Reliable and Energy-Efficient OFDM Based on Structured Compressive Sensing

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Abstract—**Compared with standard cyclic prefix OFDM (CP-OFDM), time domain synchronous OFDM (TDS-OFDM) can achieve a higher spectrum efficiency by using the known training sequence instead of CP as the guard interval. However, TDS-OFDM suffers from reduced energy efficiency and performance loss due to the existing mutual inferences. In this paper, based on the newly emerging theory of structured compressive sensing (SCS), we propose a reliable and energy-efficient TDS-OFDM transmission scheme with reduced guard interval power (which is impossible for CP-OFDM) by designing a channel estimation scheme with high accuracy. The wireless channel properties including channel sparsity and inter-channel correlation, which are usually not considered in conventional OFDM schemes, have been exploited. We further exploit the worst-case system design principle to extract multiple interference-free regions of small size to simultaneously reconstruct multiple channels of large size without iterative interference cancellation. In this way, the guard interval power in TDS-OFDM can be reduced to achieve a 20% higher energy efficiency than standard CP-OFDM, and the system reliability can be also improved in fast fading channels.**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been extensively adopted by numerous wireless communication systems like LTE, WiFi, DVB-T2, etc, and it is also widely recognized as a prominent modulation technique for future wireless communication systems [1]–[4].

Basically, there are three types of OFDM [5]: cyclic prefix OFDM (CP-OFDM), zero padding OFDM (ZP-OFDM), and time domain synchronous OFDM (TDS-OFDM). The popular CP-OFDM utilizes a CP as a guard interval to alleviate inter-block-interference (IBI) in multipath channels [6]. The CP is replaced by a ZP in ZP-OFDM to combat the channel zeros. TDS-OFDM adopts a known pseudorandom noise (PN) sequence as a guard interval as well as a training sequence (TS) for synchronization and channel estimation, so the commonly used pilots can be removed, and accordingly the spectrum efficiency can be improved [7]. TDS-OFDM is the key technology of one international digital television broadcasting standard called digital terrestrial multimedia/television broadcasting (DTMB), which has been successfully deployed in China, Laos, Cuba, and some other countries [8].

However, in multipath channels, the mutual interferences between the PN sequence and the OFDM data block make time-domain channel estimation and frequency-domain data demodulation mutually conditional, so the iterative interference cancellation algorithm [9] has to be implemented, which unfortunately cannot remove the interferences completely. Similar to the pilot boosting technique [5] in CP-OFDM, the DTMB standard increases the power of the PN sequence in TDS-OFDM to alleviate the interference and then improve the channel estimation performance. Such power boosting technique will not reduce the spectrum efficiency, but suffers from reduced energy efficiency, especially when the guard interval length should be long in broadcasting systems with the coverage radius up to tens of kilometers or even larger [8].

In this paper, based on the newly emerging theory of structured compressive sensing (SCS) [10], we propose a reliable and energy-efficient TDS-OFDM transmission scheme with reduced guard interval power by designing a channel estimation scheme with high accuracy. The wireless channel properties including channel sparsity [11] and inter-channel correlation [12], which are not considered in conventional TDS-OFDM, are exploited in the proposed scheme. We further exploit the worst-case system design principle [11] to extract multiple IBI-free regions of small size to simultaneously reconstruct multiple channels of large size without iterative interference cancellation. In this way, channel estimation can be significantly improved, then we can decrease the guard interval power in TDS-OFDM, which is infeasible in classical CP-OFDM, to improve the energy efficiency by about 20% compared with CP-OFDM, and the system reliability can be also enhanced in fast fading channels.

The rest of this paper is organized as follows. Section II presents the system model. Section III addresses the proposed TDS-OFDM based on SCS, whose energy efficiency and performance evaluation are analyzed in Section IV and Section V, respectively. Finally, conclusions are made in Section VI.

Notation: We use boldface letters to denote matrices and column vectors; $\mathbf{0}$ denotes the zero matrix; $\otimes$ denotes 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 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 $\mathbf{\Phi}$; Γ^c is the complementary set of Γ.

II. TDS-OFDM SYSTEM MODEL

As illustrated in Fig. 1, unlike standard CP-OFDM signal, the ith TDS-OFDM symbol $\mathbf{s}_i = [s_{i,0}, s_{i,1}, \cdots, s_{i,M+N-1}]^T$

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is composed of the time-domain 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, and no pilots are used in the corresponding frequency-domain OFDM data $\widetilde{\mathbf{x}}_i = \mathbf{F}_N \mathbf{x}_i$ for channel estimation [8].

