Multimedia Transmission over Power Line Channels Using Space-Time Diversity Techniques

Vasileios Zarimpas, Carlos L. Giovaneli, Bahram Honary

Department of Communication Systems, Lancaster University
Bailrigg, Lancaster, Lancashire, LA1 4YR, United Kingdom
Tel: +44 1524 592121, Fax: +44 1524 592713
E-mail: v.zarimpas@lancaster.ac.uk  c.lopezgiovaneli@lancaster.ac.uk  b.honary@lancaster.ac.uk

Abstract

The proposed paper presents a novel technique of data multiplexing enabling the transmission of multimedia data over power line channels. The multiplexing system architecture, the communication protocol and the frame structure are being highlighted. Real-time multimedia data management, traffic control and coding schemes imply high quality of service and efficiency over the hostile environment of power line channels. Additionally, the outstanding advantage of using space-time block coding (STBC) combined with adaptive decoding schemes in the presence of asynchronous impulsive noise is emphasised.

1. Introduction

Multiplexing is an essential part in a communication system where multiple data streams are transmitted simultaneously through a single link. Multimedia data streams such as video, audio and high quality digital images have special requirements that are hard to be met, especially by power line communication systems (PLC). High bandwidth, small transmission delays and channel reliability are required for on-time data stream delivery and real time playback [1]. However, the nature of the transmission medium in PLC degrades significantly the performance, since attenuation and noise levels are often excessive [2, 3]. The proposed paper evaluates the performance of multimedia transmission in impulsive noise environments and presents methods to improve the Quality of Service (QoS). Additionally, an advanced multiplexing strategy combined with a forward error correction code is demonstrated and simulation results are provided. Moreover, the utilisation of space-time block coding (STBC) techniques for high-speed multimedia data communications over power line networks has been investigated and useful results are depicted.

2. System Structure

The power line multimedia transmission system is shown in figure 1. Simultaneous connection of \( M \) different multimedia equipments \((M \leq 64)\) is feasible. The multimedia modules adapt the equipments to the data multiplexer and add, when appropriate, useful information such as data type and quality of service requirements. The data multiplexer is considered to be the heart of the system as the information received from the data source modules, in the form of data packets, is multiplexed and passed for modulation. QPSK modulation scheme with four complex constellation symbols is used.

![Fig. 1 – Power Line Multimedia System](image-url)
Space-time diversity of the modulated data when two or three transmission wires are available is performed by the Space-Time Block Coding (STBC) module. The channel module adapts the output of the STBC to the transmission channel. At the power line receiver, Linear Combining (LC), Maximum Likelihood (ML) detection and demodulation are applied. Data packets are retrieved and delivered to the corresponding multimedia applications (or equipments) by the de-multiplexer system. Further details are provided in the following sections.

3. Multimedia Infrastructure

The multimedia infrastructure, as highlighted in figure 1, consists of the multimedia equipment that handles all the processes used to acquire, present, store and retrieve multimedia information. There is a spectrum of technologies available for various applications including digital live video, audio services, still images, text and digital telemetry. Handling almost any type of data source and its ability to be updated very easily for advanced future applications consists an outstanding advantage of the power line multimedia system.

The multimedia module (figure 1), operates as an intermediary by adapting the connection interface and the communication protocol between the multimedia equipment and the multiplexer system. Control of the module is exercised by the multiplexer intelligent core (figure 2), and is real-time configurable. Information related to data type, Quality of Service (QoS), tolerance and bandwidth requirements is held into the multimedia module and is continuously provided to the multiplexer control and management centre in order to achieve maximum performance.

4. Data Multiplexer

The data multiplexer system structure is illustrated in figure 2, where M inputs ($M \leq 64$) are shown to be used to link the multimedia modules with the data Splitter/Combiner. Data Splitter/Combiner block is responsible for the data splitting, re-combination and delivery. Control information and instructions are continuously provided by the Control and Management Centre (CMC), the intelligent core of the multimedia system, via the control channel. Two distinct layers, the adaptation layer and the multiplex layer, handle the error correction/detection tasks and the multiplexing protocol functions.

4.1 Control and management centre (CMC)

The Control and Management Centre (figure 2) can be characterized as the most important and the most intelligent part of the system as by monitoring continuously multimedia modules, data traffic and quality of service requirements, multiplexer activity is being controlled. CMC is real-time reconfigurable and is designed to drive the multiplexer and the multimedia modules in the most efficient way.

