MIMO-OFDM based Broadband Power Line Communication using Antenna and Fading Diversity

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Abstract—We present multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) based broadband power line communication (BPLC) using antenna and fading diversity. We evaluate the proposed MIMO-OFDM system over multi-conductor power line channels, with or without cross-talk between the antenna paths. The proposed scheme employs maximum ratio combining (MRC) that effectively combines both the multiple antenna diversity gain and the multipath fading diversity gain over 3-phase (2×2 MIMO, outdoor) power line channels. Simulation results prove that the proposed scheme improves the bit error rate performance over the existing schemes, irrespective of whether cross-talk exists.

***Keywords-** MIMO; OFDM; broadband power line communication (BPLC); maximum ratio combining (MRC)*

I. INTRODUCTION

Smart grid (SG) is a future power grid network based on regenerative green energy; it requires high-rate data transmission technology for bidirectional information exchange among electric power providers, electricity industries, and consumers. Broadband power line communication (BPLC) that allows a reliable high-rate transmission over power cables is available at a low cost because it does not require any additional infrastructure; further, it is ubiquitous because it is available anywhere where there is electricity and is easy-to-access with a plug-in power cable. Hence, a BPLC network is a promising medium for SG and its associated services such as advance metering infrastructure. Moreover, since an international BPLC standard, IEEE 1901 [1], was adopted in 2010, there has been a growing interest in various other BPLC applications including home networks, high-speed Internet, and emergency backup networks.

A BPLC signal transmitted via an electric power cable experiences severe channel distortions such as multipath fading and impulse noise. In this study, we use the Middleton class A model [2] for handling the impulse noise and the Zimmermann frequency model [3] for handling the power line multipath fading.

In the case of a 3-phase 4-wire power cable, we implement a 2×2 multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) BPLC with maximum ratio combining (MRC). A recent literature search revealed several MIMO-OFDM BPLC schemes [4-6] that use antenna MRC (AMRC) for obtaining the spatial diversity gain. In particular, the authors in [4] first introduced a space frequency (SF)-coded MIMO-OFDM over power line channels. The authors in [5] implemented a space time (ST)-coded MIMO-OFDM for outdoor multi-conductor power cables and performed an experiment showing the capacity loss caused by antenna coupling. The authors in [6] compared the simulation results of SF-, ST-, and space time frequency (STF)-coded MIMO-OFDM over indoor power line channels and demonstrated the superiority of STF coding.

Contributions. The contribution of this paper is a novel SF-coded MIMO-OFDM scheme employing antenna and fading MRC (AFMRC) that effectively combines both multiple antenna and multipath fading diversity. Through a computer simulation, in this study, we prove that a coupling effect is not negligible with respect to the performance of a MIMO system. Simulation results also verify that the proposed scheme is superior to conventional schemes, irrespective whether cross-talk between antenna channels exists. The proposed scheme improves the bit error rate (BER) performance not only in the 2×2 MIMO system via a 3-phase 4-wire power line but also in the single-input single-output (SISO) system via a single-phase 2-wire power line; note that the SISO system uses fading MRC (FMRC) instead of AMRC. We also evaluate the system design parameters by comparing the BER when the impulse noise index A is varied.

Organization of the paper. The rest of this paper is organized as follows: Section II explains the power line channel characteristics including impulse noise and multipath fading and presents the proposed MIMO-OFDM BPLC system model over multi-conductor power line channels. Section III presents the simulation results of the proposed scheme, which are compared with those of the existing schemes. Finally, concluding remarks are given in Section IV.

II. SYSTEM MODEL

A. Impulse Noise and Fading Channel in BPLC

A BPLC channel can be characterized by both impulse noise and multipath fading owing to the multiple signal reflections caused by a power line impedance mismatch. First, for handling the impulse noise, we use the Middleton class A model [2], whose *pdf* (probability density function) is defined as

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

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

where $\sigma^2 = \sigma_G^2 + \sigma_I^2$ (σ_G^2 is the Gaussian noise variance and σ_I^2 is the pure impulse noise variance), $\tau = \sigma_G^2 / \sigma_I^2$, and A is the impulse index.

