) 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.

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

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, $| \cdot |^2$ is the modulus-squared function, and $f$ is the frequency [Hz]. FEXT Noise is shown in Fig. 5. It should be noted that the FEXT Noise is much smaller than its NEXT counterpart.

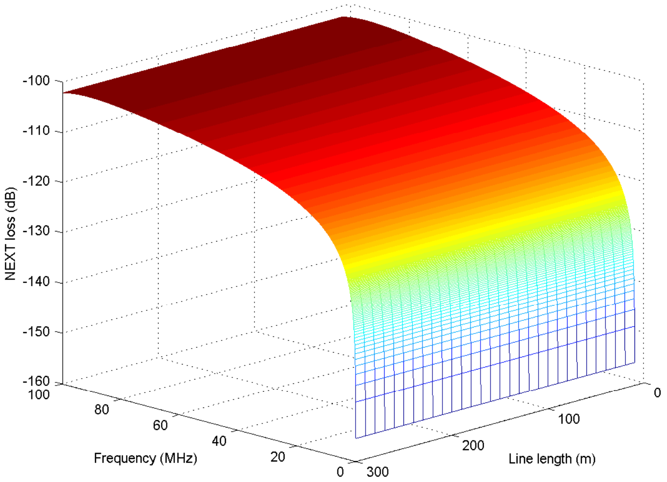

Fig. 4. NEXT Noise (dB) vs. Line length (m) and Frequency (MHz) for 0.5mm (24 AWG) copper wire

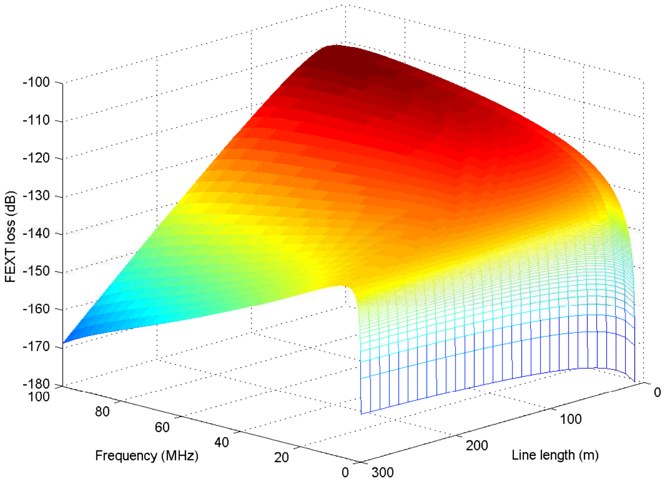

Fig. 5. FEXT Noise (dB) vs. Line length (m) and Frequency (MHz) for 0.5mm (24 AWG) copper wire

## IV. SYSTEM DESIGN

The first step is to find the relevant Power Spectral Density model of the system, which will be used for $PSD_{Disturber}$. From simulations, the PSD as shown in Fig. 6 is obtained. The 'x' (blue) marked graph represents an instant snapshot of the PSD of the CC-MC-CDMA system. After smoothing (taking a couple of these snapshots and averaging them), the "*" (orange) marked graph is obtained. A Bisquare Gauss-Newton fit was performed on the smoothed model, represented by the solid (red) line. This provides us with a simplified model to be used for the rest of the design.

