Flexible Multi-Block OFDM Transmission for High-Speed Fiber-Wireless Networks

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***Abstract*—Orthogonal frequency-division multiplexing (OFDM) has been widely used in fiber-wireless (FiWi) networks, but it suffers from reduced spectral efficiency, high peak-to-average power ratio (PAPR), and severe sensitivity to carrier frequency offset (CFO). In this paper, we propose a flexible multi-block OFDM (MB-OFDM) transmission scheme to simultaneously solve those problems. First, one guard interval is shared by multiple blocks by exploiting the slow time-varying property of the fiber-wireless channel, so the spectral efficiency could be typically improved by about 10%. Second, the proposed scheme further divides every data block into multiple small sub-blocks, whereby each sub-block is generated by an inverse fast Fourier transform (IFFT) of smaller size accordingly. It thus provides a flexible compromise between the multi-carrier and single-carrier transmissions, and reduces the PAPR and the sensitivity to CFO. In addition, a hybrid-domain channel equalization method is proposed to detect the MB-OFDM signal by utilizing the single-carrier and multi-carrier transmission formats successively. Simulation results are provided to demonstrate the enhanced performance of the proposed scheme.**

***Index Terms*—Fiber-wireless (FiWi) networks, orthogonal frequency-division multiplexing (OFDM), spectral efficiency, peak-to-average power ratio (PAPR), carrier frequency offset (CFO).**

I. Introduction

TRADITIONALLY, optical communications and wireless technologies have gained rapid progresses respectively along their own paths. The optical fiber systems could provide extensive high-capacity but can not reach everywhere, while the wireless systems could offer ubiquitous coverage but are usually bandwidth-constrained [1]–[3]. Therefore, by integrating the huge capacity of optical fiber subsystems with the mobility and ubiquity of wireless subsystems, fiber-wireless (FiWi) networks are becoming the widely recognized powerful solution to future high-speed broadband access in the next decade [4]–[7].

For the wireless subsystems of the FiWi networks, orthogonal frequency-division multiplexing (OFDM) has become the prominent transmission scheme due to its robustness against wireless multipath fading channels as well as the low-complexity implementation [2]. Most of emerging wireless standards like IEEE 802.11n, long term evolution (LTE), and LTE-advanced (LTE-A), etc., are considering OFDM as the key transmission technology [8]–[10]. On the other hand, OFDM has recently gained considerable interest in future high-speed optical fiber networks with the data rate beyond 100 Gb/s [11]–[13], whereby the superior tolerance of OFDM to optical impairments including chromatic dispersion (CD) and polarization mode dispersion (PMD) has been verified, since the optical CD and PMD have essentially similar effect as the wireless multipath channel that could be easily equalized in the electrical domain [12]. We have also studied how to compensate CD and PMD more efficiently by appropriate design of the pilots in optical OFDM systems [14]. Therefore, as a hybrid access network integrating fiber subnetworks and wireless subnetworks, FiWi could naturally adopt OFDM as the prominent transmission technology [4]–[7]. For example, a 25 Gb/s OFDM FiWi system with the 22.8 km fiber and 2 m wireless channel has been presented in [15], and another 26 Gb/s OFDM FiWi system with 115 km fiber and 3 m wireless transmission has been demonstrated in [16].

However, OFDM suffers from three main drawbacks for FiWi networks [17]: 1) The reduced spectral efficiency due to the overhead of guard interval, usually in the form of cyclic prefix (CP), for every OFDM symbol; 2) The high peak-to-average power ratio (PAPR) of OFDM signals makes FiWi networks sensitive to the nonlinear distortion caused by either the laser diode or the Mach-Zehnder modulator (MZM); 3) The severe sensitivity to the residual carrier frequency offset (CFO) would cause large inter-carrier-interference (ICI) degrading the system performance. Those problems have been individually tackled in the literature [17], [18]. To improve the spectral efficiency, the length of the guard interval (e.g., in the form of CP) between adjacent OFDM symbols is reduced in the reduced-guard-interval OFDM (RGI-OFDM) scheme at the cost of increased receiver complexity [19]. To reduce the PAPR, clipping or active constellation extension (ACE) can be used with signal distortion [20], while selected mapping (SLM) and trellis shaping (TS) without signal distortion would add redundancy to the original OFDM signals [21]. To mitigate the sensitivity to CFO, the windowing technique or the polynomial cancellation coding (PCC) based self-ICI

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cancellation scheme could be used at the cost of reducing the transmission efficiency [22].

