Multipath Channel Model for MIMO-based Broadband Power Line Communications

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***Abstract*—Broadband power line communication (BPLC) is a promising medium for network access technology by which broadband services can be offered, such as smart grid, broadband Internet access, digital entertainment, and home networking services. This paper presents a modified multipath channel model for multiple-input multiple-output (MIMO) systems and analyzes the channel capacity and bit-error-rate performance of MIMO orthogonal frequency division multiplexing (MIMO-OFDM) based BPLC over that channel model. The widely-used single-input single-output (SISO) channel model (also called Zimmermann's model) is extended to the MIMO channel model considering coupling effects among conductors.**

Keywords-MIMO; OFDM; crosstalk; channel capacity; broadband power line communication.

I. INTRODUCTION

The greatest advantage of power line communication (PLC) is that there is no need for new infrastructure, which is cost efficient in the implementation. The other merits of PLC are as follows: it contributes to low power consumption; it can be applied for the use of energy control and monitoring; it reduces the wiring and lightens the transportation system (vehicles, aircrafts, etc.). In other words, PLC is more "green". Definitely, PLC provides a green ubiquitous concept, economical realization and installation. Furthermore, Broadband PLC (BPLC) can provide high-rate or high performance data services through power line channels. Hence, it can be sufficiently capable of serving as a means of communication able to support future green-energy based smart grid applications. Since the BPLC standard (IEEE 1901) is recently adopted [1], there has been growing interest to BPLC.

Several techniques to model channel transfer characteristic of PLC networks have been presented in various literatures [2] – [4]. Zimmermann and Dostert in [3] state the variety of loads connected to the network terminals and the presence of several cable branches which cause impedance mismatches. Due to these impedance mismatches, many reflections of signal appear during its transfer along the cable. This is called multipath fading or frequency selective fading. The signal distortion experience as a result of frequency-selective fading can be significantly reduced, even if not completely eliminated, by the introduction of efficient multicarrier modulation techniques. One of these efficient multicarrier modulation techniques is orthogonal frequency division multiplexing (OFDM) [5]. OFDM is a smart technique for reliable broadband communications over a wireless channel, which reduces inter-symbol interference and can be applied in PLC [6]. Multiple-input multiple-output (MIMO) communication is a well-known technique to improve data capacity in radio transmission system and can be similarly applied to PLC by substituting transmit and receive antennas with signal feed and receive ports as well as the wireless channel with the existing electrical wiring [7], [8]. In order to investigate the performance of the MIMO power line network, a reliable MIMO multipath channel model needs to be exploited. However, until now, there is no generally established PLC channel model for MIMO based BPLC systems.

The objective of this paper is to design a multipath channel model that could be reliable in analyzing MIMO BPLC systems. We modified the widely used single-input single-output (SISO) channel model [3] into MIMO channel model which defines multi-antenna channel characteristics including coupling effects among conductors. The contributions of this paper include: (a) MIMO multipath channel characterization based from multi-conductor transmission line (MTL) theory [9]; (b) analytical model which considers crosstalk caused by coupling effects between conductors; (c) bit error rate (BER) and channel capacity analysis for a suggested MIMO-OFDM BPLC system.

For MIMO BPLC, a pair of conductors forms a single antenna path (even there has no real antenna). Thus the coupling effect among conductors should not be avoidable [9]. However, existing MIMO systems [7], [8], which have been introduced until now, do not consider crosstalk between conductors forming MIMO channels such that their simulation results are too optimistic. In this paper, the widely used multipath channel model proposed in [3], which is intended for SISO systems, is modified into a multipath channel model for MIMO systems with coupling effects.

The remainder of this paper is organized as follows: transmission line analysis and MIMO channel modeling are presented in Section II. Section III shows the coding scheme and MIMO-OFDM implementation. Section IV shows the simulation results. Concluding remarks are drawn in Section V.

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II. Transmission Line Analysis and MIMO Channel Modeling

In this section, we will discuss how the channel model of power cable is derived. MIMO is well-suited for BPLC because of its great advantages. One of its advantages is very high capacity and spectral efficiency achieved by simultaneously employing space, time, and frequency domains. A key component of MIMO BPLC is the improved communications reliability, i.e., reduced bit error rate (BER) and improved data capacity, which can be achieved with reasonable computational complexity. However, for the implementation of MIMO BPLC, coupling effects between conductors should be considered.

