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Linear Precoding Design for MIMO-PLC Systems

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Abstract: In this paper, we consider the design of linear precoding in Multiple Input Multiple Output (MIMO) Power Line Communication (PLC) systems with finite-alphabet input. First, we derive mutual information of MIMO-PLC systems with impulsive noise. Considering the non-concavity of the objective function and the low-cost requirement of PLC systems, we choose the lower bound of the mutual information as the objective function. Subsequently, we propose a novel approach to design the precoding scheme to reduce computational complexity. Specifically, our work primarily includes the following two contributions: (1) We design the right unitary matrix that is a product of two fixed unitary matrices, which only depends on the modulation mode. Hence, the results can be saved and require less computations. (2) For the power allocation matrix, we first reduce the space of power allocation using constraints of the optimal power allocation policy. Consequently, we propose a non-linear search method to obtain the optimal power allocation in small space. In regards to the computational complexity of the analysis, we conclude that the proposed precoding matrix design scheme has low complexity and is easy to implement. Moreover, the numerical results are proven to demonstrate the performance of the proposed precoding design scheme.

Key words: precoding design; MIMO-PLC; impulsive noise; finite-alphabet input

1 Introduction

Power Line Communication (PLC), which transmits information over an existing power line, has gained significant attention because of its benefits such as low-cost implementation and low-power consumption. A typical application for PLC is in the area of smart grid applications, which include automatic meter-reading, grid status real-time monitoring, smart home energy management, and vehicle-to-grid communications[1–4]. Hence, various manufacturers, operators, and standardization groups have collaborated and standardized the PLC technology. Some standards, such as Home Plug AV2 and ITU G.9963, have been adopted to implement PLC communication systems[2, 5–8].

Currently, PLC systems mainly focus on Single Input Single Output (SISO) systems, which implies that they only use signals that are coupled differentially between phase and neutral wires for communicating data[9–11]. In fact, a 3-wire power line is adopted as the standard worldwide[5, 12–15]. In China, a 3-phase 4-wire distribution power network is used and a multi-conductor power cable, which is made up of multiple conductors, is becoming popular in the low voltage and medium voltage distribution power network. For instance, a 4-conductor power cable YJV 4∗35 mm^2 is popular in China[16, 17]. In this case, Multiple Input Multiple Output (MIMO) technology, which uses more than two conductors or wires to carry information, provides significantly higher data rates and better coverage[5, 15, 18, 19]. However, the measurement results show that there exists a high degree of correlation among the channels in the MIMO-PLC systems, which causes interference between each channel and limits the channel capacity because the distance between the

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conductors or wires is less[16–19]. Hence, the key goal is to achieve higher capacity in the MIMO-PLC systems by considering the interference between each channel.

To increase channel capacity, one important approach is to adopt the precoding scheme at the transmitter to implement channel decoupling, which improves the performance of MIMO-PLC communication systems. It indicates that the pre-coded spatial multiplexing scheme, which allows channel diagonalization by Singular Value Decomposition (SVD) and power allocation by water-filling policy, is a good choice for MIMO-PLC systems[5, 15]. In this design, the precoding scheme is used to maximize the channel capacity assuming the channel input is a Gaussian input. However, recent research results show that this scheme has poor performance because of unrealistic Gaussian input assumptions[20–25]. In practical systems, the channel inputs are drawn from modulated discrete-constellation inputs. Consequently, some studies focus on the precoding design scheme to maximize mutual information, and other schemes in the area of wireless communication are proposed to achieve higher transmission rates[20–28]. Given that the mutual information is a nonlinear and a non-concave function of the precoding matrix, iterative algorithms are usually adopted to obtain the suboptimal solution and to reduce complexity. For example, the authors in Ref. [21] proposed a two-step precoding design scheme that maximizes the mutual information. In addition, some studies adopt the lower bound of the mutual information as the objective function to reduce complexity[22–24]. A common problem encountered in these methods is that their computational complexity is too high for implementation in PLC systems. Hence, designing a low-complexity precoding scheme that maximizes the mutual information and meets the requirements of PLC systems is a challenging problem.

