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A Hybrid CME-LS Channel Estimation Approach for Broadband MIMO-OFDM Systems

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Abstract— A channel estimation approach yielding both channel gains and the number of multi-paths is presented. The algorithm is based on a variation of conditional model order estimation (CME), and is proposed for MIMO-OFDM systems. The CME based estimator is shown to be viable in both fixed and mobile broadband MIMO-OFDM wireless applications, and takes advantage of determining the nonzero taps as well. The performance of the approach is compared to the popular minimum description length (MDL) algorithm for estimation of the number of channel paths, by means of simulation in the context of a 2x2 MIMO-OFDM transceiver system. Results indicate that the new algorithm is superior in channel order estimation to the MDL algorithm in MIMO-OFDM system over a noisy frequency selective fading channel.

I. INTRODUCTION

In wireless environments, signals bounce off many obstacles such as mountains, buildings, trees, etc. as they propagate between transmitters and receivers. The resultant signal at the receive antenna is, therefore, often the sum of the attenuated transmitted signal and one or more delayed versions of the transmitted signal. This received signal often suffers from intersymbol interference which degrades the signal quality to a certain extent. However, MIMO-OFDM systems are designed to take advantage of the multi-path properties in wireless communications and are capable of improving transmission rate, range and reliability simultaneously. MIMO-OFDM systems have shown great promise in a range of wireless applications and have been adopted in several wireless standards such as IEEE 802.11n, IEEE 802.16e. Such systems are also potential candidates for the fourth-generation (4G) systems [1].

In a MIMO-OFDM system, channel state information (CSI) can be used at the receiver to perform space-time decoding or diversity combining. Various model-based channel estimation approaches have been proposed for single antenna OFDM systems, founded on three main algorithms: maximum likelihood (ML) estimation; least squares (LS) estimation; and minimum mean squared error (MMSE) estimation [2]. In addition, channel estimation approaches can be further categorized as: pilot-assisted [3] - [5] and blind [6] - [8]. Blind techniques increase the effective throughput but either degrade system performance or lower convergence rate. In contrast, the pilot based method consumes more bandwidth,

yet are less complex and improves system performance significantly [9].

In most existing estimation schemes for MIMO-OFDM there is an assumption that the number of channel taps (i.e. number of propagation paths) is known. In many practical wireless applications in which the propagation environment is both complex and time-variant, this assumption is invalid. Recently, some attention has been directed to estimating the number of multi-path taps. For instance, Yang et. al. described an algorithm for this purpose [10], in which minimum description length (MDL) was first applied in OFDM. Wang et. al. documented a probabilistic data association (PDA) based time of arrival (TOA) estimation approach for a MIMO-OFDM system, which again employed MDL to detect the number of channel paths [11]. Whilst improving performance in channel model estimation, each of these hybrid approaches is relatively costly in terms of computational complexity.

In this paper, a pilot-assisted, CME based channel estimation is proposed for broadband MIMO-OFDM system with the purpose of estimating both the number of paths and channel gains in frequency selective fading channels. Given the aim of low computational complexity, least squares (LS) is selected for use with the modified CME. Moreover, the proposed CME is capable of determining the significant (nonzero) multi-channel taps, and thus has advantages in reducing the complexity as well as improving the efficiency of MIMO system. The algorithm is then verified in both fixed and mobile wireless systems. The rest of this paper is organized as follows: Section II describes a MIMO-OFDM system model. The proposed scheme is illustrated in section III. In section IV, simulations and numerical results are presented, and the comparison between the CME and MDL based approach is made. Finally, possible improvements and further development are outlined in the conclusion

II. A SPACE-TIME CODED MIMO-OFDM MODEL

A space-time coded MIMO-OFDM system is depicted Fig. 1. The system consists of N_t transmit antennas and N_r receive antennas. Orthogonal space-time coding (OSTBC) is employed for it can transform the MIMO channel into simple parallel SISO channels. At time n , a data block is mapped and encoded into i sequences of information symbols, then pilot