Second, for handling the multipath fading, we employ the Zimmermann frequency PLC channel model [3], whose transfer function at the *j*th antenna path is expressed as

$$\begin{aligned} H_j(f) &= \sum_{l=1}^{L} H_{j,l}(f) \\ H_{j,l}(f) &= g_{j,l} \cdot e^{-(\alpha_0 + \alpha_1 \cdot f^u) d_{j,l}} \cdot e^{-j2\pi f (d_{j,l}/v_p)} \end{aligned} \quad (2)$$

where L is the number of fading paths. α_0, α_1, and u are the power line cable parameters, and $|g_{j,l}| \le 1$ is the weighting factor of the *j*th antenna and the *l*th fading path [3]. $d_{j,l}/v_p$ is equivalent to the corresponding path delay $\tau_{j,l}$ (where $d_{j,l}$ represents the path length) as follows:

$$\tau_{j,l} = \frac{d_{j,l} \cdot \sqrt{\varepsilon_r}}{c_0} = \frac{d_{j,l}}{v_p}$$

where ε_r is the non-insulation dielectric constant of the cable and c_0 is the speed of light. Typically, each OFDM subcarrier has flat (constant) frequency channel characteristics because of its narrow bandwidth; hence, the frequency selective fading transfer function of (2) can be translated (digitized) and approximated as follows:

$$H_j(f)|_{f=f_c+k\Delta f} \cong H_j(k) = \sum_{l=1}^{L} H_{j,l}(k) \quad (3)$$

where f_c is the carrier frequency (which is herein assumed to indicate the lower limit of the OFDM bandwidth (BW)), Δf is the subcarrier spacing, and the frequency index $k = 0, 1, \ldots, N - 1$.

B. MIMO-OFDM BPLC System

In this study, we design a MIMO-OFDM system that contains I (transmit antennas) × J (receive antennas). In the OFDM transmitter, the *k*th subcarrier modulation signal, $S(k)$, experiences the following inverse fast Fourier transform (IFFT)

$$s(n) = \frac{1}{N} \sum_{k=0}^{N-1} S(k) e^{j2\pi nk/N} \quad (4)$$

where $s(n)$ is the *n*th (= 0, 1, …, N-1) time sample and N is the number of subcarriers.

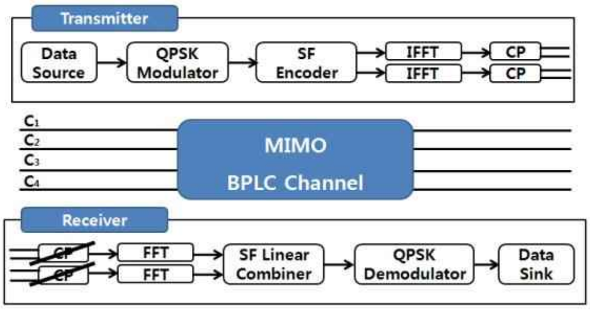
In a MIMO BPLC system, a pair of electrical wires is converted into a single antenna channel; hence, the number of transmitting and receiving antennas is typically limited to two for a 3-phase 4-wire power line and one for a single-phase 2-wire power line. Therefore, MIMO-OFDM is used either indoors or outdoors with a 3-phase 4-wire power line, whereas SISO-OFDM is mostly used indoors with a single-phase 2-wire power line. Fig. 1(a) shows the block diagram of a 2×2 MIMO-OFDM BPLC system that uses a 3-phase 4-wire power line (Fig. 1(b) shows its cross-cut interior structure). This 2×2 MIMO system has two antenna paths that consist of a single antenna path formed by C1 and C2 and another single antenna path formed by C3 and C4; C0 assumes the role of a ground connection [4]. An SF encoder is used for reducing the error probability caused by the interference in the MIMO channel. The following two SF encoder vectors $\mathbf{S_1}$ and $\mathbf{S_2}$ are formed by arranging the same subcarrier signal samples in an appropriate order (i.e., vector $\mathbf{S}_2$ is the circular-shifted version of $\mathbf{S}_1$ [4]) for this SF encoder.

