Simultaneous Multi-Channel Reconstruction for TDS-OFDM Systems

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Abstract—**Time domain synchronous orthogonal frequency division multiplexing (TDS-OFDM) has higher spectral efficiency than standard cyclic prefix OFDM (CP-OFDM), which is achieved by using a known pseudorandom noise (PN) sequence to replace the classical CP. However, due to the interference between the PN sequence and the data block, the performance of TDS-OFDM degrades severely over fast fading channels. To solve this problem, based on the distributed compressive sensing (DCS) theory, we propose an efficient way to realize simultaneous multi-channel reconstruction, which is achieved by using the inter-block-interference (IBI)-free region to reconstruct the high-dimensional sparse multipath channel. Specifically, we propose to utilize the temporal correlation of wireless channels as well as the channel property that path gains change much faster than path delays to simultaneously reconstruct multiple sparse channels. Then, we propose the parameterized channel estimation method based on simultaneous compressive sampling matching pursuit (S-CoSaMP) algorithm to achieve better channel estimation performance in fast time-varying channels. Simulation results demonstrate that the proposed scheme can achieve improved performance than conventional solutions.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is a typical multi-carrier modulation technique, which improves the spectrum utilization, the resistance of multipath fading and narrowband interference through the use of orthogonality among sub-carriers. Thus, OFDM has been widely applied in wireless communication and broadcasting systems [1].

There are basically three types of OFDM-based block transmission scheme: cyclic prefix OFDM (CP-OFDM) [2], zero padding OFDM (ZP-OFDM) [3], and time domain synchronous OFDM (TDS-OFDM) [4]–[6]. In the standard CP-OFDM scheme, CP is used as the guard interval. In ZP-OFDM, CP is replaced by zero padding. Unlike these two schemes, TDS-OFDM uses a known pseudo-random noise (PN) sequence as the guard interval as well as the training sequence (TS), which can be also used for synchronization and channel estimation. Thus, unlike CP-OFDM and ZP-OFDM, a large number of frequency-domain pilots can be saved in TDS-OFDM systems, which enables TDS-OFDM to achieve higher spectral efficiency than CP-OFDM and ZP-OFDM. In addition, fast and reliable synchronization can also be achieved.

However, the TS and the OFDM data block can cause mutual interference to each other, and such interference leads to the inaccurate time-domain channel estimation and frequency-domain data detection [7]. This issue results in two problems for TDS-OFDM. First, when the channel delay spread is long, it is hard to cancel the mutual interference, which makes high-order modulations (such as 256 QAM) are difficult to be realized. Second, the data detection and the channel estimation are mutually dependent in TDS-OFDM systems due to the mutual interference, which causes the severe performance loss in fast fading channels.

Lots of efforts have been endeavored to solve those problems [8], [9]. One exciting solution is the unique word OFDM (UW-OFDM) scheme, which alleviates the interference from the TS to the OFDM data block by using redundant pilots within the OFDM data block to generate the TS, but this solution does not solve the interference from the OFDM data block to the TS, and the inserted pilots also suffer from very high average power [10]. Another attractive solution to the interference problem of TDS-OFDM is the dual-PN OFDM (DPN-OFDM) scheme [11], where an extra PN sequence is inserted to avoid the interference from the OFDM data block to the second PN sequence. However, the extra PN sequence leads to a remarkable reduction in spectral efficiency.

In this paper, we rely on the emerging theory of distributed compressive sensing (DCS) to solve those two problems of TDS-OFDM systems [16]. Specifically, we propose to use the inter-block-interference (IBI)-free region of small size within the PN sequence to reconstruct high-dimension sparse multipath channels, where no interference cancellation is required any more. Then, based on the classical CS algorithm called compressive sampling matching pursuit (CoSaMP), we proposed the simultaneous CoSaMP (S-CoSaMP) algorithm by exploiting the joint time-frequency processing feature of TDS-OFDM. It is shown that the proposed S-CoSaMP algorithm can achieve better performance for channel reconstruction. Moreover, based on the S-CoSaMP algorithm, we further proposed a channel estimation method with further improved accuracy, where the path delays of the multi-channel can be estimated more accurately by utilizing the temporal correlation of wireless channels.

The rest of the paper is organized as follows. Section II provides a brief description of TDS-OFDM system model. Section III specifies the concept of how to integrate distributed compressive sensing with TDS-OFDM. Section IV discusses the parameterized channel estimation scheme based on S-CoSaMP. Section V presents the simulation results of the mean square error (MSE) performance and recovery probability. Finally, concludes are drawn in Section VI.

