Compressive Sensing Based Time Domain Synchronous OFDM Transmission for Vehicular Communications

Linglong Dai, Zhaocheng Wang, and Zhixing Yang

***Abstract*—Time domain synchronous OFDM (TDS-OFDM) has higher spectral efficiency and faster synchronization than standard cyclic prefix OFDM (CP-OFDM), but suffers from the difficulty of supporting 256QAM in low-speed vehicular channels with long delay spread and the performance loss over fast time-varying vehicular channels. This paper addresses how to efficiently use the compressive sensing (CS) theory to solve those problems. First, we break through the conventional concept of cancelling the interferences if present, and propose the idea of using the inter-block-interference (IBI)-free region of small size to reconstruct the high-dimensional sparse multipath channel, whereby no interference cancellation is required any more. In this way, without changing the current signal structure of TDS-OFDM at the transmitter, the mutually conditional time-domain channel estimation and frequency-domain data detection in conventional TDS-OFDM receivers can be decoupled. Second, we propose the parameterized channel estimation method based on priori aided compressive sampling matching pursuit (PA-CoSaMP) algorithm to achieve reliable performance over vehicular channels, whereby partial channel priori available in TDS-OFDM is used to improve the performance and reduce the complexity of the classical CoSaMP signal recovery algorithm. Simulation results demonstrate that the proposed scheme can support the 256QAM and gain improved performance over fast fading channels.**

***Index Terms*—Time domain synchronous OFDM (TDS-OFDM), mutual interferences, compressive sensing (CS), compressive sampling matching pursuit (CoSaMP).**

I. Introduction

NOWADAYS, people's daily lives are becoming more and more connected with vehicles like buses/cars/subways/trains, etc, so vehicular communications is an emerging technology which has attracted extensive interest in recent years [1], [2]. One of the key components of vehicular communications is the efficient and reliable information transmission scheme. Due to its high spectral efficiency and excellent robustness to multipath fading channels, OFDM has been widely adopted by numerous wireless communication systems [3], [4]. It is highly expected that OFDM will play an important role in emerging vehicular communications [2].

There are basically three types of OFDM-based block transmission schemes [5]: cyclic prefix OFDM (CP-OFDM), zero padding OFDM (ZP-OFDM), and time domain synchronous OFDM (TDS-OFDM). The standard CP-OFDM scheme widely adopted by most of the current communications standards, e.g., IEEE 802.11g/n/ac, 802.16e/m, 802.11p, utilizes the CP to eliminate the inter-block-interference (IBI) as well as inter-carrier-interference (ICI) [5]. The CP is replaced by zero samples in ZP-OFDM to tackle the channel null problem [6]. Based on the concept of joint time-frequency processing, TDS-OFDM adopts the known sequence, e.g., the pseudorandom noise (PN) sequence, as the guard interval as well as the training sequence (TS) for synchronization and channel estimation [7], [8]. Consequently, the large amount of frequency-domain pilots used in CP-OFDM and ZP-OFDM can be saved. Thus, TDS-OFDM[1] has higher spectral efficiency than CP-OFDM and ZP-OFDM. Additionally, fast and reliable synchronization can be also achieved. TDS-OFDM is the key technology of a digital television terrestrial broadcasting (DTTB) standard called digital terrestrial multimedia/television broadcasting (DTMB) [8], which has been successfully deployed in China, Cuba, Cambodia, etc. In December 2011, DTMB was officially approved by ITU as the fourth international DTTB standard [12].

However, the TS and the OFDM data block cause mutual interferences to each other, thus iterative interference cancellation has to be used to iteratively achieve reliable time-domain channel estimation and frequency-domain data detection in TDS-OFDM systems. This results in two open problems of TDS-OFDM: First, in low-speed vehicular channels, it is difficult to completely remove the residual interference when the channel delay spread is large, leading to the difficulty of supporting high-order modulations like 256QAM (currently, TDS-OFDM can support 64QAM at most [8]); Second, due to the mutual condition of accurate channel estimation and reliable data detection, the performance degradation of data detection deteriorates the accuracy of channel estimation, and

Manuscript received March 1, 2012; revised July 23, 2012.

The authors are with the Department of Electronic Engineering and the Tsinghua National Laboratory for Information Science and Technology (TNList), Tsinghua University, Beijing 100084, P. R. China (e-mail: {daill, zcwang, yangzhx}@tsinghua.edu.cn).

This work was supported by the National Natural Science Foundation of China (Grant No. 61271266), the National Key Basic Research Program of China (Grant No. 2013CB329203), the Science and Technology Foundation for the Beijing Outstanding Doctoral Dissertation Supervisor (Grant No. 20121000303), the China Postdoctoral Science Special Foundation (Grant No. 2012T50093), and the Tsinghua University-KU Leuven Bilateral Scientific Cooperation Foundation (Grant No. BIL11/21T).

Digital Object Identifier 10.1109/JSAC.2013.SUP.0513041

[1]Essentially speaking, known symbol padding OFDM (KSP-OFDM) [9] and pseudo-random-postfix OFDM (PRP-OFDM) [10], [11] schemes appeared in the literature are similar to TDS-OFDM, so we use the term "TDS-OFDM" in this paper to refer to the unified framework of TDS-OFDM, KSP-OFDM, and PRP-OFDM as well.

vice versa, so performance loss is unavoidable over fast fading channels. Great efforts have been endeavored to solve those problems [11], [13], [14], but the improvement is not obvious. 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 suffer from very high average power as well [15]. The most attractive solution to the interference problem of TDS-OFDM is the dual-PN OFDM (DPN-OFDM) scheme [16], whereby an extra PN sequence is inserted to avoid the interference from the OFDM data block to the second PN sequence, but this leads to a remarkable reduction in spectral efficiency, especially when the guard interval length should be long in vehicular communications. To the best of the authors' knowledge, there is no effective solution to decouple the mutually conditional channel estimation and data detection up to now.

In this paper, we adopt the ground-breaking theory of compressive sensing (CS) [17] to solve those two open problems of TDS-OFDM. Specifically, the contributions of this paper are summarized as below:

1) We break through the conventional concept of cancelling the interferences if present, and propose the idea of using the small-size IBI-free region of the received TS to reconstruct the high-dimensional sparse multipath channel, whereby no interference cancellation is required. In this way, without changing the current infrastructure of TDS-OFDM, the mutually conditional time-domain channel estimation and frequency-domain data detection can be decoupled;
2) Based on the classical CS algorithm called compressive sampling matching pursuit (CoSaMP), we propose the priori aided CoSaMP (PA-CoSaMP) algorithm by exploiting the joint time-frequency processing feature of TDS-OFDM, whereby the contaminated TS in TDS-OFDM is used to acquire partial priori of the channel. Compared with CoSaMP, the proposed PA-CoSaMP algorithm reduces the required number of observations by about 50%, and the complexity is reduced by about 80%;
3) Based on the PA-CoSaMP algorithm, we further propose a parameterized channel estimation method with high accuracy, whereby the path delays of the channel can be accurately estimated by PA-CoSaMP, while the path gains are acquired by the IBI-free samples under the maximum likelihood (ML) criterion. We also derive the Cramér-Rao lower bound (CRLB) of the proposed channel estimation scheme, which can be approached by the simulation results.

The remainder of this paper is organized as follows. The system model of TDS-OFDM is described in Section II. The motivation and intuitive concept of the compressive sensing based TDS-OFDM is addressed in Section III. Section IV discusses the parameterized channel estimation scheme based on PA-CoSaMP. Section V presents the performance analysis of the proposal before simulation results are provided in Section VI. Finally, conclusions are drawn in Section VII.

