Application of Multiple Antenna Channel Coded OFDM Schemes in Power Line Communication

Oludare Sokoya, *Member, IAENG*

Abstract—In this paper the performance of multiple antenna channel coded orthogonal frequency division multiplexing (OFDM) schemes are examined in a power line communication channel. The power line channel is modeled using Zimmermann model. The bit error rate curve of the mutiple antenna channel coded-OFDM schemes in a power line channel is compared with uncoded OFDM. For the power line channel, increased performance in terms of coding gain and diversity advantage is obtained for when multiple antenna channel coded OFDM schemes are used.

Index Terms—Mutiple Antenna Channel Codes, PLC, OFDM, Multipath Fading, Impilse noise.

I. INTRODUCTION

WITH the spread of Smart Grid concepts, Powerline Communication (PLC) which has been initially used for voice transmission has become one imptortance option for the data communications infrastructure [1]. PLC has become an attaractive option for conventional wired and wireless indoor transmission due to the development of robust modulation, channel coding and digital signal procession technologies. PLC offer a potentially convenient and inexpesive solution because of the unique fact that no new wires are needed. Existing power lines, which are originally installed in the rooms for power supply are used for communication. PLC is an al,tenative to other "last mile" technologies, such as Digital Subscriber Line (DSL) [2], Wireless Local Loop (WLL), Wireless Local Area Network (WLAN), etc. Many of the available PLC systems provides a maximum data rate of more than several Mbps [3]. Nevertheless, powerline grid can be characterised as a rather hostile medium for data transmission as it was initially designed for the distribution of electrical power in frequency of 50–60Hz. As a result, the PLC channel encounters some technical problems, such as impedance variations and mismatches, various forms of noises (Gaussian and impulsive noise) and narrowband interference, multipath propagation, high attenuation and other forms of channel impairments.

The transmission environment in PLC seems to be much worse than in wireless communications, which necesitate the use of advanced physical layer techniques in the PLC environment in order to benefit from its possible advantages. One way of combating the technical problems of PLC, is to employ specially designed multiple antenna channel coded OFDM with PLC in order to achieve some of the objective of a reliable communication system i.e. low error rate, low received Signal to Noise Ratio (SNR), perform well in mutipath and fading conditions, spectral efficiency and cost effective in its implementation.

Multiple antenna channel coded OFDM schemes i.e. Space-Time Block Coded-OFDM (STBC-OFDM) [4], Space-Time Trellis Coded-OFDM (STTC-OFDM) [5] and Super-Orthogonal Space-Time Trellis Coded-OFDM (SOSTTC-OFDM) [6] are bandwidth efficient multiple antenna schemes that can increase system capacity through antenna diversity. These codes use the combination of conventional channel coding design criteria, modulation techniques and multiple antenna diversity techniques in their design. Multiple antenna channel coding schemes give a better error rate performance when compared with an uncoded scheme.

In this paper, the performance of multiple antenna channel codes in a PLC scenario is studied . The error rate performance of majorly known multiple antenna channel coded OFDM schemes i.e. STBC-OFDM, STTC-OFDM and SOSTTC-OFDM is studied in powerline environment.

The outline of the paper is as follows. In section II, the power line channel models are briefly discussed. The design structure of the various multiple antenna channel codes are given in section III. The system structure is delineated in section IV. Simulation results are presented in section V, while conclusion remark are drawn in section VI

II. POWER LINE CHANNEL MODELING

The design of a good communication systems begins with a thorough understanding of the communication channel. Many researchers have proposed diferent PLC channel models and so far there is not a universally accepteble model. This is due to some characteristics of the powerline channel that makes it difficult to model. Technical problems of the powerline channel relate to:

- The frequency–varying and time–varying response.
- Transfer function with dependence of location, topology network, and connected load.
- Different types of noise – Impulse noise, background noise, narrowband noise and power wave.

In [7], PLC channel modeling research works were categorised into the following areas:

- Noise Modeling – The power spectral density of the noise is very much reliant on location and time. Also, measurement shows that it consists of colored background noise, periodic impulsive noise, narrowband noise and asynchronous impulsive noise [8]. In order to model the additive noise, statistical parameters are extracted after many measurements, resulting in random variables with specific probability density function.
- Simulation tools – Some efforts have been devoted to develop simulation tools [9]. The basic idea is to implement an algorithm based on any developed PLC channel

O, Sokoya is with the Department of Electronic Engineering, Durban University of Technology, Durban, KZN, 4000 South Africa e-mail:oludares@dut.ac.za.

models. These tools allow verifying the reliability and accuracy of the models, and sometimes having a user friendly graphic/machine interface.