Notation: Boldface letters denote matrices and column vectors; $\mathbf{0}$ denotes the zero matrix of arbitrary size; $\mathbf{F}_N$ denotes the normalized $N \times N$ discrete Fourier transform (DFT) matrix whose $(n+1, k+1)$th entry is $\exp(-j2\pi nk/N)/\sqrt{N}$; $\otimes$ presents the circular correlation; $(\cdot)^T$, $(\cdot)^H$, $(\cdot)^{-1}$, $(\cdot)^{\dagger}$, and $\|\cdot\|_p$ denote the transpose, conjugate transpose, matrix inver-

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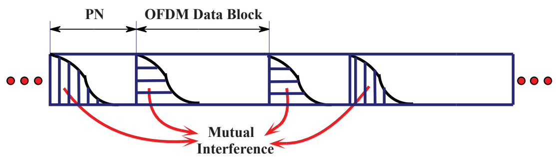

Fig. 1. Distinct features of mutual interferences in TDS-OFDM

sion, Moore-Penrose matrix inversion, and l_p norm operation, respectively; $\mathbf{x}_r$ is generated by restricting the vector $\mathbf{x}$ to its r largest components; $\mathbf{x}|_\Gamma$ denotes the entries of the vector $\mathbf{x}$ in the set Γ; $\mathbf{\Phi}_\Gamma$ denotes the column submatrix comprising the Γ columns of $\mathbf{\Phi}$; $\text{supp}\{\mathbf{\Phi}\}$ is the support of $\mathbf{\Phi}$; Γ^c is the complementary set of Γ; $a_{k,j}$ denotes the (k,j)th entry of the matrix $\mathbf{A}$; Finally, $\text{Tr}\{\cdot\}$ and $\text{E}\{\cdot\}$ are trace and expectation operators, respectively.

II. System Model

In this section, the basic principle and main problems of TDS-OFDM are reviewed first. The sparsity and inter-channel correlation of wireless channels are then discussed.

A. Basic Principles of TDS-OFDM

Unlike CP-OFDM and ZP-OFDM, TDS-OFDM replaces the CP or ZP with a known PN sequence. Besides serving as the guard interval of the subsequent OFDM data block, the PN sequence is also used as the time-domain TS for synchronization and channel estimation [12].

The ith time-domain TDS-OFDM symbol $\mathbf{s}_i = [s_{i,0}, s_{i,1}, \cdots, s_{i,M+N-1}]^T$ consists of the known PN sequence $\mathbf{c}_i = [c_{i,0}, c_{i,1}, \cdots, c_{i,M-1}]^T$ of length M and the OFDM data block $\mathbf{x}_i = [x_{i,0}, x_{i,1}, \cdots, x_{i,N-1}]^T$ of length N, which can be denoted as

$$\mathbf{s}_i = \begin{bmatrix} \mathbf{c}_i \\ \mathbf{x}_i \end{bmatrix}_{(M+N)\times 1} = \begin{bmatrix} \mathbf{c}_i \\ \mathbf{F}_N^H \widetilde{\mathbf{x}}_i \end{bmatrix}_{(M+N)\times 1}, \tag{1}$$

where $\widetilde{\mathbf{x}}_i = \mathbf{F}_N \mathbf{x}_i$ denotes the frequency-domain data.

As illustrated in Fig. 1, the PN sequence and the OFDM data block introduce mutual interference to each other in multipath channels. It is clear from Fig. 1 that reliable PN-based channel estimation requires a correctly demodulated previous OFDM data block to remove the interference. Similarly, a correct data demodulation requires accurate channel estimation to remove the interference caused by the previous PN sequence. Therefore, the classical iterative mutual interference cancellation algorithm has been proposed to refine channel estimation and data demodulation iteratively [14], [15].

