Channel Estimation for OFDM Systems over Time-Varying and Sparse Dispersive Channels

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***Abstract*—Time-varying channel gains are approximated by basis expansion model (BEM) to make the tremendous unknowns estimation feasible in orthogonal frequency division multiplexing (OFDM) systems. However, sparse dispersive channel requires overloaded subcarriers for pilot-aided estimation in the framework of BEM. This paper proposes a channel estimation scheme over time-varying and sparse dispersive channel with circular grouped pilot pattern, which occupies much less subcarriers. In this scheme, the sparse tap delays are detected with the interpolated channel frequency response and the modified BEM based estimation deals with only the detected taps, eliminating the noise interference from the null taps. The proposed estimator outperforms the existing methods applied to sparse dispersive channel with higher spectral efficiency. Our claims are verified by simulation results, which are obtained in COST207 typical urban channel model.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is a promising transmission technology over wireless channel due to its high transmission capability, robustness to multipath fading, and flexible spectrum allocation for different services. In OFDM systems, the data is divided into many parallel orthogonal substreams for transmission, leading to much longer symbol duration than the maximum multipath delay. However, the channel time-variation within one OFDM symbol duration destroys the desirable orthogonality of subcarriers on quasi-static channel assumption that the channel is deemed to be invariant during the interested period. As a result, the induced inter-carrier interference (ICI) smears the pilots for channel estimation and the performance of one-tap frequency-domain equalizer for data detection degrades significantly [1]. Therefore, effective channel estimation is the bottleneck for OFDM system performance improvement over time-varying channels.

Unlike the quasi-static channel model, fast time-varying channel encompasses tremendous unknown channel gains within OFDM symbol duration to track, the number of which is always much larger than that of the observable data on the pilot subcarrier, resulting in under-determined formula for channel estimation.

To make the estimation feasible, the linear time-varying (LTV) channel model was proposed to fit the varying tap with the average gain and the corresponding slopes [2]. This method employs the comb-type pilot pattern [3] to calculate the average gain and smooth adjacent symbol average gains with proper sloped lines. However, the comb-type pilots suffer the ICI from data subcarriers, affecting the accuracy of average gain estimation. Dual-ICI cancellation is induced to alleviate the ICI contamination on pilots [4]. However, the LTV model approximates the highly mobile channel with unfavorable modeling error.

Recently, many existing works resort to estimating the equivalent discrete-time channel taps by the basis expansion model (BEM) for better modeling accuracy [5]. In the BEM framework with the equispaced grouped pilot pattern [6], channel estimation amounts to estimating the model coefficients to reduce the substantial burden. Qu and Yang developed a windowed least-squares (LS) method for BEM based estimation to reduce the high frequency leakage due to truncated Fourier transform [7]. Two training symbols are padded to both ending of OFDM blocks to perform BEM coefficients estimation in time domain which circumvents the affection of ICI in frequency domain [8]. A novel Wiener filter for BEM based channel estimation considering the effect of ICI was proposed in [9]. To reduce the computational complexity of BEM based estimation, Lengendre polynomial fitting has been introduced to smooth the frequency response of each tap with performance improvement due to noise counteraction in low signal-to-noise ratio (SNR) environment [10].

The rationale behind BEM based estimation is to take advantage of both the response for the pilots and the corresponding ICI on the guard bands, meanwhile, preventing the disturbance of ICI from data symbols. Many subcarriers act as the guard band for the pilots. In this context, the spectral efficiency is inversely proportional to the maximum path delay with the sampling period fixed. For sparse dispersive channel which has a few nontrivial taps scattered in large delay range, the spectral efficiency for BEM based estimation is often unacceptable in practice. Zhou and Lam coined a hybrid pilot pattern with both comb-type pilot pattern to detect the sparse taps and a equispaced grouped pilot pattern to perform BEM based estimation for only those detected taps with the other tap gains null [11]. Nevertheless, hybrid pilot pattern imposes much practical complexity in the receiver design.

In this paper, a novel two-step channel estimation method over sparse dispersive channel is proposed. To track the time-variation of the tap gains and nontrivial tap delays in time, each

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OFDM symbol reserves subcarriers for circular grouped pilots, which occupy much less frequency spectrum than those in the BEM based estimation. OFDM symbols are handled block by block. First, the first few symbols interpolate all the channel frequency responses (CFRs) in time domain at all subcarriers that may occur pilots for any OFDM symbol. The sparse tap delay detection is based on the inverse Fourier transform of those CFRs according to most significant taps (MST) criterion [12]. Second, only the detected nontrivial taps are estimated in modified BEM framework and the other taps are set null to eliminate the noise interference.