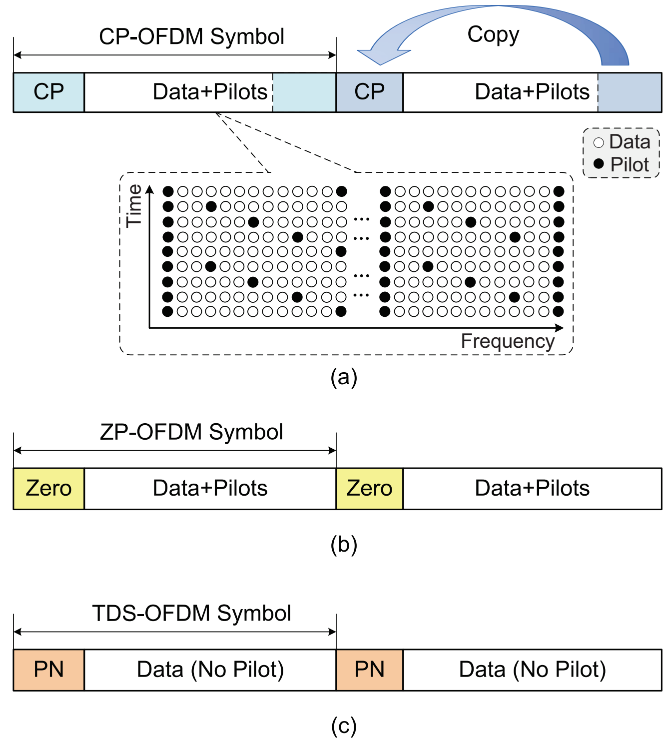

Fig. 1. Three types of OFDM-based transmission: (a) CP-OFDM; (b) ZP-OFDM; (c) TDS-OFDM.

Notation: We use boldface letters to denote matrices and column vectors; $\mathbf{0}$ denotes the zero matrix of arbitrary size; $\mathbf{F}_N$ denotes the normalized $N \times N$ fast Fourier transform (FFT) matrix whose $(n+1, k+1)$th entry being $\exp(-j2\pi nk/N)/\sqrt{N}$; $\otimes$ presents the circular correlation; $(\cdot)^T$, $(\cdot)^H$, $(\cdot)^{-1}$, $(\cdot)^{\dagger}$, and $\|\cdot\|_p$ denote the transpose, conjugate transpose, matrix inversion, Moore-Penrose matrix inversion, and l_p norm operations, respectively; $\mathbf{x}_r$ is generated by restricting the vector $\mathbf{x}$ to its r largest components, and $\sup(\mathbf{x}_r)$ denotes the location set of the r largest elements of $\mathbf{x}$; $\mathbf{x}|_\Gamma$ denotes the entries of the vector $\mathbf{x}$ in the set Γ; $\mathbf{\Phi}_\Gamma$ denotes the column submatrix comprising the Γ columns of $\mathbf{\Phi}$; Finally, $\mathrm{Tr}\{\cdot\}$ and $\mathrm{E}\{\cdot\}$ stand respectively for trace and expectation operators.

II. TDS-OFDM System Model

As shown in Fig. 1, without CP and frequency-domain pilots in standard CP-OFDM systems, one TDS-OFDM symbol $\mathbf{s} = [s_0, s_1, \cdots, s_{M+N-1}]^T$ is composed of the known time-domain PN sequence $\mathbf{c} = [c_0, c_1, \cdots, c_{M-1}]^T$ of length M and the following OFDM data block $\mathbf{x} = [x_0, x_1, \cdots, x_{N-1}]^T$ of length N, i.e.,

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

where the frequency-domain signal $\widetilde{\mathbf{x}} = [\widetilde{x}_0, \widetilde{x}_1, \cdots, \widetilde{x}_{N-1}]^T$ is the FFT output of the corresponding time-domain signal $\mathbf{x}$, i.e., $\widetilde{\mathbf{x}} = \mathbf{F}_N \mathbf{x}$. In contrast to standard CP-OFDM where plenty of frequency-domain pilots are usually inserted in $\widetilde{\mathbf{x}}$, TDS-OFDM contains no pilot in the frequency domain.

The discrete-time complex channel impulse response (CIR) $\mathbf{h} = [h_0, h_1, \cdots, h_{L-1}]^T$ comprising S resolvable propagation paths can be modeled as [18], [19]

$$h_n = \sum_{l=0}^{S-1} \alpha_l \delta[n - \tau_l], 0 \leq n \leq L - 1, \tag{2}$$

where α_l is the gain of the lth path, τ_l denotes the delay of the lth path normalized to the sampling period at the receiver, and h_n is the nth entry of the CIR vector $\mathbf{h}$:

$$h_n = \begin{cases} \alpha_l, & n = \tau_l, \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

The path delay set D is defined as

$$D = \{\tau_0, \tau_1, \cdots, \tau_{S-1}\}, \tag{4}$$

where $0 \leq \tau_0 \leq \tau_1 \leq \cdots \leq \tau_{S-1} \leq L$ can be assumed without loss of generality. The channel length L is assumed to be not larger than the guard interval length M, i.e., $L \leq M$, so that the interference between two adjacent OFDM data blocks can be avoided in TDS-OFDM systems [5].

After passing through the multipath channel, if the channel is exactly known at the receiver so that the impact of the TS on the OFDM data block can be removed, the received TDS-OFDM symbol is essentially equivalent to the ZP-OFDM symbol [6]. Then, the classical overlap and add (OLA) algorithm can be utilized to add the "tail" of the OFDM data block back to its head so that the effect of CP can be restored [6]. Then, the frequency-domain OFDM data block $\widetilde{\mathbf{y}} = [\widetilde{y}_0, \widetilde{y}_1, \cdots, \widetilde{y}_{N-1}]^T$ can be presented as

$$\widetilde{y}_k = \widetilde{x}_k \widetilde{h}_k + \widetilde{w}_k, 0 \leq k \leq N - 1, \tag{5}$$

where $\widetilde{w}_k$ denotes the additive white Gaussian noise (AWGN) with zero mean and the variance of σ^2, and $\widetilde{h}_k$ presents the channel frequency response (CFR) over the kth subcarrier

$$\widetilde{h}_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{L-1} h_n e^{-j\frac{2\pi}{N}nk}, 0 \leq k \leq N - 1. \tag{6}$$

To realize reliable detection of the unknown OFDM data $\{\widetilde{x}_k\}_{k=0}^{N-1}$ in (5) from the observations $\{\widetilde{y}_{i,k}\}_{k=0}^{N-1}$, accurate channel estimation is required. In standard CP-OFDM systems, channel information is usually achieved by first using the frequency-domain pilots to acquire the CFR over the corresponding subcarriers, and then interpolation is used to obtain the complete CFR over the entire signal bandwidth [18], [20]. In deeply frequency-selective channels with large delay spread, plenty of pilots have to be used for accurate channel tracking [20]. In contrast to the pilot-based channel estimation, TDS-OFDM without frequency-domain pilot realizes channel estimation based on the time-domain received TS $\mathbf{d} = [d_0, d_1, \cdots, d_{M-1}]^T$ denoted by

$$\mathbf{d} = \mathbf{\Psi}\mathbf{h} + \mathbf{n}, \tag{7}$$

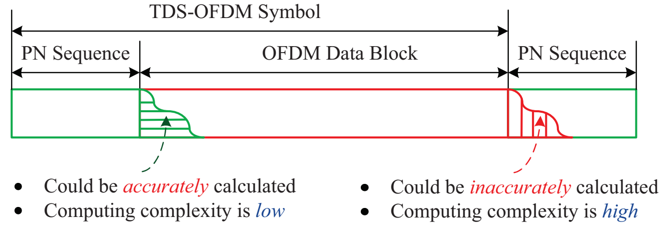

Fig. 2. Distinct features of the interferences in TDS-OFDM.