In addition, the noise in PLC systems is not Addition White Gaussian Noise (AWGN). It is shown that there are five types of additive noise in PLC communication systems[2, 29–31]: (1) colored background noise; (2) narrowband noise; (3) periodic impulsive noise synchronous to the mains frequency; (4) periodic impulsive noise asynchronous to the mains frequency; and (5) asynchronous impulsive noise. Among the five types of additive noise, the first three types usually remain stationary for a long period of time and can be regarded as background noise. However, the last two types of noise are time-varying and are generally modeled as impulsive noise, which is one of the main challenges in the design of PLC systems. Different statistical models for impulsive noise have been developed. Among the various statistical models, the most widely adopted model among researchers to describe the statistical characteristics of noise is the Middleton Class-A noise model[29, 31]. The main drawback of Middleton Class-A noise model is that it assumes independent impulsive emissions in the time domain. Another approach to model impulsive noise is to adopt Markov chains[30, 32–34]. References [30, 32] restrict the number of states to two; Ref. [34] expands on the work in Ref. [32] and proposes a multiple-state Hidden Markov Model (HMM) noise model. In this paper, we adopt the HMM noise model in Ref. [34] as our noise model because it considers noise memory in the time domain and has a generic PDF.

Based on the discussion above, we conclude that there are two factors that limit performance of MIMO-PLC systems—the high-correlation between channels and the additional impulsive noise. Hence, in this paper, we focus on the precoding design scheme to maximize the transmission rate while considering the effect of these two factors. First, we calculate the mutual information in PLC systems considering the channel input is modulated finite-alphabet input, and choose maximizing the mutual information as the objective function. Next, the problem of precoding matrix design is reformulated as two sub-problems—designing the power allocation matrix and the right unitary matrix based on the conclusion given by prior literature[20–25]. To reduce the computational complexity, we propose a sub-optimal precoding design scheme to design these matrices. For the right unitary matrix, we adopt a fixed matrix to reduce the complexity, which depends on the modulation mode. For the power allocation matrix, we adopt the constraints to reduce the search space and then adopt a simple search method in a discrete and bounded space to obtain it. Using the proposed scheme, a better transmission rate can be achieved, compared with the conventional precoding scheme in PLC systems because both the multiplex gain and the diversity gain can be obtained.

The superscripts $(\cdot)^{\rm H}$ denotes the conjugate transpose. In addition, $\|\cdot\|$ implies the Euclidean norm of the matrix or vector. $\text{diag}(\cdot)$ and $\text{Tr}(\cdot)$ represent the elements and trace of the matrix, respectively. $E[\cdot]$ denotes the expectation, which can be scalar, vector, or matrix.

The rest of the paper is organized as follows. In Section 2 the system model is briefly reviewed and the problem of precoding design is formulated as an optimizing problem with constraints. Based on this analysis, the precoding design scheme is presented in Section 3. Subsequently, the numerical results are given in Section 4. Finally, the paper is concluded in Section 5.

2 System Model and Problem Formulation

2.1 System model

When MIMO-PLC systems are considered, the system model can be given by

$$\boldsymbol{y} = \boldsymbol{HFx} + \boldsymbol{Z} \tag{1}$$

where $\boldsymbol{y}$ is the received signal, $\boldsymbol{F}$ is the precoding matrix, $\boldsymbol{x}$ is the transmitted symbols, and $\boldsymbol{Z}$ is the additional impulsive noise and background noise. In addition, $\boldsymbol{H}$ is the channel matrix of size $Q \times N$, which is given by

$$\boldsymbol{H} = \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1N} \\ H_{21} & H_{22} & \cdots & H_{2N} \\ \vdots & \ddots & \ddots & \vdots \\ H_{Q1} & \cdots & H_{Q2} & H_{QN} \end{bmatrix} \tag{2}$$

where H_{qn} is the channel coefficient between the transmitter port n and receiver port q, the value of H_{qn} depends on factors such as material and size, which can be derived by measurement and statistical modeling[5, 12, 16, 17]. For instance, the main channel parameters of the multi-conductor power line YJV 4∗35 mm^2 are given in Refs. [16, 17].