A. Modified MIMO Power Line Channel Model

In this paper, the widely used channel model [3] for SISO system is modified into MIMO system which considers the coupling effects among conductors. Zimmermann and Dostert in [3] state that PLC channel can be regarded as multipath scenario with frequency selective fading. They also state the variety of loads connected to the network terminals and the presence of several cable branches which cause impedance mismatches. These impedance mismatches produce multipath propagation of the signal in the BPLC environment. Due to impedance mismatches, many reflections of signal appear during its transfer along the cable. Summing up multi-path propagation, signal attenuation and delay leads to the channel transfer function (CTF) [3]:

$$H(f) = \sum_{p=1}^{N_p} \underbrace{g_p}_{\text{weighting factor}} \underbrace{A(f,d_p)}_{\text{attenuation portion}} \underbrace{e^{-j2\pi f d_p/V_d}}_{\text{delay portion}}, \quad (1)$$

where N_p is the total number of fading paths, g_p is the pth path weighting factor, $d_p/V_d = \tau_p$ is the pth path propagation delay, d_p is the pth path length and V_d is the phase velocity. As depicted in (1), the propagation signal is affected by attenuation, $A(f,d_p)$ increasing with the pth path distance d_p and frequency f. The cable loss derivation further gives the formula of attenuation factor, which is mainly affected by primary cable parameters, in the form of complex propagation constant [3]:

$$\gamma = \sqrt{(R' + j\omega L')(G' + j\omega C')} = \alpha + j\beta, \quad (2)$$

where the real part of the propagation constant γ is the attenuation constant α, while β is the phase constant. Since we are only interested in the attenuation constant, β is negligible. The primary cable parameters L' and C' (inductance and capacitance per unit length, respectively) can be estimated by the geometric dimensions and the material properties while R' and G' (resistance and conductance per unit length, respectively) depend on frequency. Tonello, D'Alessandro, and Lampe in [5] also state that the attenuation of a power line cable can be characterized by

$$A(f,d_p) = e^{-\alpha(f)d_p}, \quad (3)$$

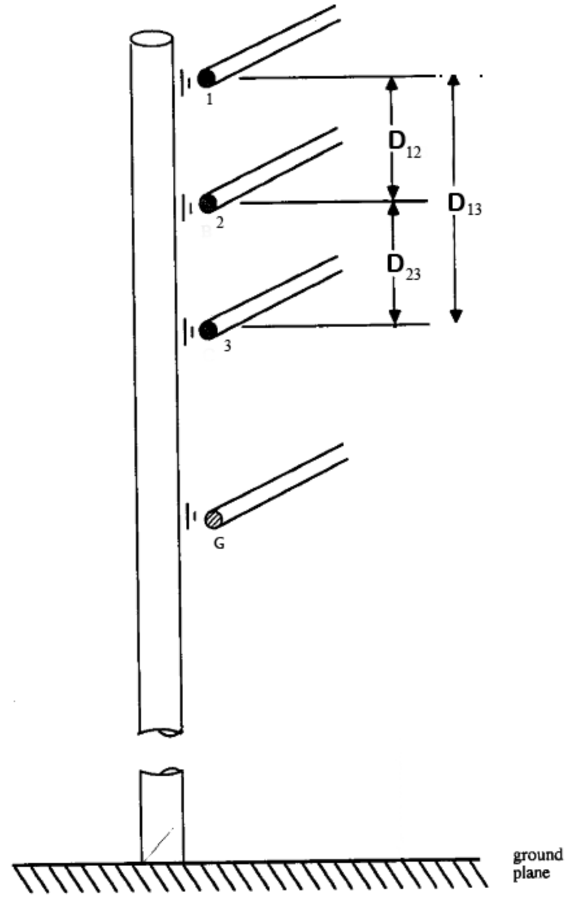

Fig. 1. Typical overhead MV power line

where α can be extracted from (2). Therefore, by substituting (3) to (1), the frequency response can be simply given as

$$H(f) = \sum_{p=1}^{N_p} g_p e^{-\alpha(f)d_p} e^{-j2\pi f d_p/V_d}. \quad (4)$$

We will enhance this SISO channel model into the MIMO channel model. If we are going to transform SISO system into MIMO system for channel capacity improvement, the parallel conductors definitely affects the other conductors due to coupling effects. This coupling effect is commonly present even on different types of multiconductor configuration: low voltage (LV) overhead, LV underground, medium voltage (MV) overhead, and MV underground. Throughout this paper, for simplicity, we mainly focus on MV overhead power lines to construct a MIMO channel, as depicted in Fig. 1.