Traffic control guarantees [1, 5] the delivery of time sensitive packets with hard deadlines. The Control and Management Centre (CMC) continuously monitors the available bandwidth (B/W) and the delay of the transmission channel. Using information that is provided by the multimedia modules, in the form of look-up tables, CMC controls the multimedia traffic. Look-up tables contain parameters concerning the minimum required data rate, the maximum acceptable delay, the priority and the acceptable bit error rate (BER) of the data source. Different data sources may have different look-up tables (due to different requirements) that can be initialized and configured according to the multimedia equipment and the type of the application. Avoiding network overload, data prioritise, and coding adaptation are the main objectives of the CMC, referring to each data packet separately. CMC decisions are passed for execution to the Splitter/Combiner block and the data coder via the control channels (see fig. 2).

**Fig. 2 – Data Multiplexer System**
Additionally, the insertion and the removal of the multimedia modules are within the framework of the Control and Management Centre (CMC) responsibilities. When multimedia equipment is attached and is available for use, insertion of the corresponding multimedia module is performed by CMC, combined with the initialization and all the configurations required and finally the creation of the link between the module and the Splitter/Combiner block. On the other hand, when a multimedia service is no longer required, the module is being disconnected and put in standby mode.

4.2 Data splitter/combiner

Data Splitter/Combiner (SC) (see fig. 2) has an outstanding role in the multimedia system. At the transmitting site data splitting is taking place. Explicit instructions are given by the Control and Management Centre (CMC) via the control channel. Two parameters are included within these instructions: SC input identification number Bi (1>Bi>M, Figure 2) and amount of data to be read from the input Bi. By following priority rules the SC generates and forwards the data packets to the Adaptation Layer (AL). At the receiving site error free packets are recombined and delivered to the corresponding multimedia module/equipment.

4.3 Multiplexing layers

There are two distinct layers that enable the effective multiplexing technique presented: the Adaptation Layer (AL) and the Multiplex (MUX) layer [6].

The information passed from the Data/Splitter to the Adaptation Layer (AL) includes an integer number of octets, which called Adaptation Layer Service Data Units (AL-SDUs). The Adaptation Layer adapts AL-SDUs to the multiplexer layer by adding additional octets to the purpose of error detection, forward error correction, sequence numbering and data recombination-encapsulation at the receiver. The information unit exchanged between peer AL entities is called an AL Protocol Data Unit (AL-PDU).

The MUX layer is responsible for transferring information received from the Adaptation Layer (AL) to the data modulator. Information is exchanged with the AL in logical units called Multiplexer Service Data Units (MUX-SDUs). A MUX-SDU always contains an integral number of octets. The MUX layer transfers the MUX-SDUs to the input of the data modulator in one or more variable length packets called Multiplexer Protocol Data Units (MUX-PDUs). These packets convey synchronization and de-multiplexing information as well as data. Detailed description of the multiplexer frame structure is given in the next section.

5. Multiplexer Frame Structure

5.1 Adaptation layer (AL)

The multiplexer frame structure is shown in Figure 2. The Splitter transfers its data through AL-SDUs to the Adaptation Layer (AL). Cyclic Redundancy Check Code (CRC-16) is computed and added to the AL-SDU in order to verify whether the decoding procedure of the forward error correction algorithm is error-free at the receiver [6]. The new field that contains AL-SDU and CRC is encoded using convolutional forward error correction code. As ITU proposes [6], Rate-Compatible Punctured Convolutional Coding (RCPC) provides a very good performance [7, 8]. By puncturing a low rate code $1/N$ periodically with period $P$ it is possible to obtain a family of codes with rates $P/(P+I)$ where $I$ varies between 1 and $(N-1)P$ [8]. The Control and Management Centre (CMC) adapts the coding rate. When noisy channel conditions occur or when the quality of service requirements is high, a message is sent to the RCPC coder by the CMC (via the control channel) to increase the correction power of the code according to the channel needs. On the other hand, when channel noise levels are relatively low and the accepted error rate is high, coding can be adapted to provide maximum efficiency.

