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Research Article

Blind Channel Estimation Based on Multilevel Lloyd-Max Iteration for Nonconstant Modulus Constellations

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In wireless communications, knowledge of channel coefficients is required for coherent demodulation. Lloyd-Max iteration is an innovative blind channel estimation method for narrowband fading channels. In this paper, it is proved that blind channel estimation based on single-level Lloyd-Max (SL-LM) iteration is not reliable for nonconstant modulus constellations (NMC). Then, we introduce multilevel Lloyd-Max (ML-LM) iteration to solve this problem. Firstly, by dividing NMC into subsets, Lloyd-Max iteration is used in multilevel. Then, the estimation information is transmitted from one level to another. By doing this, accurate blind channel estimation for NMC is achieved. Moreover, when the number of received symbols is small, we propose the lacking constellations equalization algorithm to reduce the influence of lacking constellations. Finally, phase ambiguity of ML-LM iteration is also investigated in the paper. ML-LM iteration can be more robust to the phase of fading coefficient by dividing NMC into subsets properly. As the signal-to-noise ratio (SNR) increases, numerical results show that the proposed method's mean-square error curve converges remarkably to the least squares (LS) bound with a small number of iterations.

1. Introduction

In wireless communication systems, channel state information (CSI) is necessary for coherent demodulation or precoding, and channel estimation is required at the receiver. Data-aid (DA) estimation methods make use of pilot, which is known both at transmitter and at receiver. On the contrary, blind estimation (BE) methods do not use any symbols known priorly at the receiver, thus saving transmitting power and bandwidth.

In [1], Tong et al. firstly explored cyclostational properties of an oversampled communication signal and proposed a BE method based on second-order statistics (SOS) of received signal. After that a series of BE methods based on statistical characteristics of received signal was proposed, especially signal subspaces (SS) method [2–5], which is used widely in modern communication systems, such as MIMO and OFDM. However, methods based on statistical characteristics require estimator to calculate high-order statistics of received signal. They are reliable only when the number of received symbols is large. To solve this problem, researchers introduced deterministic methods, such as estimators based on least squares (LS) principle [6] and estimators based on finite-alphabet characteristics of constellations [7]. LS method is widely used in wireless communication systems because of its reliability and simplicity. Our work focuses on it.

LS solution of DA estimation was introduced by Crozier et al. [6]. With the accurate information of pilot symbols, DA-LS estimator is the optimum estimator which reaches Cramer-Rao bound (CRB) [8]. Without pilot symbols, decision-directed (DD) LS estimator makes decision to receive symbols firstly and then uses results to estimate channel coefficients. For narrowband fading channels, Dizdar and Ylmaz [9] proposed Lloyd-Max iteration, which achieves reliable blind channel estimation for constant modulus constellations (CMC) with less received symbols. Lloyd-Max iteration is a method based on LS principle. But for nonconstant modulus constellations (NMC), it is unreliable to estimate channel blindly with single-level Lloyd-Max (SL-LM) iteration. This is due to the fact that nonconstant modulus of constellations will induce quantization errors in the first step of iterations.

For this problem, the paper proposes a BE method based on multilevel Lloyd-Max (ML-LM) iteration. By multilevel iteration and by transmitting estimation information from one level to another, the proposed method achieves accurate blind channel estimation for NMC with less received symbols. Moreover, when the number of received symbols is small, we introduce lacking constellations equalization (LCE) algorithm to reduce the influence of lacking constellations (LCs). As the signal-to-noise ratio (SNR) increases, the proposed method's mean-square error curve converges remarkably to the LS bound with a small number of iterations.

The paper is organized as follows. Section 2 gives the system model, SL-LM iteration algorithm, and proves that SL-LM iteration is unreliable for NMC. In Section 3, we introduce ML-LM iteration algorithm, LCE algorithm, and analyze the phase ambiguity. Numerical results are shown in Section 4, and Section 5 concludes the paper.

The notation is defined as follows: $j = \sqrt{-1}$. The notations $\{\cdot\}$, $\exp(\cdot)$, $(\cdot)^*$, and $E\{\cdot\}$ stand for set, exponent, complex conjugation, and expectation, respectively. Specially, $|\cdot|$ denotes the amplitude if the element is a complex number. If the element is a set, $|\cdot|$ denotes the cardinality of the set, namely, the number of elements in the set.

