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Abstract

To meet the demands of power line communication (PLC) for greater capacity and wider coverage, multiple-input multiple-output (MIMO) technology has been gradually applied to PLC, enabling high-rate data transmission. However, MIMO-PLC channels exhibit severe multipath effects and frequency-selective fading characteristics, and there is significant variation in channel quality across different subcarriers, causing existing signal detection algorithms to fail to achieve satisfactory performance. This paper proposes a detection algorithm based on condition number threshold selection. The algorithm utilizes the condition number of the channel matrix to measure channel quality, sets an optimal condition number threshold, selects the CLLL-MMSE-SQRD detection algorithm when the channel condition number is less than or equal to the threshold, and chooses the QRD-M detection algorithm when the channel condition number is greater than the threshold. Simulation results verify that the proposed algorithm can achieve the performance of optimal detection algorithms, and under 16QAM modulation, the computational complexity of this algorithm is reduced by 44% compared to the QRD-M detection algorithm, with the complexity reduction becoming more significant as the modulation order increases.

Full Text

Preamble

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Signal Detection Algorithm Based on Condition Number Threshold Selection in MIMO-PLC Systems

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Abstract: To meet the demand for larger capacity and wider coverage in power line communication (PLC), multiple-input multiple-output (MIMO) technology has been gradually applied to PLC, enabling high-speed data transmission. However, the MIMO-PLC channel exhibits severe multipath effects and frequency-selective fading, with significant quality variations across different subcarriers, which prevents existing signal detection algorithms from achieving satisfactory performance. This paper proposes a detection algorithm based on condition number threshold selection that utilizes the channel matrix condition number to measure channel quality and sets an optimal condition number threshold. When the channel condition number is less than or equal to the threshold, the CLLL-MMSE-SQRD detection algorithm is selected; otherwise, the QRD-M detection algorithm is chosen. Simulation results demonstrate that the proposed algorithm achieves performance comparable to optimal detection algorithms. Under 16QAM modulation, the algorithm' s complexity is reduced by 44% compared to the QRD-M detection algorithm, with even more significant complexity reductions as modulation order increases.

Keywords: power line communication; multiple-input multiple-output; lattice reduction; condition number; QRD-M

0 Introduction

Power line communication (PLC) systems utilize existing power line infrastructure for data communication, offering convenient deployment, low cost, wide coverage, and eliminating the need for rewiring, making them a highly promising communication technology. With the introduction of multiple-input multiple-output (MIMO) technology into PLC systems, larger data volumes can be transmitted, positioning PLC as an essential component of future Internet of Things applications. Currently, ITU-T G.hn, IEEE 1901, and HomePlug AV2 standards have adopted MIMO technology. However, MIMO-PLC channels suffer from severe multipath effects and frequency-selective attenuation, requiring high-performance detection algorithms to ensure reliable communication. Moreover, MIMO-PLC systems typically employ few antennas and rely on high-order modulation to meet high data rate requirements, which increases computational complexity as modulation order grows. Therefore, selecting signal detection algorithms that offer a favorable trade-off between performance and complexity is a highly valuable research direction.

In recent years, scholars have conducted in-depth research on signal detection algorithms for MIMO systems. Lattice reduction, an important tool in cryptography typically used for searching the shortest vector in a lattice, has been widely applied to MIMO detection. Literature [4] proposed using lattice reduction criteria to preprocess the channel matrix, improving its quality and substantially enhancing the performance of conventional linear detection algorithms. However, this algorithm only works for real-valued LLL (Lenstra-Lenstra-Lovasz) lattice reduction with high complexity. Consequently, literature [5] introduced the complex-domain CLLL (Complex LLL) lattice reduction detection algorithm, which maintains performance equivalent to the real-valued LLL algorithm while reducing complexity by half. Since power line channels are complex-valued, the CLLL lattice reduction detection algorithm is more suitable. By applying CLLL lattice reduction criteria for channel preprocessing followed by MMSE-SQRD (Minimum Mean Square Error Sorted QR Decomposition), the CLLL-MMSE-SQRD detection algorithm achieves superior performance compared to general lattice-reduction-based detection algorithms. To obtain a trade-off between performance and computational complexity, this paper introduces the condition number to measure channel quality. For subcarriers with good channel conditions, suboptimal detection algorithms can achieve optimal performance. Therefore, an appropriate signal detection algorithm can be selected for each subcarrier based on the magnitude of the channel matrix condition number. Building upon previous research, this paper proposes a detection algorithm scheme based on condition number threshold selection for MIMO-PLC systems. Due to severe multipath effects and frequency-selective fading in MIMO-PLC channels, different subcarriers exhibit significant quality variations. By setting a condition number threshold, the CLLL-MMSE-SQRD algorithm is employed for detection when channel conditions are good, offering low complexity and optimal performance. When channel conditions are poor, the QRD-M (QR decomposition with M-algorithm, a breadth-first algorithm based on real-virtual decomposition) detection algorithm is used, which has lower complexity than ML detection and achieves identical performance when retaining more nodes.