The second step is to determine the operating point of the

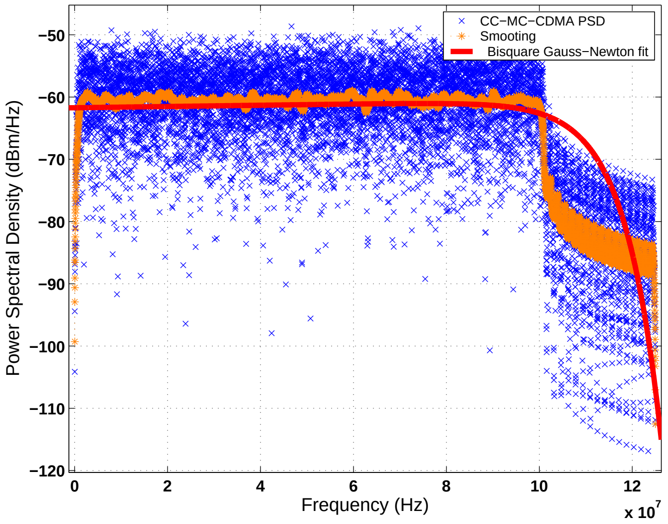

Fig. 6. Determination of the power spectral density model of a CC-MC-CDMA system

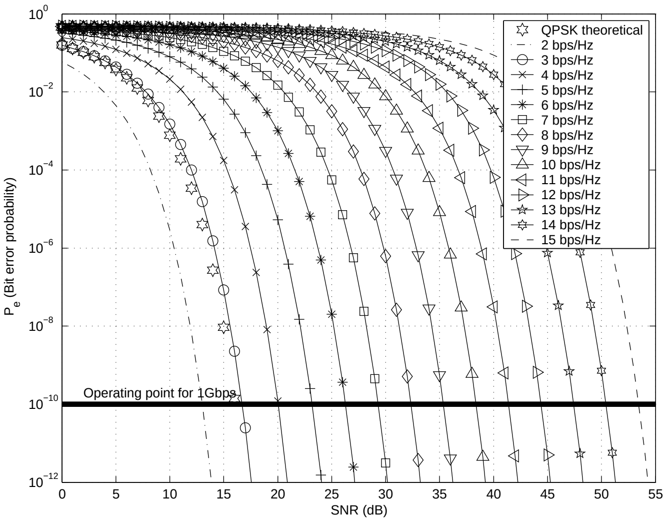

Fig. 7. $P_e$ versus $SNR$ for CC-MC-CDMA system (2048 subchannels)

system in terms of its fault tolerance. This is usually specified in terms of bit error rate (BER). Due to the fact that the system supports different modulation schemes per subcarrier, the system will have different bit-energy-to-noise ($E_b/N_o$) or signal-to-noise ratio ($SNR$) requirements (Fig. 7). The bit error rate ($P_e$) for M-QAM with N subchannels is defined as [12]:

$$P_e = \frac{\sqrt{M}-1}{\sqrt{M}\log_2\sqrt{M}} erfc\left(\sqrt{\frac{(2^{\sqrt{N}}-1)}{2^{\sqrt{N}-1}}.\frac{3.\log_2 M.Eb}{2.(M-1).N_0}}\right) \tag{11}$$

where $erfc(\cdot)$ is the complementary error function. $P_e$ follows the general trend of the probability of error for N-ary bi-orthogonal signals [13], i.e. the BER performance improves with increasing $N$, but with diminishing gain as $N \rightarrow \infty$ for each M-QAM case. The relationship between $E_b/N_o$ and $SNR$ is

$$\frac{E_b}{N_o} = \frac{S/N}{\eta} \tag{12}$$

where $\eta$ is the spectral efficiency (in bps/Hz) of the CC-MC-CDMA system. For a 1 Gbps system, a BER point of $10^{-10}$ is chosen. The system will thus make 1 bit fault for every 1 Gigabits (on average). Simple forward error correction (FEC) codes can be used to correct errors. Table II shows the minimum required $E_b/N_o$ and $SNR$ requirements, for each of the spectral efficiencies (per subchannel).

TABLE II
MINIMUM $E_b/N_o$ AND SNR REQUIREMENTS FOR A 1GBPS 2048-SUBCHANNEL CC-MC-CDMA SYSTEM @ BER=$10^{-10}$

| **Spectral efficiency $\eta$ (bps/Hz)** | **$E_b/N_o$ (dB)** | **SNR (dB)** |
|---|---|---|
| 2 | 10.03 | 13.02 |
| 3 | 11.94 | 16.70 |
| 4 | 14.07 | 20.04 |
| 5 | 16.22 | 23.16 |
| 6 | 18.53 | 26.33 |
| 7 | 20.83 | 29.24 |
| 8 | 23.27 | 32.31 |
| 9 | 25.85 | 35.35 |
| 10 | 28.33 | 38.38 |
| 11 | 31.02 | 41.45 |
| 12 | 33.55 | 44.44 |
| 13 | 36.29 | 47.40 |
| 14 | 39.00 | 50.42 |
| 15 | 41.72 | 53.41 |