2. Preliminaries

2.1. System Model. When the coherence time of the channel is large enough, channel coefficients will change very slowly in time domain. Then fading coefficients are invariant in certain intervals. When the bandwidth of the channel is narrow, the channel is frequency-nonselective, namely, flat-fading. Under this condition, the system model is established as

$$y_k = h \cdot r_k + n_k, \quad k = 1, 2, \ldots, L, \tag{1}$$

where k: indices of received symbols in time domain; r_k: transmitted constellation; n_k: zero-mean circularly symmetric complex Gaussian (ZMCSCG) random variable with variance N_0; L: number of received symbols; h: fading coefficient, which is invariant in the interval of received symbols.

Suppose that $h = a \cdot \exp(j\theta)$, where a is the fading amplitude, which satisfies Rayleigh distribution. θ is the offset phase, which satisfies uniform distribution.

2.2. Single-Level Lloyd-Max Iteration. Lloyd-Max iteration [10] is a quantization algorithm using a LS approximation. The algorithm is developed as a solution to the problem of minimizing the overall quantization noise when an analog signal is pulse code modulated. It was introduced into blind channel estimation in [9]. Suppose that modulation mode is MPSK; the algorithm procedure is the following.

(1) Suppose that the initial quanta are the MPSK constellation points:

$$q_m^0 = \alpha_m = \exp\left(j\frac{2\pi(m-1)}{M}\right), \quad m = 1, 2, \ldots, M. \tag{2}$$

(2) Defining M sets of received symbols S_m, received symbols fall into the region S_m based on the following criterion:

$$S_m = \left\{ y_k \mid |y_k - q_m| \le |y_k - q_p|,\ \forall p \ne m \right\}. \tag{3}$$

For every S_m, the center of mass of the points in it is calculated by

$$q_m^1 = \frac{1}{|S_m|}\sum_{y_k \in S_m} y_k, \quad m = 1, 2, \ldots, M, \tag{4}$$

which is found as a set of new quanta.

By repeating steps (1) and (2) until a stopping criterion is met or for a desired number of iterations, final quanta can be obtained as follows:

$$q_m = h \cdot \alpha_m, \quad m = 1, 2, \ldots, M. \tag{5}$$

Then, the estimator can be deduced as

$$\hat{h} = \frac{\sum_{m=1}^{M} q_m \cdot \alpha_m^*}{M}. \tag{6}$$

It can be noted that Lloyd-Max algorithm is based on the principle of DD-LS. In step (2), the algorithm uses the distance between y_k and q_m as the decision criterion. If y_k has a minimum distance to q_m compared to other quanta, it falls into the region S_m. It is the same as maximum likelihood (ML) decision. Furthermore, Lloyd-Max algorithm uses iteration to reduce the influence of noise and fading and has a better performance than DD-LS method.

Traditional Lloyd-Max iteration, which is called SL-LM iteration, is reliable for CMC. If the offset phase satisfies

$$\theta \in \left(-\frac{\pi}{M}, \frac{\pi}{M}\right), \tag{7}$$

phase ambiguity [9] will be eliminated. Consequently it can be ensured that, in the first step of iterations, received symbols have a minimum distance to their transmitted constellations for any value of a and then fall into the right region S_m with (3), which ensure that the following iterations are correct.

On the conditions of SNR 30 dB, QPSK modulation with initial phase $\pi/4$, received symbols with different fading coefficients are shown in Figure 1. In the figure arrows denote the constellations with minimum distance to the regions, and $\theta = \pi/P$. It can be seen that when θ satisfies the restriction of no phase ambiguity, all received symbols fall into the right regions either with a large (2.2) or with a small (0.55) a.

However, when the modulus of constellations is nonconstant, even if θ satisfies the restriction of no phase ambiguity, different a also may induce the fact that the received symbols have a minimum distance to other constellations rather than

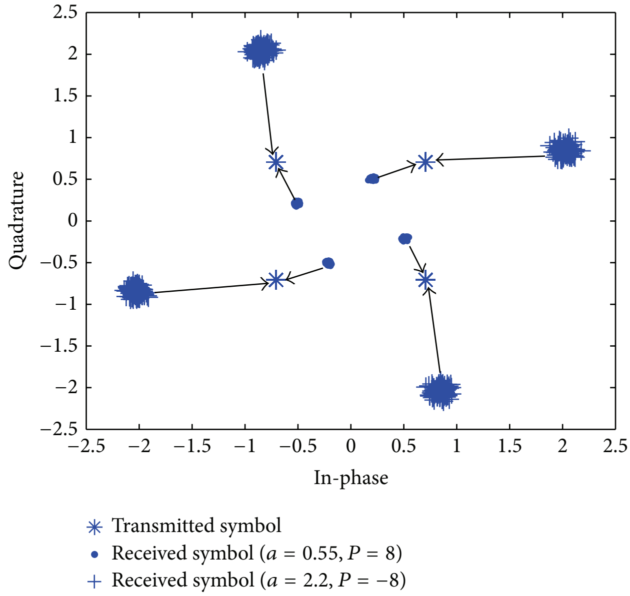

Figure 1: QPSK symbols with different fading coefficients.

