# Power Line Communication using STC/SFC/STFC over Statistical Indoor Power Line Channels

Jeonghwa Yoo and Sangho Choe

Wireless Communications Laboratory, The Catholic University of Korea

Bucheon, Republic of Korea

mundade@hanmail.net and schoe@catholic.ac.kr

***Abstract*— This paper presents a MIMO-OFDM based power line communication (PLC) system using space-frequency coding (SFC), space-time coding (STC), and space-time-frequency coding (STFC) over statistical indoor power line channels. We present a maximum ratio combining (MRC) scheme that provides both multiple antenna diversity gain and multipath fading diversity gain. By simulation, we verify that the proposed MRC is effective to both 2×2 MIMO and SISO over indoor power line channels. On the simulation, we consider both perfect and imperfect channel estimation. We also simulate SFC, STC, and STFC over power line channels, with or without crosstalk between antenna paths; STFC and STC are more robust to crosstalk than SFC; STFC with some added complexity overpowers the other coding schemes in terms of bit-error rate performance. Further, STFC is less sensitive to impulse noise index *A* than STC and SFC.**

***Keywords*— *PLC; MIMO; OFDM; MRC; multipath fading; impulse noise; crosstalk.***

## I. INTRODUCTION

Smart grid that is the renewable energy based future power line network will provide various kinds of power line access services (PAS). For that smart grid PAS, power line communication (PLC) that does not request a separate backbone network unlike other medium has become one of the main alternatives for high-speed bidirectional information exchange among electric power providers, electricity industries, and consumers. Moreover, since an international PLC standard, IEEE 1901 [1], was adopted in 2010, there has been a growing interest in various other PLC applications including home networks and emergency backup networks. PLC 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.

PLC that uses existing power lines, which are originally installed for power supply, has very poor channel environment such as limited carrier frequency ($f_c$ < 100MHz) by power cable attenuation, multipath fading, and impulse noise.

The signal processing model of PLC multipath fading channel is classified into two types: deterministic-type [2] and statistical-type [3], [4]. In the case of deterministic-type, the well-known Zimmermann model has been widely used [2] but it does not consider practical channel statistics. Hence, there are several trials of statistical-type channel models, which are mostly modified versions of Zimmermann model, such as Galli model [3], and Tonello model [4]. Tonello model first takes the uniformly-distributed reflection factors in fading paths into account but it does not show any empirical justification yet (see [3]). Therefore, throughout this paper, we use the Galli's statistical channel model to get the most realistic simulation results for our 2×2 multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) PLC system. We also employ Middleton class A model [5] for the statistical impulse noise sample generation considering the impulse characteristics, which is raised by switching the power supply, the power converters, and so on.

OFDM is widely used in power line channels since it is robust to inter-symbol interference (ISI) caused by the multipath fading delay spread [6]. In recent studies, MIMO using the spatial diversity, turbo coding, and low-density parity-check (LDPC) coding are actively investigated to reduce the transmit bit error rate (BER) and improve the performance of OFDM PLC systems [7], [8]. In this paper, via indoor power line, we implement the three different MIMO coding schemes: space-frequency coding (SFC) [8] using the frequency space diversity gain, space-time coding (STC) [8], [10] using the time space diversity gain, and space-time-frequency coding (STFC) [8] using the time and frequency space diversity gain.

By simulation, we evaluate and compare SFC/STC/STFC based 2×2 MIMO-OFDM PLC systems with the proposed maximum ratio combing (MRC) scheme over statistical PLC channels. Whereas conventional MIMO-OFDM PLC [6], [8] just considers antenna MRC (AMRC) to

 ISBN: 978-1-61208-259-2 

obtain spatial diversity gain, the presented MIMO-OFDM PLC employs antenna & fading MRC (AFMRC, also called rake receiver) that effectively combines both multiple antenna (in PLC, a pair of power line conductors forms one antenna port) and multipath fading diversity gain. Conventional MIMO PLC in [8] assumes the ideal antenna paths with no crosstalk, but the proposed MIMO PLC takes crosstalk between antenna paths into consideration.