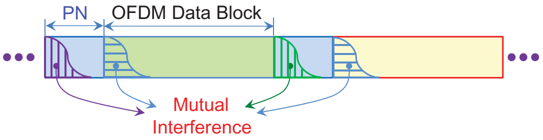

Fig. 1. TDS-OFDM signal structure and the mutual interferences between the PN sequence and the OFDM data block in multipath channels.

The key principle of TDS-OFDM is that, with the perfect channel information, the contribution of the PN sequence can be completely subtracted from the received OFDM data block in multipath channels due to PN is known to the receiver, and then the received TDS-OFDM symbol is essentially equivalent to a ZP-OFDM symbol [5], which could be easily converted to a standard CP-OFDM symbol by the simple overlap and add (OLA) scheme [13] to facilitate low-complexity channel equalization. Thus, TDS-OFDM heavily relies on accurate channel estimation based on the time-domain received PN sequence $\mathbf{d}_i = [d_{i,0}, d_{i,1}, \cdots, d_{i,M-1}]^T$ denoted by

$$\mathbf{d}_i = \mathbf{\Psi}_i \mathbf{h}_i + \mathbf{v}_i, \tag{1}$$

where $\mathbf{h}_i = [h_{i,0}, h_{i,1}, \cdots, h_{i,L-1}]^T$ is the channel impulse response (CIR) of length L during the ith TDS-OFDM symbol,

$$\mathbf{\Psi}_i = \begin{bmatrix} c_{i,0} & x_{i-1,N-1} & x_{i-1,N-2} & \cdots & x_{i-1,N-L+1} \\ c_{i,1} & c_{i,0} & x_{i-1,N-1} & \cdots & x_{i-1,N-L+2} \\ c_{i,2} & c_{i,1} & c_{i,0} & \cdots & x_{i-1,N-L+3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{i,L-1} & c_{i,L-2} & c_{i,L-3} & \cdots & c_{i,0} \\ c_{i,L} & c_{i,L-1} & c_{i,L-2} & \cdots & c_{i,1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{i,M-1} & c_{i,M-2} & c_{i,M-3} & \cdots & c_{i,M-L} \end{bmatrix},$$

and $\mathbf{v}_i$ is the additive white Gaussian noise (AWGN) vector subject to the distribution $\mathcal{CN}(\mathbf{0}, \mathbf{I}_M \sigma^2)$.

It is clear from Fig. 1 and Eq. (1) that the received PN sequence $\mathbf{d}_i$ is contaminated by the last $L-1$ samples of the previous OFDM data block $\mathbf{x}_{i-1}$. Such interference can not be easily removed, and degrades the channel estimation accuracy. One simple yet efficient solution is the dual PN padding OFDM (DPN-OFDM) scheme [14], whereby two repeated PN sequences are used in every TDS-OFDM symbol to avoid the interference from the OFDM data block to the second PN sequence. However, the extra PN sequence obviously decreases the spectrum efficiency. Another solution to alleviate such interference is to increase the power of the PN sequence for more reliable channel estimation, e.g., the amplitude factor $\alpha = \sqrt{2}$ is specified by DTMB standard [15], which means the PN sequence has a 3 dB higher power than the OFDM data block. However, power boosting of the guard interval reduces the energy efficiency of TDS-OFDM, especially when the guard interval length should be large for broadcasting systems with large coverage [8]. This motivates us to hold or even decrease the power of the PN sequence to achieve a significantly improved energy efficiency by designing a novel channel estimation scheme with high accuracy, which is the topic of the following section.

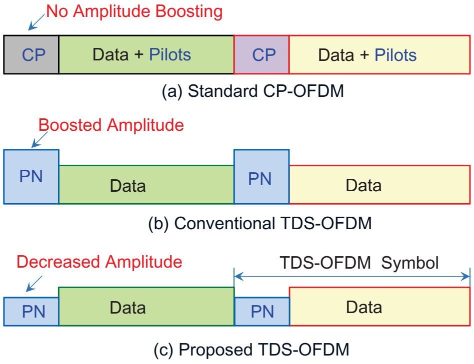

Fig. 2. Comparison of the guard interval power: (a) No power boosting in CP-OFDM; (b) Boosted power in conventional TDS-OFDM with iterative interference cancellation; (c) Decreased power in the proposed TDS-OFDM based on SCS.