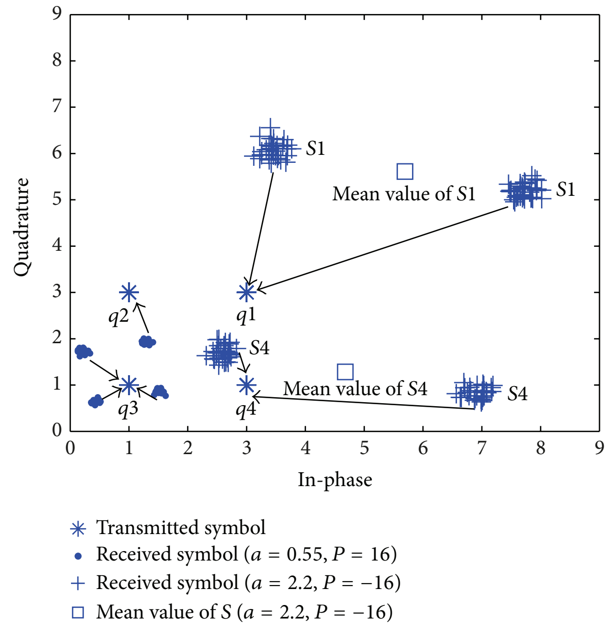

Figure 2: Square 16QAM symbols with different fading coefficients (first quadrant).

their transmitted constellations, then fall into a wrong region S_m with (3), and lead to the false estimation.

On the conditions of SNR 30 dB, square 16QAM constellations, received symbols with different fading coefficients are shown in Figure 2. In order to illuminate clearly, Figure 2 only shows the first quadrant. It is the same for other quadrants.

As we can see in Figure 2, quantization errors will be caused by a large (2.2) or small (0.55) a in the first step of iterations. When $a = 2.2$, $\theta = -\pi/16$, received symbols whose transmitted constellations are $q1$ and $q2$ fall into the region $S1$; received symbols whose transmitted constellations are $q3$ and $q4$ fall into the region $S4$. The center of $S1$ and the center of $S4$ are two new quanta. No symbol falls into $S2$ and $S3$; the new quanta are still $q2$ and $q3$. Wrong iterations and false estimation will be caused by the four wrong quanta. It is the same for $a = 0.55$, $\theta = \pi/16$.

It is proved that SL-LM iteration is unreliable for NMC. In order to solve this problem, we introduce ML-LM iteration in the following section.

3. Multilevel Lloyd-Max Iteration

3.1. Algorithm Procedure. In order to solve the problem above, we propose a BE method based on ML-LM iteration for NMC. For example, if the modulation mode is square 16QAM, the iteration process can be divided into two levels as follows.

Level 1 (L1). Divide 16QAM constellations into 4 subsets according to quadrants. Defining initial L1 quanta are the center of every subset. Received symbols fall into L1 regions with (3). We can calculate new L1 quanta and obtain the L1 estimator with (4) and (6).

Level 2 (L2). For every subset in L1, multiply constellations by the L1 estimator; the results are initial L2 quanta. For every L1 region, received symbols fall into L2 regions with (3). We can calculate new L2 quanta and obtain the L2 estimator with (4) and (6) in every L1 region. All the new L2 quanta are divided into new subsets according to L1 regions; then return to L1.

The two-level Lloyd-Max iteration consists of L1 and L2. By repeating L1 and L2 until a stopping criterion is met or for a desired number of iterations, the mean value of four L2 estimators is the final estimator.

Supposing that the NMC are

$$\alpha_m = a_m \cdot \exp\left(j\varphi_m\right), \qquad m = 1, 2, \ldots, M, \tag{8}$$

and received symbols satisfy (1), the procedure of two-level Lloyd-Max algorithm can be concluded as the following.