where $\mathbf{n}$ denotes the AWGN vector, and

$$\mathbf{\Psi} = \begin{bmatrix} c_0 & x_{N-1} & x_{N-2} & \cdots & x_{N-L+1} \\ c_1 & c_0 & x_{N-1} & \cdots & x_{N-L+2} \\ c_2 & c_1 & c_0 & \cdots & x_{N-L+3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{L-1} & c_{L-2} & c_{L-3} & \cdots & c_0 \\ c_L & c_{L-1} & c_{L-2} & \cdots & c_1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{M-1} & c_{M-2} & c_{M-3} & \cdots & c_{M-L} \end{bmatrix}_{M \times L}$$

It is clear that the received TS will be contaminated by the interference caused by the preceding OFDM data block in multipath channels, and the corresponding interference cancellation requires reliable frequency-domain data detection as well as accurate channel estimation so that the interference can be calculated at first and then be removed. On the other hand, the interference caused by the TS should be removed before data detection, which requires accurate channel estimation to compute the interference. Therefore, the mutual interferences between the received TS and OFDM data block lead to the mutually conditional relationship between the time-domain channel estimation and the frequency-domain data detection in TDS-OFDM systems, and iterative interference cancellation has to be applied to refine channel estimation as well as data detection iteratively [21], [22], which results in two open problems of TDS-OFDM as mentioned before.

III. Compressive Sensing Based TDS-OFDM

A. *Motivation*

First, we find out that the interferences have distinct features in TDS-OFDM systems. As illustrated in Fig. 2, since the OFDM data block is unknown and its perfect detection is hard to achieve over doubly selective channels, it is really difficult to completely remove the IBI caused by the OFDM data block even if the channel estimation has been obtained perfectly. Additionally, computing such IBI requires high complexity because of the large size of the OFDM data block. On the contrary, since the TS is known at the receiver, the IBI introduced by the TS can be precisely calculated only if accurate channel estimation has been achieved, and low computing complexity is required due to the small size of the TS. This observation motivates us to solve the intractable problem of mutual interferences by trying to achieve accurate channel estimation without any influence from the OFDM data block to the TS. Note that this is different from the design idea of UW-OFDM [15], which tries to alleviate the IBI from the TS to the OFDM data block instead.

Second, we find out that there exists a small IBI-free region within the received TS in practical applications due to the system design margin. Both in CP-OFDM and TS-OFDM systems, the length of the guard interval is designed to combat the worse case when the channel length is as large as the guard interval length. However, the actual channel length is usually smaller or even much smaller than the guard interval length in most practical applications [23]–[25], e.g., M is configured sufficiently large so that the receiver can work well even there is a long-delay path reflected from a faraway mountain, but one may always use the receiver in urban areas where the maximum channel length is relatively small. Moreover, even the system is specifically designed for urban usage, the system designer would always consider the system design margin that the actual channel length in most cases is smaller than the guard interval length [23]. This indicates that although the received TS in TDS-OFDM may contain some interferences from the preceding OFDM data block, there exists an IBI-free region $\mathbf{y} = [d_{L-1}, d_L, \cdots, d_{M-1}]^T$ of small size $G = M - L + 1$ immune from the IBI at the end of the received TS:

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

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

$$\mathbf{\Phi} = \begin{bmatrix} c_{L-1} & c_{L-2} & c_{L-3} & \cdots & c_0 \\ c_L & c_{L-1} & c_{L-2} & \cdots & c_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{M-1} & c_{M-2} & c_{M-3} & \cdots & c_{M-L} \end{bmatrix}_{G \times L} \tag{9}$$

denotes the Toeplitz matrix of size $G \times L$ determined by the TS $\mathbf{c}$. The actual channel length and the system design margin motivate us come to the idea of using the IBI-free region of small size to recover the high-dimensional CIR without any interference cancellation.

B. Intuitive Concept of the Proposal

As illustrated by Fig. 3, since the size of the IBI-free region G is usually small, it is impossible to find the unique solution to the underdetermined (maybe severely ill-conditioned) mathematical problem (8) if the number of observations G is smaller than the dimension of the unknown CIR vector $\mathbf{h}$, i.e., $G < L$ (or $M < 2L + 1$). That's the mathematical reason why we try to achieve a complete "pure" TS of length M ($M \geq L$) in conventional TDS-OFDM by iterative interference cancellation. Alternatively, as shown in Fig. 3(a), the DPN-OFDM scheme obtains such "pure" TS by inserting an extra TS at the cost of obviously reduced spectral efficiency, whereby the second TS of length M can be directly used to estimate the L-dimensional CIR.

However, the ground-breaking CS theory [17] has proved that the high-dimensional target signal can be perfectly reconstructed by solving the underdetermined problem (8) if the target signal is (approximately) sparse, i.e., the number of nonzero entries of the signal is much smaller than its dimension. Fortunately, numerous theoretical analysis and experimental results have verified that wireless channel is sparse in nature, i.e., in the CIR model (2), the dimension

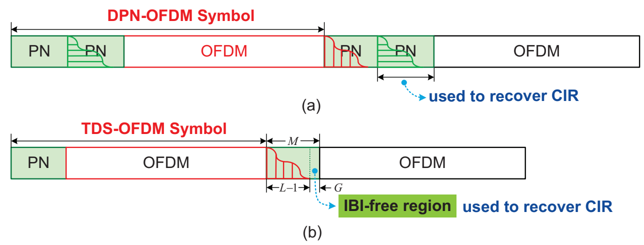

Fig. 3. Signal structure comparsion: (a) TDS-OFDM with dual PN padding (DPN-OFDM), where the second PN sequence is used for CIR recovery; (b) Compressive sensing based TDS-OFDM, where the IBI-free region of small size is used to reconstruct the high-dimensional CIR using the CS theory.

L of the CIR maybe large, but the number of active paths S with significant power is usually small ($S \ll L$), especially in wideband wireless communications [26]–[28]. Therefore, as shown in Fig. 3(b), the ideal of exploiting the IBI-free region of the received TS to accurately recover the sparse CIR without any interference cancellation becomes feasible under the new framework of CS theory. Consequently, the mutually conditional relationship between the time-domain channel estimation and frequency-domain data detection in conventional TDS-OFDM can be decoupled without changing the current infrastructure or reducing the spectral efficiency.

IV. Parameterized Channel Estimation Based on PA-CoSaMP

Accurate channel estimation is essential to realize the ideal of the compressive sensing based TDS-OFDM, and a low-complexity algorithm is important for practical implementation. This section will address those issues.

Signal recovery algorithm is a hot research topic in the CS theory [29]. Among the currently available CS signal recovery algorithms, compressive sampling matching pursuit (CoSaMP) is widely adopted in practical systems due to its high reconstruction accuracy and excellent robustness to noise [30]. However, similar to most of other signal recover algorithms, CoSaMP also requires the sparsity level of the signal, which is variable and unknown in practical systems. Moreover, CoSaMP still has high complexity for real-time implementation.