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1 System Model and Channel Characterization

1.1 MIMO-PLC System Model

Residential power line infrastructure typically uses a three-wire configuration comprising phase (P), neutral (N), and protective earth (PE) lines. Traditional PLC systems utilize PN-PN channels for information transmission, whereas MIMO-PLC systems leverage the three-wire configuration to create multi-terminal input-output structures. The MIMO-PLC system model is illustrated in Figure 1 [Figure 1: see original paper]. Based on power line coupling principles, three different transmission ports can theoretically be constructed. However, due to Kirchhoff' s law constraints, at most two of the three transmitters can transmit simultaneously. When data network transmission signals are unbalanced, a common mode (CM) receiver can be created, forming a fourth port. Therefore, the system supports up to four receiving ports.

1.2 MIMO-PLC Channel Modeling

Literature [11] proposed a MIMO-PLC system channel model based on Zimmermann' s SISO multipath channel model and Tonello' s MIMO model, introducing a random-phase multipath MIMO channel model. The channel transfer function can be expressed as:

$$\mathbf{H}(f) = \begin{bmatrix} h_{S_1D_1}(f) & h_{S_2D_1}(f) \\ h_{S_1D_2}(f) & h_{S_2D_2}(f) \end{bmatrix}$$

where S_1 denotes P-N, S_2 denotes N-PE, D_1 denotes P-N, and D_2 denotes N-PE. According to Zimmermann' s SISO channel model, the frequency-domain transfer function is:

$$h_{S_mD_n}(f) = \sum_{k=0}^{K_{mn}} A_{mn,k} \cdot e^{-\alpha_{0,mn,k}-\alpha_{1,mn,k}f^{1/2}} \cdot e^{-j2\pi f d_{mn,k}/v_p} \cdot e^{j\varphi_{mn,k}}$$

Considering path correlation phases, literature [13] proposed the MIMO model with the total channel expression for all paths:

$$\mathbf{H}(f) = \sum_{p=0}^{P} \mathbf{A}_p \cdot e^{-\alpha_{0,p}-\alpha_{1,p}f^{1/2}} \cdot e^{-j2\pi f d_p/v_p} \cdot e^{j\varphi_p}$$

The parameters $\mathbf{A}_p$, $\alpha_{0,p}$, $\alpha_{1,p}$, d_p, and φ_p are related to the channel index; specific details are available in literature [11].

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2 Lattice Reduction Technology

Lattice reduction algorithms preprocess the channel matrix to improve channel orthogonality, enabling conventional detection algorithms to achieve performance close to ML detection. The principle involves length reduction and column swapping to decrease inter-column correlation. The LLL algorithm is the most renowned lattice reduction algorithm, primarily used for real-valued lattice reduction. Since MIMO-PLC channels are complex-valued, the LLL algorithm converts the complex domain to real domain for processing, resulting in excessive complexity. Therefore, literature [5] proposed the complex-domain CLLL lattice reduction algorithm, which reduces complexity by nearly 50% compared to LLL while maintaining identical performance.

Through CLLL lattice reduction, the lattice basis matrix undergoes QR decomposition:

$$\mathbf{H} = \mathbf{Q}\mathbf{R}$$

The upper triangular matrix $\mathbf{R}$ satisfies the following length reduction and column transformation conditions:

$$\left|\Re\{R_{i,k}\}\right| \leq \frac{1}{2}\left|R_{i,i}\right| \quad \text{and} \quad \left|\Im\{R_{i,k}\}\right| \leq \frac{1}{2}\left|R_{i,i}\right|, \quad 1 \leq i < k \leq m$$

$$\delta\left|R_{k-1,k-1}\right|^2 \leq \left|R_{k,k}\right|^2 + \sum_{i=1}^{k-1}\left|R_{i,k}\right|^2, \quad k = 2, \ldots, m$$

where $\left|\Re\{R_{i,k}\}\right|$ denotes the absolute value of the real part of the element in row i, column k of the upper triangular matrix $\mathbf{R}$, the reduction parameter $\delta \in (1/2, 1]$, typically set to 0.75.