In this paper, for the theory and analysis of the proposed MIMO-OFDM system model, we consider both perfect channel estimation and imperfect channel estimation. For the simulation of imperfect channel estimation, we employ a least square estimator (see [9]), which is a simple but well-established channel estimator.

Simulation results verify that the presented MRC scheme is superior to the conventional scheme, whether or not crosstalk between antenna channels exists. This scheme improves the BER performance, not only in the 2×2 MIMO, but also in the single-input single-output (SISO); note that SISO just uses fading MRC (FMRC) rather than AMRC. In simulation, we also evaluate the proposed MIMO PLC when the impulse noise index $A$ and the ratio of impulse to Gaussian noise variance $\tau$ vary. The contributions of this paper are summarized as follows:

- Propose a SISO-/MIMO-OFDM PLC using a rake receiver;
- Fully evaluate the proposed system over statistical power line channels with fading, impulse noise, crosstalk between antenna paths;
- Analyze the proposed system with both perfect and imperfect channel estimator.

Section II describes the proposed system model including PLC channel characteristics, crosstalk in MIMO channels, SFC/STC/STFC based MIMO-OFDM, and least square channel estimation for MIMO-OFDM. Section III details simulation results of the proposed system and finally, Section IV concludes the paper.

## II. SYSTEM MODEL

### A. Impulse Noise and Fading Channel in PLC

A PLC 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 Middleton class A model [5], which *pdf* (probability density function) is defined as:

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

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

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

Second, in a PLC channel, there are two types of channel models; deterministic-one like Zimmermann model [2], and statistical-one like Galli model [3]. First, the transfer function of Zimmermann channel model [2] at the $j$th antenna path is expressed as:

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

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

where $L$ is the number of fading paths per antenna path. $\alpha_0$, $\alpha_1$, and $u$ are the power line cable parameters, and $|g_{j,l}| \le 1$ is the weighting factor of the $j$th antenna and $l$th fading path [2]. $d_{j,l} / v_p$ is equivalent to the corresponding path delay $\mathrm{T}_{j,l}$ (where $d_{j,l}$ represents its length) as follows:

$$\mathrm{T}_{j,l} = \frac{d_{j,l} \cdot \sqrt{\varepsilon_r}}{c_0} = \frac{d_{j,l}}{v_p}, \quad (5)$$

where $\varepsilon_r$ 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 due to its narrow bandwidth such that the frequency selective fading channel transfer function of (3) can be translated (digitized) and approximated as follows:

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

where $f_c$ is the carrier frequency (which is herein assumed to indicate the lower limit of the OFDM bandwidth (BW)), $\Delta f$ is the subcarrier spacing, and $k$ (= 0, 1, …, $N$ – 1, where $N$ is the number of subcarriers) is the frequency index. For the time being, operating under the assumption that a good channel estimator, such as a least square method [9] or a pilot assisted method [10], is employed, we assume the ideal channel estimate for all fading paths, i.e. $H_{j,l}(k) = \hat{H}_{j,l}(k)$.

In this paper, for practical MIMO channel simulation, we consider Galli model [2], a modified version of Zimmermann model, where the average of channel gain and delay (spread) in (4), is log-normal distributed. Since the delay is easily dealt with using a cyclic prefix (CP) of OFDM system, the proposed system model just considers the average channel gain at the $j$th antenna path and $l$th fading path, defined as

$$\bar{G}_{j,,l} = 10^{\bar{G}_{j,l}(dB)/10} = \frac{1}{N} \sum_{k=0}^{N-1} \left| H_{j,l}(k) \right|^2. \quad (7)$$

In simulation, $\bar{G}_{j,l}(dB)$ is assumed to be real, independent, and log-normally distributed in [-1, 1]. The other parameter values such as $\alpha_0$, $\alpha_1$, $u$, and so on, are assumed to be fixed (as seen in Table I, Section III).