To solve all of those problems above, in this paper we propose the flexible multi-block OFDM (MB-OFDM) transmission scheme for future high-speed FiWi networks to simultaneously improve the spectral efficiency, reduce the PAPR and mitigate the vulnerability to CFO. Specifically, we make the following three contributions in this paper:

1) Unlike the conventional OFDM transmission scheme whereby each inverse fast Fourier transform (IFFT) data block has its own guard interval within every OFDM symbol, the proposed MB-OFDM scheme adopts only one guard interval in the form of zero padding (ZP) for multiple blocks by exploiting the slow time-varying property of the fiber-wireless channel [15], [23]. In this way, the spectral efficiency could be typically improved by about 10%.

2) Every data block within the MB-OFDM transmission frame is further divided into multiple sub-blocks, whereby each sub-block is generated by an IFFT of smaller size accordingly. This mechanism makes MB-OFDM a flexible compromise between the multi-carrier and single-carrier transmissions, so the PAPR of the MB-OFDM signal could be reduced, and the sensitivity to CFO could also be alleviated.

3) The hybrid-domain channel equalization is proposed to demodulate the MB-OFDM signal, whereby the received signal in the form of multi-carrier is firstly regarded as a single-carrier signal which is recovered in the time domain, and then the FFT of reduced size is used to restore the transmitted multi-carrier signal in the frequency domain.

The remainder of this paper is organized as follows. The proposed MB-OFDM frame structure is described in Section II. The corresponding receiver design is presented in Section III. Section IV analyzes the performances of the proposed scheme. Simulation results are provided in Section V. Finally, conclusions are drawn in Section VI.

Notation: We use the upper and lower boldface letters to denote matrices and column vectors, respectively; $\mathbf{0}_{M\times N}$ denotes the $M \times N$ zero matrix; $\mathbf{F}_N$ denotes the normalized $N \times N$ fast Fourier transform (FFT) matrix whose $(n+1, k+1)$th entry is $\exp(-j2\pi nk/N)/\sqrt{N}$; $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^H$, $(\cdot)^{-1}$, and $|\cdot|$ denote the complex conjugate, transpose, Hermitian transpose, matrix inverse, and absolute operations, respectively; $\otimes$ and $\odot$ denote the cyclic convolution and component-wise multiplication of vectors, respectively; $\widehat{x}$ represents an estimate of x; $\text{angle}\{x\}$ means the angle of the complex-valued x; $\Pr(x)$ and $\mathrm{E}(x)$ denote the probability density function and statistical expectation of the random variable x, respectively. Finally, a symbol with a tilde $\tilde{}$ over it indicates a frequency-domain signal.

II. MB-OFDM Frame Structure for FiWi Networks

In this section, the system architecture of the FiWi networks is firstly outlined, and then the proposed MB-OFDM frame structure for FiWi networks is addressed in detail. Finally, the signal model over the fiber-wireless channels is presented.

A. FiWi System Architecture

The overall system architecture of the FiWi networks [4]–[7] integrating the fiber subsystems and the wireless subsystems is shown in Fig. 1. The wireless base stations and access points in wireless radio subsystems could provide ubiquitous and mobile access for end users, while the fiber subsystem could offer very high throughput by exploiting the central offices (CO) to interconnect all the wireless base stations and access points. In addition, most high-complexity processing originally implemented in the wireless base stations and access points can be shifted to the central offices, thus more dense wireless antennas could be deployed with low cost, and obviously increased data rate and enhanced coverage are expected for future high-speed FiWi networks.

