A Power Line Communications System based on Discrete Multi-Tone Modulation

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Abstract: *This paper presents the development of the physical layer for a Power Line Communications (PLC) system based on Discrete Multi-Tone (DMT) modulation. Simulation is migrated towards a real system by means of emulation. An introduction is given, followed by an overview of the proposed system. The methodology adopted is then discussed and a more detailed explanation of DMT is presented. Some simulation results are shown. Finally, channel measurement is discussed, and a summary made.*

1. Introduction

Power Line Communications (PLC) technology implements communication links over existing power transmission networks. The technology offers the prospect of being able to construct 'intelligent buildings', which contain many devices in a Local Area Network (LAN). The technology is also attractive for the provision of narrow-band communications links in less developed countries, where the installed telecommunications network is likely to be very limited.

Current PLC technology seems less able to compete in the local access arena with technologies such as Digital Subscriber Line (DSL), cable modems and broadband wireless networks. However, some commercial PLC systems aimed at access network provision have reached the trial stage, a well-known example being the Nor.Web system [1]. There are also a number of commercial intrabuilding systems, although the majority of these offer bit rates that are low by modern standards.

This work aims to address some of the major difficulties involved with the development of a PLC system. Mechanisms for the adaptation of the Discrete Multi-Tone (DMT) modulation scheme to the channel environment have been largely developed with Digital Subscriber Line systems as the intended target. The PLC channel has not been extensively studied, especially for the frequency range up to a few megahertz required for the modulation scheme under consideration.

2. The Proposed System

Figure 1 shows the proposed system in block diagram form. This paper is concerned only with the transmitter, receiver, channel and noise components of the system.

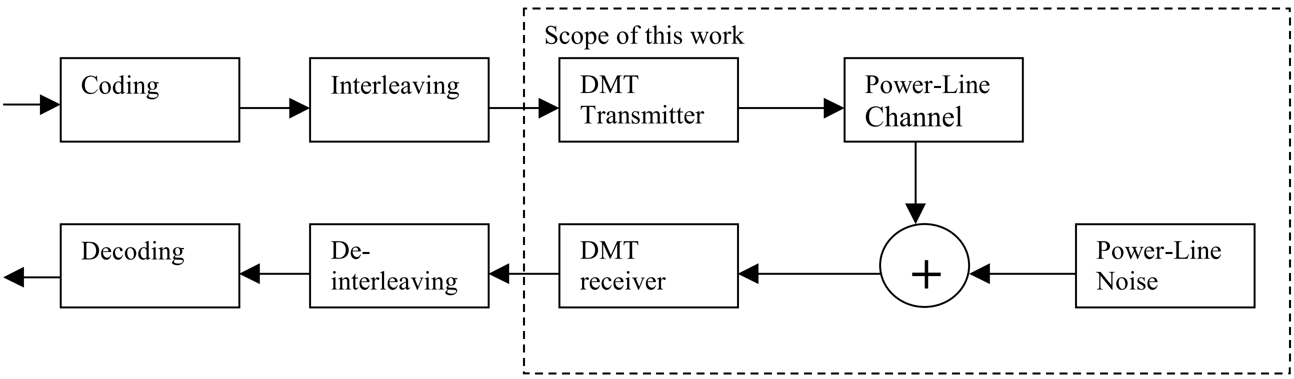

Figure 1: The Proposed System

3. Research Methodology

We are concerned here with the physical layer of the Open Standards Interconnect (OSI) model, where time-driven (continuous) simulation is used. One of the key problems with simulation is that assumptions and simplifications inevitably have to be made. It can be hard to determine if these simplifications and assumptions will have a significant effect on the 'realism' of the simulation and hence the usefulness of the results. The PLC channel poses the greatest challenge to simulate accurately. The DMT transmitter and receiver are to be implemented in DSP chips and are able to be accurately simulated. The channel is a continuous-time system, making simulation of this part of the system a more difficult problem. The presence of impulsive noise adds further difficulty. Some way is needed to move from a full simulation to a hardware realization and an intermediate step is provided by emulation, where the channel simulation model is replaced by a real channel. The transmitter and receiver simulations may then be used with the real channel and the results compared with the simulation of the complete system.

3.1. Simulation

A simulation of the DMT based PLC system has been developed in the C language, using the UNIX operating system. The simulation uses a time-driven (continuous) approach, as is appropriate for physical layer simulations of this type. The individual modules of the simulation, such as the transmitter, receiver, impulsive noise model, and so on, are written as separate software components. A program wrapper acts as an encapsulation for the modules, giving each a common interface, as well as performing data range checking. A component-based architecture has many advantages, such as ease of code re-use and ease of understanding [2]. Aside from the major system functions described in the diagram of section 2, several minor modules are also required. These perform functions such as random data generation and Bit Error Rate (BER) estimation. It is also desirable to be able to distribute the simulation over several computers because this allows BER estimation to be performed using the Monte-Carlo method without requiring excessive computation time.