III. TDS-OFDM BASED ON STRUCTURED COMPRESSIVE SENSING

As shown in Fig. 2, in this section we propose a reliable and energy-efficient TDS-OFDM transmission scheme with reduced guard interval power based on the theory of SCS. The corresponding analysis of the performance bound and the computational complexity are also provided.

A. *Channel Sparsity and Inter-Channel Correlation*

Numerous theoretical analyses and experimental results have confirmed that the wireless channels are sparse in nature, especially in broadband wireless communications [16], [17]. More specifically, the CIR $\mathbf{h}_i = [h_{i,0}, h_{i,1}, \cdots, h_{i,L-1}]^T$ comprising of S_i resolvable propagation paths can be modeled as

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

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 the path delay set D_i is defined as $D_i = \{\tau_{i,0}, \tau_{i,1}, \cdots, \tau_{i,S_i-1}\}$. Channel sparsity means $S_i \ll L$.

Moreover, time-varying wireless channel has the property of inter-channel correlation due to the fact that the path delays vary much slower than the path gains [12], e.g., even if the path gains are varying significantly from one symbol to the next symbol, the path delays during several successive TDS-OFDM symbols typically remain unchanged. The reason is that, the coherence time of the fast time-varying path gains is inversely proportionally to the system's working carrier frequency, while the path delay variation is inversely proportionally to the signal bandwidth [12], and usually the signal bandwidth is much

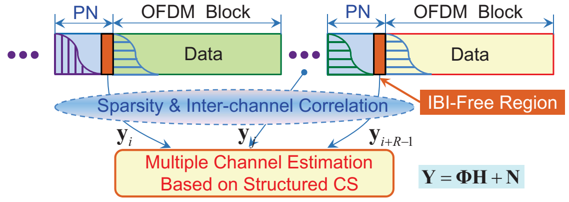

Fig. 3. IBI-free region of the received PN sequence in TDS-OFDM.

smaller than the carrier frequency. More specifically, the CIR column vectors in R consecutive TDS-OFDM symbols can be assumed to share the same sparsity pattern [10], i.e.,

$$\left\{ \begin{array}{l} S_i = S_{i+1} = \cdots = S_{i+R-1} = S, \\ D_i = D_{i+1} = \cdots = D_{i+R-1} = D, \\ \tau_{i,l} = \tau_{i+1,l} = \cdots = \tau_{i+R-1,l} = \tau_l, \end{array} \right. \tag{3}$$

where $0 \le l \le S-1$. We then define

$$\mathbf{H} = \left[\mathbf{h}_i, \mathbf{h}_{i+1}, \cdots, \mathbf{h}_{i+R-1}\right], \tag{4}$$

which is said to be jointly S-sparse, i.e., $\mathbf{H}$ has S nonzero rows with indices D in (3).

We will exploit these channel properties, which are not considered in conventional TDS-OFDM systems, to realize accurate channel estimation.

B. IBI-Free Region in TDS-OFDM

In conventional TDS-OFDM, channel estimation relies on the entire received PN sequence $\mathbf{d}_i$ in (1), which is contaminated by the previous OFDM data block $\mathbf{x}_{i-1}$, and reduced channel estimation performance is unavoidable. On the other hand, the worst-case system design principle indicates that the channel length is not larger than the guard interval length in the worst case. Therefore, the actual channel length in most practical scenarios is usually smaller or even much smaller than the guard interval length [1], [11], and then there exists an IBI-free region $\mathbf{y}_i = [d_{i,L-1}, d_{i,L}, \cdots, d_{i,M-1}]^T$ of small size $G = M - L + 1$ within the last part of the received PN sequence, and this IBI-free region not affected by interference:

$$\mathbf{y}_i = \mathbf{\Phi}_i \mathbf{h}_i + \mathbf{n}_i, \tag{5}$$

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

$$\mathbf{\Phi}_i = \begin{bmatrix} c_{i,L-1} & c_{i,L-2} & c_{i,L-3} & \cdots & c_{i,0} \\ c_{i,L} & c_{i,L-1} & c_{i,L-2} & \cdots & c_{i,1} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{i,M-1} & c_{i,M-2} & c_{i,M-3} & \cdots & c_{i,M-L} \end{bmatrix}_{G \times L} \tag{6}$$

corresponds to the last G rows of the matrix $\mathbf{\Psi}_i$ in (1). Considering the IBI-free regions of R consecutive TDS-OFDM symbols using the same PN sequences (i.e., $\mathbf{c}_i = \mathbf{c}_{i+1} = \cdots = \mathbf{c}$, which leads to $\mathbf{\Phi}_i = \mathbf{\Phi}_{i+1} = \cdots = \mathbf{\Phi}$), we have

