MIMO-OFDM based Broadband Power Line Communication with Maximum Ratio Combining

Jeonghwa Yoo, Sangho Choe

Department of Information, Communications, and Electronics
The Catholic University of Korea
Bucheon, Republic of Korea
mundade@hanmail.net, schoe@catholic.ac.kr

***Abstract*—We present a MIMO-OFDM based broadband power line communication (BPLC) with maximum ratio combining. We evaluate the proposed MIMO-OFDM over BPLC channels, with or without cross-talk between antenna paths. The suggested maximum ratio combining (MRC) scheme effectively combines both multiple antenna diversity gain and multipath fading diversity gain over 3-phase (2×2 MIMO, outdoor) or single-phase (SISO, indoor) power line channels. Simulation results prove the performance advantage of the proposed scheme, whether or not cross-talk exists, over existing schemes.**

Keywords-Broadband power line communication (BPLC), MIMO, OFDM, MRC

I. Introduction

Smart grid is the future electric power line network in which information transmission technology is used for real-time bidirectional information exchange among electric power providers, electricity industries, and consumers. Smart grid and its associated network applications (advance metering infrastructure (AMI), home networks, high-speed internet, etc) greatly increase the interest in broadband power line communication (BPLC), since BPLC allows high-speed or high performance data transmission via existing power lines without additional infrastructure, unlike cellular, WiFi, and VDSL. BPLC signal via electric power line channel experiences severe channel distortions due to multipath fading and impulse noise. In this paper, we use the Middleton class A model [1] for impulse noise and the Zimmermann frequency model [2] for power line multipath fading.

Using 3-phase 4-wire power line, we implement a 2x2 multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) BPLC with maximum ratio combing (MRC). Conventional MIMO-OFDM BPLC [3-5] just considers antenna MRC (AMRC) to obtain spatial diversity gain. The proposed MIMO-OFDM BPLC employs antenna & fading MRC (AFMRC) that effectively combines both multiple antenna and multipath fading diversity gain. We also evaluate the proposed MIMO performance when cross-talk between antenna paths exists. Simulation results verify that the proposed scheme is superior to the conventional scheme, whether or not cross-talk between antenna channels exists. The suggested scheme improves bit-error rate (BER) performance, not only in the 2x2 MIMO via 3-phase 4-wire power line, but also in the single-input single-output (SISO) via single-phase 2-wire power line; note that SISO just uses fading MRC (FMRC) rather than AMRC. We also evaluate system design parameters by comparing BER performance when the impulse noise index A varies.

II. Impulse Noise and Fading Channel in BPLC

BPLC channel can be characterized with both impulse noise and multipath fading due to multiple signal reflections caused by power line impedance mismatch. First, for impulse noise, we use the Middleton's class A model [1] whose *pdf* is defined as

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

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

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 multipath fading, we employ the Zimmermann frequency PLC channel model [2], whose transfer function at the jth antenna path is expressed as

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

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 jth antenna and lth fading path [2]. $d_{j,l} / v_p$ is equivalent to the corresponding path delay $\tau_{j,l}$ (where $d_{j,l}$ represents its 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 non-insulation dielectric constant of the cable and c_0 is the speed of light. Typically, each OFDM subcarrier has

This work (00047470-1) was supported by Business for Cooperative R&D between Industry, Academy, and Research Institute funded Korea Small and Medium Business Administration in 2011.

flat (constant) frequency channel characteristics due to its narrow bandwidth, such that 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, …, N - 1.

III. MIMO-OFDM BPLC System

In this paper, we design a MIMO-OFDM system that contains I (transmit antennas) x J (receive antennas). In the OFDM transmitter, the kth 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 nth (= 0, 1, …, N-1) time sample and N is the number of subcarriers.

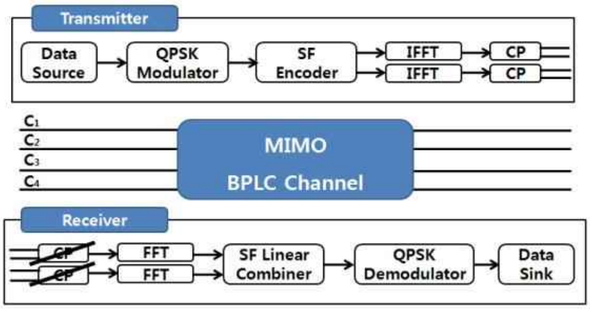
In MIMO in BPLC, unlike MIMO in wireless, a pair of electrical wires is converted into a single antenna channel, so the number of transmitting and receiving antennas is typically limited to two for 3-phase 4-wire and one for single-phase 2-wire. Therefore, MIMO-OFDM is used either indoors or outdoors 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 2x2 MIMO-OFDM BPLC system block diagram, using a 3-phase 4-wire power line (Fig. 1(b) shows its cross-cut interior structure). This 2x2 MIMO system has two antenna paths that consist of a single antenna path formed with C_1 and C_2 and another single antenna path made of C_3 and C_4; C_0 takes the role as a ground connection. A space frequency (SF) encoder is used to reduce 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.