According to Ref. [34], the additional noise $\boldsymbol{Z}$ in PLC systems is no longer stationary noise, which generally consists of impulses and can be modeled as an HMM model with finite number of states. In this case, the correlation between the noise samples can be ensured by the transition probability. In general, the HMM model can be described by its stationary state distribution, which can be obtained from the corresponding transition matrix. Assuming the number of states of the noise is restricted to 4, the stationary state distribution is $[p'_0\ p'_1\ p'_2\ p'_3]$, here $p'_m = p_m / \sum_{n=0}^{3} p_n$, $p_m = \mathrm{e}^{-A} A^m / m!$, and A is the impulsive index.

2.2 Problem formulation

According to Ref. [34], the PDF of noise $\boldsymbol{Z}$ follows the Middleton Class-A distribution. Assuming the probability of the channel in state m (m = 0, 1, 2, 3) is p'_m, the average mutual information can be expressed as

$$I = \sum_{m=0}^{3} p'_m I_m \tag{3}$$

where I_m is the mutual information in state m. For state m, considering it is as the AWGN noise, the mutual information is given by Ref. [20].

$$I_m(\boldsymbol{x};\boldsymbol{y}\,|\boldsymbol{H}) = N \log M - \frac{1}{M^N} \sum_{j=1}^{M^N} E\left[\log_2 \sum_{l=1}^{M^N} \exp(-d_{jl})\right] \tag{4}$$

where

$$d_{jl} = \left(\left\|\boldsymbol{HFe}_{jl} + z_m\right\|^2 - \|z_m\|^2\right)/\sigma_m^2,$$
$$\boldsymbol{e}_{jl} = \boldsymbol{x}_j - \boldsymbol{x}_l.$$

The variance σ_m^2 in state m is given by

$$\sigma_m^2 = (\sigma_{\mathrm{g}}^2 + \sigma_{\mathrm{i}}^2)\frac{m/A + \Gamma}{1+\Gamma} \tag{5}$$

where $\Gamma = \sigma_{\mathrm{g}}^2/\sigma_{\mathrm{i}}^2$ is the Gaussian-to-impulsive variance ratio. In addition, x_j and x_l contain N symbols and each one is taken independently from the M-ary signal constellation. Then, the problem of precoding design with finite-alphabet constraint can be expressed as

$$\begin{aligned} &\max_{\boldsymbol{F}}\ I(\boldsymbol{x};\boldsymbol{y}) \\ &\text{subject to} \sum_{i=1}^{N} \mathrm{Tr}(\boldsymbol{FF}^{\mathrm{H}}) \leqslant P_{\mathrm{t}} \end{aligned} \tag{6}$$

where P_{t} is the total transmitted power constraint. It can be observed from Formula (6) that mathematical expectation needs to be calculated to obtain the objective function, which is usually estimated through Monte Carlo simulation.

To avoid calculating the mathematical expectation, the objective function in Formula (6) should be replaced by its lower bound given by Refs. [21–24].

$$I_m(\boldsymbol{x};\boldsymbol{y}) \geqslant I_{L,m}(\boldsymbol{x};\boldsymbol{y}) = N \log M - (1/\ln 2 - 1)Q - \frac{1}{M^N}\sum_{j=1}^{M^N} \log \sum_{k=1}^{M^N} \exp\left(-\frac{\boldsymbol{e}_{jk}^{\mathrm{H}}\boldsymbol{F}_k^{\mathrm{H}}\boldsymbol{H}_k^{\mathrm{H}}\boldsymbol{H}_k\boldsymbol{F}_k\boldsymbol{e}_{jk}}{\sigma_m^2}\right) \tag{7}$$

which can be derived by the Jensen inequality. Furthermore, there is only a constant between the mutual information and its lower bound[21, 22]. Hence, we can get the mutual information from its lower bound as

$$I_m(\boldsymbol{x};\boldsymbol{y}) \approx I_{L,m}(\boldsymbol{x};\boldsymbol{y}) + (1/\ln 2 - 1)Q \tag{8}$$

We can choose maximizing the lower bound of the mutual information as the objective function replacing the objective function in Formula (6). In this case, let

$$I_L = \sum_{m=0}^{M} p'_m I_{L,m} \tag{9}$$

denote the approximation of the low bound of the average mutual information, Formula (6) can be replaced by

$$\begin{aligned} &\max_{\boldsymbol{F}} I_L(\boldsymbol{x};\boldsymbol{y}) \\ &\text{subject to } \sum_{i=1}^{N} \text{Tr}(\boldsymbol{F}\boldsymbol{F}^{\text{H}}) \leqslant P_{\text{t}}) \end{aligned} \tag{10}$$

It has been shown that the Central Process Unit (CPU) time of calculating $I_{L,m}(\boldsymbol{x};\boldsymbol{y})$ with QPSK is about 5.9×10^{-5} times those of calculating $I_m(\boldsymbol{x};\boldsymbol{y})$ when both the transmitter ports and the receiver ports are 2 in wireless communication systems[25].