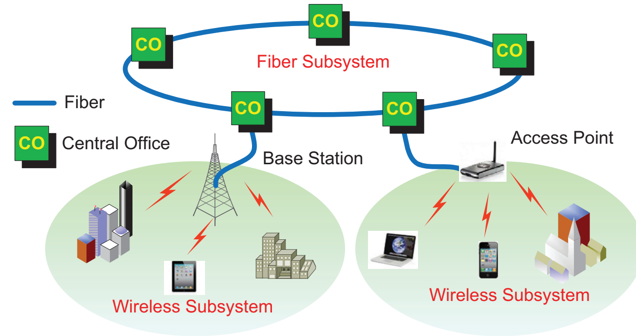

Fig. 1. System architecture of the FiWi networks integrating the optical fiber subsystems and the radio wireless subsystems.

B. Proposed MB-OFDM Frame Structure

The frame structure comparison between the conventional OFDM and the proposed MB-OFDM schemes for FiWi networks is illustrated in Fig. 2.

As shown in Fig. 2 (a), the transmission frame for most existing OFDM-based FiWi networks [4]–[7] is composed of one preamble used for joint timing/frequency synchronization and channel estimation, and the following S payload OFDM symbols using the CP of length M as the guard interval of the IFFT data block of length N. Since the fiber-wireless channel is varying slowly [15], [23], the channel information obtained during the preamble could be used to demodulate the following S OFDM symbols. The number S could be large, e.g., $S = 7$ has been adopted in [15], and $S = 267$ in [23]. For the mth OFDM symbol, the time-domain IFFT data block $\mathbf{d}_m = [d_{m,0}, d_{m,1}, \cdots, d_{m,N-1}]^T$ is generated by applying the N-point IFFT to the frequency-domain data $\widetilde{\mathbf{d}}_m = [\widetilde{d}_{m,0}, \widetilde{d}_{m,1}, \cdots, \widetilde{d}_{m,N-1}]^T$ as

$$d_{m,n} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \widetilde{d}_{m,k} e^{j\frac{2\pi}{N}nk}, \quad m = 0, 1, \cdots, S-1. \quad (1)$$

On the contrary, as shown in Fig. 2 (b), the proposed MB-OFDM transmission frame is composed of one preamble and the following two parts: 1) One super-block data $\mathbf{d} = [\overline{\mathbf{d}}_0^T, \overline{\mathbf{d}}_1^T, \cdots, \overline{\mathbf{d}}_{S-1}^T]^T$ of length SN comprising S data blocks $\{\overline{\mathbf{d}}_m\}_{m=0}^{S-1}$ without guard interval (e.g., CP in most OFDM systems) among them. The mth data block $\overline{\mathbf{d}}_m = [\mathbf{d}_{m,0}^T, \mathbf{d}_{m,1}^T, \cdots, \mathbf{d}_{m,G-1}^T]^T$ is further divided into G sub-blocks $\{\mathbf{d}_{m,g}\}_{g=0}^{G-1}$, and each sub-block of length $N' = N/G$ is generated by N'-point IFFT; 2) One ZP $\mathbf{z} = \mathbf{0}_{M\times 1}$, which is used as the guard interval of the super-block data