The rest of this paper is organized as follows. In Section II, the sparse dispersive channel model and OFDM system model are presented. The novel channel estimation for sparse dispersive channel is proposed in Section III. Section IV shows the simulation to compare the performance of the proposed and the existing methods and Section V summarizes this paper.

II. Data Model

A. Sparse Dispersive Channel Model

Suppose the wireless channel has a discrete-time baseband impulse response given by

$$h(n) = \sum_{l \in \mathcal{L}} \alpha_l(n) \delta(n-l) \tag{1}$$

where $\alpha_l(n)$ is the complex path gain of the *n*th sample and the *l*th tap. For time-varying channel, the gains are wide-sense stationary (WSS) narrow-band complex Gaussian processes with specific Doppler power spectrum and uncorrelated with respect to each other [13]. $\mathcal{L}$ denotes a index set of taps with nontrivial gains and corresponding delay $\tau_l = lT_s$, where T_s is the sampling period.

The sparse dispersive channel comprises several taps with far apart delays. In other words, the tap index set $\mathcal{L}$ satisfies the following condition

$$\max\{\mathcal{L}\} \gg \mathrm{numel}\{\mathcal{L}\} \tag{2}$$

where $\max\{\mathcal{L}\}$ represents the maximum index in $\mathcal{L}$ and $\mathrm{numel}\{\mathcal{L}\}$ is the number of elements in $\mathcal{L}$.

Generally, $\max\{\mathcal{L}\}$ is not always available over time-varying channel since it may vary for every realization. Also, the nontrivial tap selection criterion of nontrivial taps depends on current signal-to-noise (SNR) condition and the estimation parameters. So both metrics in (2) are upper bounds determined by channel statistics and other user-defined factors.

B. OFDM System Model

Consider an OFDM system with N subcarriers. The duration of an OFDM symbol including cyclic prefix (CP) is $T = (N + N_{cp})T_s$. The CP length N_{cp} is assumed to be larger than the maximum channel delay $L = \max\{\mathcal{L}\}$ to avoid inter-symbol interference (ISI). Let $\mathbf{X}_n = [X_n(0), \ldots, X_n(N-1)]^T$ be the *n*th modulated complex-valued OFDM symbol for transmission. In each symbol, some subcarriers are reserved for channel estimation at the receiver. After passing though the sparse dispersive channel depicted in (1), the output of fast Fourier transform (FFT) is given by

$$\mathbf{Y}_n = \mathbf{G}_n \mathbf{X}_n + \mathbf{W}_n \tag{3}$$

In (3), $\mathbf{Y}_n = [Y_n(0), \ldots, Y_n(N-1)]^T$, $\mathbf{W}_n$ is zero-mean complex additive white Gaussian noise with variance σ^2 and $\mathbf{G}_n$ is the CFR matrix for *n*th OFDM symbol with (p, q)th element as

$$\mathbf{G}_n(p,q) = \frac{1}{N} \sum_{k=0}^{N-1} \sum_{l \in \mathcal{L}} \alpha_{n,l}(k) e^{j\frac{2\pi}{N}k(p-q)} e^{-j\frac{2\pi}{N}ql} \tag{4}$$

where $\alpha_{n,l}(k) = \alpha_l(n(N + N_{cp}) + N_{cp} + k)$ indicates the complex gain for *n*th OFDM symbol.

For fast fading channel, the quasi-static assumption that $\alpha_{n,l}(k)$ is invariant for $k = 0, 1, \ldots, N-1$ is no longer adequate. The evident problem is the ICI due to non-zero off-diagonal entries of channel matrix $\mathbf{G}_n$ in (4) degrades the performance of pilot-aided channel estimation and the following data detection.