One common approach to solve this problem is adopting iterative method to get the local optimal solution[20–22]. However, the computational complexity of the iterative method, which is proposed for wireless communication, is considerably high and does not suit PLC systems. For PLC systems, we adopt low-complexity approach to obtain the precoding.

3 Precoding Design Scheme

We assume that the channel matrix can be decomposed as

$$\boldsymbol{H} = \boldsymbol{U_H}\boldsymbol{\Sigma_H}\boldsymbol{V}_{\boldsymbol{H}}^{\text{H}} \tag{11}$$

and the precoding matrix can be decomposed as

$$\boldsymbol{F} = \boldsymbol{U_F}\boldsymbol{\Sigma_F}\boldsymbol{V}_{\boldsymbol{F}}^{\text{H}} \tag{12}$$

by SVD, where $\boldsymbol{U_H}$,$\boldsymbol{V_H}$,$\boldsymbol{U_F}$, and $\boldsymbol{V_F}$ are unitary matrices, and $\boldsymbol{\Sigma_H}$ and $\boldsymbol{\Sigma_F}$ are nonnegative diagonal matrices containing the singular values. We let the left singular vectors of the precoding matrix be consistent with the right singular vectors of the channel matrix, such that $\boldsymbol{U_F} = \boldsymbol{V_H}$[20, 21], the channel model can be simplified to the following equivalent model:

$$\bar{\boldsymbol{y}} = \boldsymbol{\Sigma_H}\boldsymbol{\Sigma_F}\boldsymbol{V}_{\boldsymbol{F}}^{\text{H}}\boldsymbol{x} \tag{13}$$

where $\bar{\boldsymbol{y}}$ is the filtered received signal, such that $\bar{\boldsymbol{y}} = \boldsymbol{U_H}\boldsymbol{y}$. It can be easily induced that the mutual information $I(\boldsymbol{x};\boldsymbol{y})$ in Formula (10) is equivalent to $I(\boldsymbol{x};\bar{\boldsymbol{y}})$ and depends only on the power allocation matrix and the right singular vectors. Hence, the problem of precoding matrix design can be decomposed into two sub-problems—the right singular vectors or right unitary matrix of the precoding matrix design and the diagonal matrix or power allocation matrix of the precoding matrix design. Although some schemes have been proposed to obtain these two matrices in wireless communication, the main drawback in these schemes is the high-complexity to implement in PLC systems. In the following sections, we propose low-complexity design schemes for designing the two matrices.

First, we design the right unitary matrix $\boldsymbol{V_F}$. To reduce the complexity, we adopt a non-iterative method to design the right singular vectors. The proposed design scheme is the product of two unitary matrices, which is given by

$$\boldsymbol{V_F} = \boldsymbol{V}_{\text{FFT}}\boldsymbol{V}_{\text{diag}} \tag{14}$$

where $\boldsymbol{V}_{\text{FFT}}$ is a Fast Fourier Transform (FFT) matrix of size $N\times N$, and $\boldsymbol{V}_{\text{diag}}$ is a diagonal unitary matrix, which is used to rotate the phase, and is given as follows:

$$\boldsymbol{V}_{\text{diag}} = \text{diag}(1, \beta, \cdots, \beta^N) \tag{15}$$

where $\beta = \text{e}^{-\text{j}\theta_{\text{mod}}}$ and θ_{mod} is a parameter that depends only on the modulation mode, the value of which is listed in Table 1.

Next, we design the power allocation matrix. A common approach to designing a power allocation matrix is water-filling power allocation[5, 15, 35–37]. However, there are several drawbacks associated with water-filling power allocation, which are stated as follows:

(1) The noise in PLC systems consists of impulsive noise and is no longer AWGN noise[2, 29–31].