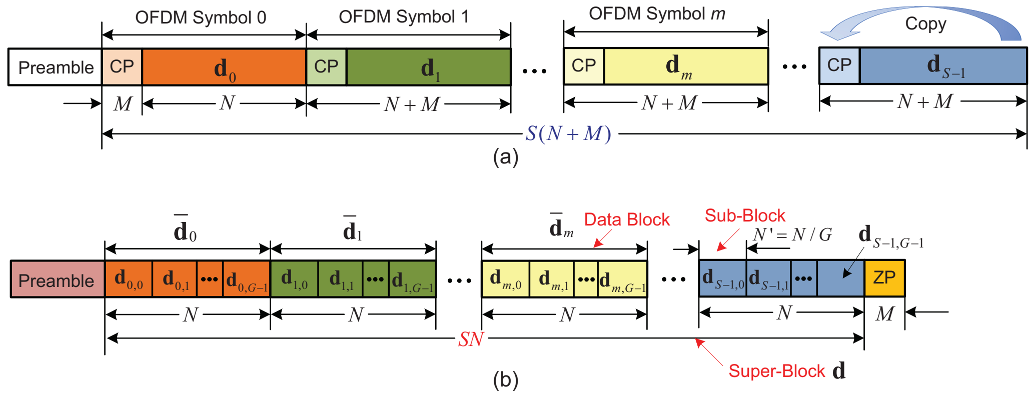

Fig. 2. Time-domain frame structure comparison: (a) The conventional OFDM scheme; (b) The proposed MB-OFDM scheme.

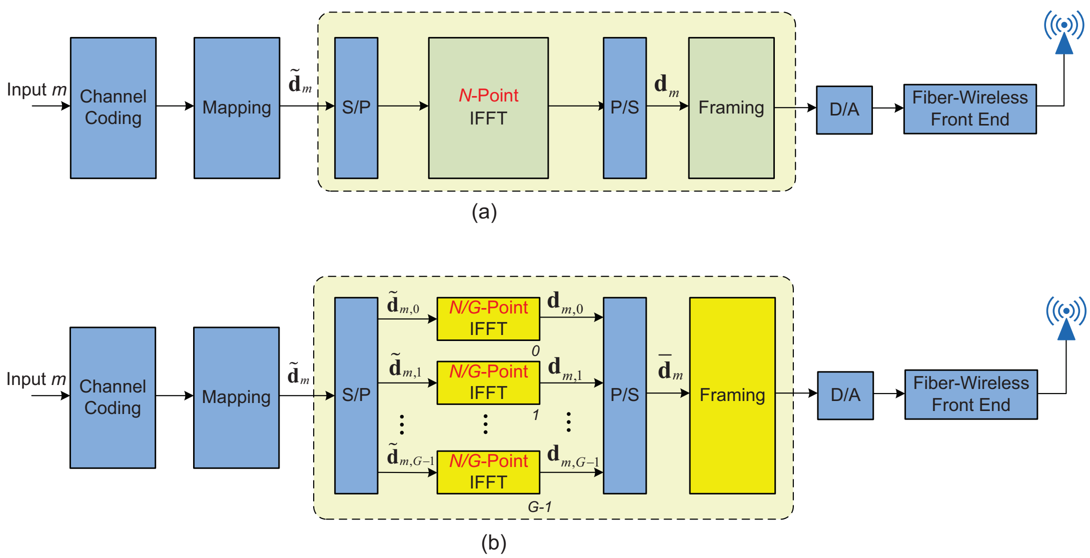

Fig. 3. Transmitter architecture comparison: (a) The conventional OFDM scheme; (b) The proposed MB-OFDM scheme.

$\mathbf{d}$. Essentially, the super-block data $\mathbf{d}$ and the following ZP $\mathbf{z}$ form a "virtual" ZP-OFDM symbol, whereby the data part is composed of S blocks corresponding to the S IFFT data blocks of the conventional OFDM symbols (here, we use the term "virtual" to distinguish the proposed frame structure from the standard ZP-OFDM signal structure [24], whereby every IFFT data block has a ZP as the guard interval).

The preamble we have proposed before in [14] will be directly used in this paper, which could achieve accurate timing and frequency synchronization due to the specially designed time-domain structure, and it can also be used for channel estimation. Normally, the length of the preamble is the same as that of a normal OFDM symbol.