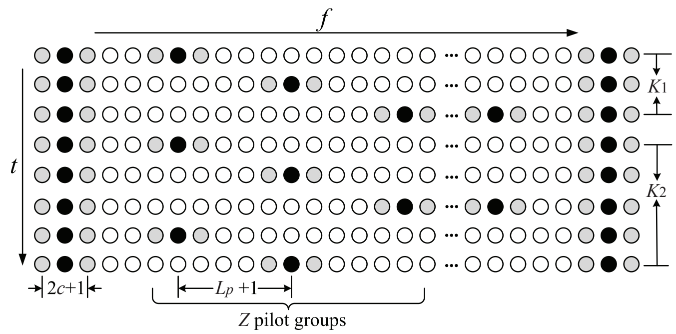

Fig. 1. Pilot pattern, where the white dot represents the user data, the gray dot represents zero guard band, and black dot represents the pilot.

III. Proposed Channel Estimation

A. Proposed Pilot Pattern

The circular grouped pilot pattern shown in Fig. 1 is adopted in this paper. In this scheme, each OFDM symbol comprises subcarriers of three types: user data (denoted by white dots), pilots (denoted by black dots), and zero guard band (denoted by gray dots). One pilot and $2c$ surrounding guard subcarriers constitute one pilot group. The guard band is employed to protect the central pilot from the detrimental ICI. N_g pilot groups are arranged in circular pattern for adjacent OFDM symbol, meant to ease both interpolation for sparse multipath delay detection and tracking of channel variation in time, see section III.B.

The circular period consists of Z pilot groups spaced by L_p subcarriers for adjacent OFDM symbols. The positions of first and last pilot group are fixed on both edges of the spectrum for ease of manipulation. In formulas, the *i*th pilot position for

nth OFDM symbol is given by

$$p_{n,i} = \begin{cases} c & i = 1 \\ N - 1 - c & i = N_g \\ c + [(1 + n_{\text{mod}(Z)}) + (i-1)Z]L_p & \text{otherwise} \end{cases} \tag{5}$$

The pilot pattern should conform to the following requirements

1) $N_g \geq L_{\text{est}}$ where L_{est} is the number of nontrivial taps to estimate.
2) $2c+1 \geq Q$ for LS estimator where Q is the number of basis functions, discussed in Section III C.
3) $2 + (N_g - 2)Z \geq L$ for scanning all taps for nontrivial ones, discussed in Section III B.

The circular factor Z trade-offs the interpolation performance and the spectral efficiency. Larger Z results in larger interpolation error together with better spectral efficiency. See [14] for elaborate analysis of time-domain interpolation error over time-varying channels. We suppose the allowable maximum pilot occupancy ratio is γ. Hence, the range of Z is

$$\frac{L-2}{N_g - 2} \leq Z \leq \frac{\gamma N - 2}{(N_g - 2)(2c+1)} \tag{6}$$

B. Sparse Multipath Detection

At the receiver, OFDM symbols are addressed block by block. Each block contains $K = K_1 + K_2$ OFDM symbols, the first K_1 of which is employed for path delay detection. Then, channel estimation within all the K symbol duration depends on the path delay distribution, since it provides the objective taps to estimate and assumes the other taps are trivial to eliminate the influence of noise. Unlike the method in [11] that $K_1, K2$ (denoted by M_1, M_2 in [11]) are predetermined at the transmitter, K_1, K_2 in the proposed method are adjusted flexibly at the receiver according to the estimated channel Doppler frequency or other factors. The ratio K_1/K is supposed to be high to fit fast fading channels.

We first obtain the channel frequency responses (CFRs) at the pilot subcarriers by LS estimation

$$G_n(p_{n,i}) = \frac{Y_n(p_{n,i})}{X_n(p_{n,i})} + \frac{W_n(p_{n,i})}{X_n(p_{n,i})} \tag{7}$$

for $n = 0, \ldots, K_1 - 1$ and $i = 1, \ldots, N_g$. It is worth noting that $G_n(p_{n,i})$ is much more accurate in fast fading channels than the counterpart in the comb-type pilot pattern due to the the protection of guard bands.

Then, time-domain interpolation provides CFRs at data subcarriers with the same index on the frequency axis but belongs to different OFDM symbols. Several techniques have been proposed to accomplish this task [3], such as linear interpolation, low-pass interpolation, spline cubic interpolation, etc. The interpolation optimization is out of the scope of this paper.