After encoding (see fig. 2) the control field (CF) is added to the AL-PDU payload. The CF (fig. 3) consists of eight fields: The sequence number (SN), the length of the AL-PDU payload, the data source Identification number (ID), an extension flag, three Forward Error Correcting Code (FEC) fields (Extended Golay) and a Cyclic Redundancy Check Code (CRC-5) field.

![Control Field (CF) Frame](image)

Sequence number and AL-PDU payload length enable data re-combination and packetisation at the receiver. The data source identification number (ID) is essential to re-combine packets of the same source at the receiver and deliver them to the corresponding multimedia module/application. The extension flag is a single bit field that can be used in the future for communication protocol expansion. The Golay (24,12,8) code is a perfect ½ rate code that can be generated by one of two generator polynomials:

\[
G_1 = 1 + X + X^5 + X^6 + X^7 + X^9 + X^{11} \quad (1)
\]

\[
G_2 = 1 + X^2 + X^4 + X^5 + X^6 + X^{10} + X^{11} \quad (2)
\]
Cyclic Redundancy Check (CRC) code is used to detect effectively E-Golay decoding errors at the receiver and to discard all the corrupted packets. The generator polynomial of the 5 bit CRC code used is given by:

$$G_{CRC5} = 1 + X^2 + X^3 + X^4 + X^5$$  \hspace{1cm} (4)

5.2 Multiplex layer (MUX)

A Multiplex Layer Service data Unit (MUX-SDU) is formed by the AL-SDU and the Control Field (CF) as illustrated in figure 2. Within the MUX layer, multiple MUX-SDUs are multiplexed into a single Packet Data Unit (MUX-PDU) and afterward forwarded for modulation. The MUX-PDU consists of a synchronisation flag, the header and the incorporated MUX-SDUs (see fig. 4)

![Fig. 4 – MUX-PDU Structure](image)

The synchronisation flag is a binary vector of length \(l_s\) given by: [7]

$$s = \{s_0, s_1, \ldots, s_{l_s-1}\}$$  \hspace{1cm} (5)

Opening and closing flags are shown in Figure 4. The closing flag serves as the opening flag of the next packet. The detection of the flag by the receiver is performed by correlation of the incoming bit stream with the synchronisation flag pattern. The correlation value \(C_t\) at a certain time \(t\) for a given synchronisation flag \(s\) and the received binary information sequence \(y = \{y_{t-1}, y_t, y_{t+1}, \ldots\}\) is defined as:

$$C_t = l_s - \sum_{i=0}^{l_s-1} s_i \oplus y_{(t-l_s+1)}$$  \hspace{1cm} (6)

where \(\oplus\) denotes the binary exclusive-or relation and \(0 \leq C_t \leq l_s\). The output of the correlator \(C_t\) is compared with a Correlation Threshold (CT). Whenever the output is equal or greater than the threshold, the receiver defines that the flag has been detected. In noisy channel conditions, large synchronisation flags are preferred to improve robustness.

The header, as illustrated in figure 5, consists of five fields: the MUX-PDU length, the number of multiplexed MUX-SDUs conveyed by the MUX-PDU, two E-Golay fields for error correction and a single CRC-8 field for error detection with a generator polynomial given by:

$$G_{CRC8} = 1 + X + X^2 + X^8$$  \hspace{1cm} (7)

The header information is essential for data demultiplexing and recombination at the receiver.

![Fig. 5 – Header Frame](image)

6. Space-Time Block Coding

The Space-Time Block Coding (STBC) and Linear Combining (LC) proposed by [2, 3] are used for further improvement of the system performance when three transmission wires are available. The MUX-PDUs produced by the multiplexer are modulated using QPSK modulation with four complex constellation symbols. By using the transmission matrix of the STBC, the information is encoded and transmitted from the three emitting points. At the receiver, three fundamental functions are incorporated: channel estimation, linear combining and maximum-likelihood detection. The MUX-PDU packet is demodulated, reconstructed and forwarded to the de-multiplexer.