The first key difference between the proposed MB-OFDM scheme and the conventional one is the guard interval. Traditionally, each OFDM symbol has its own CP (or ZP in ZP-OFDM systems) as the guard interval, and there are totally S CPs as shown in Fig. 2 (a). Since the length of guard interval is usually large enough to combat the composite effects of wireless multipath as well as optical CD and PMD in FiWi networks [1], [4], the frequently inserted CPs obviously reduce the spectral efficiency. However, the proposed scheme utilizes only one ZP as the guard interval for all of the S data blocks. The only one guard interval instead of S guard intervals could also be efficiently used for reliable data demodulation, thus the proposed MB-OFDM scheme could achieve higher spectral efficiency.

The second obvious difference between the proposed MB-OFDM solution and the conventional one lies in the way to generate the time-domain payload data. As illustrated in Fig. 2 and further explained in Fig. 3, the gth sub-block $\mathbf{d}_{m,g} = [d_{m,g,0}, d_{m,g,1}, \cdots, d_{m,g,N'-1}]^T$ $(g = 0, 1, \cdots, G-1)$ within the mth data block $\bar{\mathbf{d}}_m$ is generated by applying the N'-point IFFT $(N' = N/G)$ to the corresponding frequency-domain data $\tilde{\mathbf{d}}_{m,g} = [\tilde{d}_{m,g,0}, \tilde{d}_{m,g,1}, \cdots, \tilde{d}_{m,g,N'-1}]^T$ as below:

$$d_{m,g,n} = \frac{1}{\sqrt{N'}} \sum_{k=0}^{N'-1} \tilde{d}_{m,g,k} e^{j\frac{2\pi}{N'}nk}, \quad n = 0, 1, \cdots, N'-1. \tag{2}$$

Note that the G N/G-point IFFTs in Fig. 3(b) can be actually implemented by a single N/G-point IFFT for G times to generate G sub-blocks $\{\mathbf{d}_{m,g}\}_{g=0}^{G-1}$.

Fig. 4 compares the frequency-domain signal structure of the proposed MB-OFDM with the conventional OFDM

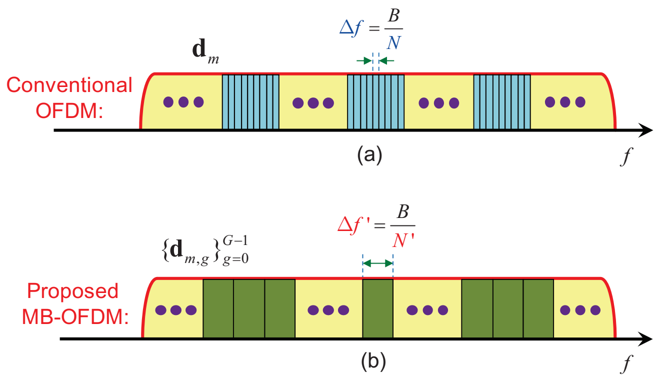

Fig. 4. Comparison of frequency-domain signal structure: (a) The conventional OFDM with the N-point IFFT; (b) The proposed MB-OFDM with the N'-point IFFT.

schemes with the same signal bandwidth B. For the conventional OFDM system where each time-domain IFFT data block is generated by N-point IFFT, the subcarrier-spacing Δf as shown in Fig. 4(a) should be

$$\Delta f = \frac{1}{T} = \frac{1}{NT_s} = \frac{B}{N}, \tag{3}$$

where T is the duration of the corresponding time-domain IFFT data block, T_s is the baseband sampling period, and $B = 1/T_s$ is the signal bandwidth. However, without changing the signal bandwidth (and the baseband sampling period as well), the proposed MB-OFDM scheme generates each sub-block by the N'-point IFFT ($N' = N/G$), so the subcarrier-spacing $\Delta f'$ as shown in Fig. 4(b) becomes

$$\Delta f' = \frac{1}{T'} = \frac{1}{N'T_s} = \frac{B}{N'} = G\Delta f, \tag{4}$$

where $T' = N'T_s$ is the duration of the corresponding sub-block in the time domain. It is clear that the subcarrier spacing $\Delta f'$ would be enlarged when the smaller IFFT size N' is used.