In MIMO system, the channel transfer function (CTF) for the ith transmit antenna to the jth receive antenna path (where $i = 1, 2, \cdots, I$ and $j = 1, 2, \cdots, J$) can be written as

$$H_{i,j}(f) = \sum_{p=1}^{N_p} g_p e^{-\alpha_{i,j}(f)d_p} e^{-j2\pi f \tau_p}. \quad (5)$$

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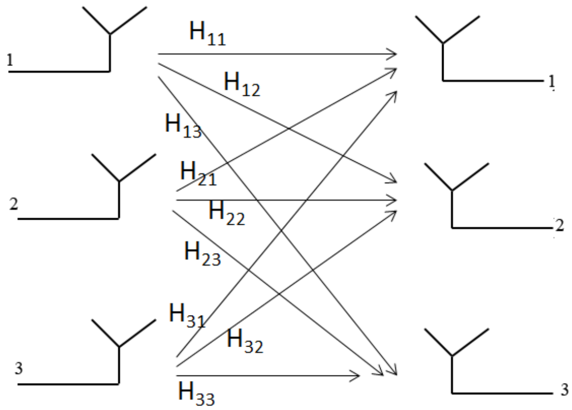

Fig. 2. 3×3 MIMO System

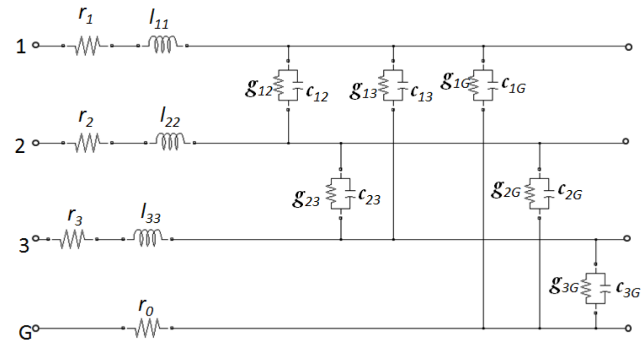

Fig. 3. Equivalent per-unit-length for multiconductor transmission line. (Note that $c_{12} = c_{21} = c_{23} = c_{32} = c_{13} = c_{31}$ and $g_{12} = g_{21} = g_{23} = g_{32} = g_{13} = g_{31}$ are assumed throughout this paper [9].)

Equation (5) can then be extended to the overall transfer function matrix:

$$H_{(MIMO)} = \begin{bmatrix} H_{1,1} & \dots & H_{1,J} \\ \vdots & \ddots & \vdots \\ H_{I,1} & \dots & H_{I,J} \end{bmatrix}, \tag{6}$$

where I is the number of transmitting antennas and J is the number of receiving antennas.

For outdoor network with three-phase conductors configuration, as shown in Fig. 1, 3×3 MIMO system can be obtained by simply pairing Wire 1 to Wire G (ground), Wire 2 to ground and Wire 3 to ground to form antenna 1, 2 and 3 respectively, as shown in Fig. 2.

For this MIMO system consisting of three transmitter and receiver ports, the channel matrix can be written as

$$H_{(MIMO)} = \begin{bmatrix} H_{1,1}(f) & H_{1,2}(f) & H_{1,3}(f) \\ H_{2,1}(f) & H_{2,2}(f) & H_{2,3}(f) \\ H_{3,1}(f) & H_{3,2}(f) & H_{3,3}(f) \end{bmatrix}, \tag{7}$$

where diagonal terms of $H_{(MIMO)}$ indicate co-channels and its anti-diagonal terms indicate cross channels. Since MIMO system is considered, the coupling effect should be considered such that the anti-diagonal terms $H_{i,j}$ (where $i \neq j$) might not be zero.