After the interpolation, $N_{ap} = 2 + Z(N_g - 2)(\geq L)$ CFRs are known for each OFDM symbol. With all the CFRs $G_n(q_i)$ for $n = 0, \ldots, K_1 - 1$, $q_i = c + (i-1)L_p$, and $i = 1, \ldots, N_{ap}$, the LS channel estimate for lth tap in time domain can be obtained by

$$\bar{h}_n(l) = \frac{1}{N_{ap}} \sum_{i=1}^{N_{ap}} G_n(q_i) e^{j2\pi l q_i / N} \tag{8}$$

We calculate the average power of lth tap for the first K_1 OFDM symbols as

$$P(l) = \frac{1}{K_1} \sum_{n=0}^{K_1 - 1} |\bar{h}_n(l)|^2 \tag{9}$$

Finally, L_{est} MST [12] are chosen according to the order of $P(l), l = 0, \ldots, L-1$ and reserve their index into the set $\mathcal{L}$ in (1).

C. Sparse Channel Estimation and Data Detection

In the BEM framework, the lth time-domain channel tap for nth OFDM symbol can be formulated by

$$\alpha_{n,l} = \sum_{q=0}^{Q-1} \mathbf{b}_q c_q(l) + \mathbf{v}_l \tag{10}$$

where Q is the number of basis functions $\mathbf{b}_q$, $c_q(l)$ denote the coefficients to estimate first, and $\mathbf{v}_l$ is the modeling error.

Substituting (10) into (3) and after some algebra, we have the estimation formula as [5]

$$\mathbf{Y}^{(p)} = \mathbf{D}\tilde{\mathbf{c}} + \mathbf{V} \tag{11}$$

where

$$\begin{gathered} \mathbf{D}_{QN_g \times QL_{\text{est}}} = [\mathbf{D}_0, \mathbf{D}_1, \ldots, \mathbf{D}_{Q-1}] \cdot \left(\mathbf{I}_Q \otimes \tilde{\mathbf{X}}^{(p)} \right) \\ \tilde{\mathbf{c}} = \left[\mathbf{c}_0^T, \mathbf{c}_1^T, \ldots, \mathbf{c}_{Q-1}^T \right]^T \\ \mathbf{D}_q = \mathbf{F} \text{diag}\{\mathbf{b}_q\} \mathbf{F}^H \\ \mathbf{c}_q = [c_q(\text{vec}(\mathcal{L}))]^T \\ \tilde{\mathbf{X}}^{(p)} = \sqrt{N} \cdot \text{diag}\{\mathbf{X}^{(p)}\} \mathbf{F}(\mathbf{p}_x, \text{vec}(\mathcal{L})) \end{gathered}$$

In the above formula arrays, the superscript ^{T}, ^{H} denote the transpose and Hermitian operation, respectively. $\text{vec}(\mathcal{L})$ is the vector from the set $\mathcal{L}$ with ascent order, which is always not successive for dispersive channel. The superscript $^{(p)}$ indicates the vector with only the interested subcarriers for estimation [5], and $\mathbf{p}_x$ are the corresponding subcarriers index vector for pilots. $\mathbf{F}$ denotes the normalized Fourier matrix with the entries as $\mathbf{F}(m,n) = \exp(-j2\pi mn/N)/\sqrt{N}$ and $\mathbf{F}(\mathbf{x}, \mathbf{y})$ is the corresponding submatirx with row indexes in $\mathbf{x}$ and column indexes in $\mathbf{y}$. $\otimes$ stands for Kronecker product. $\text{diag}\{\mathbf{x}\}$ indicates a diagonal matrix with $\mathbf{x}$ as its diagonal.

Similar derivation can be found in [11]. QL_{est} BEM coefficients require enough observable data for feasible estimation. In other words, the condition $2c + 1 \geq Q$ is a necessity to provide enough ICI-free observable data for the pilot-aided channel estimation.

Next, the BEM coefficients can be calculated by LS estimator as

$$\tilde{\mathbf{c}} = \mathbf{D}^\dagger \mathbf{Y}^{(p)} \tag{12}$$

where the superscript † denotes Moore-Penrose inverse operation and the estimation error term is omitted for simplicity.

Given the coefficients, the CFR matrix $\mathbf{G}_n$ can be obtained for each OFDM symbol. Then, the QR-detection proposed in [15] takes advantage of CFR matrix for data symbol recovery with free ICI.

First, we perform QR-decomposition to matrix $\mathbf{G}_n$

$$\mathbf{G}_n = \mathbf{Q}_n \mathbf{R}_n \tag{13}$$

where $\mathbf{Q}_n$ is a $N \times N$ unitary matrix and $\mathbf{R}_n$ is a upper triangular matrix.