$$\begin{aligned} \mathbf{S}_1 &= [S_1(0), \ldots, S_1(\tfrac{N}{2}-1), S_1(\tfrac{N}{2}), \ldots, S_1(N-1)]^T \\ \mathbf{S}_2 &= [S_2(\tfrac{N}{2}), \ldots, S_2(N-1), S_2(0), \ldots, S_2(\tfrac{N}{2}-1)]^T \end{aligned} \quad (5)$$

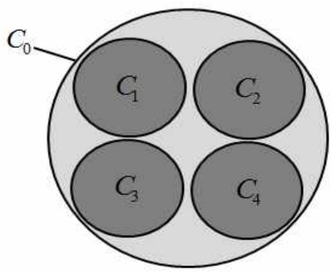
where $S_1[k] = S_2[k]$, (k = 0, 1, …, N-1) and $(\cdot)^T$ refers to the transpose of $(\cdot)$. $\mathbf{S_1}$ and $\mathbf{S_2}$ are respectively converted to the corresponding time sample vectors, $\mathbf{s_1}$=*IFFT*{$\mathbf{S_1}$} and $\mathbf{s_2}$=*IFFT*{$\mathbf{S_2}$}, through the IFFT process (see (4)) and then transmitted to the receiver via each antenna path. In the system shown in Fig. 1(a), this transmission process occurs at the signal encoder and modulator, and the corresponding receiving process is processed at the linear combiner and detector. A cyclic prefix (CP) is added to the OFDM modulated sample vectors ($\mathbf{s_1}$, $\mathbf{s_2}$) before their transmission to prevent inter-symbol interference (ISI) caused by the multipath delay. The signal received via the fading channel undergoes the SF decoding process, i.e., fast Fourier transform (FFT), an inverse circular-shift operation, and then the MRC process, to recover its data stream after the removal of the added CP.

1) MRC without Cross-Talk

For simplifying the simulation, we assume that there is no coupling between the two antenna paths (this assumption is practically reasonable for the carrier frequency f_c < 25 MHz [6].).



(a)



(b)

Figure 1. (a) 2×2 MIMO-OFDM PLC system block diagram; (b) 3-phase 4-wire power line interior structure.

The diversity gain of a conventional system that uses AMRC is obtained by multiplying its optimum weight to the different spatial antenna paths. The system proposed in this paper employs AFMRC, a combined technique of AMRC and FMRC. The proposed system has one receiver per fading path to achieve the FMRC gain. Assuming the same transmit signal via the jth antenna L fading paths, i.e., $S_j(k) = S_{j,1}(k) = S_{j,2}(k) = \ldots = S_{j,L}(k)$, we can write the jth (j = 1,2) antenna received signal $Y_j(k)$ at the kth subcarrier as

$$Y_j(k) = \sum_{l=1}^{L} Y_{j,l}(k) = \sum_{l=1}^{L} \sqrt{\frac{E_s}{2}} H_{j,l}(k) S_j(k) + X_{j,l}(k) \tag{6}$$

where E_s represents the average energy of the transmit signal. $X_{j,l}(k)$ represents the jth antenna path and the kth subcarrier noise component, that is the result of the FFT operation of the time axis impulse plus Gaussian noise signal $x_{j,l}(n)$ with the variance σ^2 (see (1)). In this study, we assume ideal fading channel estimation to simplify the simulation [7].

In the application of the proposed MRC (AFMRC) to the single-phase 2-wire SISO BPLC (just using FMRC) and the 3-phase 4-wire 2×2 MIMO BPLC, we express the output $\hat{S}$ (detected signal) of the maximum likelihood (ML) receiver as

$$\hat{S}(k) = \begin{cases} \arg\min_{S \in \mathcal{S}} \left| \sum_{l=1}^{L} Y_l(k) H_l^*(k) - S \right|^2 & \text{for SISO} \\ \arg\min_{S \in \mathcal{S}} \left| \sum_{j=1}^{J} \sum_{l=1}^{L} Y_{j,l}(k) H_{j,l}^*(k) - S \right|^2 & \text{for MIMO} \end{cases} \tag{7}$$

where $(\cdot)^*$ refers to the conjugate of $(\cdot)$ and $\mathcal{S}$ indicates the signal constellation set. AFMRC improves the system performance as compared to the conventional MRC (AMRC), where $\hat{S}(k) = \arg\min_{S \in \mathcal{S}} \left| \sum_{j=1}^{J} Y_j(k) H_j^*(k) - S \right|^2$. However, as shown in (7), the receiver complexity of the AFMRC-based SISO/MIMO system increases L-fold due to the addition of FMRC. Even in the case of the indoor single-phase 2-wire SISO channel, the proposed scheme has the FMRC diversity gain.