3.2. Emulation

The line coupling circuitry for the emulation consists of a wide-band operational amplifier, followed by a high-pass filter to isolate the mains voltage from the other equipment. The receiving end is similar but the filter is moved to the amplifier input. The signal to be put on the channel is supplied by a high-speed arbitrary waveform generator. The data is then collected at the output by a digital storage oscilloscope. Finally, a general-purpose interface bus connection is used to transfer the received data to a PC for analysis.

4. Discrete Multi-Tone Modulation

A general treatment of DMT is given by reference [3]. Conceptually, the frequency band to be used for transmission is split into a number of sub-channels. Each sub-channel has data modulated onto it by means of Quadrature Amplitude Modulation (QAM). The QAM constellation of the sub-channel is determined by a measure of its ability to support error-free data transmission. Evaluation of this capacity is done on the basis of the Signal-to-Noise Ratio (SNR) as seen at the receiver. The DMT modulation adapts to the characteristics of the channel being used for transmission. The total data rate of the transmission system is the sum of the data rates of the sub-channels. The modulation is implemented digitally by means of a Fast Fourier Transform (FFT). The FFT ensures that the sub-channels are orthogonal and thus minimizes interference between sub-channels. Such interference still occurs, due to the side-lobes produced by the transform. The data bits are mapped onto constellations, which are viewed as an Argand diagram in order to produce a single complex number for each sub-channel. The complete set of complex numbers for all of the sub-channels is then transformed by the FFT. The resulting time domain data is then fed to a digital to analogue converter in serial form. This process produces a single DMT symbol. Adjacent symbols are separated by a guard period formed by prefixing each symbol with a copy of the last few samples of the transmitted sequence. A DMT system operates in two distinct modes – training and data transmission. The training mode evaluates the channel environment, and allocates appropriate numbers of bits to each sub-channel. The data transmission mode performs the actual transfer of user data.

4.1. Bit Allocation

The number of bits allocated to a sub-channel depends on the SNR in the sub-channel, and upon the selected noise margin. Bit allocation algorithms aim either to maximize data rate for a given margin [4], i.e. to make the system rate adaptive, or to maximize the margin for a fixed data rate [5]. It was found that the latter approach is likely to be impractical for PLC systems, due to the very variable nature of the channel. Since the BER is directly related to the margin, it is important for the margin to stay close to the desired value. The data rate steps for the former case are very fine, because of the large number of subchannels and the use of 8 possible QAM constellations. This may cause problems with higher layers and with interleaving. An approach somewhere between the two extremes would solve these problems, with the margin allowed to vary slightly in order to permit the data rate steps to be coarser.

5. Channel Models

A PLC channel model has been developed from first principles [6]. This model is concerned with the effect of a single propagation path. Some published work [7] presents a channel model that allows for the effects of multipath propagation. It is known that multipath is significant in local access type PLC systems. Channel measurements for the intrabuilding case will determine weather they are significant.

5.1. Noise Models

Radio frequency interference and impulsive noise dominate the noise environment found on power lines. Additionally, the background nose is typically not white [7] but coloured noise, decreasing with frequency. The impulsive noise is found to be partially synchronous to harmonics of the mains frequency [8]. Modules have been developed for the simulation of coloured noise and impulsive noise. The modelling of impulsive noise is especially challenging. A Poisson process governs the pulse interarrival times, while the pulse magnitudes follow a lognormal distribution. Choice of an appropriate pulse shape is important, in order to represent the power spectrum of real noise impulses [9].

6. Simulation Results

The channel, noise and bit allocation sections of the simulation have been used to give an indication of typical bit allocations with the various channel models. White noise of

–110 dBW was used. The model of [7] results in approximately 880 bits per symbol, with 512 sub-channels, giving a data rate of approximately 3.6 Mb/s at a sampling frequency of 1104 kHz. The channel models of [6] point to rather higher data rates, around 5 Mb/s, although these represent what would be only parts of a real network. Simulations of the whole system are now required to estimate typical error rates and to establish the amount of noise margin that is required to deal with the noise environment.

7. Channel Measurement

In order to verify the results of simulations by the use of emulation, it is necessary to have a model that represents the real channel to be used. Work is in progress to perform some measurements of the complex transfer function of the power distribution wiring around one of the UCL laboratories. Complex transfer function measurement is being carried out by transmission of a maximum length pseudo-random sequence, followed by estimation of the transfer function by a cross-correlation.

8. Summary

A simulation of the PLC system transmitter, receiver and channel has been developed. The hardware necessary to verify simulation results by means of emulation has also been constructed. Initial simulation results give an indication that the achievable data rate is of the order of 3 - 5 Mb/s. Work is underway to perform some measurements of the complex transfer function of intrabuilding channels.

Acknowledgments

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