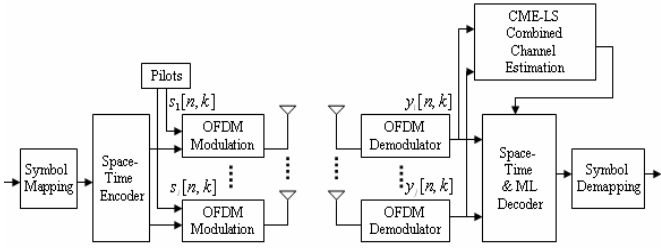


Fig. 1. MIMO-OFDM system

symbols are inserted and signal sequence $s_i[n, k]$, ($k=0, 1, \dots, K$; $i=1, 2, \dots, N_t$) can be obtained. K is the number of sub-channels, and i represents the i th transmit antenna. Hence, the output signal of the FFT operation at the receiver is expressed as

$$y_j[n, k] = \sum_i H_{ij}[n, k] s_i[n, k] + w_j[n, k], \quad (1)$$

where $H_{ij}[n, k]$ is the channel frequency response at the k th tone of the OFDM symbol transmitted from the i th transmit antenna to j th receive antenna at time n . $w_j[n, k]$ denotes the additive Gaussian white noise at antenna j with zero mean and variance σ^2 . The noise variance σ^2 is assumed unknown in the system. In order to perform decoding and diversity combining at receiver, $H_{ij}[n, k]$ should be detected. A hybrid CME and LS estimation approach is described in the following section.

III. PROPOSED CME-LS CHANNEL ESTIMATION

Determination of the number of model parameters is critical in determining an optimal solution in communication systems. An effective approach, conditional model order estimator (CME), is proposed in [12]. The algorithm is based on a maximum a posteriori (MAP) rule, and can be used to acquire essential parameters in terms of maximizing the conditional probability density function (PDF) of the data, without any requirements of prior knowledge. The CME rule described in [12] chooses the hypothesis that maximizes

$$L_{xTi}(\mathbf{x}) = p_x(\mathbf{x}; \boldsymbol{\theta}_i | H_i) / p_{Ti}(\mathbf{T}i(\mathbf{x}); \boldsymbol{\theta}_i | H_i). \quad (2)$$

If the noise variance is unknown, the system can be modeled as a Gaussian linear system,

$$\mathbf{x} = \mathbf{H}\boldsymbol{\theta} + \mathbf{w}, \quad (3)$$

where \mathbf{H} is $N \times p$ matrix, $\boldsymbol{\theta}$ is $p \times 1$ matrix, \mathbf{w} is noise vector $\{\mathbf{w} \sim N(0, \sigma^2 \mathbf{I})\}$. The complete derivation is illustrated in [12]. Finally, the CME rule is simplified so as to choose the model order i that minimizes

$$\begin{aligned} \text{CME}(i) &= \ln \hat{\sigma}_i^2 \times (N - i - 2) / 2 \\ &+ \frac{1}{2} \ln |\mathbf{H}_i^T \mathbf{H}_i| + \ln \{ [\pi(N - i)]^{(N-i)/2} / \Gamma(\frac{N-i}{2}) \} \end{aligned} \quad (4)$$

N is the number of data used to determine the model order, $i=1, 2, \dots, M$, M is the maximum possible order, Γ is gamma and $\Gamma(n+1)=n!$, $[\]^T$ stands for transpose of a matrix, and the sufficient statistic for unknown parameters is

$$\hat{\sigma}_i^2 = \frac{1}{N-i} (\mathbf{x} - \mathbf{H}_i \hat{\boldsymbol{\theta}}_i)^T (\mathbf{x} - \mathbf{H}_i \hat{\boldsymbol{\theta}}_i), \quad (5)$$

$$\hat{\boldsymbol{\theta}} = (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \mathbf{x}. \quad (6)$$

This paper proposes the use of a modified CME to estimate the number of channel paths in a MIMO-OFDM system.

A. Estimation of the Number of Channel Paths

In order to apply the CME criterion in MIMO-OFDM systems and reduce the complexity of the original CME algorithm, pilots are applied in the process of estimation.

With the assistance of pilots, $\hat{\boldsymbol{\theta}}$ should be known as ($\hat{\boldsymbol{\theta}} \approx \boldsymbol{\theta}$), and thus the detection for $\hat{\boldsymbol{\theta}}$ in (6) is unnecessary. According to [12], the sufficient statistic can be defined as,

$$\mathbf{T}(\mathbf{y}_j) = [\mathbf{s}, \hat{\sigma}_i^{j^2}]. \quad (7)$$

Using the system mode of section II, the CME criterion is simplified and redefined as:

$$\begin{aligned} p_x(\mathbf{y}_j; \mathbf{s}_i, \sigma_i^{j^2}) &= (2\pi\sigma_i^{j^2})^{-\frac{P}{2}} \\ &\times \exp\left[-\frac{1}{2\sigma_i^{j^2}} (\mathbf{y}_j - \sum_{i=1}^{N_t} \mathbf{H}_i^j \mathbf{s}_i)^T (\mathbf{y}_j - \sum_{i=1}^{N_t} \mathbf{H}_i^j \mathbf{s}_i)\right] \end{aligned} \quad (8)$$

$$\begin{aligned} p_x(\mathbf{T}(\mathbf{y}_j); \mathbf{s}_i, \sigma_i^{j^2}) &= p(\mathbf{s}_i; \sigma_i^{j^2}) \times p(\hat{\sigma}_i^{j^2}; \sigma_i^{j^2}) \\ &= [(2\pi)^P |\sigma_i^{j^2} (\mathbf{H}_i^{j^T} \mathbf{H}_i^j)^{-1}|]^{-1/2} \times [(P-l)\hat{\sigma}_i^{j^2} / \sigma_i^{j^2}]^{(P-l)/2-1} \\ &\times \exp\left[-\frac{(P-l)}{2\sigma_i^{j^2}} \hat{\sigma}_i^{j^2}\right] \cdot \{(P-l) / [\sigma_i^{j^2} \times 2^{(P-l)/2} \Gamma(\frac{P-l}{2})]\} \end{aligned} \quad (9)$$

$$(\hat{\sigma}_i^j)^2 = \frac{1}{P-l} \left(\mathbf{y}_j - \sum_{i=1}^{N_t} \mathbf{H}_i^j \mathbf{s}_i \right)^T \left(\mathbf{y}_j - \sum_{i=1}^{N_t} \mathbf{H}_i^j \mathbf{s}_i \right). \quad (10)$$

Therefore, from (2), (7), (8), (9),

$$\begin{aligned} L_{xTi}(y) &= p_x(\mathbf{y}; \mathbf{s}_i, \sigma_i^j) / p_{Ti}(\mathbf{T}i(\mathbf{y}); \mathbf{s}_i, \sigma_i^j) \\ &= \Gamma\left(\frac{P-l}{2}\right) / \{ [\pi(P-l)]^{(P-l)/2} |\mathbf{H}_i^{j^T} \mathbf{H}_i^j|^{1/2} (\hat{\sigma}_i^j)^{(P-l)/2-1} \} \end{aligned} \quad (11)$$

Equation (11) can be finally expressed as

$$\begin{aligned} \text{CME}_{ij}(l) &= [(P-l-2)/2] \times \ln(\hat{\sigma}_i^j)^2 + \\ &\frac{1}{2} \ln |(\mathbf{H}_i^j)^T \mathbf{H}_i^j| + \ln \{ [\pi(P-l)]^{(P-l)/2} / \Gamma(\frac{P-l}{2}) \} \end{aligned} \quad (12)$$

where $(\hat{\sigma}_i^j)^2$ is given in (9), \mathbf{H}_i^j is the estimated channel frequency response between i th transmitter antenna and j th

receiver antenna obtained by LS estimation, s_i are the pilots delivered from i th antenna, P is the total number of pilots and $l=1, 2, \dots, L$, where L stands for maximum possible number of channel paths. Therefore, the number of channel paths can be finally detected by minimizing CME,

$$\hat{l} = \arg \min_l \{CME_{ij}(\mathbf{y}_j, l)\}. \quad (13)$$

In order to acquire the number of channel taps, the channel frequency response is required. Here a least squares (LS) approach is used for this purpose due to its low computational complexity. However the proposed CME can be combined with other channel detection methods such as minimum mean square error (MMSE) estimation, which are capable of achieving better performance.

B. Pilot Assisted LS Estimator

The frequency selective channel is assumed to be Rayleigh-fading, with frequency response: \mathbf{H}_{ij}^p and impulse response: $h_{ij}[l]$, $l=0, 1, \dots, L-1$, corresponding to the channel between i th transmit-antenna and j th receive-antenna, and L is the number of channel taps. The received pilot symbols at the j th receive antenna are

$$\mathbf{y}_j^p = \sqrt{\varepsilon_p} \sum_i \mathbf{H}_{ij}^p \mathbf{s}_i^p + \mathbf{w}_j^p, p \in I_p, \quad (14)$$