- Transfer function modeling – Transfer function can be modeled either using an emperical approach (i.e. modeling parameters are determined from measurements) or a deterministic approach (i.e. modeling parameters are obtained from a theoretical basis). The emperical approach is easy to implement and computationally efficient but susceptible to measurement errors while the deterministic approach is computationally more intensive than the emperical approach. The advantage of the deterministic approach is that changes to the transfer function can be predicted [10]. In this paper, deterministic approach is adopted.

Any modeling approach for the transfer function can be both time and frequency dependent and also dependent on the location of the transmitter and the receiver in the specific powerline infrastructure.

As mentioned earlier, a PLC channel can be characterised with both impulsive noise and multipath fading, as a result of the multiple signal reflections caused by power line impedance mismatch. The most suitable model for the impulsive noise is the Middleton Class A model [11], which probability density function is defined as:

$$P_X(x) = \sum_{m=0}^{\infty} e^{-A} \frac{A^m}{m!} \frac{1}{\sqrt{2\pi\sigma_m^2}} e^{-\frac{x^2}{2\sigma_m^2}}, \qquad (1)$$

$$\sigma_m^2 = \sigma^2 \frac{m/A + \tau}{1 + \tau}, \qquad (2)$$

where $\sigma^2 = \sigma_G^2 + \sigma_I^2$ (σ_G^2 is the Gaussian noise variance and σ_I^2 is the impulse noise variance), $\tau = \frac{\sigma_G^2}{\sigma_I^2}$, and A is the impulse index. Also, in a PLC channel, there are two types of channel models; deterministic-one like Zimmermann model [12], and statistical-one like Galli model [13]. The transfer function of Zimmermann model at the jth antenna path is expressed as:

$$H_j(f) = \sum_{l=1}^{L} H_{j,l}(f), \qquad (3)$$

$$H_{j,l}(f) = g_{j,l} \cdot e^{-(\alpha_0 + \alpha_1 \cdot f^u)d_{j,l}} \cdot e^{j2\pi f(d_{j,l}/v_p)}, \qquad (4)$$

where L is the number of fading paths per antenna path. α_0, α_1 and u are the power line cable parameters, and $|g_{j,l}| \leq 1$ is the weighting factor of the jth antenna and the lth fading path. $d_{j,l}/v_p$ is equiivalent to the corresponding path delay $T_{j,l}$ (where $d_{j,l}$ represent its length):

$$T_{j,l} = \frac{d_{j,l} \cdot \sqrt{\epsilon_r}}{c_0} = \frac{d_{j,l}}{v_p}, \qquad (5)$$

where ϵ_r is the non insulation dielectric constant of the cable and c_0 is the speed of light. The frequency selective fading channel transfer function in (3) can be translated into the OFDM domain by approximating it as follows:

$$H_j(f)|_{f=f_c+k\Delta f} \cong H_j(k) = \sum_{l=1}^{L} H_{j,l}(k), \qquad (6)$$

where f_c is the carrier frequency, Δf is the subcarrier spacing, and $k \ (= 0, 1, ..., N-1$, where N is the number of subcarriers) in the frequency index.

III. Multiple Antenna Channel Codes

Multiple antenna channel codes can be combined with OFDM to produce a system that can achieve spectra efficiency and increase throughput in a network. These codes are bandwidth efficient and do not sacrifice diversity over a the channel. Brief description of these channel codes is given in the following sections.

A. Space-Time Block Code

Alamouti first presented a transmit diversity technique, for two transmit antennas, with a simplified decoding algorithm [14]. This scheme was later called STBC in [15]. Based on these later works, the Alamouti codes were extended to more than two transmit antennas using the theory of orthogonal design. The theory of orthogonal design enables the use of a simple maximum-likelihood decoder that is based on linear combining at the receiver. Based on this theory, two types of STBC can be generated. The first type, real orthogonal design, is based on real constellation such as pulse amplitude modulation, while the second type, complex orthogonal design, is based on complex constellations, e.g. phase-shift keying and quadrature amplitude modulation. The transmission matrix for a two transmit antenna complex orthogonal design is given by:

$$\mathbf{C} = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix}. \qquad (7)$$

B. Space-Time Trellis Code

STTC was invented by Tarokh et al. [16] as a way of combining signal processing with a multiple antenna system to produce a system with an improved gain over the earlier transmit diversity schemes [17]. The STTC proposed in [16] was handcrafted and gives the best compromise in terms of constellation size, data rate, diversity advantage and trellis complexity when compared with other space time trellis coded schemes [17].