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

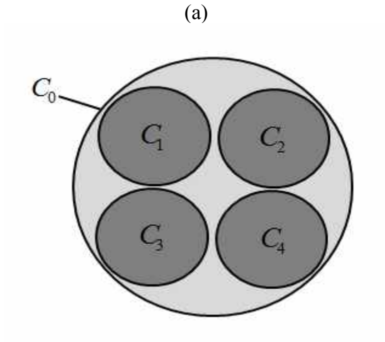
where $S_1[k]$= $S_2[k]$, (k=0,1, …, N-1) and $(\cdot)^T$ refers to the transpose of (·). $\mathbf{S_1}$ and $\mathbf{S_2}$ are respectively converted to the corresponding time sample vectors, $\mathbf{s_1}$=$IFFT\{\mathbf{S_1}\}$ and $\mathbf{s_2}$=$IFFT\{\mathbf{S_2}\}$, through the IFFT process (see (4)) and then transmitted to the receiver via each antenna path. In Fig. 1(a), this transmitting process is occurred at the signal encoder and modulator, and corresponding receiving process is processed at the linear combiner and detector. The 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) due to multipath delay. The signal received via the fading channel undergoes the SF decoding process, i.e., fast Fourier transform (FFT), inverse circular-shift operation, and then MRC process, to recover its data stream after removing the added CP.

A. MRC without Cross-Talk

Assume there is no coupling between the two antenna paths to simplify the simulation (this assumption is practically reasonable for the carrier frequency $f_c \leq 25$ MHz [5].).



(a)



(b)

Figure 1. 2x2 MIMO-OFDM PLC system block diagram, (b) 3-phase 4-wire power line interior structure.

The conventional system using AMRC has diversity gain by multiplying its optimum weight to 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., $S_j(k)=S_{j,1}(k)=S_{j,2}(k)=\ldots=S_{j,L}(k)$, the jth (j=1,2) antenna received signal $Y_j(k)$ at the kth subcarrier is written as

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

where E_s represents the average energy of the transmit signal. $X_{j,l}(k)$ is the jth antenna path and 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 variance σ^2(see (1)). In this paper, we assume ideal fading channel estimation to simplify the simulation.

When applying the proposed MRC (AFMRC) to the single-phase 2-wire SISO BPLC (just using FMRC) and the

3-phase 4-wire 2x2 MIMO BPLC, the output $\hat{S}$ (detected signal) of the maximum likelihood (ML) receiver can be respectively expressed as

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

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

B. MRC with Cross-Talk

The presented MIMO system, seen in Fig. 1 (a), might have a cross-talk (its capacity loss might not be negligible (but less than 16%), especially for $f_c \geq 25$ MHz [5].) between two parallel antenna channels that degrades system performance. The 2x2 MIMO channel matrix $\mathbf{H}$ with non-zero cross-talk terms, indicating the ith transmit jth receive antenna path gain $H_j^i(k) \neq 0$ (where $i \neq j$), can be expressed as follows:

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

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

$$CR = \frac{C_{nct} - C_{ct}}{C_{nct}} \times 100\% \quad (9)$$

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

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

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

IV. 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 those of a conventional system [4]. Assume a multipath fading PLC channel with L=6, whose simulation parameters are the same as in Table I of [4]. For simplicity, we also assume the same fading channel parameters for the two antenna paths[1)]. We set N = 1024, the CP size = 120 (unit: sample), f_c = 25 MHz, Δf (frequency spacing) = 1 KHz, BW = 1.024 MHz for the simulation; hence the maximum data rate is about 1.83 Mbps.

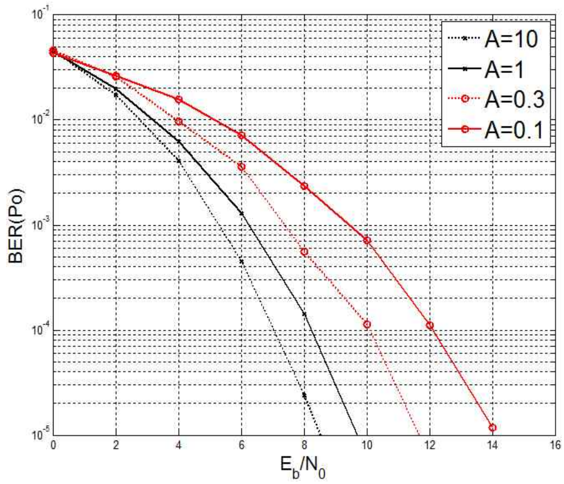


Figure 2. BER Comparison of 2x2 MIMO PLC when A varies.

Fig. 2 compares BER of 2x2 MIMO BPLC when the impulse noise index A varies. For this experiment, we set τ=0.1. Whilst for large A (≥ 1), noise channel characteristics approach Gaussian, for small A (<1), it is similar to impulse noise. Thus, BER decreases as A increases, as shown in Fig. 2. For example, for A=10, we can get approximately 1 dB gain at BER=10^{-5} compared to A=1, 3 dB gain compared to A=0.3, and 5.5 dB gain compared to A=0.1. Practically, in the BPLC channel environment, A has a value within the range of 0.0001 to 0.35, so we choose A=0.3 for the next experiment [4].