(2) It needs to be iterative for implementation in the real-time systems, and has high computational complexity. Hence, it is not applicable in PLC systems[22–24].

(3) The channel input signals are taken from a finite set of symbols, assuming that Phase-Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) is adopted[20–25, 35, 36].

From the above discussion, we understand that drawbacks (1) and (3) make the conventional water-filling power allocation no longer optimal in PLC systems, and drawback (2) makes it difficult

Table 1 Value of $\boldsymbol{\theta}_{\text{mod}}$ for different modulation modes.

Modulation	θ_{mod}
BPSK	1.0
QPSK	0.6
8PSK	0.6
16QAM	0.8
64QAM	0.8

to implement in real-time PLC systems. To get good performance and avoid iterative computing, an exhaustive searching method is proposed[24]. Unfortunately, the complexity is about $(K+1)^N$, where K is the step size and is too high to implement in the PLC systems. In Refs. [15, 37], the authors proposed a simple mercury water-filling power allocation policy, where only three power levels are used. However, it will incur performance loss, as described in Section 4. In this paper, we mainly use three constraints to reduce the allocated power space:

(1) The power allocation result satisfies $\sum_{i=1}^{N} P_i = P$. In other words, we should use all the power to transmission information because higher allocated power can achieve higher mutual information.

(2) If the singular value for two sub channels has the relationship $\boldsymbol{\Sigma}_{\boldsymbol{H},i} \geqslant \boldsymbol{\Sigma}_{\boldsymbol{H},i+1}$, the corresponding allocated power inequality $P_i \geqslant P_{i+1}$ should be satisfied. It can be easily induced from the principle of water filling.

(3) When $\boldsymbol{V_F}$ is given, Formula (7) is a concave function of squared singular value of the precoding matrix $\boldsymbol{\Sigma}_{\boldsymbol{F}}^2$—the proof is given in Ref. [22].

Based on these constraints and assuming the allocated power for the i-th port is P_i, we obtain the power allocation policy given in Fig. 1. In Fig. 1, the numbers of ports for transmitter and receiver are both assumed to be 3 considering the practical physical constraints in PLC systems, and "P_i_up" and "P_i_low" denote the upper bound and the lower bound of the allowed power for port i, respectively. In addition, "MI_F" denotes the achievable mutual information when precoding $\boldsymbol{F}$ is adopted, while "MI_P_i_Pre" denotes the previous mutual information when P_i is adopted.

The proposed power allocation policy is divided mainly into three parts shown as follows:

(1) Initialization: Allocate the power uniformly among the ports, and calculate the corresponding precoding $\boldsymbol{F}$ and mutual information "MI_F".

(2) Update P_1 including the up bound and the low bound of P_1, where P_1 is the power allocated in Port 1. The updating depends on the changing of value of mutual information. If the value of mutual information is increasing, then update the low bound; otherwise, update the up bound.

(3) Update P_2 including the up bound and the low bound of P_2 for each P_1, where P_2 is the power allocated in Port 2. The role of updating is similar to the case of P_1.

We observe that $P_3 = P - P_1 - P_2$. In addition, the thresholds $T_{\rm h1}$ and $T_{\rm h2}$ are used to control the accurate and iterative number, which is called "step size" in this