In this section, by fully exploiting the distinct joint time-frequency processing feature of TDS-OFDM, we propose the PA-CoSaMP based parameterized channel estimation scheme, whereby partial priori of the channel available in TDS-OFDM is exploited to reduce the complexity and improve the performance of the classical CoSaMP algorithm. The parameterized channel estimation based on PA-CoSaMP is composed of three steps: 1) TS-based partial channel priori acquisition; 2) CS-based path delay estimation using PA-CoSaMP; 3) ML-based path gain estimation. The following three subsections will address those three steps, respectively.

A. TS-Based Partial Channel Priori Acquisition

Although the proposed TDS-OFDM scheme relies on the IBI-free region for high-dimensional CIR reconstruction, the complete received TS (including the part contaminated by the previous OFDM data block) can also be exploited to acquire partial priori of the channel even though a reliable channel estimation is not expected. Based on the good autocorrelation property[2] of the TS, without interference cancellation, the received contaminated TS is directly correlated with the local known TS to generate the rough channel estimate $\overline{\mathbf{h}}$ as

$$\overline{\mathbf{h}} = \frac{1}{M}\mathbf{c} \otimes \mathbf{d} = \mathbf{h} + \mathbf{v}, \tag{10}$$

where $\mathbf{v}$ denotes the channel's AWGN as well as the effect of interference caused by the preceding OFDM data block. As illustrated in Fig. 4, where the Vehicular B channel [31] with the signal-to-noise ratio (SNR) of 5 dB is considered, although the rough channel estimate $\overline{\mathbf{h}}$ is not accurate due to the absence of IBI removal, the good autocorrelation property of the TS ensures that part of the main characteristics of the channel can be preserved.

From the rough channel estimate $\overline{\mathbf{h}}$, part of the channel priori can be acquired. First, the path gains in $\overline{\mathbf{h}}$ are discarded directly, and only the path delays of the most significant taps are retained in the initial path delay set

$$D_0 = \{l : \left\|\overline{h}_l\right\|_2 \geq p_{th}\}_{l=0}^{L-1}, \tag{11}$$

where p_{th} is the power threshold configured according to [32]. Second, the channel sparsity level S can be approximated by

$$S = S_0 + a = \|D_0\|_0 + a, \tag{12}$$

where $S_0 = \|D_0\|_0$ denotes the initial channel sparsity level, and a is a compensation number used to combat the interference effect, since some low-power active paths maybe treated as noise in $\overline{\mathbf{h}}$. Third, the channel length L can be estimated by

$$\widehat{L} = \max\{D_0\} + b, \tag{13}$$

where b is a variable parameter used to define the IBI-free region comprising the last $G = M - \widehat{L}$ samples of the received TS. It is worth noting that unlike CP-OFDM systems where compressive sensing can be also utilized to reduce the pilot overhead [26], [27], the partial channel priori is usually unavailable since there is no time-domain TS. Those partial priori obtained in TDS-OFDM is essential for practical CS-based signal recovery algorithm with improved performance as well as reduced complexity in the next step.

B. CS-Based Path Delay Estimation Using PA-CoSaMP

The key idea of CoSaMP is that $\mathbf{p} = \mathbf{\Phi}^H\mathbf{\Phi}\mathbf{h}$ 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 in an iterative manner until a halting criterion is met [30]. However, similar to other signal recovery algorithms in the CS literature, CoSaMP assumes the known sparsity level, which is unavailable in most fast varying systems. Moreover, it only relies on the sparse nature of the target signal, but improved performance is expected if more properties of the signal are considered. In this subsection, based on the basic principle of CoSaMP, we propose the PA-CoSaMP algorithm, whereby the priori of the channel obtained above is exploited to improve the reconstruction performance and reduce the complexity of the signal recovery algorithm in practice. The pseudocode of the proposed PA-CoSaMP algorithm is summarized in Algorithm 1.

[2]The synchronization in TDS-OFDM also requires the good autocorrelation property of the TS.

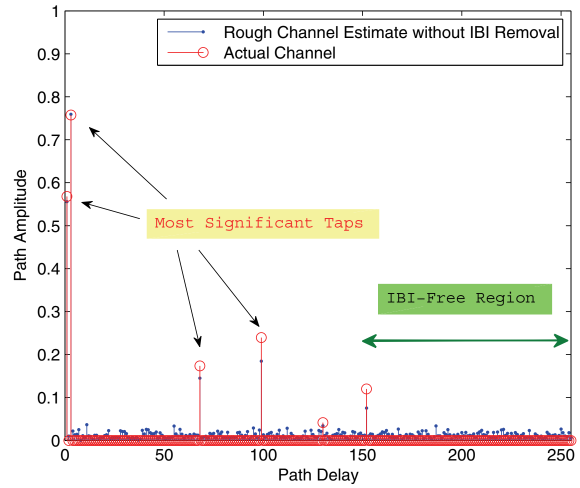

Fig. 4. TS-based partial channel priori acquisition without IBI removal over the Vehicualr B channel with the SNR of 5 dB.

Comparing the proposed PA-CoSaMP algorithm with the classical CoSaMP scheme [30], we can find that they share quite simliar procedure, but they are different in the following three aspects:

1) **Initialization**. Unlike CoSaMP where the initial approximation of the target signal $\mathbf{a}^0$ is set as a zero vector because no priori of the signal is available, we approximate the initial guess as $\mathbf{a}^0\big|_{D_0} \leftarrow \mathbf{\Phi}_{S_0}^{\dagger}\mathbf{y}$ by exploiting the obtained partial path delays D_0 of the CIR (or equivalently, the locations of the corresponding nonzero elements). Accordingly, the initial residual signal $\mathbf{u} \leftarrow \mathbf{y} - \mathbf{\Phi}\mathbf{a}^0$ is used in PA-CoSaMP to replace its counterpart $\mathbf{u} \leftarrow \mathbf{y}$ in CoSaMP.
2) **Large component identification**. Unlike CoSaMP where the $2S$ largest components of the signal proxy $\mathbf{p}$ are identified in each iteration, we leave the $2S_0$ largest entries unchanged, and identify the next $2(S - S_0)$ largest ones instead.
3) **Halting criterion**. Instead of the fixed number of iterations S usually adopted in CoSaMP, only $S - S_0$ times of iterations are required in PA-CoSaMP.

After the CIR estimate $\widehat{\mathbf{h}}$ has been obtained by the proposed PA-CoSaMP algorithm, again the path gains of $\widehat{\mathbf{h}}$ are discarded, and only the path delays of the S nonzero taps of the S-sparse estimate $\widehat{\mathbf{h}}$ are retained in the final path delay set

$$D = \{\tau_l : \left|\widehat{h}_{\tau_l}\right| > 0\}. \tag{14}$$

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

Input: 1) Initial path delay set D_0, channel sparsity level S, initial channel sparsity level S_0;
2) Noisy measurements $\mathbf{y}$, observation matrix $\mathbf{\Phi}$.
Output: S-sparse estimate $\widehat{\mathbf{h}}$ of the CIR.
$\mathbf{a}^0\big|_{D_0} \leftarrow \mathbf{\Phi}^{\dagger}_{S_0}\mathbf{y}$;
$\mathbf{u} \leftarrow \mathbf{y} - \mathbf{\Phi}\mathbf{a}^0$;
$k \leftarrow \mathbf{0}$;
for $k < S - S_0$ **do**
  $k \leftarrow k+1$;
  $\mathbf{p} \leftarrow \mathbf{\Phi}^H\mathbf{u}$;
  $\Gamma \leftarrow \sup(\mathbf{p}_{2(S-S_0)})$;
  $\Omega \leftarrow \Gamma \cup \sup(\mathbf{a}^{k-1})$;
  $\mathbf{b}|_{\Omega} \leftarrow \mathbf{\Phi}^{\dagger}_{\Omega}\mathbf{u}$;
  $\mathbf{b}|_{\Omega^c} \leftarrow \mathbf{0}$;
  $\mathbf{a}^k \leftarrow \mathbf{b}_S$;
  $\mathbf{u} \leftarrow \mathbf{y} - \mathbf{\Phi}\mathbf{a}^k$;
end
$\widehat{\mathbf{h}} \leftarrow \mathbf{a}^k$;