$$\mathbf{Y} = \left[\mathbf{y}_i, \mathbf{y}_{i+1}, \cdots, \mathbf{y}_{i+R-1}\right]_{G \times R} = \mathbf{\Phi}\mathbf{H} + \mathbf{N}, \tag{7}$$

where $\mathbf{N} = \left[\mathbf{n}_i, \mathbf{n}_{i+1}, \cdots, \mathbf{n}_{i+R-1}\right]_{G \times R}$.

Although the IBI-free region is not contaminated by the previous OFDM data block, its size G is smaller or even much smaller than the channel length L, so it is impossible to solve the underdetermined problem (7) under the framework of linear processing. However, the considered mathematical model (7) complies with the newly developed theory of SCS [10], which is an extension of the standard CS theory [18], [19], for efficiently solving the underdetermined problem by exploiting the signal sparsity nature as well as the signal structure. According to the SCS theory, the jointly sparse multiple channels within $\mathbf{H}$ can be simultaneously reconstructed by solving the following nonlinear optimization problem [10]:

$$\widehat{\mathbf{H}} = \arg \min_{\mathbf{H} \in \mathbf{C}^{L \times R}} \|\mathbf{H}\|_{p,q}, \quad \text{subject to } \mathbf{Y} = \mathbf{\Phi}\mathbf{H}, \tag{8}$$

where $\|\mathbf{H}\|_{p,q}$ denotes the $l_{p,q}$ norm of the matrix $\mathbf{H}$. Typically an $l_{2,0}$ norm is used [10].

C. TDS-OFDM Channel Estimation Based on SCS

This section proposes a reliable yet low-complexity channel estimation scheme by utilizing the well-known signal reconstruction algorithm called as simultaneous orthogonal matching pursuit (SOMP) [20] and the specific signal structure of TDS-OFDM.

1) Correlation Based Channel Priori Acquisition: Relying on the good auto-correlation properties of the PN sequence, without interference removal, the received contaminated PN sequence is directly correlated with the local known PN sequence to generate a first rough channel estimate $\overline{\mathbf{h}}_i$:

$$\overline{\mathbf{h}}_i = \frac{1}{M} \mathbf{c}_i \otimes \mathbf{d}_i = \mathbf{h}_i + \mathbf{u}_i, \tag{9}$$

where $\mathbf{u}_i$ denotes the interference effect caused by the previous OFDM data block as well as the AWGN. The good autocorrelation properties of the PN sequence ensure that the main characteristics of the channel, especially the time delays of significant paths, can be preserved.

Based on the rough channel estimates $\overline{\mathbf{h}}_i$ during several consecutive TDS-OFDM symbols, the number of observation vectors R needed to generate the observation matrix $\mathbf{Y}$ in (7) can be determined by checking the locations of the most significant taps within the rough estimates. Then, the path gains in $\overline{\mathbf{h}}_i$ are discarded, and the initial partial support of the jointly sparse channels could be approximated by

$$D_0 = \{l : \frac{1}{R} \sum_{j=i}^{i+R-1} \left|\overline{h}_{j.l}\right|^2 \ge p_{th}\}_{l=0}^{L-1}, \tag{10}$$

where p_{th} is a power threshold used to determine the main paths, which can be configured according to [21], and $S_0 = \|D_0\|_0$ is the initial channel sparsity level. Then, the channel length can be also determined so that the IBI-free region can be selected accordingly.

2) Adaptive SOMP Based Joint Sparsity Pattern Recovery: Based on the basic principle of well-known sparse signla recovery algorithm SOMP [20], we propose the adaptive SOMP (A-SOMP) algorithm, which is adaptive to variable