 ISBN: 978-1-61208-259-2 

### B. Crosstalk in MIMO channels

In MIMO channels, there exists crosstalk between antenna paths; note that each antenna path in a MIMO PLC system is formed with a pair of power line conductors. This crosstalk may cause the capacity loss of the MIMO PLC system such that it is not negligible, especially for $f_c \geq 25$ MHz [6]. The 2×2 MIMO channel matrix $\mathbf{H}(k)$ with non-zero crosstalk terms, indicating the $i$th transmit $j$th receive antenna path gain $H_j^i(k) \neq 0$ (where $I \neq j$), can be expressed as follows:

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

Let the channel capacity with or without crosstalk be denoted as $C_{ct}$ and $C_{nct}$, respectively. The capacity-loss ratio (CR) by crosstalk can be defined as [6]

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

where the channel capacity is [14]

$$C = \sum_{k=0}^{N-1} \int_{f_c + k\cdot\Delta f}^{f_c+(k+1)\Delta f} \log_2 \det\left( \mathbf{I}_I + \frac{S_{psd}(f)\mathbf{H}(k)\mathbf{H}^H(k)}{N_{psd}(f)\cdot I} \right) df. \tag{10}$$

$S_{psd}(f)$ and $N_{psd}(f)$ represent the transmitted signal power spectral density and colored noise (impulse plus Gaussian noise) power spectral density, respectively. $I$ is the number of transmit antennas, $\mathbf{I}_I$ is the identity matrix of size $I$, and $(\cdot)^H$ refers to the Hermitian of (·).

### C. SFC/STC/STFC based MIMO-OFDM PLC System

We implement a SFC/STC/STFC based 2×2 MIMO-OFDM PLC system. In a MIMO PLC system, since a pair of electrical wires is converted into a single antenna channel, the number of transmitting and receiving antennas is typically limited to one for 1-phase 2-wire and two for 1-phase 3-wire (including one wire for common ground (or protective earth)). Therefore, MIMO-OFDM is used with a 1-phase 3-wire power line, whereas SISO-OFDM is mostly used with a 1-phase 2-wire power line. This 2×2 MIMO system has two antenna paths that consist of a single antenna path formed with two wires and another antenna path made of other two wires.

In the OFDM transmitter, the $k$th (= 0, 1, …, $N$-1) subcarrier modulation signal, $S(k)$, experiences the following inverse fast Fourier transform (IFFT):

$$s(n) = \frac{1}{N}\sum_{k=0}^{N-1} S(k)e^{j2\pi nk/N}, \tag{11}$$

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

First, in the case of a SFC based 2×2 MIMO, whose encoder diagram is shown in Fig. 1(a), we can obtain the spatial and frequency diversity which is used to reduce the error probability caused by the interference in the MIMO channel.

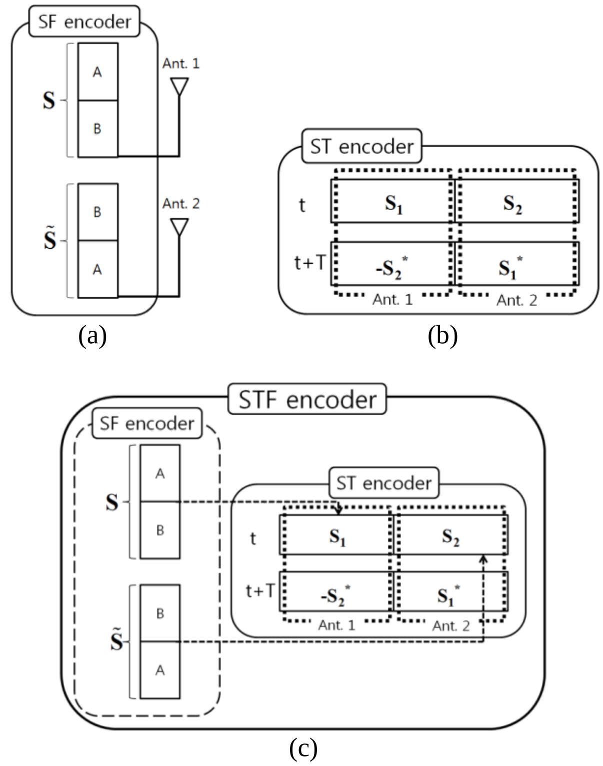


Figure 1. (a) 2×2 SFC encoder (b) 2×2 STC encoder (c) 2×2 STFC encoder.