where \mathbf{w}_j^p is additive white Gaussian noise (AWGN), ε_p is the transmitted power per pilot symbol, I_p denotes the position of pilot sub-carriers, and P is the number of pilots. Using [13], for both transmitter and receiver diversity scheme, the following is defined

$$\mathbf{G}_i = (\varepsilon_p \mathbf{F}_p \mathbf{D}^H(\mathbf{s}_i^p) \mathbf{D}(\mathbf{s}_i^p) \mathbf{F}_p^H)^{-1} \times (\sqrt{\varepsilon_p} \mathbf{D}(\mathbf{s}_i^p) \mathbf{F}_p^H)^H, \quad (15)$$

and the LS estimate of channel impulse is given by

$$\hat{\mathbf{h}}_{ij} = \mathbf{G}_i \mathbf{y}_j^p, \quad (16)$$

where \mathbf{F} is a $L \times K$ matrix $[\mathbf{F}]_{l,k} = \exp(j2\pi(l-1)(k-1)/K)$, \mathbf{f}_{ip} , ($i, p=1, \dots, I_p$) is p th column of \mathbf{F} , $\mathbf{F}_p = [\mathbf{f}_{1p}, \dots, \mathbf{f}_{I_p p}, \dots, \mathbf{f}_{I_p p}]$, and thus $\mathbf{F} = [\mathbf{f}_1, \dots, \mathbf{f}_n, \dots, \mathbf{f}_K]$; \mathbf{s}_i^p is the transmitted pilot symbols. In addition, $D(x)$ stands for a diagonal matrix with x in its diagonal, and $[\]^H$ is the Hermitian transpose. Thus, the estimated channel frequency response is

$$\hat{\mathbf{H}}_{ij} = \mathbf{f}_n^H \hat{\mathbf{h}}_{ij}. \quad (17)$$

Overall, the hybrid CME-LS algorithm can be regarded as a decision feedback approach which is shown in Fig.2.

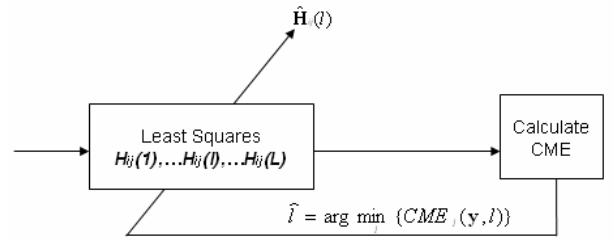


Fig. 2. Hybrid CME-LS channel estimation

IV. SIMULATION AND RESULTS

A 2×2 MIMO-OFDM system with Alamouti space-time code [14], which is the best known OSTBC, is employed to demonstrate the performance of proposed hybrid approach in multi-path Rayleigh fading channels.

A. Performance Comparison for CME & MDL

The performance of CME and minimum description length (MDL) is compared through simulation. MDL has been employed in OFDM system in [10] and MIMO-OFDM in [11]. According to [12], the MDL for MIMO system can be expressed as,

$$MDL_{ij}(l) = (P/2) \ln(\hat{\sigma}_i^2)^2 + [(L+1)/2] \ln P \quad (18)$$

$$(\hat{\sigma}_i^2)^2 = (\mathbf{y}_j - \sum_i \mathbf{H}_{ij}^p \mathbf{s}_i)^T (\mathbf{y}_j - \sum_i \mathbf{H}_{ij}^p \mathbf{s}_i) / P \quad (19)$$

$$\hat{l} = \arg \min_l \{MDL_{ij}(\mathbf{y}_j, l)\} \quad (20)$$

2000 OFDM symbols are employed to compare the performance of CME and MDL. Each OFDM symbol contains K sub-carriers ($K=256$) in which P ($P=8$) pilots are utilized to detect both number of channel taps and channel gains, the cyclic prefix (CP) number is chosen as $G=K/4=64$. With the aim of testing the proposed approach, the assumption that the maximum delay of multi-path fading channels is less than the cyclic prefix period and can thus be ignored, is made. The channel model is assumed quasi-static.

Fig. 3 indicates the comparison of probability of correct detection of channel model order between CME and MDL at different SNR when the number of channel paths $L=1, 2, 3$ and 4, respectively. Given that the model order estimator is affected by noise significantly, the detection begins from SNR=10 dB. The results show that the CME is superior to MDL in estimation of the number of channel paths. It should be noted that there is an upper limit to the quantity of taps that can be accurately estimated based on the number of pilot tones used. According to the research, in order to correctly detect L , the number of pilots P should be: $P \geq 2L+1$, and thus no more than 3 channel paths can be detected in the simulation above since only 8 pilot symbols are employed. Using the same simulation parameters as above and in the case of SNR=20dB, a probability of only around 30% is achieved for $L=4$ (See Fig.3).