Algorithm 1: Priori aided CoSaMP (PA-CoSaMP)

C. ML-based Path Gain Estimation

After the path delays have been obtained, the entries outside the path delay set D (note that $\|D\|_0 = S$) are set to zeros, so the signal model (8) is simplified as

$$\mathbf{y} = \mathbf{\Phi}_D\mathbf{h}_S + \mathbf{n}, \tag{15}$$

It is clear from (15) that there remains only S instead of L ($S \ll L$) unknown nonzero path gains in the CIR vector $\mathbf{h}$, which can be estimated by solving an overdetermined equation under the ML criterion:

$$\widehat{\mathbf{h}}_S = \mathbf{\Phi}^{\dagger}_D\mathbf{y} = \left(\mathbf{\Phi}^H_D\mathbf{\Phi}_D\right)^{-1}\mathbf{\Phi}^H_D\mathbf{y}. \tag{16}$$

Finally, the path delay and path gain estimates form the CIR estimate as $\widehat{\mathbf{h}}\Big|_D = \widehat{\mathbf{h}}_S$.

V. Performance Analysis

This section provides the performance analysis of the proposed scheme in terms system spectral efficiency, the CRLB of the parameterized channel estimation based on PA-CoSaMP, as well as the computational complexity.

A. Spectral Efficiency

Table I compares the spectral efficiency of typical OFDM schemes in terms of the percentage [22] of the ideal OFDM system having no overhead (including time-domain guard interval and frequency-domain pilots). Apart from fast and reliable synchronization, the main advantage of TDS-OFDM over standard CP-OFDM is the improved spectral efficiency due to the removal of frequency-domain pilots. The penalty for those merits is the required iterative interference cancellation due to the mutual interferences between the PN sequence and the OFDM data block. In the DPN-OFDM scheme, two identical PN sequences are used in every TDS-OFDM symbol to avoid the interference from the OFDM data block to the second PN sequence, but the spectral efficiency is reduced.

TABLE I
Spectral Efficiency Comparison

Guard Interval Length	CP-OFDM	TDS-OFDM	DPN-OFDM	Proposed Scheme
$M = N/4$	60.00%	80.00%	66.67%	80.00%
$M = N/8$	77.78%	88.89%	80.00%	88.89%
$M = N/16$	88.23%	94.12%	88.89%	94.12%

However, the proposed compressive sensing based TDS-OFDM requires no modification of the current infrastructure, so high spectral efficiency can be inherited.

In the extreme case that the actual channel length equals to the guard interval length, we can extend the TS in TDS-OFDM a little longer so that the IBI-free region can be always guaranteed. Note that TS extension would reduce the spectral efficiency, but the penalty is very small since the proposed PA-CoSaMP signal recovery algorithm only requires small number of observations in the order $\mathcal{O}\left(S\log_2(L/S)\right)$ [30]. For example, in the case of $M = N/8$, the length-256 TS can be extended by 30 samples, and the spectral efficiency will be reduced from 88.89% to 87.75%, which means the penalty of spectral efficiency is only 1.14%.

B. CRLB of the Parameterized Channel Estimation

According to the signal model (15) where the AWGN vector $\mathbf{n}$ is subject to the distribution $\mathcal{CN}(\mathbf{0}, \sigma^2\mathbf{I}_G)$, the conditional probability density function (PDF) of $\mathbf{y}$ with the given $\mathbf{h}_S$ is

$$p_{\mathbf{y}|\mathbf{h}_S}\left(\mathbf{y};\mathbf{h}_S\right) = \frac{1}{\left(2\pi\sigma^2\right)^{G/2}}\exp\left\{-\frac{1}{2\sigma^2}\|\mathbf{y} - \mathbf{\Phi}_D\mathbf{h}_S\|_2\right\}. \tag{17}$$

Then, using the vector estimation theory [33], we can derive the CRLB of the unbiased estimator $\widehat{\mathbf{h}}_S = \mathbf{\Phi}^{\dagger}_D\mathbf{y}$ (16) as

$$\mathrm{CRLB} = \mathrm{E}\left\{\left\|\widehat{\mathbf{h}}_S - \mathbf{h}_S\right\|_2\right\} = \frac{S\sigma^2}{G}. \tag{18}$$

Compared with the TS-based channel estimator in conventional TDS-OFDM systems, where the best mean square error (MSE) performance is σ^2 if interference has been completely removed, the parameterized channel estimator based on PA-CoSaMP can achieve much better MSE performance, since S is smaller than G, i.e., $S < G$.

Note that if the matrix $\mathbf{\Phi}_D$ does not have orthogonal columns, the CRLB (18) cannot be achieved by the practical channel estimator. However, due to the random property of the PN sequence used in TDS-OFDM as well as the random locations of active paths of wireless channels, the matrix $\mathbf{\Phi}_D$ has imperfect but approximate orthogonal columns (he requirement of near orthogonality is equivalently similar to the restricted isometry property (RIP) property of the observation matrix widely studied in the CS theory, and the performance guarantee of Toeplitz observation matrix has been theoretically proved in [34]). Thus, the CRLB can be asymptotically approached, which will be validated by the simulation results in Section VI.

C. Computational Complexity

Regarding to the proposed parameterized channel estimation method based on PA-CoSaMP, (10) in the first step can be efficiently implemented by M-point FFT to realize the M-point circular correlation, so the corresponding complexity is $\mathcal{O}\left((M/2)\log_2 M\right)$. In the third step, (16) requires the complexity of $\mathcal{O}(GS^2+S^3)$ for the ML solution.

The main computational burden of the parameterized channel estimation is the PA-CoSaMP algorithm used to acquire path delay information in the second step. Although the classical CoSaMP signal recovery method is designed for practical applications, it still has high complexity for real-time implementations, because the significant components of the target signal have to be identified iteratively. Since each iteration has the complexity of $\mathcal{O}\left(4GS^2+8S^3\right)$, the overall complexity of CoSaMP comprising S iterations is $\mathcal{O}\left(4GS^3+8S^4\right)$. However, as has been discussed in Section IV-B, only $S-S_0$ iterations are required by PA-CoSaMP, since some of the locations of significant taps have been obtained already, the complexity of PA-CoSaMP is reduced to $\mathcal{O}\left((S-S_0)\left(4GS^2+8S^3\right)\right)$. Moreover, as will be shown later, compared with CoSaMP, the number of observations required by PA-CoSaMP is reduced by about 50% to achieve the similar recovery performance as that of CoSaMP, so the complexity of PA-CoSaMP is substantially lower than that of CoSaMP, e.g., if three out of the total six path delays has been obtained in the first step of TS-based partial channel priori acquisition, the complexity can be reduced by about 80%.

It is worth noting that in some applications where the CIR length is small (so the IBI is not severe) and each active path has relatively high power, the TS-based rough channel estimation can already acquire all the path delay information of the CIR, so the PA-CoSaMP algorithm will not be carried out anymore.

