A DISCRETE MULTITONE POWER LINE COMMUNICATIONS SYSTEM

*T. Esmailian**, *P.G. Gulak, and F.R. Kschischang*

Department of Electrical and Computer Engineering
University of Toronto
10 King's College Road, Toronto, Ontario M5S 3G4, CANADA

ABSTRACT

Recently in-building power lines have been considered as a medium for high speed data transmission for applications like home networking and internet access. Frequency selectivity and time variation of this medium in addition to the high level of narrow-band and impulsive interference makes multi-carrier modulation, and especially its popular variant discrete multitone (DMT), an attractive modulation candidate for this application. This paper presents the results of our measurements of the high frequency characteristics of ordinary in-building power lines, as well as simulation results of a DMT transceiver system in an in-building power line environment.

1. INTRODUCTION

Power line cables have been used as a communication medium for many years. Recently, applications like home automation, local area networks and internet access have drawn more attention to the use of in-building power lines. The key advantage of in-building power lines is the existence of abundant pre-installed wires and wall outlets. However, because power line cables are not designed for communication, they provide some challenges for a modem designer. Frequency selectivity and time variation of the channel frequency response, high levels of noise, and regulatory issues are some of the main considerations.

Spread spectrum has been used as a robust modulation scheme in frequency selective fading channels and in systems where narrow-band interference mitigation is necessary. This modulation method has been and is being used in power line communication systems [1][2]. The main disadvantage of a spread spectrum approach is that it is difficult to achieve an optimal (water-pouring) power spectrum, so full utilization of the available spectrum is difficult to achieve. DMT systems, on the other hand, can easily achieve a water-pouring-like power spectrum that maximizes the data rates that can be transmitted reliably. DMT systems have been used for high speed data transmission over telephone lines [3]. The good performance of these systems over frequency selective channels as well as their robustness to impulsive and narrow-band noise make them attractive candidates for high speed data transmission over power lines.

*Supported by a Motorola University Partnerships in Research grant.

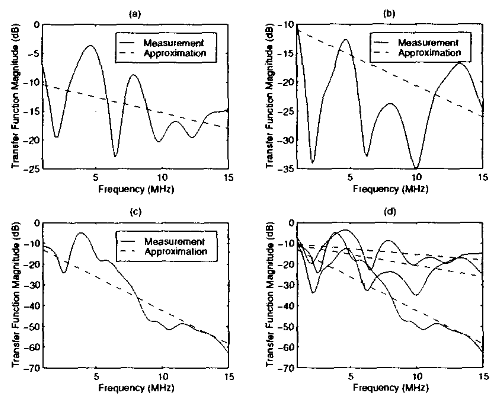

Figure 1: Channel frequency response magnitude and mathematical approximation for (a) 10 m, (b) 20 m, and (c) 60 m in-building power line cables. (d) comparison of all three measurements.

We have made measurements on the channel characteristics and the results are presented in Section 2. In Section 3, bounds for the channel capacity are computed. In Section 4 the simulated performance of a DMT transceiver in an in-building power line environment is presented.

2. CHARACTERISTICS OF POWER LINES AS A COMMUNICATION MEDIUM

Two essential characteristics of any communications medium are frequency response and noise. The frequency response of a power line is far from ideal; the channel is frequency selective and slowly time varying as various devices are switched in and out of the power line circuit. We have studied and measured the intra-building power line cable frequency response in [4]. Figure 1 shows some of our measurements. The frequency response exhibits considerable

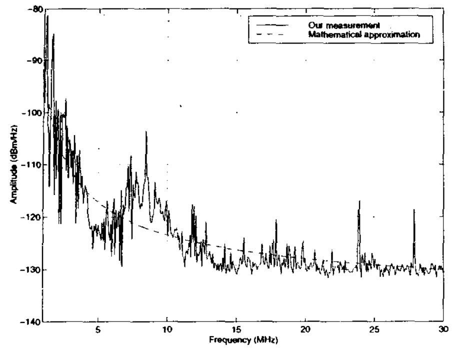

Figure 2: A sample of noise power spectral density in a university building and mathematical approximation [4].