The following two SF encoder vectors $\mathbf{S}$ and $\tilde{\mathbf{S}}$ are formed by arranging the same subcarrier signal samples in an appropriate order (i.e., vector $\tilde{\mathbf{S}}$ is the circular-shifted version of $\mathbf{S}$ [8]) for this SF encoder.

$$\mathbf{S} = [S(0),...,S(\frac{N}{2}-1),S(\frac{N}{2}),...,S(N-1)]^T, \tag{12}$$

$$\tilde{\mathbf{S}} = [\tilde{S}(\frac{N}{2}),...,\tilde{S}(N-1),\tilde{S}(0),...,\tilde{S}(\frac{N}{2}-1)]^T, \tag{13}$$

where $S(k) = \tilde{S}(k)$, ($k$=0,1, …, $N$-1) and $(\cdot)^T$ refers to the transpose of (·). $\mathbf{S}$ and $\tilde{\mathbf{S}}$ are respectively converted to the corresponding time sample vectors, $\mathbf{s}$=$IFFT\{\mathbf{S}\}$ and $\tilde{\mathbf{s}}$ =$IFFT\{\tilde{\mathbf{S}}\}$, through the IFFT process (see (11)) and then transmitted to the receiver via each antenna path. The cyclic prefix (CP) is added to the OFDM modulated sample vectors ($\mathbf{s}$, $\tilde{\mathbf{s}}$) before their transmission, in order to prevent inter-symbol interference (ISI) due to the maximum delay spread $\mathrm{T}_{\max} = \max_l \mathrm{T}_l$. This transmission process occurs at the modulator and SFC encoder, and its corresponding reception process takes place at the SFC decoder and demodulator [11]. The received signal via the power line channel goes through the SFC decoding process at the SFC receiver, including the fast Fourier transformation (FFT) (OFDM demodulation) and MRC process, to recover its data stream after removing the added CP.

Whereas conventional MIMO schemes in [8] use AMRC to achieve diversity gain by multiplying their optimum weights to different antenna paths, the proposed MIMO system employs AFMRC (also called rake receiver), a combined technique of AMRC and FMRC. The used scheme has one finger (one receiver) for each fading path to achieve the FMRC gain. The receiver complexity of the AFMRC based MIMO increases $L$-fold as a result of adding FMRC. At the receiver, the received signal via the $j$th (=1, 2) receive antenna $l$th (=1, 2, …, $L$) fading path after the FFT process (which is the reverse process of the IFFT in (11)) is given as

$$Y_{j,l}(k) = \sum_{i=1}^{I} \sqrt{\frac{E_s}{I}} H_{j,l}^{i}(k) S_i(k) + N_{j,l}(k), \tag{14}$$

where $E_s$ represents the average energy of the transmit signal and $S_i(k)$ is the transmit signal from the $i$th transmission antenna. $N_{j,l}(k)$ indicates the noise component that is the result of the FFT operation of the time axis impulse plus Gaussian noise signal $n_{j,l}(n)$ with variance $\sigma^2$ (see (1)). At the rake receiver, the received signal in (14) is first translated as

$$\bar{Y}_j(k) = \sum_{l=1}^{L} Y_{j,l}(k) \hat{H}_{j,l}^{j*}(k), (j = 1, 2), \tag{15}$$

where we can see that all fading path signals multiplied with corresponding channel estimate conjugates are combined. Before the $j$th antenna received signals in (15) are added together, note that they pass through the reverse process of the circular-shifted process in (12) and (13). Hence, by the SFC decoding process, we derive