VI. Simulation Results and Discussion

This section investigates the performance of the compressive sensing based TDS-OFDM in vehicular communications. The six-tap (i.e., $S=6$) Vehicular B channel model [31] 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 relative receiver velocity of 20 km/h and 140 km/h are used to present the low-speed and high-speed vehicular channels, respectively. 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. Since almost all practical OFDM systems use channel coding for reliable performance, we adopt the powerful low-density parity-check (LDPC) code with the block length of 64, 8000 bits and code rate of 2/3 as specified in [35]. The well-known iterative decoding algorithm called belief propagation (BP) [36] is used with the maximum iteration number of 50.

Fig. 5 shows a snapshot of the proposed parameterized CIR estimation result based on PA-CoSaMP over the Vehicular B channel with the SNR of 20 dB. The CIR recovered by classical CoSaMP algorithm is also included for comparison. It is clear that the proposed method can produce very exact CIR estimate compared with the actual channel, including both the path delays and path gains. In addition, PA-CoSaMP has superior path delay estimation performance to CoSaMP, which detects the fourth active path with very low power (25.2 dB lower than the strongest one) by mistake.

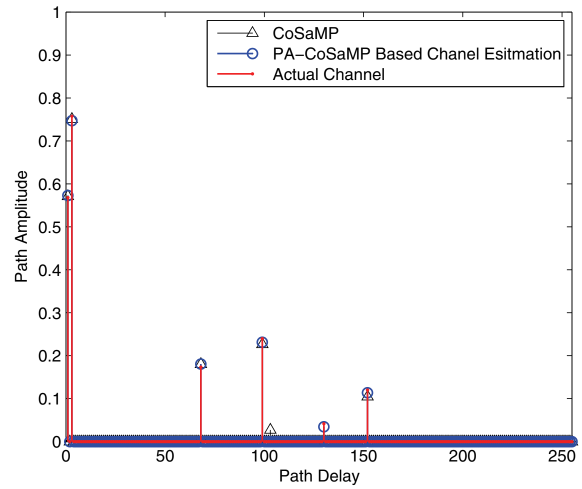

Fig. 5. Snapshot of the proposed parameterized channel estimation based on PA-CoSaMP.

Fig. 6 compares the signal reconstruction performance of the proposed PA-CoSaMP algorithm with that of the classical CoSaMP scheme when a varying number of measurements is utilized. Another widely used CS signal recovery algorithm called regularized orthogonal matching pursuit (ROMP) [37] is also considered for comparison. It is clear that when the observation number is small, e.g., $M<40$, the proposed PA-CoSaMP algorithm performs better than CoSaMP, while they share similar performance when M becomes large. This indicates that for a given performance requirement, PA-CoSaMP requires fewer number of measurements due to the exploitation of the partial channel priori.

To further evaluate the performance gain of the proposed PA-CoSaMP algorithm in terms of required number of measurements for reliable signal reconstruction, Fig. 7 presents the correct signal recovery probability when different number of observations is used under the fixed SNR of 20 dB. Here, the correct recovery is defined as the estimation MSE is lower than 10^{-2}. Compared with the classical CoSaMP algorithm where 40 measurements are required to ensure near one probability of correct signal recovery, only 20 samples are sufficient for the proposed PA-CoSaMP scheme, which means the required number of observations is reduced by about 50%. This is caused by the fact that some information of the target signal, e.g., the locations of partial large components, has been known as priori in PA-CoSaMP, while the standard CoSaMP has no such information [30]. 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. Meanwhile, as mentioned in Section V-C,

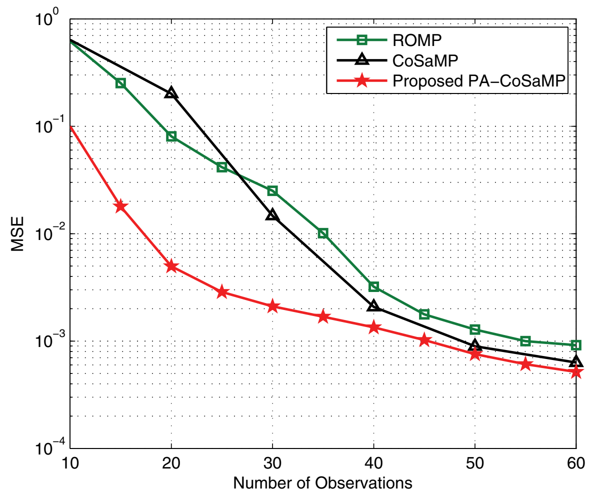

Fig. 6. Signal reconstruction performance when varying number of measurements is utilized.

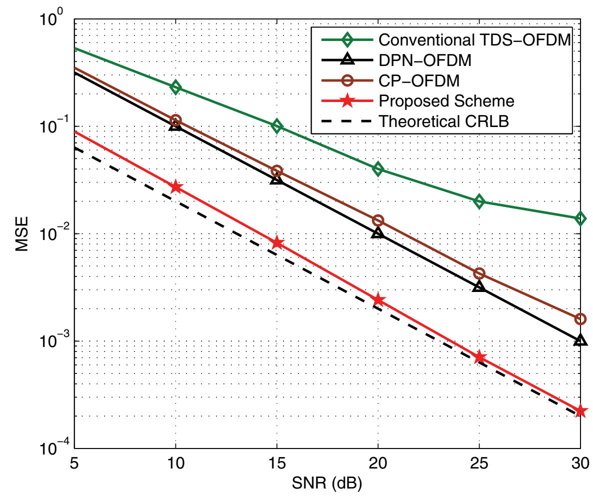

Fig. 8. MSE performance comparison between the proposed parameterized channel estimation based on PA-CoSaMP and its conventional counterparts.

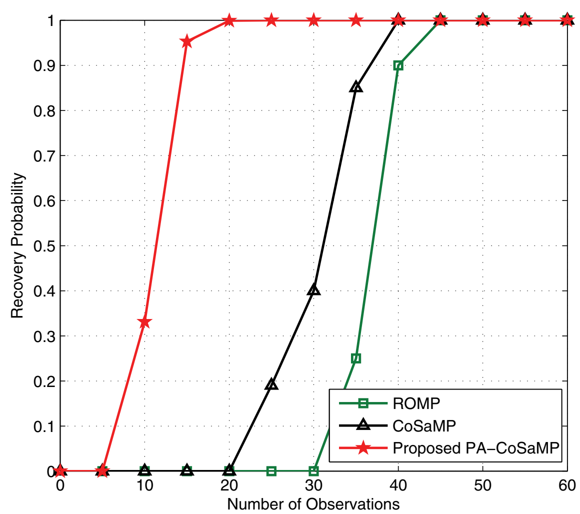

Fig. 7. Correct signal recovery probability when different number of observations is adopted.

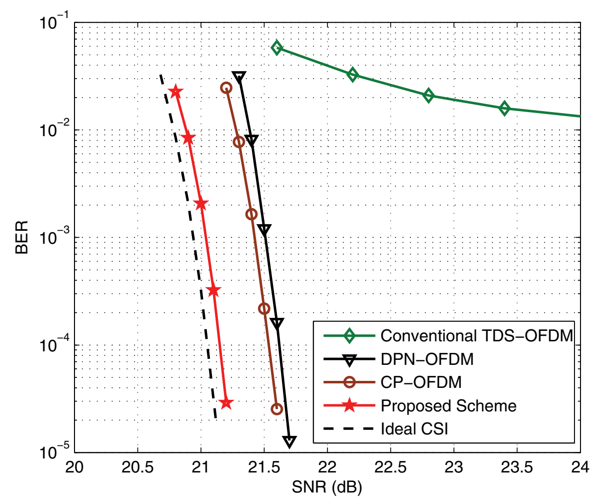

Fig. 9. BER performance comparison when 256QAM is adopted in the Vehicular B channel with the mobile speed of 20 km/h.

the complexity of PA-CoSaMP can also be reduced, since the size of the observation matrix becomes smaller.