The unimodular matrix $\mathbf{T}$ generated by the CLLL lattice reduction algorithm contains complex integer elements. The relationship between the initial basis matrix and the reduced new basis matrix is:

$$\mathbf{H}_{\text{reduced}} = \mathbf{H}\mathbf{T}$$

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3 Detection Algorithm Based on Condition Number Threshold Selection

3.1 MIMO-PLC Channel Condition Number Determination

The computational complexity of the proposed algorithm depends on the selection probability, which is determined by the optimal threshold setting. The algorithm' s complexity equals that of QRD-M when the optimal threshold $k_{\text{th}} = 1$, and approaches that of CLLL-MMSE-SQRD when k_{th} tends to infinity. To achieve a trade-off between performance and complexity, the optimal threshold k_{th} is set to an intermediate value.

The condition number of the channel matrix is used to measure channel quality. The cumulative probability distribution function of the channel matrix condition number is given by [14]:

$$\Pr\{\kappa(\mathbf{H}) > k_{\text{th}}\} \approx \exp\left(-\frac{2}{N_t}(k_{\text{th}}^2 - 1)\right)$$

where $\Pr\{\kappa(\mathbf{H}) > k_{\text{th}}\}$ represents the probability of selecting the QRD-M detection algorithm, N_t denotes the number of transmit antennas, N_r denotes the number of receive antennas, and $\kappa(\mathbf{H})$ is the condition number of channel matrix $\mathbf{H}$.

The probability of selecting the CLLL-MMSE-SQRD detection algorithm is:

$$\Pr\{\kappa(\mathbf{H}) \leq k_{\text{th}}\} = 1 - \exp\left(-\frac{2}{N_t}(k_{\text{th}}^2 - 1)\right)$$

From this expression, the channel matrix condition number is related to the number of transmit antennas and the selection probability. Since MIMO-PLC systems have a fixed number of transmit antennas ($N_t = 2$), the condition number threshold is only affected by p_{th}. As p_{th} increases, the condition number threshold increases; as p_{th} decreases, the threshold decreases, thereby altering both algorithm performance and computational complexity. Therefore, p_{th} must be determined based on specific communication requirements.

The detection algorithm based on condition number threshold selection can be expressed as:

$$\hat{\mathbf{x}}_{\text{TH}} = \begin{cases} \hat{\mathbf{x}}_{\text{CLLL-MMSE-SQRD}}, & \kappa(\mathbf{H}) \leq k_{\text{th}} \\ \hat{\mathbf{x}}_{\text{QRD-M}}, & \kappa(\mathbf{H}) > k_{\text{th}} \end{cases}$$

where $\hat{\mathbf{x}}_{\text{TH}}$ represents the estimated transmitted signal using the condition number threshold selection detection algorithm, $\hat{\mathbf{x}}_{\text{CLLL-MMSE-SQRD}}$ denotes the estimate from the CLLL-MMSE-SQRD algorithm, and $\hat{\mathbf{x}}_{\text{QRD-M}}$ denotes the estimate from the QRD-M algorithm. The algorithm flowchart is shown in Figure 2 [Figure 2: see original paper].

3.2 CLLL-MMSE-SQRD Detection Algorithm

Since the Sorted QR Decomposition (SQRD) detection algorithm offers good performance, this section introduces the lattice-reduction-aided SQRD detection algorithm. This approach combines lattice reduction technology with sorted QR decomposition detection by first performing sorted QR decomposition on the extended channel matrix, then applying CLLL lattice reduction, and finally conducting successive interference cancellation. The specific steps are:

a) Extend the channel matrix to an augmented channel matrix and the received signal to an augmented received signal:

$$\tilde{\mathbf{H}} = \begin{bmatrix} \mathbf{H} \\ \sigma_n \mathbf{I}_{N_t} \end{bmatrix}, \quad \tilde{\mathbf{y}} = \begin{bmatrix} \mathbf{y} \\ \mathbf{0}_{N_t \times 1} \end{bmatrix}$$

b) Perform sorted QR decomposition on the augmented signal matrix. Columns are sorted according to their two-norm magnitude, ordering all layers from highest to lowest reliability to determine the detection sequence.