$$\hat{Y}(k) = \sum_{j=1}^{2} \tilde{Y}_j(k), \tag{16}$$

where $\tilde{Y}_j(k)$ is the reverse circular shifted version of $\bar{Y}_j(k)$. Finally, by the maximum likelihood (ML) based maximum ratio combining (called AFMRC) scheme, the recovered symbol is obtained as $\hat{S}(k) = \underset{S\in\Omega}{\arg\min} \,|\, \hat{Y}(k) - S\,|^2$, where $\Omega$ indicates the total signal symbol space.

Second, in the case of a STC based 2×2 MIMO, whose encoder diagram is shown in Fig. 1(b), we can obtain the spatial and temporal diversity to improve the system performance. The two transmission vectors in this STC transmitter, $\mathbf{S_1} = \{ S_1(k) \mid k = 0,1, …, N - 1\}$ and $\mathbf{S_2} = \{ S_2(k) \mid k = 0,1, …, N - 1\}$ are independent each other and $(\cdot)^*$ refers to the conjugate of $(\cdot)$. In Fig. 1(b), we observe that at time $t$, $\mathbf{S}_1$ and $\mathbf{S}_2$ are assigned to antenna 1 and antenna 2, respectively, and at time $t$+$T$ (where $T$ is the OFDM symbol time), $-\mathbf{S}_2^*$ and $\mathbf{S}_1^*$ are assigned to antenna 1 and antenna 2, respectively.

At the receiver, the received signal via the $j$th (=1, 2) receive antenna $l$th (=1, 2, …, $L$) fading path after the FFT process is given as

$$Y_{j,l}(k,t) = \sum_{i=1}^{2} \sqrt{\frac{E_S}{2}} H_{j,l}^{i}(k,t) S_i(k,t) + N_{j,l}(k,t), \tag{17}$$

$$Y_{j,l}(k,t+T) = \sum_{i=1}^{2} \sqrt{\frac{E_S}{2}} H_{j,l}^{i}(k,t+T) S_i(k,t+T) + N_{j,l}(k,t+T), \tag{18}$$

where $Y_{j,l}(k,t)$ and $Y_{j,l}(k,t+T)$ are the received signals at the time $t$ and $t$+$T$, respectively. At the rake receiver, the received signal in (17) and (18) is first translated as

$$\bar{Y}_j(k,t) = \sum_{l=1}^{L} Y_{j,l}(k,t) \hat{H}_{j,l}^{j*}(k,t), \tag{19}$$

$$\bar{Y}_j(k,t+T) = \sum_{l=1}^{L} Y_{j,l}(k,t+T) \hat{H}_{j,l}^{j*}(k,t+T), \tag{20}$$

where we can note that all fading path signals multiplied with corresponding channel estimate conjugates are combined. Then, by the STC decoding process, we derive

$$Y_1'(k) = \bar{Y}_1(k,t) + \bar{Y}_2^*(k,t+T), \tag{21}$$

$$Y_2'(k) = -\bar{Y}_1^*(k,t+T) + \bar{Y}_2\,(k,t), \tag{22}$$

Finally, at the ML based AFMRC process, we can recover the following two symbols from the two derived signals in (21) and (22),

$$\hat{S}_1(k) = \underset{S\in\Omega}{\arg\min} \left| Y_1'(k) - S \right|, \tag{23}$$

$$\hat{S}_2(k) = \underset{S\in\Omega}{\arg\min} \left| Y_2'(k) - S \right|. \tag{24}$$

Third, in the case of STFC based 2×2 MIMO, it extends the signal space of STC to the frequency axis such that we can achieve the frequency diversity besides the spatial and temporal diversity; its encoder has a serially-combined structure of SFC and STC [8], as shown in Fig. 1(c). In the STFC transmitter, the input of STC is the two output vectors of SFC encoder, i.e., $\mathbf{S}$ and $\tilde{\mathbf{S}}$ (see (12) and (13)).