frequency dependent variation, due to the specific wiring configurations encountered. In macroscopic terms, however we see a clear trend of greater attenuation at larger frequencies and at larger distance between transmitter and receiver. This macroscopic trend is captured in a simple two-parameter model in which

$$| H(d, f) |= 10^{-(\alpha \cdot d \cdot f+\beta)} \tag{1}$$

In this model, α and β are constants depending on the structure and thickness of the cables, f is frequency in MHz and d is the distance between transmitter and receiver in meters. Similar models have been used to characterize telephone line channels; for example, the magnitude of the channel frequency response of a perfectly terminated telephone loop with length d is modelled in [6] as

$$|H(d, f)| = e^{-d.\theta(f)} \tag{2}$$

Using a least mean square fitting method, α and β in (1) can be computed for each measurement. Some typical values for these constants (for our university building) are: $\alpha = 0.0027$ and $\beta = 0.5$.

There are two essential types of additive noise in power line channels: background noise and impulsive noise. Figure 2 shows a sample of the background noise power spectral density (PSD) in a university building and its corresponding mathematical approximation. This power spectrum was measured using a spectrum analyzer and interface circuit as described in [5]. The background noise PSD shows significant frequency dependent fluctuations due to the various noise sources at different locations. However, in macroscopic terms, it exhibits a clear trend of decreasing as frequency increases. This macroscopic trend can be captured in the following simple three-parameter model

$$S_n(f) = a + b \cdot |f|^c \ \ dBm/Hz, \tag{3}$$

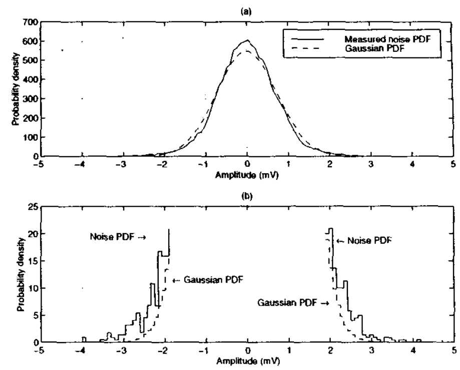

Figure 3: (a) Probability distribution of the measured background noise compared with a Gaussian signal with the same variance, (b) tails of same distribution.

where a and b and c are constants and f is frequency in MHz. Table 1 provides parameter values for our best and worst case measurements.

	a	b	c
Best case	-140	38.75	-0.720
Worst case	-145	53.23	-0.337

Table 1: Value of parameters of noise model for best and worst measurement cases.

Figure 3 shows a sample of background noise amplitude distribution compared to a Gaussian distribution with the same variance. There is a standard technique, the so-called *chi-square test*, to verify how well the approximation of the measured probability density dunction (PDF) matches a priori known PDF [7]. In our example we compare the distribution of measured noise samples with a Gaussian distribution with the same variance. Although the background noise distribution looks Gaussian, however because of heavy tails of background noise distribution compared to a Gaussian distribution (as can be seen in Figure 3(b)) the result of chi-square test shows that the background noise is unlikely to be Gaussian.

The major source of impulsive noise in power lines are devices that are connected to the power line circuit. Electric motors, silicon-controlled rectifiers (SCR's) and switching devices are some of the major impulsive noise generators. Electric drills, light dimmers and switching power supplies are some examples for appliances that generate impulsive noise. Figure 4 shows examples of impulsive noise generated by an electric drill and a light dimmer. Three important properties of impulsive noise are: amplitude, width and inter-arrival time.

Detailed measurements for some appliances are documented in [5]; we found, for example, that a light dimmer

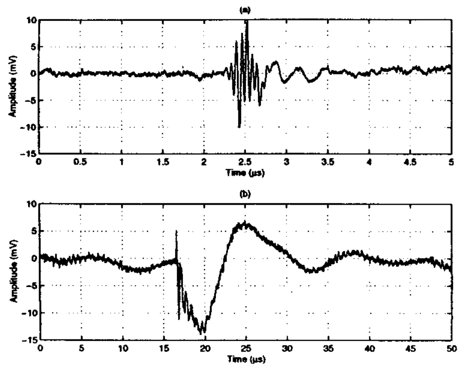

Figure 4: One sample of impulsive noise generated by (a) an electric drill, (b) a light dimmer.