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Input: 1) Initial partial support $D_0$, initial channel
          sparsity level $S_0$, channel sparsity level $S$;
       2) Noisy measurements $\mathbf{Y}$, observation matrix $\mathbf{\Phi}$.
Output: $S$-sparse estimate $\widehat{\mathbf{H}}$ containing multiple CIRs.
$\Omega \leftarrow D_0$;
$k \leftarrow S_0$;
$\widehat{\mathbf{H}}_k\Big|_\Omega \leftarrow \mathbf{\Phi}_\Omega^\dagger \mathbf{Y}$;
$\mathbf{R} \leftarrow \mathbf{Y} - \mathbf{\Phi}\widehat{\mathbf{H}}_k\Big|_\Omega$;
while $k \leq S$ do
    $k \leftarrow k + 1$;
    $\mathbf{E} \leftarrow \mathbf{\Phi}^H \mathbf{R}$;
    $\Gamma \leftarrow \arg\max_{k} \sum_j |e_{k,j}|$;
    $\Omega \leftarrow \Omega \cup \Gamma$;
    $\widehat{\mathbf{H}}_k\Big|_\Omega \leftarrow \mathbf{\Phi}_\Omega^\dagger \mathbf{Y}$, $\widehat{\mathbf{H}}_k\Big|_{\Omega^c} \leftarrow \mathbf{0}$;
    $\mathbf{R} \leftarrow \mathbf{Y} - \mathbf{\Phi}\widehat{\mathbf{H}}_k$;
end
$\widehat{\mathbf{H}} \leftarrow \widehat{\mathbf{H}}_k$;
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Algorithm 1: Adaptive SOMP (A-SOMP)

channel conditions, and exploits the channel priori to reduce the complexity. The pseudocode of the proposed A-SOMP algorithm is summarized in Algorithm 1, which differs from SOMP [20] in the following three aspects:

1) **Number of iterations**. Since the partial support is already known, A-SOMP only executes $S - S_0$ iterations instead of S iterations in SOMP.
2) **Initialization**. Since the initial support is known, the initial residual signal $\mathbf{R} \leftarrow \mathbf{Y} - \mathbf{\Phi}\widehat{\mathbf{H}}_k\Big|_\Omega$ is used to replace its counterpart $\mathbf{R} \leftarrow \mathbf{0}$ in SOMP, whereby $\mathbf{\Phi}_\Omega^\dagger\mathbf{Y}$ is the initial estimate of channel matrix $\mathbf{Y}$.
3) **Adaptation**. A-SOMP is adaptive to the channel sparsity level, the number of observation vectors, as well as the number of iterations.

After $\widehat{\mathbf{H}}$ has been obtained by the proposed A-SOMP algorithm, again the path gains within $\widehat{\mathbf{H}}$ are discarded, and the path delays of the nonzero taps are estimated by the support of $\widehat{\mathbf{H}}$ as follows

$$\widehat{D} = \mathrm{supp}\{\widehat{\mathbf{H}}\}. \tag{11}$$

Note that $S - S_0$ instead of S iterations are carried out by the proposed A-SOMP algorithm, so it reduces the complexity of SOMP by a factor of S_0/S. For example, the complexity is reduced by about 66.67% if four out of six channel path delays have been obtained by the channel priori acquisition step.

3) ML Based Path Gain Estimation: After the path delays have been obtained, the signal model (7) is simplified to

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

where $\mathbf{h}_{iS}$ is generated by restricting the vector $\mathbf{h}_i$ to its S largest components, and $\mathbf{\Phi}_{\widehat{D}}$ is the submatrix comprising the $\widehat{D}$ columns of $\mathbf{\Phi}$. It is clear from (14) that there remains only S instead of L ($S < G \ll L$) unknown nonzero path gains in the CIR vector $\mathbf{h}_i$, which can be estimated by solving an over-determined equation under the ML criterion:

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

Finally, the path delay and path gain estimates form the complete CIR estimate as $\widehat{\mathbf{h}}_i\Big|_{\widehat{D}} = \widehat{\mathbf{h}}_{iS}$.

Similar operations (13) could be carried out to obtain the estimates of the remaining $R - 1$ CIR vectors to finally accomplish the simultaneous multi-channel reconstruction.

D. Performance Bound Analysis

For performance evaluation, we have derived the theoretical Cramér-Rao lower bound (CRLB) of the proposed channel estimation scheme based on SCS as

$$\mathrm{CRLB} = \mathrm{E}\left\{\left\|\widehat{\mathbf{h}}_S - \mathbf{h}_S\right\|_2\right\} = \frac{S\sigma^2}{G}. \tag{14}$$

Compared with conventional TDS-OFDM with iterative interference cancellation, whose best mean square error (MSE) performance is σ^2 (the noise level) if mutual interferences can be completely removed, the proposed scheme achieves a much better MSE performance, since S is smaller or even much smaller than G, i.e., $S < G$.