At the STFC receiver, first, by the STC decoding process of (19), (20), (21), and (22), we obtain $Y_1'(k)$ and $Y_2'(k)$. Then, by the SFC decoding process, including the reverse operation of circular shift and combining, we derive

$$Y''(k) = \sum_{j=1}^{2} \tilde{Y}_j(k), \tag{25}$$

where $\tilde{Y}_j(k)$ is the reverse circular shifted version of $Y_j'(k)$ $(j = 1, 2)$. Finally, at the ML based AFMRC process, the recovered symbol is obtained as $\hat{S}(k) = \underset{S\in\Omega}{\arg\min} \,|\, Y''(k) - S\,|^2$.

### D. Least square Channel estimation for MIMO-OFDM system

In this paper, we use a least square estimator for the channel estimation. Least square channel estimation [9] is performed after the FFT operation at the receiver. For the channel estimation, the pilot signals which are already known at the receiver are used. In the OFDM system, adjacent $G$ subcarriers are grouped without overlapping. In this paper, we assume that each group has almost the same channel. In each group, the first subcarrier is the pilot subcarrier. Therefore, the total $M$ (= $N/G$) pilot subcarriers are used for channel estimation. In [9], they assume that all the pilot signals have an equal complex value $c$. The transmitted signals on the $k$th subcarrier are expressed as

$$S_i'(k) = S_i'(mG+g) = \begin{cases} c, & \text{for } g=0 \\ \text{Information Data}, & \text{otherwise} \end{cases} \quad (26)$$

where $m$ = 0, 1, …, $M$-1 and $g$ = 0, …, $N/G$-1 (for each $m$).

The received signal can be expressed as

$$Y_{j,l}(k) = \sqrt{\frac{E_s}{2}} H^j_{j,l}(k) S_i'(k) + N'_{j,l}(k), \quad (27)$$

where $N'$ is the crosstalk plus noise term (assume that the crosstalk term is Gaussian distributed). Since all the pilot signals have $c$ value, $M$ estimated channels at the each pilot subcarriers can be written as

$$\hat{H}^j_{j,l}(mG) = \frac{Y_{j,l}(mG)}{c} = H^j_{j,l}(mG) + \frac{N_{j,l}(mG)}{c}. \quad (28)$$

Finally, the channel estimate will be expressed as

$$\hat{H}^j_{j,l} = \frac{\sum_{m=0}^{M-1} \hat{H}^j_{j,l},(mG)}{M}. \quad (29)$$

In (28), $N'(mG)/c$ is a noise plus crosstalk component of the estimated channel. The estimated channel will have a large value of this component when the signal to noise ratio is small. 2×2 MIMO using SFC or STC has twice as many noise component than SISO when the signals from the two antenna paths are combined (STFC has twice more noise component compared to SFT or STC). The affection of this noise component is shown in simulation results.

## III. Simulation Results

We simulate the proposed system model with the QPSK constellation under power line channel conditions. The simulation assumes a PLC multipath fading channel with $L$=6, e.g., whose parameters in Zimmermann model are shown in Table I of [8]. For simplicity, we also assume the same fading channel parameters for the two antenna paths — in the case of PLC channels using indoor power lines; the changing of channel parameters between the antenna paths is almost negligible in practice [7]. We set $N$ = 1024 (in the case of STFC, $N$ equals 2048 for the same data rate), the CP size = 120 (unit: samples), $f_c$ = 30 MHz, $\Delta f$ (frequency spacing) = 10 KHz, and BW = 10.24 MHz for the simulation; hence the maximum data rate is approximately 18.3 Mbps.