Second, from equation (3), the output can be written as

$$\mathbf{Y}'_n = \mathbf{Q}_n^H \bar{\mathbf{Y}}_n = \mathbf{R}_n(\mathbf{X}_n - \mathbf{X}^{(p)}) + \mathbf{Q}_n^H \mathbf{W}_n \tag{14}$$

where $\bar{\mathbf{Y}}_n = \mathbf{Y}_n - \mathbf{G}_n \mathbf{X}^{(p)}$, $\mathbf{X}^{(p)}$ is obtained by making the data subcarriers zeros, i.e., only the pilot subcarriers have non-zero values.

On basis of description above, the input symbols $\mathbf{X}_n$ can be calculated by iterative method without ICI, since $\mathbf{R}_n$ is a upper triangular matrix.

$$\tilde{X}_n(k) = \frac{\mathbf{Y}'_n(k) - \sum_{m=k+1}^{N} \mathbf{R}_n(k,m)\hat{X}_n(m)}{\mathbf{R}_n(k,k)} \tag{15}$$

$$\hat{X}_n(k) = \mathcal{O}(\tilde{X}_n(k)) \tag{16}$$

where $\mathcal{O}(\cdot)$ denotes the mapping operation to the nearest constellation point.

D. Computational Complexity Analysis

The purpose of this section is to determine the implementation complexity in terms of the number of the multiplications needed for K OFDM symbols. CFR calculation at pilot subcarriers (7) requires $K_1 N_g$ complex multiplications. Linear interpolation is adopted here, requiring $K_1(N_g - 2)(Z - 1)$ complex multiplications. Then, the power calculation of each tap takes $L N_{ap} K_1$ complex multiplications. BEM coefficients formula (12) needs one Moore-Penrose inverse operation of size $QN_g \times QL_{\text{est}}$, but with pilots known at receiver and fixed multipath delay for K OFDM symbols, $\mathbf{D}^\dagger$ has to be calculated only once. Also, $Q^2 N_g L_{\text{est}}$ complex multiplications are required for BEM coefficients in (12).

IV. Performance Evaluation by Simulation

The COST207 typical urban model [16] with 6 resolvable taps is deployed to evaluate the performance of the proposed channel estimation. The channel power intensity profile is listed in Table I. The number of the subcarriers of the OFDM system N is equal to 512, and the CP length N_{cp} is equal to 64. With the system bandwidth $W = 10\text{MHz}$, the symbol duration $T = 57.6\mu\text{s}$, the CP duration $T_c = 6.4\mu\text{s}$, which is larger than the maximum path delay in Table I. The transmitted signal is QPSK modulated.

The pilot pattern parameters for the proposed estimation are as follows: $N_g = 12$, $c = 2$, $M = 7$, $K_1 = 10$, and $K_2 = 30$. The LS estimator [3] and LTV model [2] use 80 comb-type pilots. Thus, for the proposed estimation, the occupied subcarriers by pilots and guard bands amount to $N_g(2c+1) = 60$, which is less than the comb-type pilot pattern. Besides, generalized complex exponential BEM (GCE-BEM) [17] with basis order $Q = 3$ is employed for sparse path estimation. We let $L_{\text{est}} = 7$ to comprise all the 6 taps with a little toleration of detection error.

TABLE I
COST207 Channel Power Intensity Profile

Tap	Delay(μs)	Gains(dB)	Doppler spectrum
1	0	-3	Jakes [13]
2	0.2	0	Jakes
3	0.6	-2	Gauss I
4	1.6	-6	Gauss I
5	2.4	-8	Gauss II
6	5.0	-10	Gauss II

TABLE II
Minimum Pilot Occupancy Ratio Comparison

Algorithm	Minimum pilot occupancy ratio	Example
LS [3]	$\frac{N_{cp}}{N}$	12.5%
LTV model [2]	$\frac{N_{cp}}{N}$	12.5%
BEM [5]	$\frac{N_{cp}(2c+1)}{N}$	63.4%
Estimation in [11]	$\frac{K_1 N_{cp}}{KN} + \frac{K_2 Q(2c+1) L_{\text{est}}}{KN}$	18.5%
The proposed	$\frac{L_{\text{est}}(2c+1)}{N}$	6.8%