E. Computational Complexity

The computational complexity of the proposed scheme in terms of the required number of complex multiplications is $\mathcal{O}(RM + (S - S_0)RG(L + S^2) + RGS^2)$ for R consecutive TDS-OFDM symbols. As $S \ll L \leq M$, the proposed channel estimation scheme based on SCS has the linear computational complexity of $\mathcal{O}((S - S_0)RGL)$, which is affordable for modern receivers.

IV. ENERGY EFFICIENCY

The energy efficiency of practical OFDM systems is

$$\eta_0 = \frac{N_{\mathrm{data}}}{N_{\mathrm{data}} + \beta^2 N_{\mathrm{pilot}}} \times \frac{N}{N + \alpha^2 M} \times 100\%, \tag{15}$$

where β and α denotes the amplitude factor imposed on the frequency-domain pilots and time-domain guard interval, respectively. For example, $\beta = 4/3$ in CP-OFDM has been specified by the DVB-T2 standard [4], and similarly, $\alpha = \sqrt{2}$ in conventional TDS-OFDM has been specified by the DTMB standard [15]. On the contrary, the proposed scheme can reduce the guard interval power by relying on the powerful SCS theory to significantly improve the channel estimation performance.

When the amplitude factor $\alpha = 1/\sqrt{2}$ is considered for the proposed scheme, Table I summaries the energy efficiency comparison of different OFDM transmission systems. It is clear that in typical single frequency network (SFN) applications when $M = N/4$ [15], the conventional TDS-OFDM has very similar energy efficiency as standard CP-OFDM. However, the proposed TDS-OFDM transmission scheme based on SCS has a 23.66% higher energy efficiency than standard CP-OFDM. Although such improvement becomes slightly smaller

TABLE I
ENERGY EFFICIENCY COMPARISON.

	CP-OFDM[a]	TDS-OFDM[b]	DPN-OFDM[c]	Proposed Scheme[d]
$M = N/4$	65.23%	66.67%	66.67%	88.89%
$M = N/8$	72.48%	80.00%	80.00%	94.12%
$M = N/16$	76.75%	88.89%	88.89%	96.97%

[a] We consider the typical example that the pilot occupation ratio in CP-OFDM is about 11.29%, which is specified by the 4K mode of the DVB-T2 standard [4].
[b] The amplitude factor of the PN sequence is $\alpha = \sqrt{2}$ as specified by DTMB standard [15].
[c] The amplitude factor of the PN sequence is $\alpha = 1$ according to [14].
[d] The amplitude factor of the PN sequence is $\alpha = 1/\sqrt{2}$ as an typical example.

when the guard interval length is decreased, more than 20% higher energy efficiency[1] can be still achieved when $M = N/8$ or $M = N/16$.

V. SIMULATION RESULTS AND DISCUSSION

Simulations are carried out to investigate the performance of the proposed reliable and energy-efficient TDS-OFDM transmission scheme based on SCS. The simulation setup is configured according to typical wireless broadcasting systems [8]. The signal bandwidth is 7.56 MHz located at the central radio frequency of 770 MHz. The FFT size $N = 4096$ and the guard interval length $M = 256$ are adopted. The modulation scheme uses 64QAM and 256QAM, and a low-density parity-check (LDPC) code with block length 64,8000 bits and code rate 0.6 as specified in [4] is considered. The six-tap Vehicular B channel model [4] with the maximum delay spread of 20 μs is adopted.

Fig. 4 shows the MSE performance comparison between the proposed channel estimation based on SCS and its counterparts in conventional TDS-OFDM, DPN-OFDM, and CP-OFDM systems in Vehicular B channel. To ensure the channel estimation performance when the SNR is low, the last $G = 30$ samples of the IBI-free region are selected for the joint CIR reconstruction. It is clear that the proposed scheme outperforms the conventional systems by more than 5 dB when the target MSE of 10^{-2} is considered. Moreover, the actual MSE performance approaches the theoretical CRLB (14) when the SNR becomes high. The accurate channel estimation is mainly contributed by the fact that the channel properties including channel sparsity and inter-channel correlation are fully exploited by the proposed scheme.