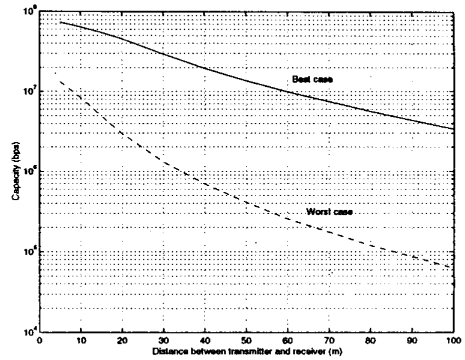

Figure 5: Channel capacity of in-building power lines for different length channels and a transmit power of 1 μW.

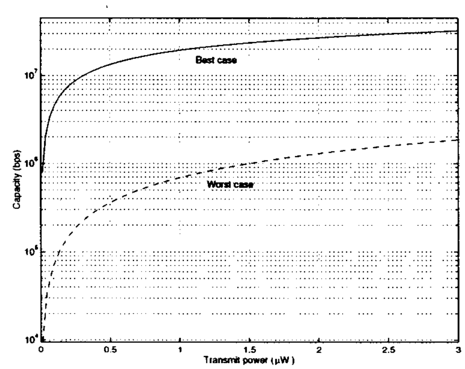

Figure 6: Channel capacity of a 40 m in-building power line cable.

produces impulse noise with a mean amplitude of 13 mV, a mean width of 5 μs, and an approximately exponentially distributed inter-arrival time with a mean of 3 ms. Such measurements are important to define in-building power line noise models for generating impulsive noise samples for simulation purposes.

3. CHANNEL CAPACITY

Based on the channel properties, frequency response and background noise power spectrum, and with the assumption of a Gaussian distribution[1] for the noise it is possible to estimate the channel capacity. Using the water-pouring method [8], based on the measurements for the channel characteristics, an estimate of the channel capacity is calculated for different cable lengths and a transmit power of 1 μW. The result is shown in Figure 5. The best case is calculated using the best PSD limit for noise. The worst case is calculated using the worst limit for noise PSD and assuming a 6 dB margin for the channel frequency response. (A 6 dB margin means multiplying the frequency response by a factor of 1/2 for taking into account the possibility of some deviations from our measurements.) Figure 6 illustrates the channel capacity bounds for a 40 m power line cable. It can be seen that using a transmit power of 3 μW the channel capacity is between 2 Mbps and 30 Mbps.

4. DMT SIMULATION RESULTS

We have simulated the performance of a DMT transceiver in an in-building power line environment. Figure 7 shows the basic structure of a DMT transmitter and receiver. The frequency response of a 20 m in-building power line cable used for this simulation is shown in Figure 1(b). The utilized noise power spectrum is shown in Figure 2. In the simulation a bandwidth of 14 MHz (frequency range of 1 MHz up to 15 MHz) is divided to 256 subchannels, each with approximately 54 kHz of bandwidth. Assuming a block transmission rate of 50 kHz, the block duration is 20 μs. Considering a bit rate of 2 Mbps and 40 samples for the cyclic prefix, the sampling rate at the transmitter as well as the receiver is $552 \times 50000 = 27.6$ MHz. A target bit error rate of 10^{-7} was assumed in this simulation.

The next step in the simulation is assigning energy and bits to each subchannel using a so-called *loading algorithm* [9]. Based on the total transmit energy budget and considering equal probability of error on all subchannels, there are several different types of loading algorithm. In this simulation we have used the loading algorithm in [10]. In this algorithm, those subchannels that have signal-to-noise ratios below a certain threshold are completely turned off (not used). The constellation size for other subchannels is chosen based on the the noise power and attenuation in each subchannel. Also a uniform distribution of energy in all

[1] Although the actual noise is not Gaussian, assuming a Gaussian distribution and using a water-pouring method establishes a lower bound for the channel capacity.

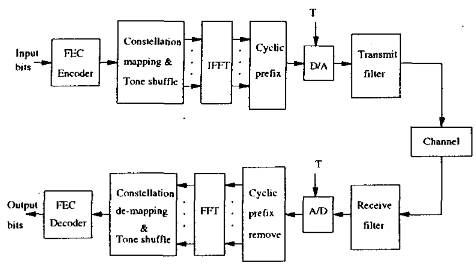

Figure 7: Block diagram of a DMT transmitter and receiver.

subchannels is considered. Figure 8 shows the distribution of bits in each of 256 subchannels for different transmit powers. It can be seen that the loading algorithm uses only a fraction of the available subchannels. Figure 9 shows the data rate achieved for different transmit powers and for different noise margins. A 3 dB, 6 dB, or 12 dB noise margin means that the noise power spectral density is increased by a factor of 2, 4, or 16. Even with a large noise margin, using as little transmit power as 4 μW, transmission rates approaching 2 Mbps are achievable even without channel coding.