B. Sparsity and Inter-Channel Correlation of Wireless Channels

Accurate estimation for wireless channels is significant for TDS-OFDM. By exploiting the specific feature incorporated in channels, we can get better channel performance. For multipath channels, the length-L channel impulse response (CIR) $\mathbf{h}_i = [h_{i,0}, h_{i,1}, \cdots, h_{i,L-1}]^T$ comprising of S_i resolvable propagation paths in the ith TDS-OFDM symbol can be modeled as [17]–[21]

$$h_{i,n} = \sum_{l=0}^{S_i-1} \alpha_{i,l}\delta[n-\tau_{i,l}], 0 \le n \le L-1, \tag{2}$$

where $\alpha_{i,l}$ is the gain of the lth path, $\tau_{i,l}$ is the delay of the lth path normalized to the sampling period at the receiver, and $h_{i,n}$ is the nth entry of the CIR vector

$$h_{i,n} = \begin{cases} \alpha_{i,l}, & n = \tau_{i,l}, \\ 0, & \text{otherwise}. \end{cases} \tag{3}$$

The path delay set D_i is defined as

$$D_i = \{\tau_{i,0}, \tau_{i,1}, \cdots, \tau_{i,S_i-1}\}, \tag{4}$$

where $0 \le \tau_{i,0} < \tau_{i,1} < \cdots < \tau_{i,S_i-1} \le L-1$ can be assumed without loss of generality, and $L \le M$ is supposed to avoid IBI between two adjacent data blocks. A large number of theoretical analyses have proven that the signal transmitting through wireless channels are sparse in nature due to the limited number of significant scatters, i.e., the number of active path which contain the majority of channel energy is usually much smaller than the whole dimension of the CIR (i.e., $S_i \ll L$).

On the other hand, due to the temporal correlation in the practical wireless channels, it has been observed that the path delays vary much slower than the path gains. This is due to the fact that the coherence time of path gains is inversely proportional to the system's carrier frequency, while the duration for path delay variation is inversely proportional to the signal bandwidth. This leads to the assumption that the path gains are varying apparently from one symbol to another over fast time-varying channels, while the path delays during each successive symbols remain almost unchanged. So the TDS-OFDM symbols can be supposed to share the common sparsity pattern [20], i.e.,

$$\begin{cases} S_i = S_{i+1} = \cdots = S_{i+R-1} = S, \\ D_i = D_{i+1} = \cdots = D_{i+R-1} = D, \\ \tau_{i,l} = \tau_{i+1,l} = \cdots = \tau_{i+R-1,l} = \tau_l, \end{cases} \tag{5}$$

where $0 \le l \le S-1$. For simplicity, we define

$$\mathbf{H} = [\mathbf{h}_i, \mathbf{h}_{i+1}, \cdots, \mathbf{h}_{i+R-1}], \tag{6}$$

that is to say, $\mathbf{H}$ has S nonzero rows with indices belonging to the set D.

The sparsity and the temporal correlation are fully utilized to solve the main problems of TDS-OFDM, which are not usually considered in traditional OFDM systems.

III. Signal Model of TDS-OFDM Based on Simultaneous Multi-Channel Reconstruction

Unlike the traditional TDS-OFDM and DPN-OFDM scheme in Fig. 2(a), (b) [13], we proposed a TDS-OFDM scheme based on distributed compressive sensing method to reconstruct the multi-channel simultaneously.

As shown in Fig. 2(c), for channel estimation, this scheme utilizes the IBI-free region in the last part of the received TS sequence. The following two reasons support the existence of IBI-free region in practical systems [12]:

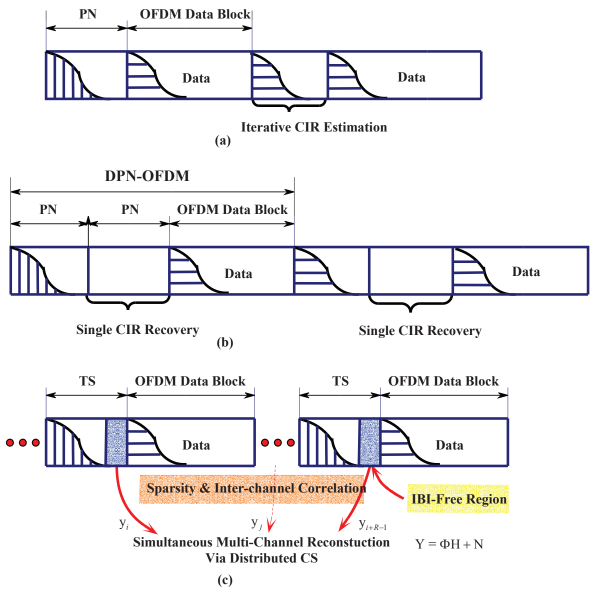

Fig. 2. The proposed DCS-aided TDS-OFDM scheme based on simultaneous multi-channel reconstruction, compared with traditional schemes: (a) the conventional TDS-OFDM scheme; (b) the dual PN padding OFDM (DPN-OFDM) scheme; (c) the proposed DCS-aided TDS-OFDM scheme.