2) MRC with Cross-Talk

The proposed MIMO system, shown in Fig. 1(a), might have cross-talk (its capacity loss might not be negligible (but less than 16%), especially in the case of $f_c \geq 25$ MHz [6].) between two parallel antenna channels; this cross-talk degrades the system performance. The 2×2 MIMO channel matrix **H** with non-zero cross-talk terms, indicating the ith transmit and jth receive antenna path gain $H_j^i(k) \neq 0$ (where $i \neq j$), can be expressed as follows:

$$\mathbf{H} = \begin{bmatrix} H_1^1(k) & H_2^1(k) \\ H_1^2(k) & H_2^2(k) \end{bmatrix} \tag{8}$$

Let the channel capacity with and without the cross-talk be denoted as C_{ct} and C_{nct}, respectively. The capacity-loss ratio (CR) estimated by using the cross-talk can be defined as [5]

$$CR = \frac{C_{nct} - C_{ct}}{C_{nct}} \times 100\% \tag{9}$$

where $C = \mathrm{BW} \log_2 \det(\mathbf{I}_I + \frac{\mathrm{SNR}}{I} \mathbf{H}\mathbf{H}^H)$. I is the number of transmit antennas; SNR, the signal-to-noise ratio; and $\mathbf{I}_I$, an identity matrix of size I. The output $\hat{S}$ of the proposed MIMO MRC receiver can be expressed as

$$\hat{S}(k) = \arg\min_{S \in \mathcal{S}} \left| \sum_{j=1}^{J} \sum_{l=1}^{L} Y_{j,l}(k) H_{j,l}^{j*}(k) - S \right|^2, \tag{10}$$

where $Y_{j,l}(k) = \sum_{i=1}^{I} \frac{\sqrt{E_s}}{2} H_{j,l}^{i}(k) S_i(k) + X_{j,l}(k).$

III. SIMULATION RESULTS

We simulate the proposed system model with the QPSK constellation under the power line channel conditions, and compare its uncoded BER results to that of a conventional system [6]. We assume a multipath fading PLC channel with L = 6, whose simulation parameters are the same as those given in Table I of [6]. For the sake of simplicity, we also assume the same fading channel parameters for the two antenna paths[1)]. We set N = 1024, CP size = 120 (unit: sample), f_c = 25 MHz, Δf (frequency spacing) = 1 KHz, and BW = 1.024 MHz for the simulation; hence, the maximum data rate is approximately 1.83 Mbps.

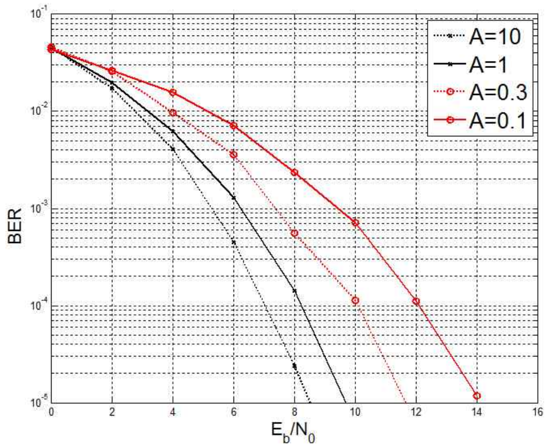


Figure 2. BER Comparison of 2×2 MIMO PLC for different values of A.