Fig. 2 compares the BER performance between conventional MRC method and the proposed MRC method on SISO-/MIMO-OFDM system. First, in the case of MIMO-OFDM system using 2×2 SFC or 2×2 STC, the proposed MRC (AFMRC) obtains the performance gain of about $2dB$ at $10^{-4}$ BER compared to conventional MRC (AMRC). Second, in the case of MIMO using 2×2 STFC, AFMRC provides the $2dB$ gain at BER=$10^{-4}$ compared to AMRC. Fig. 2 also compares conventional method (with no MRC) and the suggested method (with FMRC) on SISO-OFDM system. For SISO with FMRC, we can get approximately $2dB$ gain at BER=$10^{-4}$ compared to SISO with no MRC. Therefore, FMRC for SISO system and AFMRC for MIMO system are more effective according to these simulation results. It also verifies that AFMRC is similarly effective at MIMO systems using SFC, STC, or STFC.

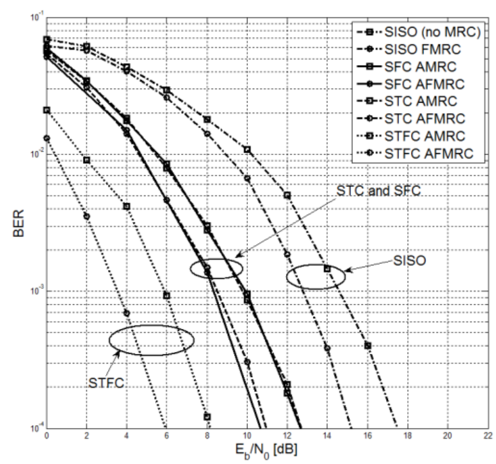


Figure 2. Performance comparison of SISO/MIMO-OFDM with different MRC schemes ( $A = 0.3,\ \tau = 0.1$ ).

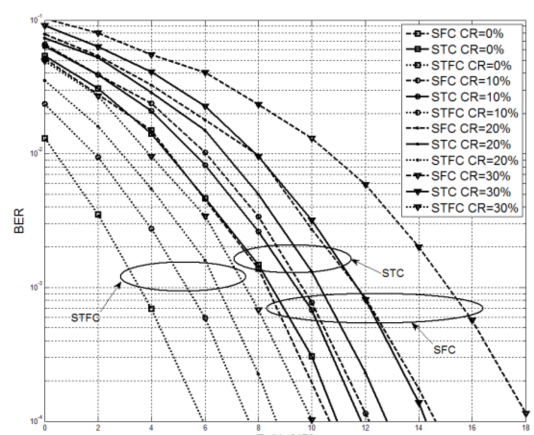


Figure 3. BER comparison of SFC, STC, and STFC based MIMO-OFDM PLC when crosstalk exists ( $A = 0.3,\ \tau = 0.1$ ).

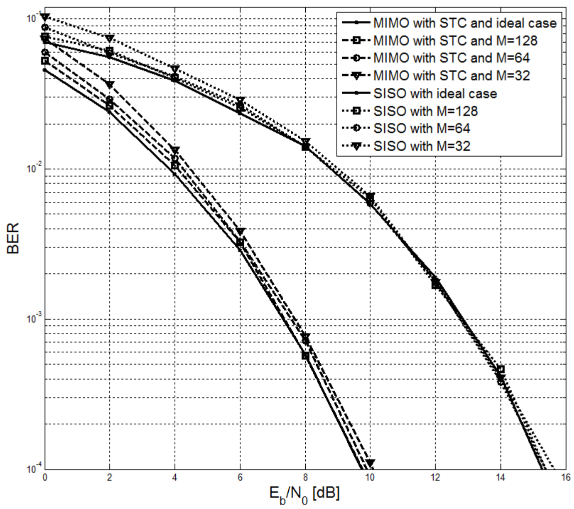


Figure 4. BER comparison of SISO/MIMO PLC with least-square channel estimator when $M$ varies ( $A = 0.3,\ \tau = 0.1$ ).