The encoder system of an STTC is based on a one-input symbol at a time and a sequence of output symbols, whose length represents the number of transmit antennas.

The trellis diagram for a four-STTC is shown in Figure 1. At each time t , the encoder is in a generic state. The input bit streams to the space-time encoder are divided into groups of two bits, $a_1 a_2$. Each group 00, 01, 10 or 11 then selects one of the four branches originating from the corresponding state. The branches are then mapped for every transmit antenna into one of the four constellation points on the QPSK constellation. The edge labels $y_1 y_2$ in Figure 1 are associated with the four transitions from top to bottom and indicate that symbols y_1 and y_2 are transmitted simultaneously over the first and second antennas, respectively. The encoder moves to the next state after transmission of the couple of symbols. At the decoder, based on the received estimate and using the maximum likelihood (ML) method, a decoding algorithm is then used to search for the best path. Viterbi algorithm is then used to search for the path with the least decoding metric.

C. Super-Orthogonal Space-Time Trellis Code

By combining the advantages of both STTC and STBC, a new channel code for multiple antenna systems called

$y_1y_2\ y_1y_2\ y_1y_2\ y_1y_2$

00 01 02 03

10 11 12 13

20 21 22 23

30 31 32 33
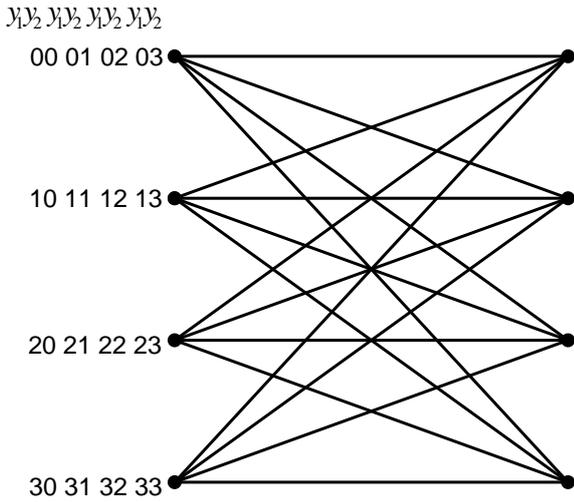
Fig. 1.   Four-state QPSK STTC

X_0,X_1

Y_0,Y_1

(a)

X_0,X_1

Y_1,Y_0

X_1,X_0

Y_0,Y_1

(b)

Fig. 2.   Two-state (a) and four-state (b) QPSK SOSTTC

SOSTTC was developed [18]. The SOSTTC uses sets of super-orthogonal block codes (SOBC) and set partitioning technique in its construction. The sets of SOBCs are obtained by rotating the original block code by an angle θ. This code gives an improved coding gain and diversity order when compared with other space-time coding schemes, i.e. STTC [16] and STBC [14]. The main idea behind SOSTTC is to consider STBCs as a modulation scheme for multiple transmit antennas and assign an STBC with specific constellation symbols to transitions emanating from a state. For a $T \times N_t$ STBC, picking a trellis branch emanating from a state is equivalent to transmitting TN_t symbols from the N_t transmit antennas in T time intervals. By doing so, it is guaranteed that the diversity of the corresponding STBC is preserved. The SOBC transmission matrix used in the design of SOSTTC for $N_t = 2$ is given by:

$$\mathbf{X}(x_1, x_2, \theta) = \begin{bmatrix} x_1 e^{j\theta} & x_2 \\ -x_2^* e^{j\theta} & x_1^* \end{bmatrix}. \tag{8}$$

In equation (8) $x_i \in e^{j\frac{2\pi\acute{a}}{M}}$ represent the M-PSK signal constellation. The angular rotation θ is equivalent to $2\pi\acute{a}/M$ where $\acute{a} = 0, 1, \cdots, M - 1$. Despite the angular rotation of the transmitted signal, the matrix elements of equations (8) are still members of the M-PSK constellation and the signal constellation is not expanded. For BPSK signal constellation, $\theta = 0$ or π while for a QPSK signal constellation, $\theta = 0$ or $\pi/2$ or π or $3\pi/2$. When θ in equation (8) is zero, the Alamouti code is obtained.