The third step is to determine the SNR of the CC-MC-CDMA system for two cases:

- Insertion loss only (Fig. 8)
- Insertion loss, NEXT noise and FEXT noise (Fig. 9)

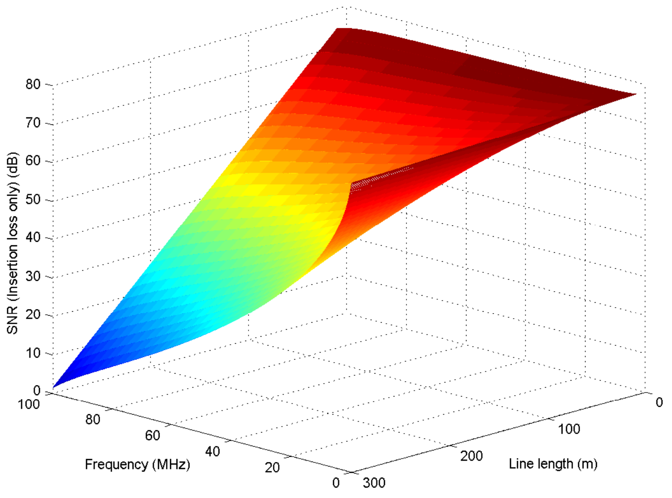

Fig. 8. Signal to noise (SNR) (dB) vs. Line length (m) and Frequency (MHz) for 0.5mm (24 AWG) copper wire

## V. RESULTS AND DISCUSSION

From the PSD for the disturbers (NEXT noise) (Fig. 4) and the PSD of the CC-MC-CDMA transceiver under consideration (Fig. 6), it can be observed that the disturbers are located more than 40dB below the actual PSD of the system. As shown in Fig. 10 (taken from [7]), the addition of more users does not affect the performance of the system. Thus, it can be concluded that NEXT and FEXT does not have

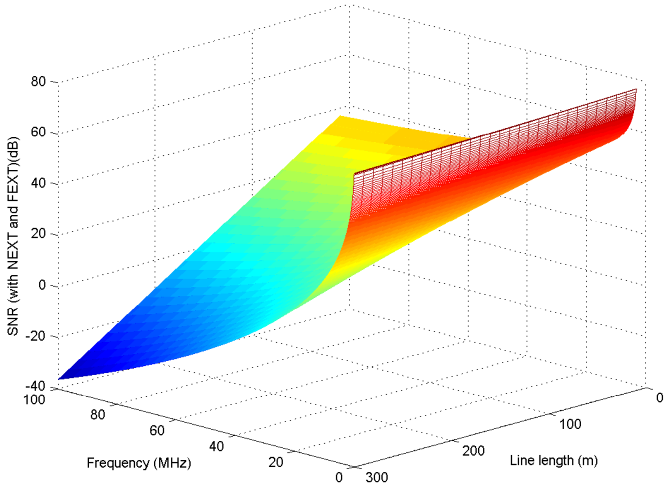

Fig. 9. Signal to noise (SNR) (dB) vs. Line length (m) and Frequency (MHz) for 0.5mm (24 AWG) copper wire

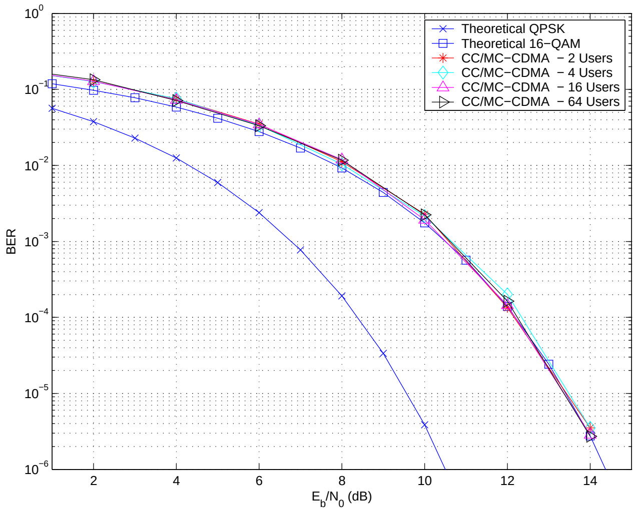

Fig. 10. BER performance for a 40dB NEXT level CC-MC-CDMA system

an effect on the performance of a CC-MC-CDMA system. However, the system is still affected by Insertion loss, which is an inherent property of the copper wire.