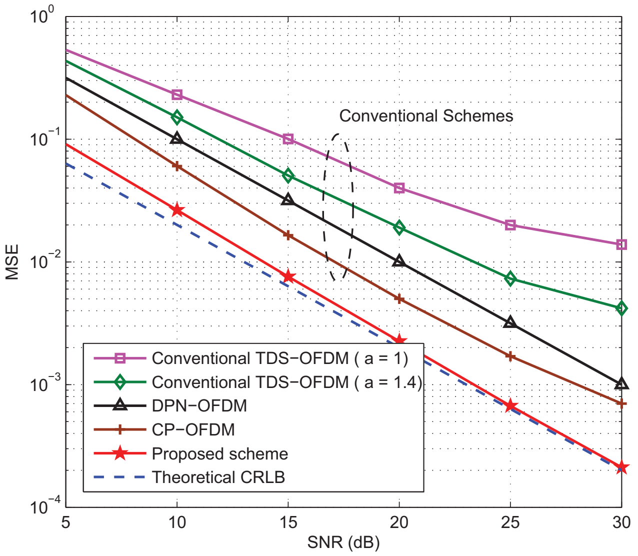

Fig. 4. Channel estimation performance comparison in the Vehicular B multipath channel with large delay spread.

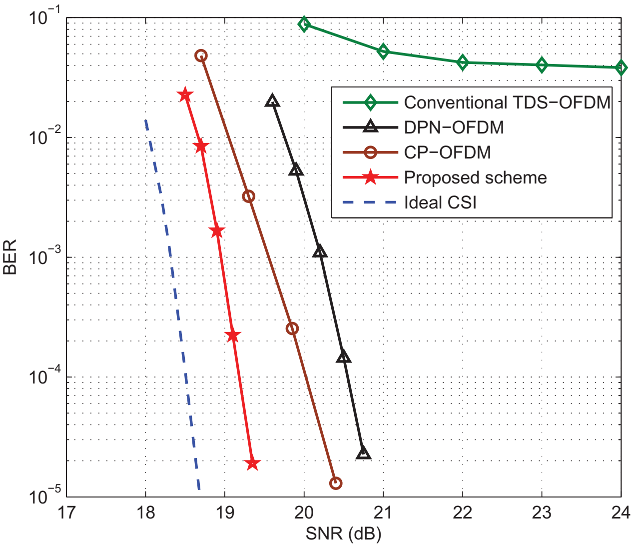

Fig. 5. BER performance comparison when HDTV is delivered in fast fading Vehicular B channel with the velocity of 120 km/h.

Fig. 5 shows the BER performance comparison in fast time-varying channels when 64QAM modulation and the LDPC code rate of 0.6 are configured, which is the primary working mode of DTMB to provide high-definition TV (HDTV) services with a data rate of 24.4 Mbps [8]. It is known that reliable HDTV delivery can be achieved over static or low-speed channels, but it is highly expected that HDTV can also be delivered in high-speed vehicles. From Fig. 5, we can observe that the conventional TDS-OFDM scheme cannot support HDTV delivery in fast fading channels, whereby the inaccurate channel estimation as shown in Fig. 4 cannot be used for reliable mutual interference cancellation and data demodulation. However, the proposed scheme can achieve reliable HDTV delivery with a BER performance only 0.5 dB away from the ideal CSI case. We can also find that the proposed scheme outperforms DPN-OFDM and CP-OFDM by a SNR gain of 1.4 dB and 0.8 dB at a BER of 1×10^{-4}, respectively.

Finally, the impact of guard interval power on the system

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[1] The energy efficiency can be further improved by decreasing the guard interval power a little more, but a compromise should be made between improved energy efficiency and decreased accuracy of channel estimation.

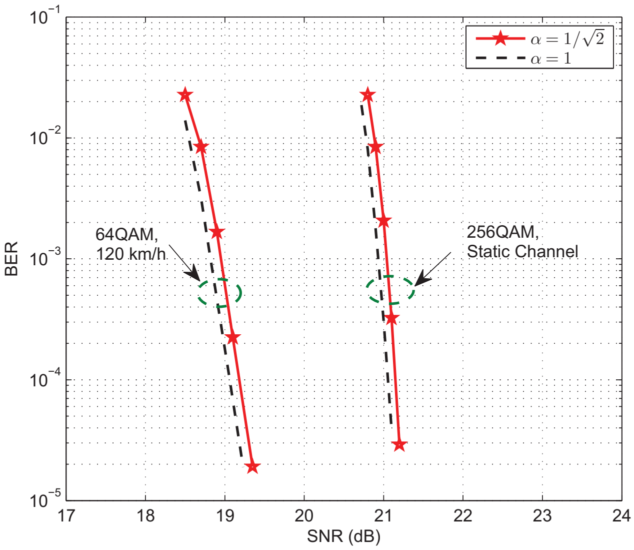

Fig. 6. The impact of guard interval power on the system BER performance.