c) Apply CLLL lattice reduction to the decomposed $\mathbf{Q}$ and $\mathbf{R}$ matrices to obtain new matrices $\mathbf{Q}'$ and $\mathbf{R}'$.

d) Left-multiply the augmented received signal by $\mathbf{Q}'^H$ to obtain:

$$\mathbf{z} = \mathbf{Q}'^H \tilde{\mathbf{y}} = \mathbf{R}'\mathbf{x} + \mathbf{w}'$$

e) Perform successive interference cancellation. Starting from the lowest layer, signals are detected layer by layer based on the upper triangular matrix properties to obtain equivalent transmitted signal estimates:

$$\hat{z}_i = \frac{z_i - \sum_{j=i+1}^{N_t} R'_{i,j}\hat{x}_j}{R'_{i,i}}$$

f) Multiply the equivalent transmitted signal estimate $\hat{\mathbf{z}}$ by the unimodular matrix $\mathbf{T}$ to obtain the transmitted signal estimate:

$$\hat{\mathbf{x}} = \mathbf{T}\hat{\mathbf{z}}$$

The CLLL-MMSE-SQRD detection algorithm outperforms linear detection algorithms based on CLLL lattice reduction. By utilizing QR decomposition, its complexity is significantly lower than ML detection, offering a favorable trade-off between performance and complexity.

3.3 QRD-M Detection Algorithm

The QRD-M detection algorithm is a simplified version of the maximum likelihood detection algorithm. To reduce the computational complexity of ML detection, QR decomposition and M-algorithm are employed, achieving a performance-complexity trade-off by limiting the number of surviving constellation points per layer and the searched set.

The QRD-M detection algorithm implementation consists of four steps:

a) Perform sorted QR decomposition. Decompose an $N_r \times N_t$ channel matrix $\mathbf{H}$ into a unitary matrix $\mathbf{Q}$ and an $N_t \times N_t$ upper triangular matrix $\mathbf{R}$. The received signal is rewritten as $\mathbf{y} = \mathbf{QRx} + \mathbf{w}$.

b) Left-multiply by $\mathbf{Q}^H$ to obtain $\mathbf{v} = \mathbf{Rx} + \mathbf{w}'$, where $\mathbf{v}$ and $\mathbf{w}'$ are the equivalent received signal and noise vectors.

c) Convert spatial search to tree search. Starting from the bottom layer of the upper triangular matrix, estimate each layer’ s transmitted signal values sequentially. The estimation method is:

$$\hat{x}_i = \arg\min_{x_i \in \mathcal{C}} \left| v_i - \sum_{j=i}^{N_t} R_{i,j} x_j \right|^2$$

where $\mathcal{C}$ represents the standard constellation points. Each layer calculates the cumulative metric values for retained nodes. The k retained nodes at layer l have cumulative metric values:

$$E_{l,k} = \sum_{i=l}^{N_t} \left| v_i - \sum_{j=i}^{N_t} R_{i,j} \hat{x}_j \right|^2$$

d) The QRD-M detection algorithm begins detection from the last layer, calculating cumulative metric values at each layer and retaining the M nodes with smallest cumulative metrics as parent nodes for the next layer. By limiting the number of retained constellation points per layer, the exhaustive search complexity is reduced. The node with the smallest cumulative metric at the top layer is selected as the final detection result.

Figure 3 [Figure 3: see original paper] illustrates the tree structure of QRD-M (M=3) detection algorithm for MIMO-PLC systems with QPSK modulation.

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4 Performance Simulation

4.1 Complexity Analysis

The complexity of the CLLL-MMSE-SQRD detection algorithm primarily comprises the complexity of CLLL lattice reduction and MMSE-SQRD algorithms. The CLLL lattice reduction complexity is mainly affected by iteration count, with an upper bound of $O(N_t^3 \log N_t)$. Each iteration requires length reduction and column vector swapping with complexity $O(N_t^2)$, resulting in overall CLLL complexity of $O(N_t^4)$. The MMSE-SQRD algorithm complexity is $O(N_r N_t^2)$. Therefore, the average complexity of CLLL-MMSE-SQRD detection is:

$$\delta_{\text{CLLL-MMSE-SQRD}} = O(N_t^4) + O(N_r N_t^2)$$

The average complexity of QRD-M detection is:

$$\delta_{\text{QRD-M}} = O(N_r N_t^2) + M \cdot \sum_{i=1}^{N_t} |\mathcal{C}|^i$$

where M represents the number of retained nodes per layer and $|\mathcal{C}|$ denotes constellation size.