The attenuation constant $\alpha_{i,j}$ in the attenuation portion of $H_{i,j}$ in (5) can be extracted from

$$\alpha_{i,j} = \text{Real}\left\{ \left(\sqrt{(R'' + j\omega L'') .* (G'' + j\omega C'')} \right)_{i,j} \right\}, \tag{8}$$

where the operator $.*$ indicates the element-wise matrix multiplication. This element-wise operation of (8) allows us to derive $\alpha_{i,j}$ for a specific antenna channel, $H_{i,j}$, while assuming all other channel inputs except i are zero (by MTL theory [9], it implies that we can derive $\alpha_{i,j}$ while assuming all other circuit inputs except i are zero , i.e., $V_m = 0$ & $I_m = 0$ for $\forall m, m \neq i$). R'', L'', C'' and G'' correspond to transmission line matrices [9], which represent the mutual interactions between conductors. The equivalent per-unit-length (p.u.l) parameter model [9] can be used to characterize the overhead transmission line, as shown in Fig. 3.

The resistance matrix is

$$R'' = \begin{bmatrix} r_1 + r_0 & r_0 & r_0 \\ r_0 & r_2 + r_0 & r_0 \\ r_0 & r_0 & r_3 + r_0 \end{bmatrix}, \tag{9}$$

where r_0 is the ground resistance while r_1, r_2 and r_3 are the resistances for line *N* (which indicates line 1, line 2 or line 3 in Fig. 3) per unit length and computed as

$$r_1 = r_2 = r_3 = \frac{1}{2}\sqrt{\frac{\pi f \mu_c}{\sigma_c}},$$

where *f*, μ_c and σ_c are the wave frequency, permeability and conductivity of conducting material, respectively.

The inductance matrix is

$$L'' = \begin{bmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{bmatrix}, \tag{10}$$

where the diagonal terms for L'' are the self-inductances for line *N* per unit length and the anti-diagonal terms for L'' are the mutual inductances. The computation for self-inductance per unit length is given as

$$l_{11} = l_{22} = l_{33} = \frac{\mu_o}{2\pi} \ln \frac{GMD}{GMR_L},$$

where

$$GMD = \sqrt[3]{D_{12} D_{13} D_{23}}.$$

Note that geometric mean distance (*GMD*) is a function of equivalent conductor spacings D_{12}, D_{13} and D_{23} between three phase conductors when assuming that the line has one conductor per phase (which is applicable for overhead power line cables). μ_o is the permeability of dielectric material between conductors and geometric mean radian (GMR_L) is the actual conductor radius *r*.

The anti-diagonal terms in (10) represent the mutual inductances between conductors and can be computed as

$$l_{12} = l_{21} = k\sqrt{l_{11}l_{22}}$$
$$l_{13} = l_{31} = k\sqrt{l_{11}l_{33}}$$
$$l_{23} = l_{32} = k\sqrt{l_{22}l_{33}}$$

where the constant k is called the coefficient of coupling, and lies in the range $0 \leq k \leq 1$.

The capacitance matrix is

$$C'' = \begin{bmatrix} c_{11} & -c_{12} & -c_{13} \\ -c_{21} & c_{22} & -c_{23} \\ -c_{31} & -c_{32} & c_{33} \end{bmatrix}, \tag{11}$$

where c_{11}, c_{22} and c_{33} are the self-capacitances for line N per unit length and given as

$$c_{11} = c_{1G} + c_{12} + c_{13},$$
$$c_{22} = c_{2G} + c_{21} + c_{23},$$
$$c_{33} = c_{3G} + c_{31} + c_{32},$$

where c_{NG} (i.e., c_{1G}, c_{2G} or c_{3G}) are the capacitances between line N and ground (G), which can be computed as

$$c_{NG} = \frac{2\pi\varepsilon_o}{\ln\frac{GMD}{GMR_C}}.$$

ε_o is the permittivity of dielectric material between conductors and GMR_C is the actual conductor radius r. The anti-diagonal terms in C'' (11) represent the mutual capacitances, denoted by c_m $(= -c_{12} = -c_{13} = ... = -c_{23})$, between conductors and can be calculated as

$$c_m = 4\pi\varepsilon_o.$$

The conductance matrix is

$$G'' = \begin{bmatrix} g_{11} & -g_{12} & -g_{13} \\ -g_{21} & g_{22} & -g_{23} \\ -g_{31} & -g_{32} & g_{33} \end{bmatrix}, \tag{12}$$

where g_{11}, g_{22} and g_{33} are the self-conductances for line N per unit length and given as