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 [6].

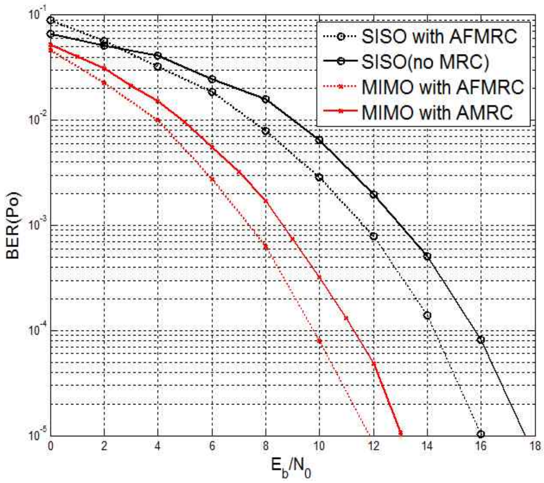


Figure 3. Performance comparison of SISO/MIMO-OFDM with different MRC schemes (assuming A = 0.3).

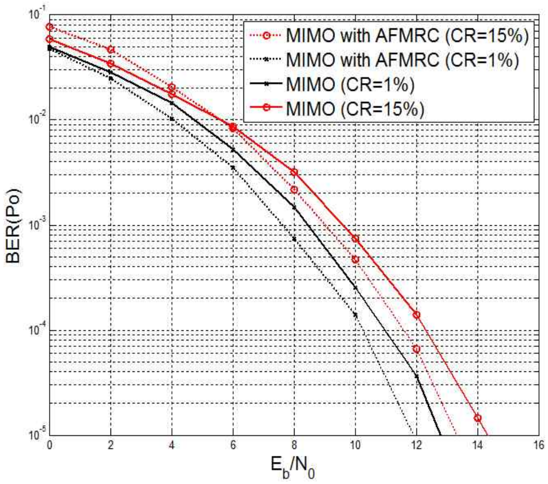


Figure 4. Performance of MIMO-OFDM with cross-talk (assuming A = 0.3).

Fig. 3 compares BER performance between conventional AMRC and the suggested AFMRC on SISO/MIMO-OFDM. First, in the case of MIMO, AFMRC obtains the performance gain of about 1 dB at 10^{-5} BER compared to AMRC. Fig. 3 compares conventional method (with no MRC) and the proposed method (with FMRC) on SISO-OFDM; it shows a 1.5 dB improvement based on 10^{-5} BER for the proposed scheme. Therefore, the simulation verifies the proposed SISO/MIMO-OFDM is more effective, both in the indoor single-phase and outdoor 3-phase, than conventional SISO/MIMO-OFDM.

Fig. 4 shows the MIMO BPLC system performance effect by cross-talk. The proposed scheme has about 0.7~0.8 dB gain over the conventional scheme at 10^{-5} BER. When CR increases 1% to 15%, the BER performance of both schemes is degraded about 1 dB.

V. CONCLUSIONS

We have proposed a MIMO-OFDM based BPLC using AFMRC that combines multi-antenna MRC (AMRC) and multipath fading MRC (FMRC). We have evaluated the proposed MIMO over BPLC channels with or without cross-talk between antenna paths. Computer simulation verified the proposed scheme is more effective in both the indoor single-phase (SISO) and outdoor 3-phase (MIMO) BPLC applications than conventional schemes.

REFERENCES

[1] N. Andreadou and F.-N. Pavlidou, "PLC channel: impulse noise modeling and its performance evaluation under difference array coding schemes," IEEE Trans. on Power Delivery, vol. 24, no. 2, pp. 585-595, April 2009.

[2] M. Zimmerman and K. Dostert, "A multipath model for the powerline channel," IEEE Trans. Commun., vol. 50, no. 4, pp. 553-559, April 2002.

[3] C. L. Giovaneli, B. Honary, and P. G. Farrell, "Space-frequency coded OFDM system for multi-wire power line communications," Proc. IEEE ISPLC 2005, pp. 191-195, April 2005.

[4] B. Adebisi, S. Ali, and B. Honary, "Space-frequency and space-time-frequency M3FSK for indoor multiwire communications," IEEE Trans. on Power Delivery, vol. 24, no. 4, pp. 2361-2367, October 2009.

[5] L. Hao, and J. Guo, "A MIMO-OFDM scheme over coupled multi-conductor power-line communication channel," Proc. IEEE ISPLC 2007, pp. 198-203, March 2007.

[6] R. Hashmat, P. Pagani, and T. Chonavel, "MIMO communications for inhome PLC networks: measurements and results up to 100 MHz," Proc. IEEE ISPLC 2010, pp. 120-124, March 2010.