The trellis diagram for a two-state and a four-state SOSTTC scheme is given in Figure 2. In the trellises in Figure 2, each path converging and diverging to a state consists of eight parallel paths. The state labels, i.e. $\mathbf{X}_i$ and $\mathbf{Y}_i$ are sets of SOBC given in equation (9).

$$\begin{aligned} \mathbf{X}_0 &\equiv \{(\pm 1, \pm 1, 0), (\pm j, \pm j, 0)\} \\ \mathbf{X}_1 &\equiv \{(\pm 1, \pm j, 0), (\pm j, \pm 1, 0)\} \\ \mathbf{Y}_0 &\equiv \{(\pm 1, \pm 1, \pi), (\pm j, \pm j, \pi)\} \\ \mathbf{Y}_1 &\equiv \{(\pm 1, \pm j, \pi), (\pm j, \pm 1, \pi)\} \end{aligned} \tag{9}$$

In each set of the SOBC e.g. $\mathbf{X}_i$, eight different block codes are possible. These block codes are obtained by substituting
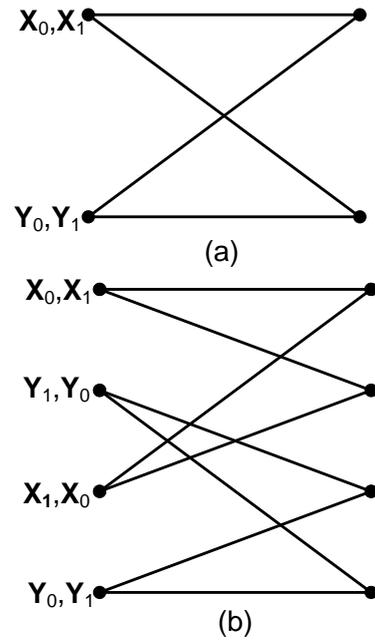
the symbol elements $\{+1, -1, j, -j\}$, for a QPSK symbol constellation into the orthogonal matrix given in equation (8). The corresponding orthogonal block codes are then transmitted on the trellis branch.

In flat fading channel, multiple antenna channel codes (i.e. STTC, STBC and SOSTTC) exploit the spatial diversity present in the multiple transmit/receiver antennas to produce codes that are effective in combating fading and enhancing the data rate. The maximum diversity gain possible in a flat fading channel is the product of the number of transmit and receive antennas.

Whereas in frequency selective fading channel, mutiple antenna channel codes and OFDM can potentially exploit the multipath diversity possible in the frequency selective fading channel. As a result of the multipath diversity, the maximum diversity possible for the channel codes in an OFDM environment is therefore a product of the number of transmit antennas and receive antennas and the channel impulse response length.

Some of the mutiple antenna channel codes with OFDM that have been introduced in the literature include STTC-OFDM [19], STBC-OFDM [4] and SOSTTC-OFDM [6].

IV.   SYSTEM STRUCTURE

The general layout of the simulation can be seen in the figure 3 below. The data to be transmitted is first coded with

Input data → Space-Time Encoder → OFDM Modulator → Power line Channel → OFDM Demodulator → Space-Time Decoder → Output data
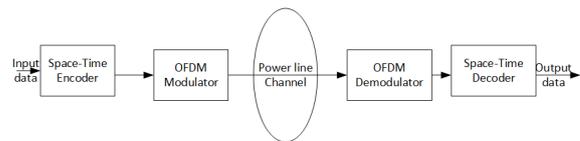
Fig. 3.   System Structure

the mutiple antenna channel codes i.e. space-time encoding. This space-time codes have inherent in the ability to lower the error rate performance. The modulation scheme under

examination is Quadrature Phase Shift Keying (QPSK). The signal power for the modulation scheme is normalised to unity. The OFDM modulation scheme is suitable for PLC due to its ability to deal with multipath propagation, intersymbol interference and frequency selective channels. The space-time codes that is used in this study utilizes two emitting points/ antenna and one receiving points/ antenna.