(1) Divide NMC α_m into 4 subsets:

$$\begin{aligned} A_1 &= \left\{\alpha_{1,1}, \alpha_{1,2}, \ldots, \alpha_{1,M/4}\right\}, \\ A_2 &= \left\{\alpha_{2,1}, \alpha_{2,2}, \ldots, \alpha_{2,M/4}\right\}, \\ A_3 &= \left\{\alpha_{3,1}, \alpha_{3,2}, \ldots, \alpha_{3,M/4}\right\}, \\ A_4 &= \left\{\alpha_{4,1}, \alpha_{4,2}, \ldots, \alpha_{4,M/4}\right\}, \end{aligned} \tag{9}$$

which satisfy

$$\left|A_1\right| = \left|A_2\right| = \left|A_3\right| = \left|A_4\right|. \tag{10}$$

The mean value of a set A is the center of A:

$$E\{A\} = \frac{1}{|A|} \sum_{\alpha_i \in A} \alpha_i. \tag{11}$$

Then, the subsets satisfy

$$\left|E\left\{A_1\right\}\right| = \left|E\left\{A_2\right\}\right| = \left|E\left\{A_3\right\}\right| = \left|E\left\{A_4\right\}\right|. \tag{12}$$

(2) Define initial L1 quanta as

$$\begin{aligned} q_1^1 &= E\left\{A_1\right\}, & q_2^1 &= E\left\{A_2\right\}, \\ q_3^1 &= E\left\{A_3\right\}, & q_4^1 &= E\left\{A_4\right\}. \end{aligned} \tag{13}$$

(3) Define L1 regions of received symbols S_i^1 as

$$S_i^1 = \left\{y_k \mid \left|y_k - q_i^1\right| \le \left|y_k - q_j^1\right|, \ \forall j \ne i\right\}. \tag{14}$$

If S_i^1 is null set, then

$$S_i^1 = \left\{q_i^1\right\}. \tag{15}$$

Calculate the L1 estimator of fading coefficient as follows:

$$\widehat{h}_1 = \frac{1}{4} \cdot \sum_{i=1}^{4} \frac{E\left\{S_i^1\right\} \cdot E\left\{A_i\right\}^*}{\left|E\left\{A_i\right\}\right|^2}. \tag{16}$$

(4) Initial L2 quanta are deduced as

$$q_{i,j}^2 = \alpha_{i,j} \cdot \widehat{h}_1, \quad i = 1, 2, 3, 4; \ j = 1, 2, \ldots, \frac{M}{4}. \tag{17}$$

(5) Define L2 regions of received symbols $S_{i,j}^2$ for every i as follows:

$$S_{i,j}^2 = \left\{y_k \mid \left|y_k - q_{i,j}^2\right| \le \left|y_k - q_{i,l}^2\right|, \forall l \ne j, y_k \in S_i^1\right\}. \tag{18}$$

If $S_{i,j}^2$ is null set, then

$$S_{i,j}^2 = \left\{q_{i,j}^2\right\}. \tag{19}$$

Calculate the L2 estimator of fading coefficient as follows:

$$\widehat{h}_2 = \frac{1}{4} \cdot \sum_{i=1}^{4} \frac{\left((4/M) \sum_{j=1}^{M/4} E\left\{S_{i,j}^2\right\}\right) \cdot E\left\{A_i\right\}^*}{\left|E\left\{A_i\right\}\right|^2}. \tag{20}$$

If a desired number of iterations are met, (20) is the final estimator. If not, then new L1 quanta are deduced as

$$q_i^1 = \frac{4}{M} \sum_{j=1}^{M/4} E\left\{S_{i,j}^2\right\}, \tag{21}$$

and return to step (3).

In practice, the number of iteration levels should be set properly. For some high-order modulation modes, such as 256QAM, we must increase the number of levels to guarantee the well performance of the algorithm.

3.2. Lacking Constellations Equalization. If the number of received symbols is small, it is a high probability event that transmitted constellations of all received symbols have not included all NMC. If a constellation has not been transmitted in the interval of received symbols, we call it lacking constellation (LC). If LCs exist, $E\{S_i^1\}$ will be a biased estimator of fading L1 quantum in (16), and the L1 estimator will be biased. As shown in Figure 3, square 16QAM constellations in the first quadrant, $q1$ is a LC, and the mean value of $S1$ is biased from fading L1 quantum.