$$g_{11} = g_{1G} + g_{12} + g_{13},$$
$$g_{22} = g_{2G} + g_{21} + g_{23},$$
$$g_{33} = g_{3G} + g_{31} + g_{32},$$

where g_{NG} (i.e., g_{1G}, g_{2G} or g_{3G}) are the conductances between line N and ground (G), which can be computed as

$$g_{NG} = 2\pi f c_{NG} \tan\delta.$$

δ is the skin depth of the conducting material. The anti-diagonal terms in G'' (12) represent the mutual conductances, denoted by g_m $(= -g_{12} = -g_{13} = ... = -g_{23})$, between conductors and can be calculated as

$$g_m = 2\pi f c_m \tan\delta.$$

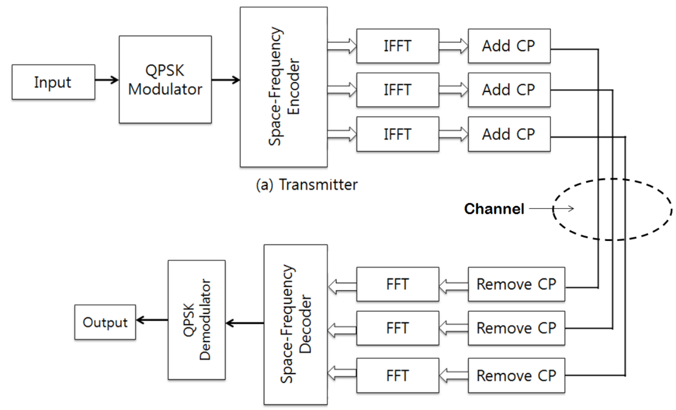

Fig. 4. Block diagram of the proposed 3×3 MIMO-OFDM System

Performing the required mathematical operation in each element of the transmission parameter matrices to solve for the attenuation factor $\alpha_{i,j}$ in (8), (i.e., $\alpha_{1,1} = \sqrt{(r_1 + r_0 + j\omega l_{11})(g_{11} + j\omega c_{11})}$, $\alpha_{1,2} = \sqrt{(r_0 + j\omega l_{12})(g_{12} - j\omega c_{12})}$, $\ldots$, $\alpha_{3,3} = \sqrt{(r_3 + r_0 + j\omega l_{33})(g_{33} + j\omega c_{33})}$), the channel matrix in (7) can be obtained. Hence, this overall transfer function includes crosstalk between conductor. This procedure can be also implemented with the primary line parameters computation for other cases such as indoor with three wires and outdoor with underground power lines as well. For further details of computing those line parameters, please refer to [9] and [10].

III. Coding Scheme and MIMO-OFDM

Fig. 4 shows the block diagram of a MIMO-OFDM system. In the transmitter side, input signal is fed to the QPSK encoder/modulator block. Accordingly, the modulated symbols are mapped in space frequency (SF) encoder [12]. Then, inverse fast Fourier transform (IFFT) and cyclic prefix (CP) insertion for each antenna path are performed sequentially.

The symbols are then transmitted to the receiver via a MIMO BPLC channel, as shown in Fig. 2. Multiple antennas are applied in order to achieve many desirable objectives for wireless communications, such as capacity increase without bandwidth expansion, transmission reliability enhancement, and co-channel interference suppression for multi-user transmission. The receiver performs the reverse operation of the transmitter. The received signal is carried out by cyclic prefix removal, FFT operation, space frequency decoding, QPSK demodulation and channel decoding. Especially, through the demodulation process, maximum ratio combining (MRC) can be executed to combat the damaging effects of channel fading and effectively combine multiple antenna and multipath fading signals [13]. In this paper, the antenna and fading MRC (AFMRC) scheme [13] is implemented in order to achieve improved bit-error-rate (BER), which is a combining technique of multiple antenna MRC (AMRC) and multipath fading MRC (FMRC).