Table II shows the minimum pilot occupancy ratio comparison of several popular estimations, such as LS and frequency-domain interpolation method [3], estimation in LTV model [2], conventional BEM estimation [5], hybrid pilot pattern for estimation [11] and the proposed estimation. For sparse dispersive channel, BEM estimation is poor in spectral efficiency since the pilot clusters for so many taps occupy large proportional of all the subcarriers. LS and LTV model takes the comb-type pilot pattern without any guard band, while hybrid pilot pattern consists of both comb-type and grouped pilot design. The proposed estimation adopts the circular designer, having the minimum required pilots and the guard bands. The data in example column of Table II exploits the parameter in this simulation. The conventional BEM estimation which is spectral inefficient and estimation with hybrid pilot pattern which requires two-mode receiver are not included for subsequent simulation analysis.

Fig. 2 compares the performance of the proposed, the LS and the LTV model for normalized Doppler frequency shift $f_d T = 0.01$ and $f_d T = 0.04$ in terms of normalized minimum square error (NMSE). In low SNR condition, the proposed estimation is inferior because sparse BEM estimation takes advantages of the ICI from the pilots for better accuracy, but the noise disturbs the ICI acquisition. When $\text{SNR} > 25\text{dB}$, NMSE of the proposed estimator are much better than LS and LTV model. The reason that merits our attention is two-folded. First, the sparse multipath detection eliminates the noise from

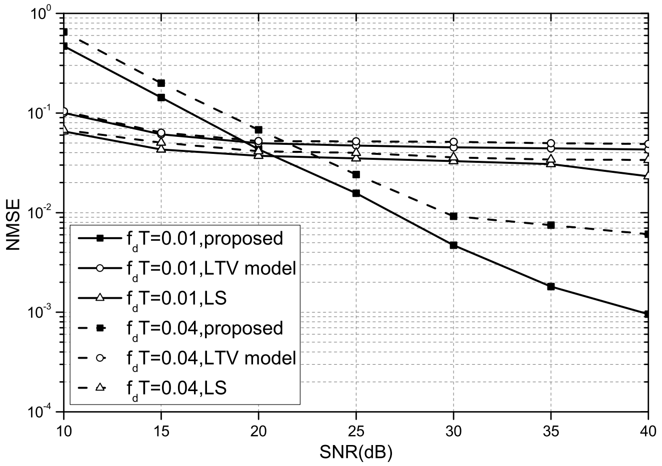

Fig. 2. Normalized MSE of the proposed, the LS, and the LTV model for normalized Doppler shift $f_d T = 0.01$ and $f_d T = 0.04$, respectively.

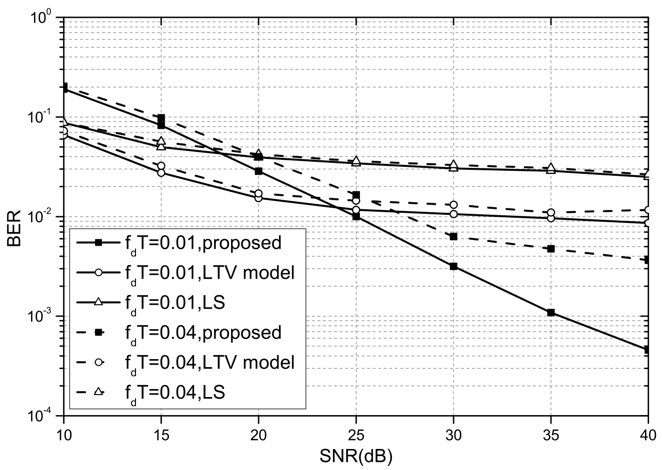

Fig. 3. BER of the proposed, the LS, and the LTV model for normalized Doppler shift $f_d T = 0.01$ and $f_d T = 0.04$, respectively.

the other null taps. Second, estimation in the BEM framework results in less modeling error relative to the frequency-domain interpolation in LS estimation and time-domain linear interpolation for LTV model. The proposed estimation avoids the spectral inefficiency problem of conventional BEM estimation, maintaining the satisfactory modeling accuracy.