For this case, we introduce LCE algorithm. For square 16QAM constellations, the L1 quantum can be determined only by 3 constellations in an L1 region S_i^1. If 1 LC exists only, the fading L1 quantum can still be determined. If over 2 LCs exist, S_i^1 is useless for L1 estimator. Then, we can delete it in (16) and eliminate the influence of biased fading L1 quantum. LCE can be used after (15). If not every L1 region has over 2 LCs, LCE can eliminate the influence of LCs.

For square 16QAM constellations, LCE algorithm can be concluded as follows.

(1) For every S_i^1 ($i = 1, 2, 3, 4$), calculate the maximum distance between symbols as follows:

$$\begin{aligned} d = \max \{ & d_{s,t} = \left|y_s - y_t\right| \mid y_s, y_t \in S_i^1, \\ & s, t = 1, 2, \cdots, \left|S_i^1\right| \}. \end{aligned} \tag{22}$$

(2) Define the number of transmitted constellations c_i ($i = 1, 2, 3, 4$) in every S_i^1. As shown in Figure 3, if $c_i = 3$ or 4, $d = d1$; if $c_i = 2$, $d = d2$. Ignore $c_i = 0$ or 1 because of their low probability. So c_i can be estimated as follows.

Initialize N_1, N_2, N_3, and N_4 as null sets. For $y_k \in S_i^1$, y_1 falls into N_1. For $k = 2, 3, \ldots, |S_i^1|$, calculate

$$d_t = \left|y_k - E\left\{N_t\right\}\right|, \quad \text{if } N_t \text{ is not null}. \tag{23}$$

If $d_t \le d/4$, y_k falls into N_t; if $d_t > d/4$, for every t, y_k falls into null set N_s. Finally, c_i equals the number of nonnull sets. If the transmitted constellations of received symbols are the same, received symbols fall into same sets.

(3) For every S_i^1, if $c_i = 3$, define sets N_u, N_v which satisfy

$$\left|E\left\{N_u\right\} - E\left\{N_v\right\}\right| = \max \left\{\left|E\left\{N_s\right\} - E\left\{N_t\right\}\right| \mid s, t = 1, 2, 3\right\}. \tag{24}$$

Calculate the fading L1 quantum f_i as follows:

$$f_i = \begin{cases} E\left\{S_i^1\right\}, & c_i = 4, \\ \dfrac{E\left\{N_u\right\} + E\left\{N_v\right\}}{2}, & c_i = 3. \end{cases} \tag{25}$$

If a region satisfies $c_i = 3$ or 4, it is useful. Suppose the number of useful regions is C. If $C = 0$, LCE is false; L1 estimator of fading coefficient can still be calculated with (16).

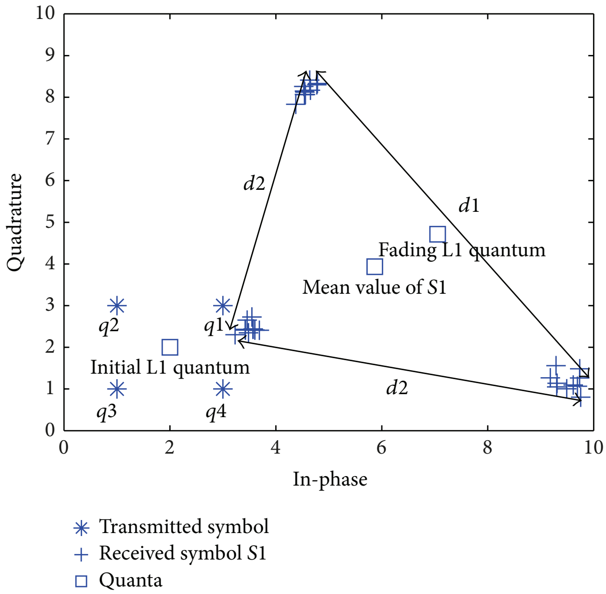

Figure 3: LC in square 16QAM constellations (first quadrant).