BER performance is evaluated in Fig. 6. In contrast to the conventional TDS-OFDM scheme which increase the power of the PN sequence to guarantee the receiver performance, the guard interval power can be decreased in the proposed scheme to further improve the energy efficiency. Compared to the case when $\alpha = 1$, i.e., the PN sequence power is not reduced, we can observe that a negligible SNR loss will be introduced when $\alpha = 1/\sqrt{2}$, e.g., the SNR loss is less than 0.1 dB both in a static and a fast fading channel. Although decreasing the guard interval power results in a reduced MSE performance of the channel estimation based on SCS, the estimated channel is still accurate enough for reliable cancellation of the mutual interference and data demodulation.

VI. CONCLUSIONS

It is impossible to change the guard interval power in standard CP-OFDM. However, we propose to reduce the guard interval power in TDS-OFDM to improve the energy efficiency by about 20% compared with CP-OFDM. This is achieved by designing a channel estimation with high accuracy based on the theory of structured compressive sensing. The wireless channel properties including channel sparsity and inter-channel correlation, which are usually not considered in conventional OFDM schemes, are exploited in the proposed scheme. We further exploit the worst-case system design principle to extract multiple IBI-free regions of small size to simultaneously reconstruct multiple channels of large size without iterative interference cancellation. The performance bound and the computational complexity of the proposed scheme are also provided. Simulation results show that reliable transmission like HDTV delivery can be also achieved in fast fading channels.

ACKNOWLEDGMENTS

This work was supported by National Key Basic Research Program of China (Grant No. 2013CB329203), National Natural Science Foundation of China (Grant Nos. 61271266 and 61201185), and grant-in-aid for the Japan Society for the Promotion of Science (JSPS) fellows (Grant No. 2402366), and the ZTE fund project CON1307250001.

REFERENCES

[1] 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.

[2] J. Ketonen, M. Juntti, and J. Cavallaro, "Performance-complexity comparison of receivers for a LTE MIMO–OFDM system," *IEEE Trans. Signal Process.*, vol. 58, no. 6, pp. 3360–3372, June 2010.

[3] C. Yuen, Y. Wu, and S. Sun, "Four transmit diversity schemes for coded OFDM systems with four transmit antennas," *Journal of Communications*, vol. 3, no. 4, pp. 1–7, Sept. 2008.

[4] *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.

[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] R. Mo, Y. H. Chew, and C. Yuen, "Information rate and relay precoder design for amplify-and-forward MIMO relay networks with imperfect channel state information," *IEEE Trans. Veh. Technol.*, vol. 61, no. 9, pp. 3958–3968, Nov. 2012.

[7] C. Pan, L. Dai, and Z. Yang, "TDS-OFDM based HDTV transmission over fast fading channels," *IEEE Trans. Consum. Electron.*, vol. 59, no. 1, pp. 16–23, Feb. 2013.

[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] 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.

[10] M. Duarte and Y. Eldar, "Structured compressed sensing: from theory to applications," *IEEE Trans. Signal Process.*, vol. 59, no. 9, pp. 4053–4085, Sept. 2011.

[11] L. Dai, Z. Wang, and Z. Yang, "Compressive sensing based time domain synchronous OFDM transmission for vehicular communications," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 460–469, Sept. 2013.

[12] I. Telatar and D. Tse, "Capacity and mutual information of wideband multipath fading channels," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1384–1400, July 2000.

[13] 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.

[14] 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.

[15] *Framing Structure, Channel Coding and Modulation for Digital Television Terrestrial Broadcasting System.* International DTTB Standard, GB 20600-2006, Aug. 2006.

[16] 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.

[17] W. Dai and O. Milenkovic, "Subspace pursuit for compressive sensing signal reconstruction," *IEEE Trans. Inf. Theory*, vol. 55, no. 5, pp. 2230–2249, May 2009.

[18] D. Donoho, "Compressed sensing," *IEEE Trans. Inf. Theory*, vol. 52, no. 4, pp. 1289–1306, 2006.

[19] W. Dai, T. Xu, and W. Wang, "Simultaneous codeword optimization (SimCO) for dictionary update and learning," *IEEE Trans. Signal Process.*, vol. 60, no. 12, pp. 6340–6353, Dec. 2012.

[20] Y. Eldar and H. Rauhut, "Average case analysis of multichannel sparse recovery using convex relaxation," *IEEE Trans. Inf. Theory*, vol. 56, no. 1, pp. 505–519, Jan. 2010.

[21] 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.