Fig. 3 shows the OFDM system performance for the three estimator under different Doppler shifts conditions. The phenomenon that LS estimation with better MSE than LTV model manifests poor performance with respect to BER coincides with the aforementioned incapability of one-tap equalization over time-varying channel. That's why the QR-detection is induced. For LS estimation, only diagonal elements of the CFR matrix are used, while the LTV model takes the ICI into consideration by virtue of QR-detection, resulting in better detection performance. Also, the proposed estimation leads to less BER in high SNR environment with more accurate channel estimation.

V. Conclusion

In this paper, we present channel estimation over sparse dispersive channel in OFDM systems. A new circular pilot pattern has also been proposed to make the BEM based estimation spectral efficient. Only the detected nontrivial taps are handled with the others null, canceling most of the noise. The simulation demonstrates the priority of the proposed estimation over the existing methods. It's worth mentioning that the proposed estimation is vulnerable to the MST detection error due to interpolation inaccuracy, which is affected by the Doppler shift and the pilot circular period.

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References

[1] X. Cai and G. B. Giannakis, "Bounding performance and suppressing intercarrier interference in wireless mobile OFDM," *IEEE Transactions on Communications*, vol. 51, no. 12, pp. 2047-2056, Dec. 2003.

[2] Y. Mostofi and D. C. Cox, "ICI mitigation for pilot-aided OFDM mobile systems," *IEEE Transactions on Wireless Communications*, vol. 4, pp. 765-774, 2005.

[3] S. Coleri, M. Ergen, A. Puri, and A. Bahai, "Channel estimation techniques based on pilot arrangement in OFDM systems," *IEEE Transactions on Broadcasting*, vol. 48, pp. 223-229, 2002.

[4] K. Kyungchul, L. Sungeun, M. Hyunkee, C. Sooyong, and H. Daesik, "New OFDM Channel Estimation with Dual-ICI Cancellation in Highly Mobile Channel," *IEEE Transactions on Wireless Communications*, vol. 9, pp. 3155-3165, 2010.

[5] Z. Tang, R. C. Cannizzaro, G. Leus, and P. Banelli, "Pilot-assisted time-varying channel estimation for OFDM systems," *IEEE Transactions on Signal Processing*, vol. 55, pp. 2226-2238, 2007.

[6] A. Stamoulis, S. N. Diggavi, and N. Al-Dhahir, "Intercarrier interference in MIMO OFDM," *IEEE Transactions on Signal Processing*, vol. 50, pp. 2451-2464, 2002.

[7] F. Qu and L. Yang, "On the estimation of doubly-selective fading channels," *IEEE Transactions on Wireless Communications*, vol. 9, pp. 1261-1265, 2010.

[8] L. Huang Chang, C. Chao-Wei, and W. Shyue-Win, "Channel estimation for OFDM system with two training symbols aided and polynomial fitting," *IEEE Transactions on Communications*, vol. 58, pp. 733-736, 2010.

[9] K. Zhong, X. Lei, and S. Q. Li, "Wiener filter for basis expansion model based channel estimation," *IEEE Communications Letters*, vol. 15, pp. 813-815, Aug 2011.

[10] T. Hrycak, S. Das, G. Matz, and H. G. Feichtinger, "Practical estimation of rapidlly varying channels for OFDM systems", to be published.

[11] W. Zhou and W.-H. Lam, "Channel estimation and data detection for OFDM systems over fast-fading and dispersive channels," *IEEE Transactions on Vehicular Technology*, vol. 59, pp. 1381-1392, 2010.

[12] H. Minn and V. K. Bhargava, "Investigation into time-domain approach for OFDM channel estimation," *IEEE Transactions on Broadcasting*, vol. 46, pp. 240-248, 2000.

[13] W. C. Jakes, Microwave mobile communications, IEEE Press, New York, 1974.

[14] S. Tomasin and M. Butussi, "Analysis of interpolated channel estimation for mobile OFDM systems," *IEEE Transactions on Communications*, vol. 58, pp. 1578-1588, 2010.

[15] H. Hijazi and L. Ros, "Joint data QR-detection and Kalman estimation for OFDM time-varying Rayleigh channel complex gains," *IEEE Transactions on Communications*, vol. 58, pp. 170-178, 2010.

[16] M. Failli, "Digital land mobile radio communications COST 207," tech. rep., European Commission, 1989.

[17] G. Leus, "On the estimation of rapidly time-varying channels," in *Euro.Signal Process. Conf. (EUSIPCO), 2004*, pp. 2227-2230, 2004.