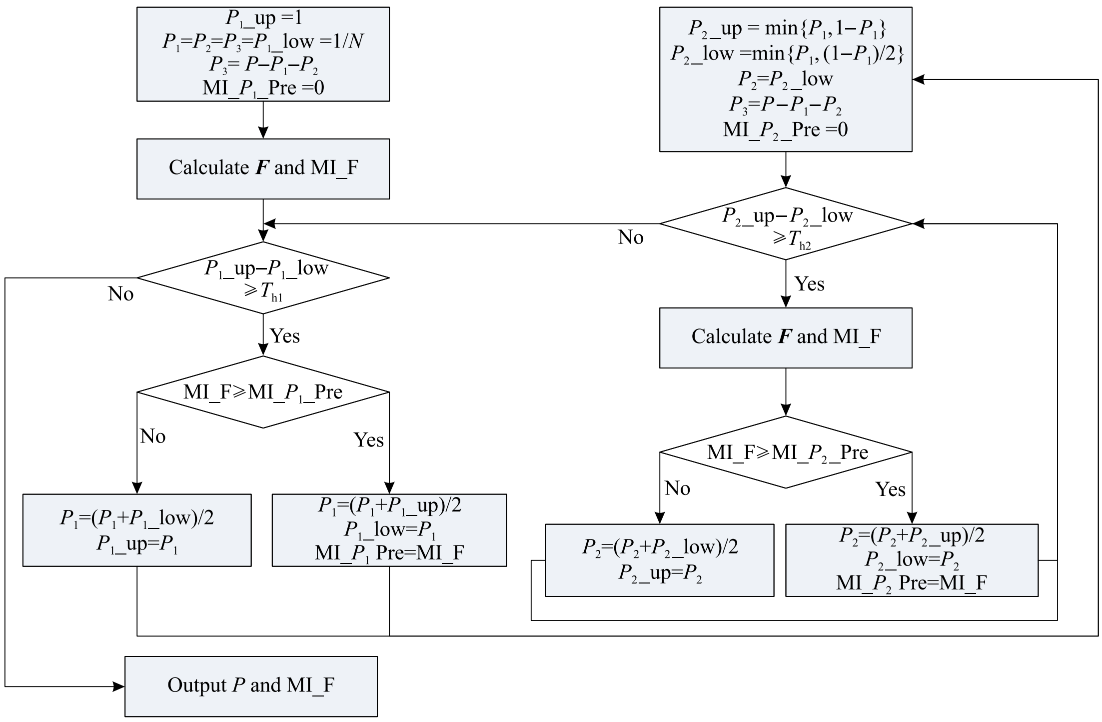

Fig. 1 Flow chart for power allocation policy when the port configuration is 3×3 (3 transmitter ports, 3 receiver ports).

paper. If the number of ports is 2, then $P_2 = P - P_1$ and the part for updating P_2 in Fig. 1 can be removed. Hence, the power allocation policy can be applied to the case when the number of ports is 2. In addition, the power allocation policy in Fig. 1 can also be generalized to the case of more number of ports in a similar manner.

The iterative numbers of the power allocation policy for different port configurations and step sizes are listed in Table 2. From Table 2, we observe that the proposed policy needs much less iterative number compared with the search method described in Ref. [24], especially when port configuration is high and the step size is small. For example, when port configuration is 3×3 and step size is 0.1, the worst-case iterative number of the proposed power allocation policy is about 1.1% of the conventional scheme. In addition, when port configuration is 2×2, it requires a similar iterative number with the simple mercury water-filling power allocation policy in Refs. [15, 37].

4 Performance Evaluation

In the simulation, the SNR is defined as

$$\text{SNR} = \frac{\text{Tr}(\boldsymbol{H}\boldsymbol{H}^{\text{H}})}{N(\sigma_{\text{g}}^2 + \sigma_{\text{i}}^2)} \tag{16}$$

Considering the physical constraints in the PLC systems, the numbers of the ports for transmitter and receiver are both assumed to be 2 or 3. In addition, the transmission characteristics of the channel in power distribution network are obtained from the measurement results of the distribution networks in China[16, 38].

First, we demonstrate the mutual information versus SNR for different values of (A, Γ) in Fig. 2. We observe that when A is small, the mutual information is high for a given value of Γ. However, when A is large, the mutual information becomes less, which is consistent with Refs. [31, 33], since the noise becomes similar to the Gaussian channel when A is large[31] and Gaussian noise is the worst-case noise with respect to channel capacity[39–41]. Hence, we should design the precoding matrix based on the non-Gaussian noise to achieve higher transmission rate. In addition, for a given value$A$, if Γ is large, then the mutual information becomes small. In the following section, we choose (A, Γ) = (0.1, 0.8).