Therefore, for $L \geq 4$, the 8 pilot estimator is insufficient. Increasing the number of pilots will increase the estimation

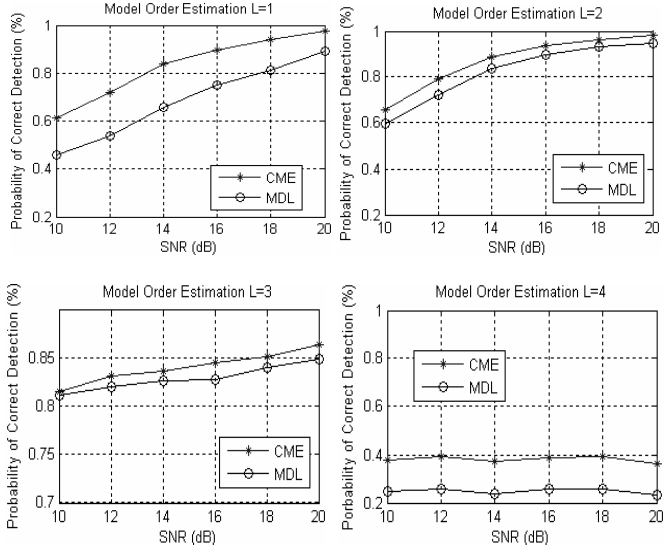


Fig.3. Comparison of probability of correct detection between CME & MDL with 8 pilots

accuracy for more complex propagation environments, but will also reduce bandwidth efficiency. In many common propagation environments, it may be possible to assume that there are only 3 or less dominant transmission paths. Where such an assumption does not hold, more pilots should be employed, despite the consumption of additional bandwidth. For a more complex wireless environment, 16 pilot symbols are used and accuracy results are given in Fig.4. In this case, more pilots are utilized and the number of channel paths that can be correctly detected increases. A comparison of both estimators in Table I shows that CME still outperforms MDL overall.

Simulated BER performance for BPSK modulation is depicted in Fig. 5. Here LS estimation - with known number of taps ($L=4$), CME-LS and MDL-LS estimation are compared. It can be seen that the performance of CME is quite close to LS with known L . At higher SNRs the CME

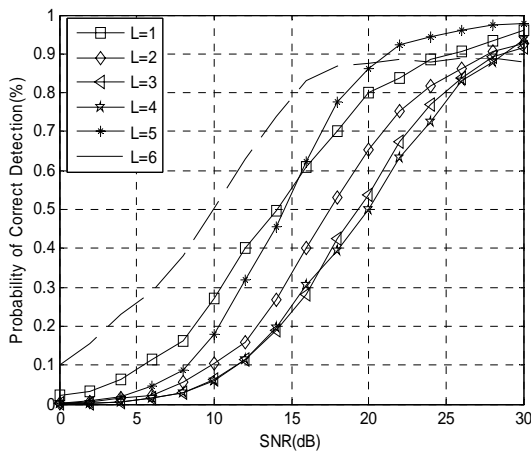


Fig.4. Probability of correct detection for CME with 16 pilots

TABLE I
COMPARISON OF CME & MDL WITH 16 PILOTS

SNR=30dB	Algorithm	Actual number of taps (L)					
		L=1	L=2	L=3	L=4	L=5	L=6
Probability of correct detection	CME	96.70%	93.45%	91.30%	90.50%	98.60%	88.40%
	MDL	75.00%	94.65%	88.60%	87.90%	56.75%	54.55%

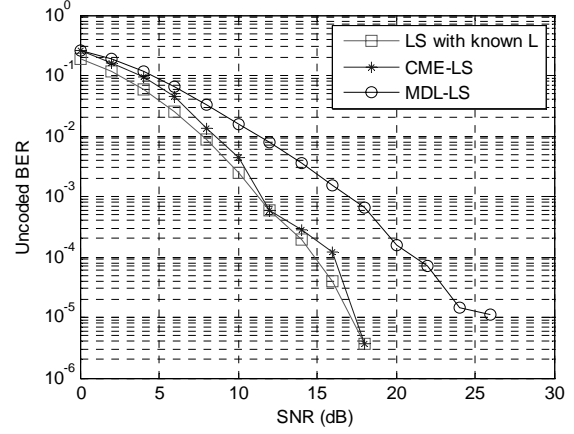


Fig.5. Comparison of BER performance of LS with known number of taps (L), CME-LS & MDL-LS with 16 pilots

detector works quite well and achieves better performance than that of MDL-LS, demonstrating its advantage in such situations. However, by taking the computational complexity into account, MDL is better than CME, the ratio of average CPU time requirement of MDL is only 80% to that of the proposed CME. Nevertheless, the proposed algorithm is preferred due to its significant performance gain.