The Class A noise is characterised by three parameters, which are impulsive index A, the variace of the AWGN component σ_g^2 and ratio τ. In this paper, A is set to equal to 0.1, $\sigma_g^2 = 10^-3W$ and $\tau = 0.001$. The parameter A determine the "impulsivement" of Clas A noise (i.e. it is the product of the mean number of impulses per second and the mean length of an impulse in seconds).

V. PERFORMANCE EVALUATION AND SIMULATION RESULTS

For the performance evaluation of the proposed sytems, a simulation was developed in Matlab. The figures presented in this paper were obtained by averaging the results of multiple simulations runs, in order to minimize the statistical errors and assures the validity of the results. The proposed system simulation is shown to demonstrate the bit error rate (BER) performance of the mutiple antenna coded OFDM schemes, i.e., STBC-OFDM, STTC-OFDM and SOSTTC-OFDM in a power line environment. The simulation assumes a PLC multipath fading channel (using the deterministic-one like Zimmermann model [12]) with $L = 2$, $N_t = 2$ and $N_r = 1$. The total power of the transmitted coded symbol was normalized to unity and a frame length of 256 bits was used at the transmitter.
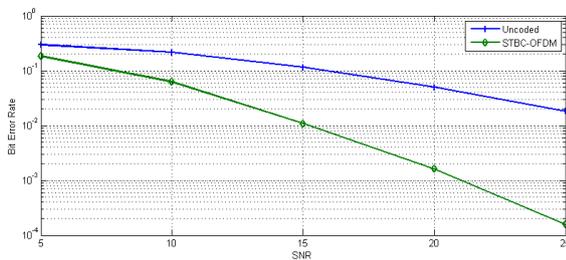
Fig. 4.   BER performance for PLC channel using QPSK STBC-OFDM
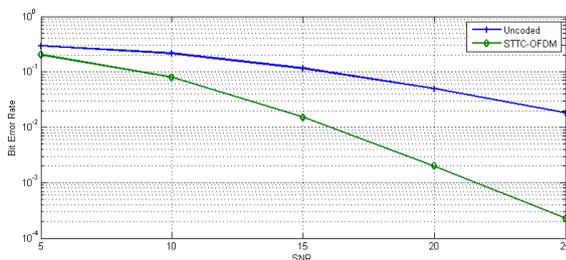
Fig. 5.   BER performance for PLC channel using QPSK 4-state STTC-OFDM

In Figures 4, 5 and 6, the BER performance of mutiple antenna channel coded OFDM schemes and uncoded OFDM with power line channel is given. The figures show that there is a coding gain advantage of the mutiple antenna channel coded OFDM schemes when compared with uncoded OFDM
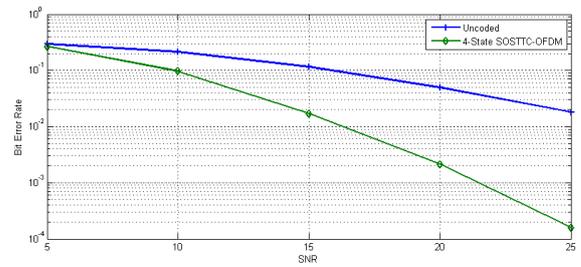
Fig. 6.   BER performance for PLC channel using QPSK 4-state SOTTC-OFDM

in a power line channel. This is evident in the downward shift of the BER curves. In the figures, it is also apparent, based on the slope of the graph, that the mutiple antenna channel coded OFDM schemes in maintains it diversity advantages considering the impulsive nature of the noise component of the power line environment.

VI. CONCLUSION

In this paper the BER performance of mutiple antenna channel coded OFDM schemes, i.e. STBC-OFDM, STTC–OFDM and SOSTTC-OFDM, in a power line environment, is considered. The mutiple antenna channel coded OFDM schemes appear to be quite beneficial in terms of BER performance when compared with uncoded OFDM in this environment. The mutiple antenna channel coded OFDM schemes show an increased coding gain advantage and diversity adavantage . In general this study demonstates that power line environment can profit a lot when mutiple antenna channel coded OFDM schemes are incoporated in its design.

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Oludare Sokoya received his BSc (Eng) from Obafemi Awolowo University, Nigeria, MSc(Eng) from University of KwaZulu-Natal and a PhD in Electronic Engineering from the University of Pretoria. Dr. Sokoya is currently a Senior lecturer and the current Chair of the Communication Field of Studies at the Durban University of Technology. His research interests are in advanced physical layer technologies for wireless and wired communication.