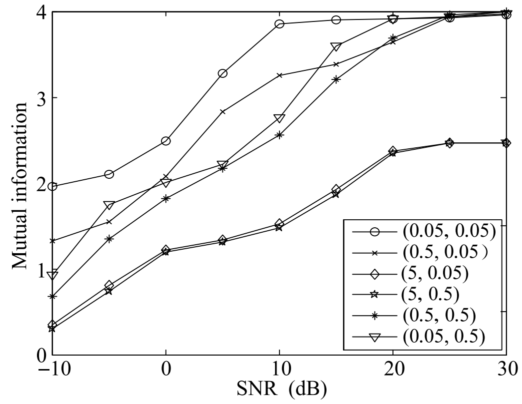

Fig. 2 Mutual information versus SNR for different noise parameters.

Table 2 Complexity analysis.

Port configuration	Step size	Iterative number (Proposed scheme, worst case)	Iterative number (scheme in Ref. [24])
2×2	0.10	4	121
	0.20	3	36
	0.25	3	25
3×3	0.10	15	1331
	0.20	6	216
	0.25	5	125

To verify the performance advantages of the proposed precoding matrix, we give the numerical results of the mutual information for different design schemes of precoding matrix in Figs. 3 and 4. In Figs. 3 and 4, “Proposed” denotes the proposed scheme in this paper, “Beamforming” denotes the one-stream beam forming scheme in Refs. [5, 37], “Water filling” denotes the scheme of diagonalization precoding with water filling, and “Simplified M/WF” denotes the precoding scheme in Refs. [5,15,37]. In addition, the modulation mode is QPSK in both figures. From the figures, we observe the following:

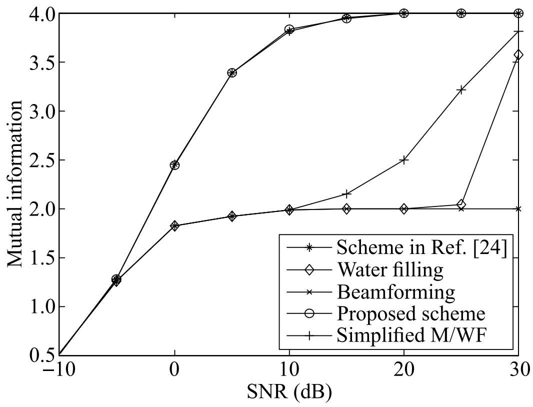

Fig. 3 Mutual information for different precoding schemes (Port configuration: 2×2).

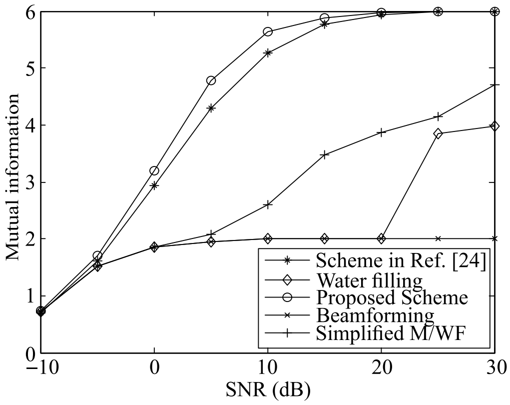

Fig. 4 Mutual information for different precoding schemes (Port configuration: 3×3).

(1) The proposed scheme can achieve higher transmission rate compared with the other scheme, especially when SNR is moderate (between 0 dB and 20 dB for QPSK) and the number of the ports is 2 or 3.

(2) The conventional "Water filling" scheme is not suitable for PLC systems.

(3) The "Beamforming" scheme can only work well when SNR is low, as shown in Ref. [22].

(4) The "Simplified M/WF" shows substantial gain over "Water filling". However, it is inferior to the proposed scheme and there is a large performance gap between them.

To show the proposed scheme can be applicable to PLC systems, we show the results of CPU time for various schemes with different system configurations in Table 3. In this simulation, the codes for both methods are written in MATLAB and the simulations are executed on an Intel E4500 2.20 GHz duo core processor. From Table 3, it can be observed that the proposed scheme requires less time compared with the scheme in Ref. [24] for arbitrary SNR. In addition, please note that the CPU time of the proposed scheme can further be reduced by saving all the possible results of the product of the right singular vectors $\boldsymbol{V_F}$ and the power allocation matrix $\boldsymbol{\Sigma_F}$ at the cost of some additional memory, assuming that the search space is small and the cost is reasonable. Hence, the proposed scheme has an acceptable complexity and can be implemented in real-time when QPSK and 8PSK are adopted.