B. CME-LS in Nonzero Taps Estimation

In practice, wireless multi-path channels are dominated by a relatively small number of significant paths, and detecting nonzero taps becomes a critical approach in reducing algorithm complexity and improving system efficiency. The proposed approach is also verified as an effective method for determining the number of key taps in a MIMO-OFDM system. Examples obtained from the simulation with 8 pilots are shown in Table II. 100 packets of data are utilized as the input signal, the actual number of multi-path taps is set to 3, with one of the paths having a much lower power than the others. ($P_{hi}=|h_i|^2 < 2|w|^2$, $|w|^2$ is noise power, $i=1,2,3$). According to Table II, the majority of the packets only detect two paths in spite of three taps being present in the system (e.g. SNR=20dB, 99 out of 100 packets determine that the

TABLE II
CME IN NON-ZERO TAPS DETECTION FOR MIMO-OFDM

	SNR(dB)	Model Order under Estimation			
		1	2	3	4
Number of Estimated	10	5	72	20	3
Order ($N_{i=1}$)	15	2	90	8	0
	20	0	99	1	0

number of taps is 2). The performance of the proposed CME improves significantly as noise decreases.

C. CME-LS for Fixed Broadband MIMO-OFDM System

Parameters for a fixed wireless system are set according to IEEE 802.16-2004 [15], each OFDM symbol contains K sub-carriers ($K=256$) in which 192 tones are used for data transmission and P ($P=8$) pilots are utilized to detect both channel taps and channel gains, the remaining sub-carriers are employed as lower and upper guards. The cyclic prefix (CP) number is chosen as $G=K/4=64$. The system bandwidth is 1.75MHz, and the sampling factor is 8/7. Since 256 sub channels are used, the useful symbol time is 128 μ s and CP time is 32 μ s. The system is operating on SUI-4 channel model, which is shown in Table III

TABLE III
SUI-4 CHANNEL MODEL

	Tap 1	Tap2	Tap3
Delay [μ s]	0	1.5	4.0
Power [dB]	0	-4	-8
Doppler [Hz]	0.20	0.15	0.25

BPSK is used in the simulation. The probability of correct detection for CME-LS in fixed broadband MIMO-OFDM is shown in Fig.6. 2000 OFDM symbols are utilized in the simulation. The comparison of BER performance between CME-LS estimation and LS with known number of channel taps L is depicted in Fig.7. The results confirm that CME-LS works well in estimation the number of multi channel paths in fixed Broadband wireless system.

D. CME-LS for Mobile Broadband MIMO-OFDMA System

The mobile system simulation is based on the IEEE 802.16e [16] standard, where MIMO-OFDMA is applied instead of MIMO-OFDM. OFDMA (Orthogonal Frequency-division Multiple Access) uses the same techniques as OFDM, but allows for a multiple-access function. Downlink partial usage of sub-channels (DL-PUSC) is employed, and sub-carriers are divided into physical clusters, each of which contains 14 adjacent subcarriers. In contrast to full usage of sub-channels (FUSC), the pilots for PUSC allocated to subchannels, with each subchannel having its own pilot arrangement [16]. For OFDMA, the physical clusters are renumbered into logical cluster, which are then divided into 6 sub-channel major groups and finally allocated to several segments of the downlink sub-frame. In a segment, a user is only able to obtain information from the clusters allocated to him, and at least one group of cluster shall be allocated. In this paper, the channel estimation is carried out per group, assume that only one major group allocated to a user in a segment, and thus we can focus on demonstration of the proposed channel estimation approach in the broadband mobile system. According to IEEE 802.16e, there are four OFDMA symbol structures with FFT sizes of 128, 512, 1024 and 2048, respectively. The OFDMA symbol parameters for simulation and the channel model "Vehicular A" are shown in Table IV and Table V, respectively.