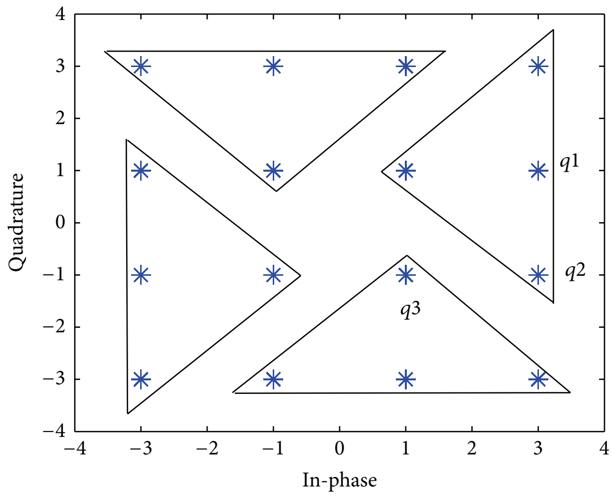

Figure 4: Subsets of square 16QAM constellations.

If $C = 1, 2, 3, 4$, L1 estimator of fading coefficient can be deduced as

$$\hat{h}_1 = \frac{1}{C} \cdot \sum_i \frac{f_i \cdot E\{A_i\}^*}{|E\{A_i\}|^2}, \quad c_i = 3 \quad \text{or} \quad 4. \tag{26}$$

For other high-order modulations, the geometry of constellations is more complex. In an L1 region, how many constellations can determine an L1 quantum is not fixed. In practice, LCE should be modified based on the modulation mode.

3.3. Phase Ambiguity Analysis. Phase ambiguity is a classical problem in blind channel estimation. The reason can be concluded that we cannot determine the transmitted constellation of a received symbol. Some valuable ideas have been given to eliminate it, such as differential modulation and coding [9], few pilot symbols [5], which is called semiblind estimation (SBE). If we cannot make use of communication scheme, large distance between constellations can reduce the influence of phase ambiguity. For ML-LM iteration, we can make the distance between subsets maximum by dividing NMC into subsets properly. Then the restriction range of no phase ambiguity can be maximum.

For square 16QAM constellations, as shown in Figure 4, if we divide constellations into subsets according to quadrants, then the minimum phase difference between subsets is $2 \cdot \arctan(1/3)$, and the 2 nearest constellations are q_1 and q_2. In the first step of iteration, if we want to ensure that the received symbols fall into right regions, the restriction range of no phase ambiguity is

$$\theta \in \left(-\arctan\frac{1}{3}, \arctan\frac{1}{3}\right). \tag{27}$$

If we divide constellations into subsets according to Figure 4, then the minimum phase difference between subsets is $\pi/4 - \arctan(1/3)$, and the 2 nearest constellations are q_2 and q_3. Then, the restriction range of no phase ambiguity is

$$\theta \in \left(-\frac{1}{2} \cdot \left(\frac{\pi}{4} - \arctan\frac{1}{3}\right), \frac{1}{2} \cdot \left(\frac{\pi}{4} - \arctan\frac{1}{3}\right)\right). \tag{28}$$

Because $1/2 \cdot (\pi/4 - \arctan 1/3) < \arctan 1/3$, ML-LM iteration can be more robust to the offset phase by dividing NMC into subsets according to quadrants than according to Figure 4.

4. Numerical Results

In this section, we test the performance of ML-LM iteration through Monte Carlo simulation. The modulation mode is square 16QAM. Suppose that the fading coefficient is

$$h = h_I + j \cdot h_Q = a \cdot \exp(j\theta), \tag{29}$$

where h_I and h_Q are zero-mean real Gaussian random variables with variance σ^2 and independent of each other. In the simulation $\sigma^2 = 1$. The amplitude a of h is a Rayleigh-distributed random variable; its mean value and variance [11] are

$$E\{a\} = \left(2\sigma^2\right)^{1/2} \frac{\sqrt{\pi}}{2}, \qquad \operatorname{var}\{a\} = \left(2 - \frac{\pi}{2}\right)\sigma^2. \tag{30}$$

The offset phase θ is a uniform-distributed random variable. Considering the phase ambiguity, we assume that θ satisfies (27).

In Figures 5, 6, 7, 8, and 9, the x-axis shows the received SNR of the channel:

$$\text{SNR} = \frac{|h|^2}{N_0}. \tag{31}$$

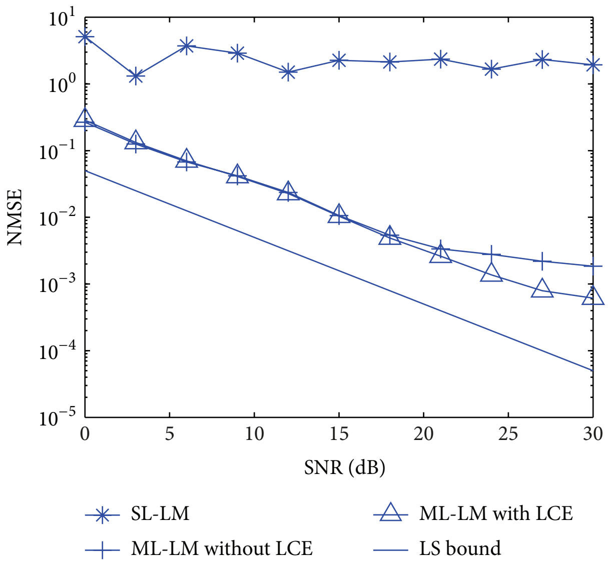

FIGURE 5: NMSE comparisons of SL-LM and ML-LM iteration when $L = 20$ (with and without LCE).

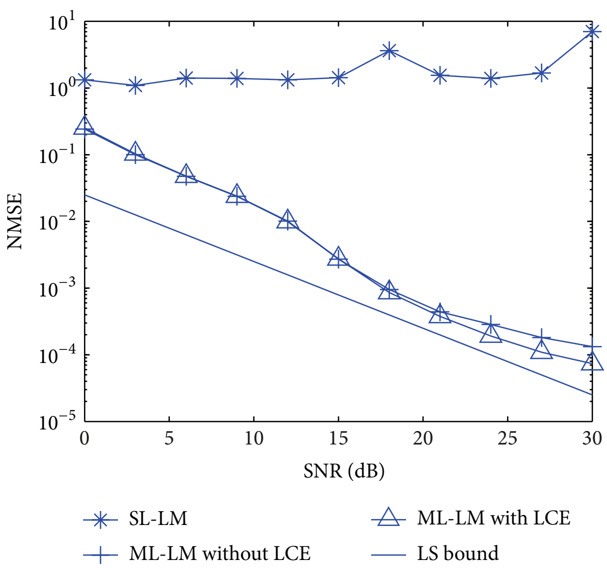

FIGURE 6: NMSE comparisons of SL-LM and ML-LM iteration when $L = 40$ (with and without LCE).

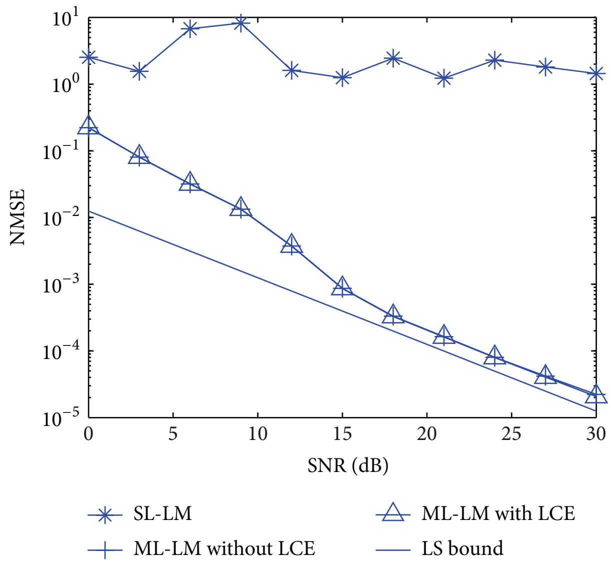

FIGURE 7: NMSE comparisons of SL-LM and ML-LM iteration when $L = 80$ (with and without LCE).

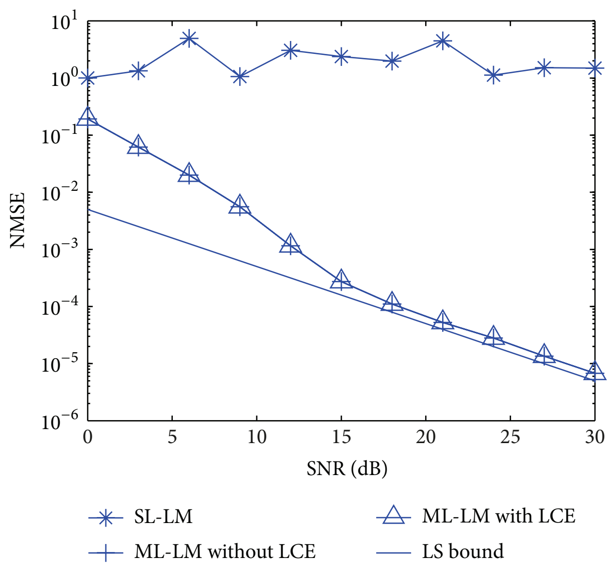

FIGURE 8: NMSE comparisons of SL-LM and ML-LM iteration when $L = 200$ (with and without LCE).