8. Simulation Results

Three independent data sources were connected to the system while simulating the power line multimedia system namely: compressed video, audio and high quality digital image. With maximum packet length set to 1000 bits, source modules generated data packets of varying length. A total number of 30 million bits was generated in each simulation (one simulation for every 1dB step of SNR). CRC-16, CRC-5 and CRC-8 error detection codes were used to track any encoding errors at the receiver. The extended Golay code (24,12,8) with generator polynomial, equal to:

$$G = 1 + X^2 + X^4 + X^5 + X^6 + X^{10} + X^{11}$$

was placed to protect the Control Field and the Header of the communication protocol as described previously. Four byte (32-bit) synchronisation flag was used with correlation threshold CT=28 and bit patterns given by [6]:

“0011 1100 0110 1110 1010 0001 0010 1100”

The simulated power line channel is assumed to distort by complex memoryless Additive White Class A Noise (AWCN) according to Middleton’s model [9]. Since the Class A noise is memoryless, it can be interpreted as a worst-case scenario to model impulsive noise on a power line [10]. The variance \(\sigma^2\) of the Class A noise was set to \(\frac{1}{2}\) SNR and the noise parameters to \(A=0.1\) and \(T=10^{-3}\) [3].
The performance results using the system transmitting over a single-input single-output (SISO) power line channel (single phase transmission) and over Multiple Input Multiple Output (MIMO) power line channel (three phases transmission) are illustrated in figures 6, 7, 8 and 9. Figure 6, 7, 8 shows the bit error performance of the Rate-Compatible Punctured Convolutional Code (RCPC) of rate \( \frac{1}{2}, \frac{1}{3}, \frac{1}{4} \). It can be observed that for bit error rate equal to \( 10^{-5} \), the \( \frac{1}{2} \) and \( \frac{1}{3} \) rate RCPC(SISO) codes gave a gain of about 10dB and 18dB respectively compared to the uncoded SISO data, whereas the \( \frac{1}{4} \) RCPC(SISO) code gave a gain of 4dB compared with the \( \frac{1}{3} \) RCPC(SISO) for BER=\( 10^{-5} \).

The performance of the power line multimedia system increased further when STBC was used. For the \( \frac{1}{2}, \frac{1}{3}, \frac{1}{4} \) rate RCPC (MIMO) codes, the gain at BER=\( 10^{-5} \) were 7dB, 6dB and 4.5dB respectively, compared with the RCPC (SISO) scheme.

Figure 9 presents the percentage of synchronisation flag misdetections, and wrongly decoded headers and control fields of SISO and MIMO systems. For SISO scheme, header decoding performed slightly better (gain of 2dB for 1% errors) than the Control Field decoding because of its smaller length (CF length=96bits, HEADER length=48bits), whereas synchronisation flag detection results were very satisfying even in low SNR levels.

For MIMO scheme, the percentage of synchronisation flag misdetections and wrongly decoded headers and control fields was higher than the SISO for SNR less that 1dB as displayed in figure 9. This loss in performance is closely related to the very nature of the impulsive noise.
and its effects on the maximum-likelihood decoding. For SNR more than 1dB and percentage of errors less than 0.01, the gain of the STBC system over the SISO system was about 6dB.

9. Conclusions

In this paper multimedia transmission over power line channel using Space-Time Block Coding (STBC) has been investigated. The proposed system is capable to use multiple independent multimedia equipments/interfaces which can be connected real-time and simultaneously transmit data or otherwise they can be removed. Concurrent multimedia transmission is achievable by using the presented multiplexing technique. The data multiplexer/de-multiplexer has been designed to be real-time configurable, maximizing the performance. Traffic control and data prioritise methods applied to the Control and Management Centre (CMC) offer safe delivery of time sensitive data and improved Quality of Service (QoS). Additionally, the adaptive Rate-Compatible Punctured Convolutional Code (RCPC) is proved very flexible and substantial for achieving maximum efficiency and robustness in the hostile power line environment. Furthermore, the frame structure of the multiplexer has been designed to achieve low overheads, high data protection and multiplexing flexibility. The use of Space-Time Block Coding with Linear Combining within the system is crucial. Simulation results demonstrate significant improvement of the performance when 3-phase QPSK/STBC scheme is used instead of the conventional QPSK/SISO scheme in the presence of Additive White Class A Noise (AWCN). The performance of the power line multimedia system can be further improved by using data interleaving techniques and adaptive STBC schemes [3].

References

[8] J. Hagenauer, April 1988, “Rate-Compatible Punctured Convolutional Codes (RCPC Codes) and their Applications”, IEEE Transactions on Communications, 36, 4