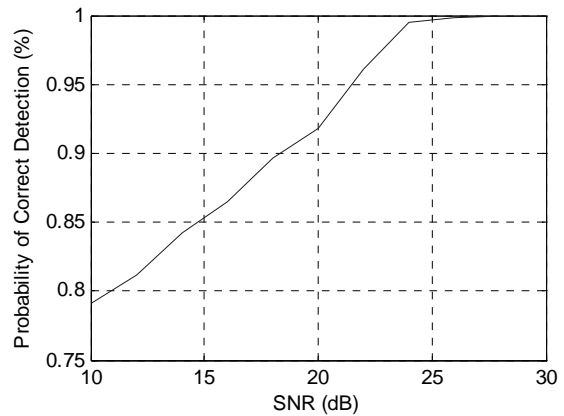


Fig.6. Probability of correct detection for CME-LS with 8 pilots

TABLE IV
SYSTEM PARAMETERS FOR MOBILE SYSTEM

parameter	
FFT size	1024
Number Of used subcarriers	841
Number of guard subcarriers	92+91
Cyclic prefix	1/8
Channel bandwidth (MHz)	10
Sampling frequency (MHz)	11.2
Subcarrier spacing (KHz)	10.94
Useful symbol time (μ s)	91.4
CP time (μ s)	11.4
OFDM duration (μ s)	102.9

TABLE V
"VEHICULAR A" CHANNEL ENVIRONMENT

Tap	Time delay (μ s)	Average power (dB)
1	0	0
2	0.31	-1
3	0.71	-9
4	1.09	-10
5	1.73	-15
6	2.51	-20

For OFDMA with 1024 subcarriers, there are two kinds of groups: one contains 12 clusters and another includes 8 clusters; 2 pilots are inserted in each cluster according to the standards [16]. In the simulation, we choose to show the performance of the group with 8 clusters, and thus 16 pilot symbols can be used. QPSK modulation is utilized. The comparison of BER performance between CME-LS and LS with known number of channel paths (L) is presented in Fig.8. The Doppler shift for the mobile system is set as $fd=40\text{Hz}$, where Rayleigh fading is generated by Jake's model. The results indicated that the proposed algorithm is capable of obtaining almost the same results as that with known channel tap length in mobile broadband MIMO-OFDM system.

V. CONCLUSION

In this paper, the proposed pilot-assisted CME based channel estimation algorithm has been shown to be a viable approach in determining the number of channel paths, especially nonzero paths, for broadband MIMO-OFDM systems in the absence of prior knowledge of model parameters. A comparison of the performance between the modified CME and MDL has shown that the former is superior. Although the simulations have been done in relatively simple wireless environments, i.e. the number of channel taps is less than or equal to 3, it is possible to apply the estimation scheme in more complex environments by increasing the number of pilot tones. The algorithm also is verified its capacity in both fixed and mobile MIMO-OFDM wireless system based on IEEE 802.16d/e standard. While the modified CME algorithm is combined with LS channel estimation, it is not restricted to this approach and can be combined with other estimation schemes. For example, a hybrid CME-MMSE algorithm could improve the system BER performance at the cost of increased computational complexity. The benefit of the CME approach to estimating the number of channel paths has been established. Further research into hybrid methods employing this approach is warranted, and hardware demonstration is in consideration.

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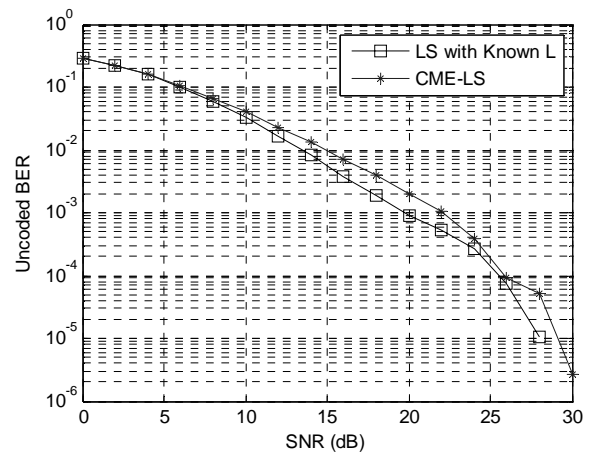


Fig.8. Comparison of BER performance between CME-LS & LS with known number of channel taps (L) in mobile system

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