Fig. 2 presents a comparison of the BER of the 2×2 MIMO BPLC system when the impulse noise index A is varied. For this experiment, we set τ = 0.1. While for a large value of A (≥ 1), the noise channel characteristics approach those of Gaussian noise, for a small value of A (<1), they are similar to those of impulse noise. Hence, the BER decreases when the value of A increases, as shown in Fig. 2. For example, in the case of A = 10, we can obtain approximately 1-dB gain at BER = 10^{-5} as compared to the case of A = 1, 3-dB gain as compared to the case of A = 0.3, and 5.5-dB gain as compared to the case of A = 0.1. Practically, in the BPLC channel environment, A has a value within the range of 0.0001 to 0.35; hence, we choose A = 0.3 for the next experiment [6].

Fig. 3 shows a comparison of the BER performance between the conventional AMRC and the proposed AFMRC in the SISO/MIMO-OFDM systems. First, in the case of the MIMO system, AFMRC results in a performance gain of approximately 1 dB at BER = 10^{-5} as compared to AMRC. Fig. 3 also shows a comparison of the conventional method (with no MRC) and the proposed method (with FMRC) in the case of the SISO-OFDM system; it shows a 1.5-dB improvement in the case of BER = 10^{-5} for the proposed scheme. Therefore, the simulation verifies that the proposed SISO/MIMO-OFDM system is more effective, in the case of both an indoor single-phase power line and an outdoor 3-phase power line, than the conventional SISO/MIMO-OFDM system.

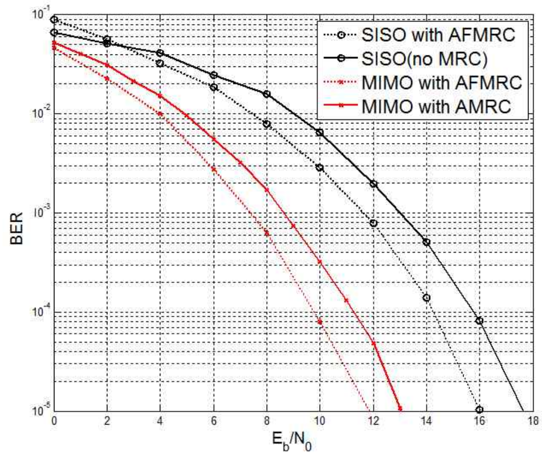


Figure 3. Performance comparison of SISO/MIMO-OFDM with different MRC schemes (assuming A = 0.3).

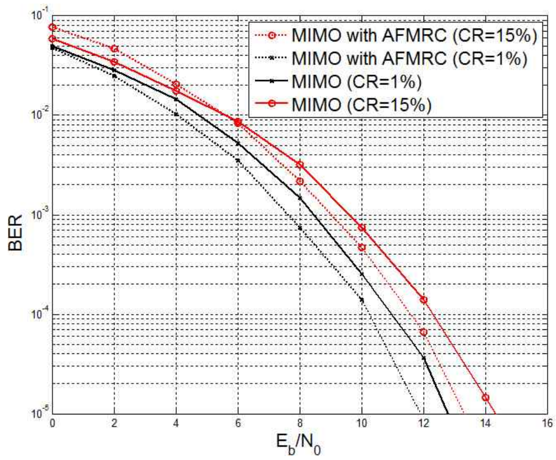


Figure 4. Performance of MIMO-OFDM with cross-talk (assuming A = 0.3).

Fig. 4 shows the performance of an SF-based MIMO BPLC system with cross-talk. The proposed scheme has a gain of approximately 0.7–0.8 dB over the conventional scheme at the BER = 10^{-5}. When the CR value increases from

[1)] In the case of PLC channels using 3-phase 4-wire power line, the changing of channel parameters between the antenna paths is almost negligible in practice [8].

1% to 15%, the BER performance of both schemes degrades by approximately 1 dB. As a result, it is observed that the effect of crosstalk on the performance of an MIMO-OFDM system is not negligible.

IV. CONCLUSIONS

We proposed an MIMO-OFDM-based BPLC system with antenna and fading MRC (AFMRC) that effectively combines multiple antenna and multipath fading diversity. We evaluated the proposed MIMO-OFDM system over multi-conductor power line channels with or without cross-talk between the antenna paths. The computer simulation verified that the proposed scheme was more efficient in terms of system performance in the case of both the indoor single-phase (SISO) and the outdoor 3-phase (MIMO) BPLC applications than the conventional schemes.

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