The y-axis shows the normalized mean-square error (NMSE) over 3000 Monte Carlo runs:

$$\mathrm{NMSE} = \frac{1}{N_M} \sum_{i=1}^{N_M} \left(\frac{\left| h_i - \widehat{h}_i \right|}{\left| h_i \right|} \right)^2, \tag{32}$$

where $N_M = 3000$.

The lower bound in Figures 5–9 is the NMSE bound of LS estimator [9]:

$$\mathrm{NMSE}_{\mathrm{LS}} = \frac{N_0}{L \cdot E^2 \{a\}}. \tag{33}$$

The number of iterations $I = 5$. Figures 5–8 show the NMSE comparisons of SL-LM and ML-LM iteration with different numbers of received symbols L. As the figures show, with less received symbols, SL-LM iteration's NMSE curves cannot converge to the LS bound as SNR increases. When $L \geq 80$, ML-LM iteration's NMSE curves converge remarkably to the LS bound. Moreover, both with and without LCE, ML-LM iteration's NMSE curves are the same. When $L < 80$, ML-LM iteration's NMSE curves decrease as SNR increases but cannot converge. It is because LCs exist. When SNR $\geq$ 18 dB, ML-LM iteration with LCE has a better performance than without LCE. The smaller the L is, the more obvious the performance improvement is.

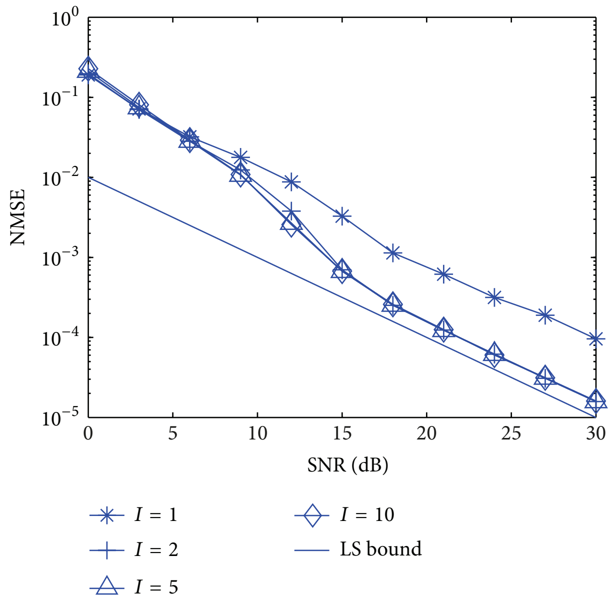

Figure 9: NMSE comparisons of ML-LM iteration for different numbers of iterations.

When $L = 100$, NMSE comparisons of ML-LM iteration for different I are shown in Figure 9. As we can see, ML-LM iteration's NMSE curves converge remarkably to the LS bound only by 2 iterations. Comparing with SL-LM iteration, which needs 10 iterations [9], although in every iteration ML-LM has a higher complexity, the whole complexity of ML-LM iteration may lower.

5. Conclusion

Because of its high information rate, NMC are widely used in modern communication system. For blind channel estimation based on SL-LM iteration, NMC will result in quantization errors in the first step of iterations. The paper proposes a blind channel estimator based on ML-LM iteration for NMC. By dividing NMC into subsets, Lloyd-Max iteration is used in multilevel. Estimation information is transmitted from one level to another. Then quantization errors are eliminated. Moreover, when $L < 80$, LCE algorithm is introduced to reduce the influence of LCs and improves the performance of ML-LM iteration. When $L \geq 80$, the proposed method's NMSE curve converges remarkably to the LS bound with a small number of iterations. Consequently it is suitable for some modern communication schemes which require high-speed estimation.

For multipath channels, which produce frequency selectivity, the proposed scheme can be combined with orthogonal frequency division multiplexing (OFDM) scheme to achieve blind channel estimation. For every subchannel in OFDM, the channel is flat-fading and still satisfies the model in (1). Then, ML-LM iteration can be used in every subchannel.

Phase ambiguity of ML-LM iteration is also analyzed in the paper. The restriction range of no phase ambiguity can be maximum by dividing NMC into subsets properly. How to eliminate the restriction of phase ambiguity will be researched in future work.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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