Fig. 8 shows the MSE performance comparison between the proposed parameterized channel estimation based on PA-CoSaMP and its counterparts in conventional TDS-OFDM, DPN-OFDM, and CP-OFDM systems. 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 [21], while the second received PN sequence is directly used for channel estimation in DPN-OFDM system [16]. For CP-OFDM system, the comb-type frequency-domain pilots are used to acquire the CFR over the corresponding subcarriers, and then the low-complexity linear interpolation is used to achieve the CFR over the entire signal bandwidth [23]. It is clear from Fig. 8 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 PA-CoSaMP signal recovery algorithm, and the path gains can then be reliably estimated by the observations within the IBI-free region under the ML criterion. Moreover, the actual MSE performance approaches the theoretical CRLB (18) when SNR becomes high.

Fig. 9 compares the LDPC-coded bit error rate (BER) performance when 256QAM is adopted in the slow time-varying channel with the mobile speed of 20 km/h. The BER performance with the ideal channel state information (CSI) is also included as the benchmark for comparison. We can observe that the conventional TDS-OFDM system can not support the high-order modulation scheme 256QAM due to the residual interference can not be completely removed. However,

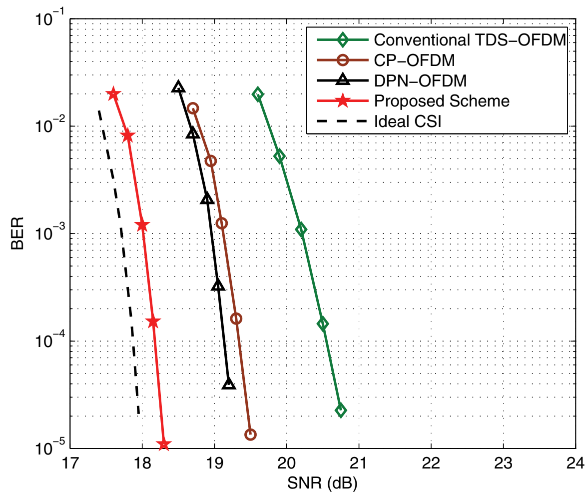

Fig. 10. BER performance comparison when 16QAM is adopted over the fast fading channel with the mobile speed of 140 km/h.

the compressive sensing based TDS-OFDM proposed in this paper can support 256QAM well. Moreover, contributed by the decoupling of time-domain channel estimation and frequency-domain data detection, as well as the high channel estimation accuracy as demonstrated in Fig. 8, the proposed scheme also enjoys superior BER performance to DPN-OFDM and CP-OFDM. In addition, the actual BER curve is only about 0.1 dB away from the ideal CSI case, which indicates the excellent performance of the proposed scheme.

Fig. 10 shows the BER performance when 16QAM is adopted over the fast fading channel with the mobile speed of 140 km/h. It is clear that the proposed scheme also has the best performance in fast time-varying channels. At the target BER of 10^{-4}, it outperforms the conventional TDS-OFDM system by about 2.3 dB, and has the SNR gain of more than 0.9 dB compared with CP-OFDM and DPN-OFDM. Note that TDS-OFDM has higher spectral efficiency than both CP-OFDM and DPN-OFDM. The enhanced reliability over fast fading channels is contributed by two reasons. First, the CIR estimate, which can be updated every TDS-OFDM symbol, achieves the substantially improved accuracy due to the proposed parameterized channel estimation based on PA-CoSaMP. Second, the time-domain channel estimation and frequency-domain data detection are decoupled in the proposed scheme by using the IBI-free region to reconstruct the high-dimensional sparse CIR, whereby the conventional iterative interference cancellation algorithm with poor performance over fast fading channels is not required any more.

VII. Conclusions

Without changing the current infrastructure or sacrificing the spectral efficiency, this paper proposes the compressive sensing based TDS-OFDM transmission scheme to solve two open problems of conventional TDS-OFDM systems. Compared with classical CoSaMP algorithm, the proposed PA-CoSaMP can reduce the complexity by about 80% due to channel priori is used, and the required number of observations for reliable signal recovery is reduced by about 50%. The MSE performance of the proposed parameterized channel estimator based on PA-CoSaMP outperforms the conventional schemes by more than 5 dB, and approaches the theoretical CRLB when SNR becomes high. Under the framework of the proposal, TDS-OFDM can support 256QAM well with the BER performance 0.1 dB away from the ideal CSI case, and the performance over fast fading channels can also be improved by about 2.3 dB. Furthermore, the methods in this paper can be directly applied in other multi-carrier systems including KSP-OFDM, PRP-OFDM, UW-OFDM, as well as in the UW single carrier (SC) communication systems.

Acknowlegement

The authors would like to thank Prof. Yahong Rosa Zheng from the Missouri University of Science and Technology for her valuable suggestions for this paper during her visit to Tsinghua University.

References

[1] M. Raya, P. Papadimitratos, I. Aad, D. Jungels, and J. Hubaux, "Eviction of misbehaving and faulty nodes in vehicular networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1557–1568, Oct. 2007.

[2] H. Hartenstein and K. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Commun. Mag.*, vol. 46, no. 6, pp. 164–171, June 2008.

[3] H. Yang, "A road to future broadband wireless access: MIMO-OFDM-based air interface," *IEEE Commun. Mag.*, vol. 43, no. 1, pp. 53–60, Jan. 2005.

[4] Z. Wang and R. Stirling-Gallacher, "Frequency reuse scheme for cellular OFDM systems," *Electron. Lett.*, vol. 38, no. 8, pp. 387–388, Apr. 2002.

[5] L. Dai, Z. Wang, and Z. Yang, "Time-frequency training OFDM with high spectral efficiency and reliable performance in high speed environments," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 4, pp. 695–707, May 2012.

[6] B. Muquet, Z. Wang, G. Giannakis, M. De Courville, and P. Duhamel, "Cyclic prefixing or zero padding for wireless multicarrier transmissions?" *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 2136–2148, Dec. 2002.

[7] Z. Yang, L. Dai, J. Wang, J. Wang, and Z. Wang, "Transmit diversity for TDS-OFDM broadcasting system over doubly selective fading channels," *IEEE Trans. Broadcast.*, vol. 57, no. 1, pp. 135–142, Mar. 2011.

[8] L. Dai, Z. Wang, and Z. Yang, "Next-generation digital television terrestrial broadcasting systems: Key technologies and research trends," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 150–158, June 2012.

[9] D. Van Welden and H. Steendam, "Near optimal iterative channel estimation for KSP-OFDM," *IEEE Trans. Signal Process.*, vol. 58, no. 9, pp. 4948–4954, Sep. 2010.

[10] M. Muck, M. De Courville, and P. Duhamel, "A pseudorandom postfix OFDM modulator-semi-blind channel estimation and equalization," *IEEE Trans. Signal Process.*, vol. 54, no. 3, pp. 1005–1017, Mar. 2006.

[11] J. Lin, "Channel estimation assisted by postfixed pseudo-noise sequences padded with zero samples for mobile orthogonal-frequency-division-multiplexing communications," *IET Commun.*, vol. 3, no. 4, pp. 561–570, Apr. 2009.

[12] *Error-Correction, Data Framing, Modulation and Emission Methods for Digital Terrestrial Television Broadcasting*, Recommendation ITU-R BT. 1306-6, Dec. 6, 2011.