Lastly, the capacity of the system is considered for two cases:

- With NEXT and FEXT considered (Fig. 11)
- Only with Insertion loss (Fig. 12 and Fig. 13)

It was found that the CC-MC-CDMA system shows an exceptionally good theoretical system capacity. The system can support 1 Gbps up to 240m over a single wire pair. This is in contrast to the comparable system (not using CC-MC-CDMA) where NEXT decreases the line length to only 40m.

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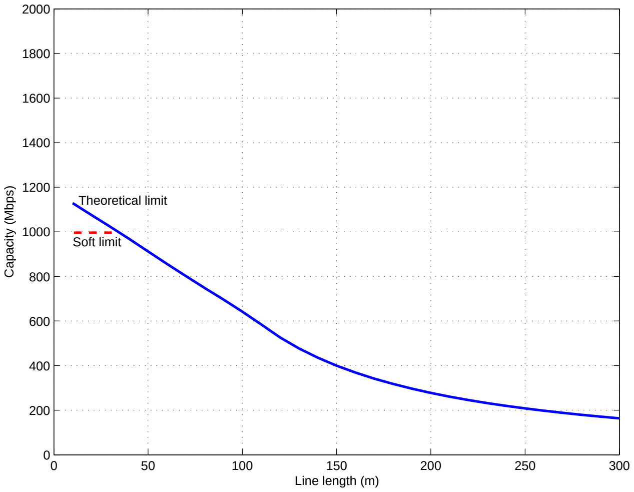

Fig. 11. Capacity of the system, if NEXT and FEXT was considered vs. Line length (m) for 0.5mm (24 AWG) copper wire

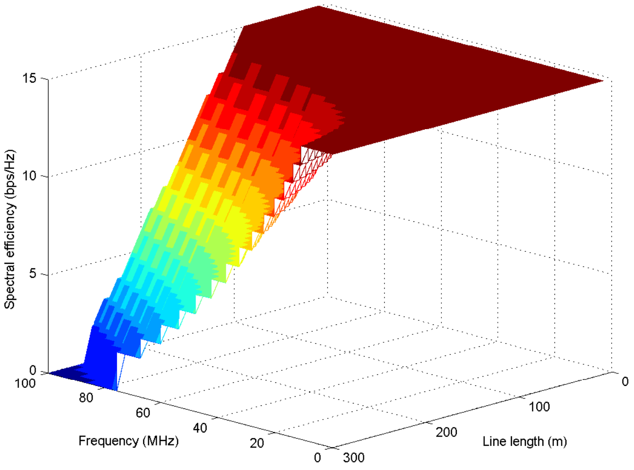

Fig. 12. Spectral allocation (bps/Hz) of the CC-MC-CDMA system vs. Line length (m) and Frequency (MHz) for 0.5mm (24 AWG) copper wire

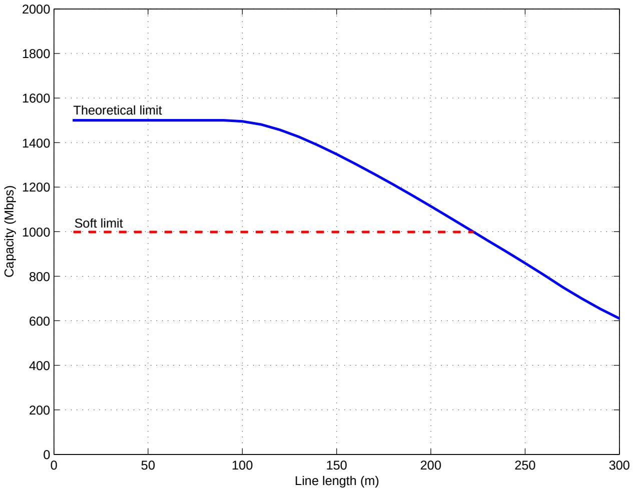

Fig. 13. Capacity of the CC-MC-CDMA system vs. Line length (m) for 0.5mm (24 AWG) copper wire

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