1) In practical OFDM system, the guard interval length M is designed to be longer than the largest channel delay M, i.e., $M > L$, so even in the worst case, the system performance can be ensured.
2) The maximum channel delay can vary individual from individual in various scenarios. In the rural area, the time delay spread of channels are usually large, while in the urban area, that can be very small. Hence, the length of the guard interval M is usually longer or much longer than the length of the practical CIR L.

Therefore, within received TS for each TDS-OFDM symbol, we can guarantee an IBI-free region of the size G:

$$G = M - L + 1. \tag{7}$$

We observe that in TDS-OFDM systems, the mutual interferences between PN sequences and OFDM symbols have distinct features. Because the OFDM data block is unknown and its detection is hard to achieve perfectly, even if we estimate the channel of previous OFDM symbol correctly, the removal of IBI which caused by the mutual interference between TS and data block is difficult to achieve. However, TS is known at the receiver, the interference introduced by TS sequence can be detected precisely by the accurate channel estimation. This motivates us that we can solve the problem from the other perspective by trying to get the accurate channel estimation from the part in TS sequence where no mutual interference exists.

Also, we can find the IBI-free region within the received TS sequence. In CP-OFDM and TDS-OFDM systems, the guard interval is designed to solve the worst cases when the channel length is the same as the guard interval length. However, in practical scenarios such as the urban area, the actual channel length is much smaller than the guard interval length in most cases. Such priori information indicates that the received TS in TDS-OFDM may contain an IBI-free region of small size G, where no interference exists at the end of the received TS [20]:

$$\mathbf{y}_i = \mathbf{\Phi}_i \mathbf{h}_i + \mathbf{n}_i, \tag{8}$$

where $\mathbf{n}_i$ is the additive white Gaussian noise (AWGN) subject to the distribution $\mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I}_G)$, and

$$\mathbf{\Phi}_i = \begin{bmatrix} c_{i,L-1} & c_{i,L-2} & \cdots & c_{i,0} \\ c_{i,L} & c_{i,L-1} & \cdots & c_{i,1} \\ \vdots & \vdots & \vdots & \vdots \\ c_{i,M-1} & c_{i,M-2} & \cdots & c_{i,M-L} \end{bmatrix}_{G\times L} \tag{9}$$

denotes the Toeplitz matrix of size $G \times L$ determined by the time-domain TS.

Furthermore, the inter-channel correlation property of wireless channels can also be exploited to improve the performance of the proposed scheme. When different PN sequences are used in different TDS-OFDM symbols, i.e., we have different $\mathbf{c}_i$ and different $\mathbf{\Phi}_i$.Then considering the utilized IBI-free regions in TDS-OFDM signal models, we have

$$\begin{aligned} \mathbf{y}_i &= \mathbf{\Phi}_i \mathbf{h}_i + \mathbf{n}_i, \\ \mathbf{y}_{i+1} &= \mathbf{\Phi}_{i+1} \mathbf{h}_{i+1} + \mathbf{n}_{i+1}, \\ &\vdots \\ \mathbf{y}_{i+R-1} &= \mathbf{\Phi}_{i+R-1} \mathbf{h}_{i+R-1} + \mathbf{n}_{i+R-1}, \end{aligned} \tag{10}$$

and $\mathbf{n}_i$ denotes the AWGN matrix, and the columns of $\mathbf{H}$ in (8) share the same locations of nonzero elements, so the support (indices of nonzero rows) of the matrix $\mathbf{H}$ is just $\mathbf{D}$. The formulated mathematical model precisely complies with the newly developed theory of DCS, which is an extension of the standard CS theory.

Under the framework of DCS theory, the jointly sparse multiple CIRs within several successive OFDM symbols can be simultaneously reconstructed by finding the entries sharing the same joint location of total minimum energy:

$$\widehat{\mathbf{h_i}} = \arg \min_{\mathbf{H} \in \mathbf{C}^{L\times 1}} \|\mathbf{h}_{i,k}\|, \text{subject to } \|\mathbf{y}_i - \mathbf{\Phi}_i \mathbf{h}_i\|_{2,0} \leq \xi^2, \tag{11}$$

where $k \in D$, and ξ^2 denotes the impact of the unknown noise N on the signal recovery accuracy. $l_{2,0}$ denotes the 2 norm of the vector $\mathbf{h_i}$,and in this case $\xi^2 = R\sigma^2$.