Fig. 3 compares the BER performance of 2×2 STC, 2×2 SFC, and 2×2 STFC based MIMO-OFDM PLC when the crosstalk between antenna channels exists. Assume that AFMRC is applied to all these MIMO coding schemes. We can observe that as the crosstalk ratio (CR) increases, STC has a relatively reduced BER compared to SFC. Especially, for CR > 10%, the relative performance gain difference between STC and SFC becomes greater. It indicates that STC is less sensitive to crosstalk than SFC. In Fig. 3, we can find out that STFC has a similar tendency as STC. It looks that as CR increases the STFC (STC as well) performance is degraded linearly while the SFC performance is degraded exponentially; specifically, for the 10% increase of CR, the coding gain of STFC degrades 1.5*dB* (similar in STC) in the average sense while that of SFC degrades 1.2*dB* for the increment of CR 0% to 10% and 2.2*dB* for CR=10% to 20%, and 3.5*dB* for CR=20% to 30%. Therefore, STC and STFC have robustness to crosstalk and STFC with additional complexity improves the BER performance of STC further.

In Fig. 4, we evaluate the BER performance of SISO-OFDM PLC and STC-based 2×2 MIMO-OFDM PLC using least square channel estimation methods with different number of pilot subcarriers. Fig. 4 shows that BER decreases as the number of pilot subcarriers increases. It confirms that if we have a larger number of pilot subcarriers, we can estimate the channel more exactly (since the noise component in (28) becomes smaller). Fig. 4 also shows that the BER curve is going to approach to the ideal case as $E_b/N_0$ [*dB*] increases. In the case of MIMO PLC, the ideal channel estimator has 0.5*dB* gain at the BER=$10^{-2}$ compared to the least square channel estimator with $M$=32 pilot subcarriers. However, at the BER=$10^{-4}$, the gain difference between those two schemes reduces (about 0.1 to 0.2*dB*); for the larger $M$, that difference gets smaller. In the case of SISO, we can observe the similar tendency of BER curves as in MIMO.

However, in Fig. 4, we can observe that SISO improves the BER performance a little bit compared to STC-based MIMO, since the latter requests two times more noise component than the former. SFC-based MIMO shows the similar performance results (even their results are not included here due to the space limit).

## IV. Conclusions

We proposed a MIMO-OFDM based PLC using AFMRC. We compared SFC, STF, and STFC based MIMO-OFDM over statistical indoor power line channels, with or without crosstalk between antenna paths. By computer simulation, we verified that the proposed MRC scheme is effective to both SISO PLC and MIMO PLC applications. It is shown that STC and STFC are more robust to crosstalk than SFC; STFC with additional complexity overpowers STC and SFC in terms of BER over power line channels. Further, we also simulated the proposed MIMO model with imperfect channel estimation.

## References

[1] IEEE standard for broadband over power line networks: Medium access control and physical layer specifications, IEEE Standard 1901, 2010.

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

[3] S. Galli, "A simplified model for the indoor power line channel," in Proc. IEEE ISPLC 2009, Apr. 2009, pp. 13-19.

[4] M. Tonello, "Wideband impulse modulation and receiver algorithms for multiuser power line communications," EURASIP Journal on Advances in Siganl Processing, vol. 2007, article ID 96747, 2007, pp. 1-14.

[5] J. Haring and A.J. H. Vinck, "Coding for impulsive noise channels," in Proc. IEEE ISPLC 2001, Feb. 2001, pp. 103-108.

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

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

[8] 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, Oct. 2009, pp. 2361-2367.

[9] S. Wei and P. Zhiwen, "Iterative LS channel estimation for OFDM systems based on transform-domain processing," in Proc. IEEE WiCom 2007, Sept. 2007, pp. 416-419.

[10] N. Kawabata, H. Koga, O. Muta, and Y. Akaiwa, "A high-speed power-line communication system with band-limited OQAM based multi-carrier transmission," IEICE Trans. on Commun., vol. E92-B, no. 2, Feb. 2009, pp. 473-483.

[11] H. Jafarkhani, Space-Time Coding Theory and Practice, Cambridge Univ. Press, 2005, ch. 11.