5. CONCLUSION

In this paper the possibility of using a DMT system for high speed data transmission over ordinary in-building power lines is investigated. The channel capacity calculations using measured data demonstrates the possibility of multi-megabit per second data transmission over this medium. The simulation results show that using a relatively small amount of power (a few μW) and with a noise margin of up to 12 dB, high speed data transmission (a few Mbps) is possible. Figure 9 reveals that with a 12 dB noise margin relative to the average measured noise PSD, using only a power of about 3 μW, transmission at 1.5 Mbps over in-building power lines is feasible, a rate which can support, e.g., transmission of MPEG compressed video.

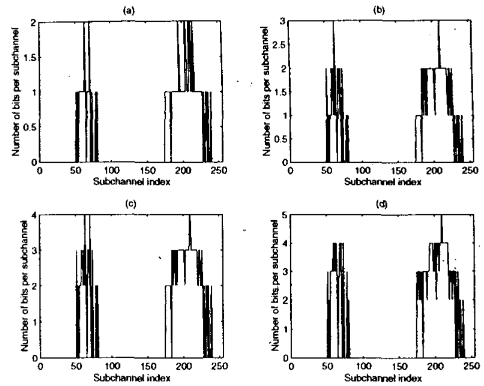

Figure 8: Bit distribution in subchannels for (a) 1 μ W, (b) 2 μ W, (c) 6 μ W, and (d) 10 μ W of transmit power.

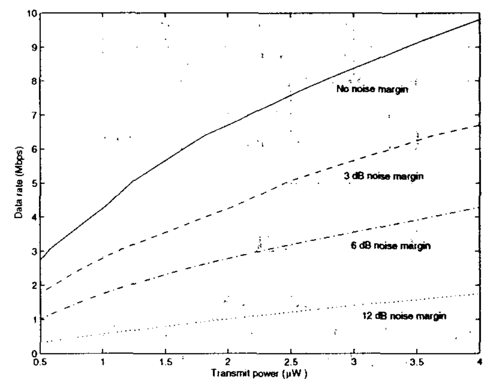

Figure 9: Effect of different noise margins on data rate.

6. REFERENCES

[1] P. K. Van Der Gracht and R. W. Donaldson, "Communication Using Pseudonoise Modulation on Electric Power Distribution Circuits," *IEEE Trans. on Commun.*, vol. COM-33, pp. 964–974, Sept. 1985.

[2] K. M. Dostert, "Frequency-Hopping Spread-Spectrum Modulation for Digital Communications Over Electrical Power Lines," *IEEE J. on Selected Areas in Commun.*, vol. 8, pp. 700–710, May 1990.

[3] J. S. Chow, J. C. Tu, and J. M. Cioffi, "A Discrete Multitone Transceiver System for HDSL Applications," *IEEE J. on Selected Areas in Commun.*, vol. 9, pp. 895–908, Aug. 1991.

[4] T. Esmailian, "Frequency Response Measurement of Power Lines," Ph.D. thesis progress report, University of Toronto, June 1999.

[5] —, "Noise Measurement in Power Lines," Ph.D. thesis progress report, University of Toronto, Aug. 1999.

[6] J.-J. Werner, "The HDSL Environment," *IEEE J. on Selected Areas in Commun.*, vol. 9, pp. 785–800, Aug. 1991.

[7] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes in C*, Cambridge University Press, 1988.

[8] R. G. Gallager, *Information Theory and Reliable Communications*, John Wiley & Sons, 1968.

[9] P. S. Chow, J. M. Cioffi, and J. A. C. Bingham, "A Practical Discrete Multitone Transceiver Loading Algorithm for Data Transmission over Spectrally Shaped Channels," *IEEE Trans. on Commun.*, vol. 43, pp. 773–775, Feb./Mar./Apr. 1995.

[10] A. Leke and J. M. Cioffi, "A Maximum Rate Loading Algorithm for Discrete Multitone Modulation Systems," *Proc. of GLOBECOM'97*, vol. 3, pp. 1514–1518, 1997.