[13] J. Lin, "Least-squares channel estimation assisted by self-interference cancellation for mobile PRP-OFDM applications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2008, pp. 578–583.

[14] ——, "Least-squares channel estimation assisted by self-interference cancellation for mobile pseudo-random-postfix orthogonal-frequency division multiplexing applications," *IET Commun.*, vol. 3, no. 12, pp. 1907–1918, Dec. 2009.

[15] M. Huemer, C. Hofbauer, and J. B. Huber, "Non-systematic complex number RS coded OFDM by unique word prefix," *IEEE Trans. Signal Process.*, vol. 60, no. 1, pp. 6073–6085, Jan. 2012.

[16] J. Fu, J. Wang, J. Song, C. Pan, and Z. Yang, "A simplified equalization method for dual PN-sequence padding TDS-OFDM systems," *IEEE Trans. Broadcast.*, vol. 54, no. 4, pp. 825–830, Dec. 2008.

[17] E. Candès and M. Wakin, "An introduction to compressive sampling," *IEEE Signal Process. Mag.*, vol. 25, no. 2, pp. 21–30, Feb. 2008.
[18] B. Yang, K. Letaief, R. Cheng, and Z. Cao, "Channel estimation for OFDM transmission in multipath fading channels based on parametric channel modeling," *IEEE Trans. Commun.*, vol. 49, no. 3, pp. 467–479, Mar. 2001.
[19] A. Iyer, C. Rosenberg, and A. Karnik, "What is the right model for wireless channel interference?" *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2662–2671, May 2009.
[20] M. Morelli and U. Mengali, "A comparison of pilot-aided channel estimation methods for OFDM systems," *IEEE Trans. Signal Process.*, vol. 49, no. 12, pp. 3065–3073, Dec. 2001.
[21] J. Wang, Z. Yang, C. Pan, and J. Song, "Iterative padding subtraction of the PN sequence for the TDS-OFDM over broadcast channels," *IEEE Trans. Consum. Electron.*, vol. 51, no. 11, pp. 1148–1152, Nov. 2005.
[22] L. Dai, Z. Wang, and S. Chen, "A novel uplink multiple access scheme based on TDS-FDMA," *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, pp. 757–761, Mar. 2011.
[23] H. Minn, V. K. Bhargava, and K. B. Letaief, "A robust timing and frequency synchronization for OFDM systems," *IEEE Trans. Wireless Commun.*, vol. 2, no. 4, pp. 822–839, July 2003.
[24] G. Stuber, J. Barry, S. Mclaughlin, Y. Li, M. Ingram, and T. Pratt, "Broadband MIMO-OFDM wireless communications," *Proc. IEEE*, vol. 92, no. 2, pp. 271–294, Feb. 2004.
[25] B. Su and P. Vaidyanathan, "Subspace-based blind channel identification for cyclic prefix systems using few received blocks," *IEEE Trans. Signal Process.*, vol. 55, no. 10, pp. 4979–4993, Oct. 2007.
[26] W. Bajwa, J. Haupt, A. Sayeed, and R. Nowak, "Compressed channel sensing: A new approach to estimating sparse multipath channels," *Proc. IEEE*, vol. 98, no. 6, pp. 1058–1076, June 2010.
[27] C. Berger, Z. Wang, J. Huang, and S. Zhou, "Application of compressive sensing to sparse channel estimation," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 164–174, Nov. 2010.
[28] Z. Wang, L. Dai, and J. Wang, "Priori information aided compressive sensing for time domain synchronous OFDM," *Electron. Lett.*, vol. 48, no. 13, pp. 800–801, June 2012.
[29] M. Duarte and Y. Eldar, "Structured compressed sensing: From theory to applications," *IEEE Trans. Signal Process.*, vol. 59, no. 9, pp. 4053–4085, Sep. 2011.
[30] D. Needell and J. Tropp, "Cosamp: Iterative signal recovery from incomplete and inaccurate samples," *Commun. ACM*, vol. 53, no. 12, pp. 93–100, Dec. 2010.
[31] *Guideline for Evaluation of Radio Transmission Technology for IMT-2000*, Recommendation ITU-R M. 1225, 1997.
[32] F. Wan, W. Zhu, and M. Swamy, "Semi-blind most significant tap detection for sparse channel estimation of OFDM systems," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 57, no. 3, pp. 703–713, Mar. 2010.
[33] S. M. Kay, *Fundamentals of Statistical Signal Processing, Volumn I: Estimation Theory*. New Jersey, USA: Prentice-Hall, 1993.
[34] J. Haupt, W. Bajwa, G. Raz, and R. Nowak, "Toeplitz compressed sensing matrices with applications to sparse channel estimation," *IEEE Trans. Inf. Theory*, vol. 56, no. 11, pp. 5862–5875, Nov. 2010.
[35] *Digital Video Broadcasting (DVB); Frame Structure, Channel Coding and Modulation for a Second Generation Digital Terrestrial Television Broadcasting System (DVB-T2)*, ETSI Standard, EN 302 755, V1.3.1, Apr. 2012.
[36] J. Chen, A. Dholakia, E. Eleftheriou, M. Fossorier, and X. Hu, "Reduced-complexity decoding of LDPC codes," *IEEE Trans. Commun.*, vol. 53, no. 8, pp. 1288–1299, Aug. 2005.
[37] D. Needell and R. Vershynin, "Signal recovery from incomplete and inaccurate measurements via regularized orthogonal matching pursuit," *IEEE J. Sel. Topics Signal Process.*, vol. 4, no. 2, pp. 310–316, Feb. 2010.

Linglong Dai (M'11) received his B.S. degree from Zhejiang University in 2003, the M.S. degree (with the highest honor) from the China Academy of Telecommunications Technology (CATT) in 2006, and the Ph.D. degree (with the highest honor) from Tsinghua University in 2011. He is now a Post Doctoral Fellow with the Department of Electronic Engineering, Tsinghua University, Beijing, China. His research interests are in wireless communications with the emphasis on OFDM, MIMO, synchronization, channel estimation, multiple access techniques, and wireless positioning. He has published over 30 journal and conference papers. He was awarded the 2011 Tsinghua Excellent Ph.D. Graduate, the 2011 Tsinghua Academic Star, and the 2012 Beijing Excellent Doctoral Dissertation.

Zhaocheng Wang (M'06-SM'11) received his B.S., M.S., and Ph.D. degrees from Tsinghua University in 1991, 1993, and 1996, respectively. From 1996 to 1997, he was with Nanyang Technological University (NTU) in Singapore as a Post Doctoral Fellow. From 1997 to 1999, he was with the OKI Techno Centre (Singapore) Pte. Ltd., first as a research engineer and then as a senior engineer. From 1999 to 2009, he worked at SONY Deutschland GmbH, first as a senior engineer and then as a principal engineer. He is currently a Professor at the Department of Electronic Engineering, Tsinghua University. His research areas include wireless communications, digital broadcasting, and millimeter wave communications. He holds 29 granted US/EU patents and has published over 70 technical papers. He has served as a technical program committee co-chair/member of many international conferences. He is a Senior Member of IEEE and a Fellow of IET.

Zhixing Yang (M'00-SM'11) received his B.S. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 1970. He is now a full professor at the Department of Electronics Engineering of Tsinghua University, Beijing, China. He is the executive director of the State Key Laboratory on Microwave and Digital Communications, China, and the executive director of the development group of the digital television terrestrial broadcasting state standard for China. He has received several national awards and holds dozens of patents. His research interests are in high-speed data transmission over broadband digital television terrestrial broadcasting, wireless links, wireless communication theory, and communication systems design. He is a Senior Member of IEEE.