IV. Simultaneous Multi-Channel Reconstruction Based on S-CoSaMP

A. S-CoSaMP Based Joint Sparsity Pattern Recovery

The key idea of CoSaMP is $\mathbf{p} = \mathbf{\Phi}^H \mathbf{\Phi} \mathbf{h}$, which is a proxy of the target signal $\mathbf{h}$, since the large components of $\mathbf{p}$ approximate the corresponding entries of $\mathbf{h}$, then the strongest S components of $\mathbf{h}$ can be identified until a halting criterion is met. Similar to the other signal recovery algorithms in the CS literature, CoSaMP assumes the known sparsity level, which is unavailable in most fast varying systems. We proposed the S-CoSaMP algorithm based on the basic principle of CoSaMP, whereby the reconstruction performance can be improved in practice. The pseudocode of the proposed S-CoSaMP algorithm is summarized in Algorithm 1. Compared

Input: Noisy measurements $\mathbf{Y}$, observation matrix $\mathbf{\Phi}$, estimated channel sparsity level S.
Output: S-sparse estimate $\widehat{\mathbf{H}}$ containing multiple CIRs.
for $i \leq R$ **do**
  while $k \leq S$ **do**
    $k \leftarrow k+1$;
    $\mathbf{p}_i \leftarrow {\mathbf{\Phi}_i}^H \mathbf{u}_i$;
    $\mathbf{\Gamma}_i \leftarrow \sup(\mathbf{p}_{i(2\times S)})$;
    $\mathbf{\Omega}_i \leftarrow \mathbf{\Gamma}_i \cup \sup(\mathbf{a}^{k-1})$;
    $\mathbf{b}_i|_{\Omega_i} \leftarrow \mathbf{\Phi}^{\dagger}_{\Omega_i}\mathbf{u}_i$;
    $\mathbf{b}_i|_{\Omega_i^c} \leftarrow \mathbf{0}$;
    $\mathbf{a}_i^k \leftarrow \mathbf{b}_{iS}$;
    $\mathbf{u}_i \leftarrow \mathbf{y}_i - \mathbf{\Phi}_i\mathbf{a}^k$;
  end
  $i \leftarrow i+1$;
  $\widehat{\mathbf{h}}_i \leftarrow \mathbf{a}^k$;
end
$\widehat{\mathbf{H}} \leftarrow \left[\widehat{\mathbf{h}}_i, \widehat{\mathbf{h}}_{i+1}, \cdots, \widehat{\mathbf{h}}_{i+R-1}\right]$;

Algorithm 1: Simultaneous CoSaMP (S-CoSaMP)

to the classical CoSaMP scheme, we can find they share quite similar procedure, but they are different in the following aspects:

1) **PN sequence**. Unlike CoSaMP where all the PN sequence is the same in every TDS-OFDM symbol, we assume every TDS-OFDM symbol has their own PN sequence, so that different TS and Toeplitz matrix are used in channel recovery, which is more general in practical OFDM scene, whereby the reconstruction accuracy can be improved.
2) **Simultaneity**. Unlike classical CoSaMP which processes every symbol separately and call the algorithm iteratively, S-CoSaMP reconstruct the multi-channel simultaneously, whereby improve the performance and lower the time complexity.

In classical CS theory, where both the locations of nonzero components and the corresponding coefficients are considered, however, we only utilize the S-CoSaMP algorithm to acquire the path delays of the CIR, while the path gains are left to be estimated in the step below.

B. ML-based Path Gain Estimation

After the path delays have been obtained, the signal model is simplified as

$$\mathbf{y}_i = \mathbf{\Phi}_D \mathbf{h}_{iS} + \mathbf{n}_i, \tag{12}$$

where $\mathbf{h}_{iS}$ is generated by restricting the vector $\mathbf{h}_i$ to its S largest components. It is clear from (13) that there remain only S instead of L ($S < G \ll L$) unknown nonzero path gains in the CIR vector, which can be estimated by solving an over-determined set of equations under the LS criterion:

$$\widehat{\mathbf{h}}_{iS} = \mathbf{\Phi}^{\dagger}_D \mathbf{y}_i = \left({\mathbf{\Phi}_D}^H \mathbf{\Phi}_D\right)^{-1} {\mathbf{\Phi}_D}^H \mathbf{y}_i. \tag{13}$$

Finally, the path delay and path gain estimates form the complete CIR estimate simultaneously.