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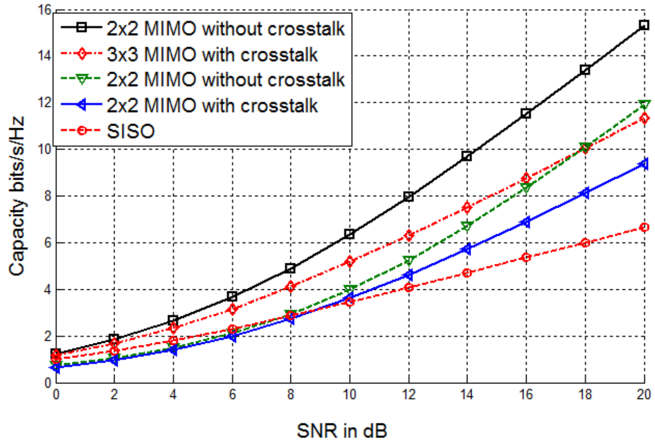

Fig. 5. SISO and 3×3 MIMO channel capacity

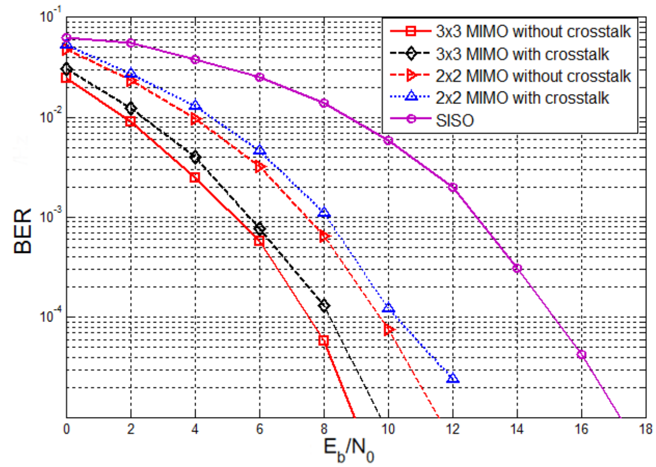

Fig. 6. BER performance comparison of SISO and MIMO with and without crosstalk

TABLE I
SIMULATION PARAMETERS

Parameters	Value
Transfer rate	6.4 Mbit/s
Baseband modulation	QPSK OFDM
Baseband Nyquist bandwidth	2 MHz
Information transfer rate	8 Mbps
Spacing between tones	15.625 KHz
Maximum path delay	0.5 sec
OFDM symbol duration	65μ sec
MIMO channel model	2×2 and 3×3 path quasi-static
Number of OFDM tones (N)	128
Noise model	Middleton's impulsive noise [15]
Cyclic Prefix Length	16
Additive White Class A Noise (AWCN) A parameter [15]	0.1

IV. DATA AND RESULTS

The MIMO channel capacity via power line channels has been simulated using the water filling algorithm [11]. In that algorithm, the optimum power to the parallel subchannels, represented by the diagonal elements of the MIMO channel matrix $H_{(MIMO)}$, is obtained by performing the singular value decomposition on that matrix. In Fig. 5, the channel capacity for a SISO system, a 2×2 MIMO system (which can be obtained for indoor case with three conductors [14]) and a 3×3 MIMO system over MV overhead power lines has been plotted. As can be seen from Fig. 5, the channel capacity of 3×3 MIMO system is 2.15 times greater than SISO. Fig. 5 also depicts the comparison of MIMO without crosstalk and with crosstalk. It is observable that crosstalk damages the data capacity of 3×3 MIMO system up to 20%.

For the BER performance evaluation, the MIMO-OFDM system presented in Section III is simulated with the parameters listed on Table I. For practical simulation, power line impulse noise [15] is also added to the simulated channel. The performance of MIMO-OFDM is also compared with SISO-OFDM over the power line channel. The BER performance of the proposed model is evaluated both in SISO and MIMO systems and plots are provided in Fig. 6. It can be depicted that the proposed MIMO systems show performance improvement over the conventional SISO system. At the BER of 10^{-4}, for example, MIMO-OFDM has a performance gain of about 8dB (in energy per bit to noise power spectral density ratio (E_b/N_0)) over SISO-OFDM. Fig. 6 also shows the BER results of MIMO with crosstalk consideration, where a performance degradation of 0.7dB can be noticed for both 2×2 and 3×3 MIMO at the BER of 10^{-4}.

V. CONCLUSION

This paper has developed a modified multipath model for MIMO BPLC systems, where the overall channel transfer function taking into account the crosstalk between conductors forming antenna channels has been derived. This paper has also analyzed channel capacity and BER performance of a MIMO-OFDM BPLC system over MV overhead power line channels.

ACKNOWLEDGMENT

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