For the proposed condition number threshold selection algorithm, complexity depends on the selection probability. The average complexity is:

$$\delta_{\text{TH}} = p_{\text{th}} \cdot \delta_{\text{CLLL-MMSE-SQRD}} + (1 - p_{\text{th}}) \cdot \delta_{\text{QRD-M}}$$

where p_{th} represents the probability of selecting the CLLL-MMSE-SQRD detection algorithm, obtained from the condition number CDF expression.

4.2 Parameter Settings

This section presents simulation analysis of the proposed condition number threshold selection detection algorithm, where channel quality is assessed via condition number to select appropriate detection algorithms. To verify algorithm performance in MIMO-PLC systems, MATLAB simulations were conducted for various QRD-M parameter values and different condition number thresholds.

Key simulation parameters are listed in Table 1 .

Table 1 Simulation Parameters

Parameter	Value
System	MIMO-PLC
Modulation	QPSK/16QAM
Coding	Turbo Code
Channel	MIMO-PLC Channel

Figure 4 [Figure 4: see original paper] shows the MIMO-PLC channel characteristics, demonstrating frequency-selective fading properties. Due to different access loads on each subchannel, attenuation and phase variations differ across subcarriers, with some subcarriers experiencing amplitude attenuation below -50 dB. Although MIMO-PLC systems improve bandwidth utilization and capacity by increasing subchannel count, significant quality variations exist across different subcarriers.

Figure 5 [Figure 5: see original paper] illustrates the MIMO-PLC channel matrix condition number distribution across 511 subcarriers. Since the condition number is defined as the ratio of maximum to minimum singular values, its minimum value is 1. The results show that over 75% of samples have condition numbers below 20, while condition numbers above 20 indicate poor channel quality. Setting the optimal threshold within this range ensures sufficient high-quality channels can use low-complexity suboptimal algorithms, avoiding unnecessary computational overhead.

Figure 6 [Figure 6: see original paper] compares detection algorithm performance under QPSK modulation. The QRD-M algorithm with M=3 achieves performance identical to ML detection at SNR = 24 dB. Therefore, the proposed algorithm selects QRD-M with M=3 for QPSK modulation. Figure 7 [Figure 7: see original paper] shows the proposed algorithm' s performance at different thresholds ($k_{\text{th}} = 5, 10, 15$). The algorithm with $k_{\text{th}} = 5$ performs best, closely approaching QRD-M M=3 performance. As the threshold increases, performance degrades because the CLLL-MMSE-SQRD algorithm only achieves optimal performance on high-quality channels, while using it on poor-quality channels degrades overall performance.

Figures 8 [Figure 8: see original paper] through 10 [Figure 10: see original paper] present results for 16QAM modulation. The proposed algorithm selects QRD-M with M=8 for poor channel conditions. Performance comparison shows the proposed algorithm with threshold $k_{\text{th}} = 5$ approaches ML algorithm performance. Figure 10 [Figure 10: see original paper] indicates the probability of selecting CLLL-MMSE-SQRD detection is $p_{\text{th}} = 0.527$, yielding a 44% complexity reduction compared to QRD-M M=8. When the optimal threshold falls below 5, the probability of selecting QRD-M increases, raising computational complexity. To achieve a suitable performance-complexity balance, $k_{\text{th}} = 5$ is chosen, providing significant complexity reduction with minimal performance loss. The complexity reduction becomes more pronounced as modulation order increases.

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5 Conclusion

This paper proposes a detection algorithm based on condition number threshold selection for MIMO-PLC systems. When the current channel matrix condition number is below or equal to the threshold, the CLLL-MMSE-SQRD detection algorithm is employed, offering low complexity while achieving optimal performance under good channel conditions. When the condition number exceeds the threshold, the QRD-M detection algorithm is used, which achieves optimal detection performance with high node retention while maintaining lower complexity than ML detection. The selection strategy ensures controlled complexity overhead. Under 16QAM modulation with $k_{\text{th}} = 5$, the proposed algorithm reduces complexity by approximately 44% compared to QRD-M M=8. Simulation results validate that the proposed algorithm' s performance matches that of QRD-M M=8, with complexity becoming increasingly advantageous at higher modulation orders.

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Note: Figure translations are in progress. See original paper for figures.