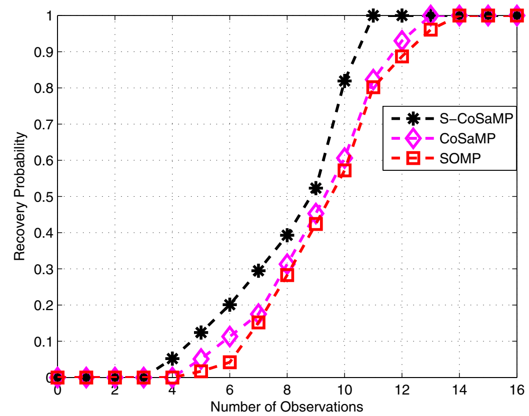

Fig. 3. Correct signal recovery probability when different number of observations is adopted.

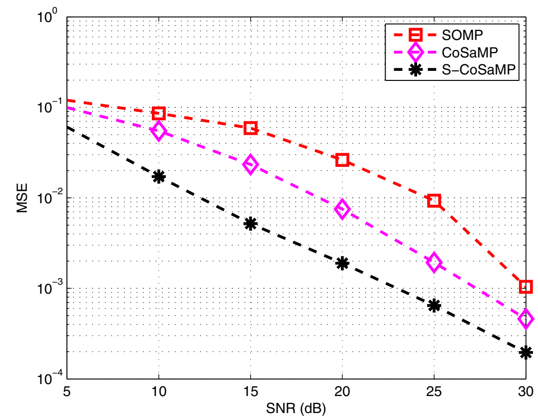

Fig. 4. MSE performance comparison between the proposed parameterized channel estimation based on S-CoSaMP and its conventional counterparts.

V. Simulation Results

This section investigates the performance of the distributed compressive sensing based TDS-OFDM in vehicular communications. The six-tap (i.e., S = 6) Vehicular B channel model [22] defined by 3GPP widely used to emulate the wireless channel in vehicular scenarios is adopted in the simulation. The signal bandwidth is configured as 7.56 MHz locating at the central radio frequency of 6 GHz. The modulation scheme 256QAM in low-speed vehicular channels and 16QAM in fast time varying vehicular environments are both considered. The FFT size of N = 2048 and the guard interval length of M = 256 are adopted. The maximum delay spread of the Vehicular B channel is 20 μs, which is equivalent to the channel length L = 153, so the size of the IBI-free region is 103.

Fig. 3 presents the correct signal recovery probability when different number of observations is used under the fixed SNR of 30 dB. Here, the correct recovery is defined as the estimation MSE is lower than 10^{-2}. Compared with the classical CoSaMP algorithm where 13 measurements are required to ensure near one probability of correct signal recovery, only 11 samples are sufficient for the proposed S-CoSaMP scheme, which means the required number of observations is reduced by about 15.4%. The reduced number of required observations means a smaller size of the IBI-free region, so the proposed TDS-OFDM system can combat multipath channels with longer length.

Fig. 4 shows the MSE performance comparison between the proposed parameterized channel estimation based on S-CoSaMP and its counterparts in conventional TDS-OFDM. To ensure good channel estimation performance when SNR is low, the last G = 30 samples of the IBI-free region are selected as the observation vector for CIR reconstruction. For the conventional systems, the iterative interference cancellation with the iterative number of three is carried out to achieve reliable time-domain channel estimation in conventional TDS-OFDM system. It is clear from Fig. 4 that the proposed scheme outperforms the conventional systems by more than 5 dB when the target MSE of 10^{-2} is considered. This is because the path delays of the channel can be accurately indentified by the enhanced S-CoSaMP signal recovery algorithm, and the path gains can then be reliably estimated by the observations within the IBI-free region.

VI. Conclusions

In this paper, we have developed a more spectrum- and energy-efficient alternative to the standard CP-OFDM scheme, whereby the theory of DCS is exploited to enable TDS-OFDM to support high-order modulation schemes in realistic static channels with large delay spread. This is achieved by utilizing the sparsity and inter-channel correlation of wireless channels in a simultaneous multi-channel reconstruction procedure, whereby multiple IBI-free regions of very small size within consecutive TDS-OFDM symbols are used under the framework of DCS. The reconstruction exploits the properties that temporal correlation of wireless channels as well as the channel property that path gains change much faster than path delays. Then, the proposed parameterized channel estimation method based on simultaneous CoSaMP (S-CoSaMP) algorithm achieves better performance over fast time-varying channels. In this way, not only an obviously improved channel reconstruction accuracy is achieved, but also the mutually conditional time-domain channel estimation and frequency-domain data detection in conventional TDS-OFDM can be decoupled without the use of iterative interference cancellation.

Acknowledgment

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