Given the time-varying characteristic of PLC system, adaptive modulation is suitable for increasing spectral efficiency[15, 19, 42] since it chooses the modulation mode based on channel state. The numerical results of the mutual information of the proposed precoding matrix

Table 3 CPU time for different system information (port configuration, modulation mode, step size).

System information	SNR (dB)	Proposed scheme (s)	Scheme in Ref. [24] (s)
2×2 QPSK 0.1	−10	0.188 090	3.934 062
	0	0.190 682	3.872 820
	10	0.211 284	3.859 413
	20	0.187 744	3.909 597
	30	0.194 164	3.980 981
2×2 QPSK 0.2	−10	0.124 178	1.232 302
	0	0.134 256	1.191 871
	10	0.137 867	1.192 343
	20	0.128 582	1.222 716
	30	0.125 652	1.219 248
2×2 8PSK 0.2	−10	1.573 021	17.827 608
	0	1.445 183	17.971 651
	10	1.426 591	18.055 579
	20	1.427 779	18.074 933
	30	1.478 758	17.987 938
3×3 QPSK 0.2	−10	0.505 664	106.333 364
	0	0.494 698	105.697 457
	10	0.487 097	105.587 768
	20	0.502 352	105.743 209
	30	0.488 825	105.840 215

with different modulation modes at different SNRs are depicted in Fig. 5. From Fig. 5, it can be observed that when SNR is higher, higher modulation mode can obtain higher transmission rate. For example, when SNR=20 dB, the achievable transmission rate for 64QAM is about 9.5 bps/Hz, but for QPSK, this value becomes 4, and for BPSK it is only 2. Hence, in this case, transmission rate gap between different modulation modes is very large and higher modulation mode should be chosen. However, when SNR is lower, the transmission rate gap between different

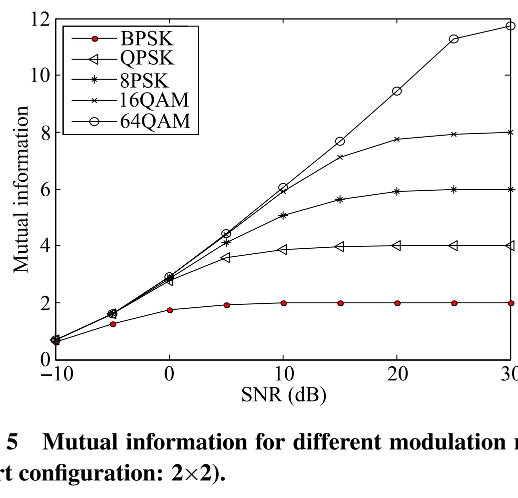

Fig. 5 Mutual information for different modulation modes (Port configuration: 2×2).

modulation modes become smaller. When SNR is very low (-10 dB, for example), the transmission rate gap approaches to almost zero. In other words, the achievable transmission rates for different modulation modes are almost the same at low SNR. However, higher modulation mode has greater complexity and the receiver is more sensitive to imperfect. Hence, lower modulation mode should be chosen in this case.

5 Conclusions

The performance of MIMO-PLC systems is mainly limited by high-correlation channel and impulsive noise. In this paper, we propose an approach to design the linear precoding matrix to reduce the channel interference and impulsive noise, and improve the mutual information of the system. First, we derive the achievable rate region of MIMO-PLC systems for arbitrary number of ports. Next, we adopt its approximation to reduce the computational complexity. Based on this, we proposed a novel design scheme of linear precoding matrix in the MIMO-PLC systems, with the objective of maximizing mutual information considering the finite-alphabet input. We let the left singular matrix of the precoding matrix be the same as the right unitary matrix of the channel matrix, and then the problem of precoding matrix design is reformulated into two sub-problems—designing the power allocation matrix and right unitary matrix. First, we design the right unitary matrix. We adopt a fixing unitary matrix to avoid the iterative computation, which has high complexity. Next, we adopt a non-linear search method in a reduced space to obtain the power allocation matrix. The result of complexity analysis shows that the proposed precoding design scheme, with the objective of maximizing mutual information, has significantly lower computational complexity compared with the previous schemes. In addition, the numerical results also show that the proposed policy has good performance compared with the traditional precoding schemes in PLC systems.

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