In conventional OFDM-based FiWi networks, the IFFT size is usually configured large to keep the overhead caused by the frequently inserted CPs within a certain degree, so the resulting subcarrier spacing is usually much smaller than the system coherent bandwidth [1], [4]. Therefore, it is possible to reduce the IFFT size to some extent without sacrificing the system performance. However, N' could not be too small. In the extreme case of $N' = 1$, the proposed MB-OFDM scheme becomes the single-carrier transmission, and the merits of multi-carrier transmission would vanish. Therefore, the proposed MB-OFDM scheme provides a flexible compromise between the conventional OFDM multi-carrier and single-carrier transmissions by configuring the appropriate parameter N' according to the system requirements.

The design of using smaller IFFT size N' does not sacrifice the spectral efficiency since multiple data blocks in MB-OFDM share only one guard interval. On the contrary, a conventional OFDM system usually adopts the relatively large IFFT size N because it requires every IFFT block to have its own guard interval. The direct reason of using the reduced IFFT size to generate the time-domain sub-blocks in MB-OFDM is to reduce the PAPR and alleviate the sensitivity to residual CFO of OFDM signals, which will be theoretically analyzed in Section IV and verified in Section V, respectively.

Note that different values of the parameters S, N, M, G could be supported by the proposed MB-OFDM scheme to further improve the system flexibility according to different system requirements.

C. Channel Model of Fiber-Wireless Systems

After the fiber-wireless channel, the received data $\mathbf{r} = [r_0, r_1, \cdots, r_{SN-1}]^T$ corresponding to the transmitted super-block data $\mathbf{d}$ should be [17]

$$r_n = \sum_{l=0}^{L-1} h_l d_{n-l} + w_n, \quad n = 0, 1, \cdots, SN-1, \tag{5}$$

where d_{n-l} is the $(n-l)$th entry of the super-block data $\mathbf{d}$ as shown in Fig. 2, $\mathbf{h} = [h_0, h_1, \cdots, h_{L-1}]^T$ is the time-domain channel impulse response (CIR) of the fiber-wireless link, h_l denotes the gain of the lth path including the wireless multi-path effect as well as the optical impairment effects like CD, PMD, and polarization dependent loss (PDL) [17], L denotes the channel length, w_n presents the additive white Gussian noise (AWGN) caused by the optical amplified spontaneous emission (ASE) [17] and electronic noise. Note that the ZP length M should be larger than the channel length L to avoid the interferences between adjacent transmission frames.

III. MB-OFDM Receiver Design

Fig. 5 presents the receiver architecture of the proposed MB-OFDM transmission scheme. After fiber-wireless front end and analog-to-digital (A/D) conversion, the preamble [14] is used for joint timing and frequency synchronization, and it can also be used for channel estimation [25]. Then, we propose the hybrid-domain channel equalization to remove the fiber-wireless channel impairments. Finally, constellation demapping and channel decoding are used to recover the transmitted signal.

Motivated by the fact that the MB-OFDM scheme actually unifies the modeling of the multi-carrier and single-carrier transmissions, we propose the hybrid-domain channel equalization of the MB-OFDM signal as illustrated by the dashed block of Fig. 5. Unlike the classical frequency-domain equalization (FDE) where one N-point FFT is applied to obtain the frequency-domain data for each OFDM symbol, the proposed hybrid-domain channel equalization is composed of the time-domain signal detection with a pair of SN-point FFT/IFFT and then the frequency-domain signal recovery with SG $\frac{N}{G}$-point FFTs.

First, the slow time-varying property of channel in FiWi networks will be exploited to achieve the cyclicity reconstruction of the received "virtual" ZP-OFDM symbol of large size by extending the classical overlap and add (OLA) algorithm [24] used for a single standard ZP-OFDM symbol of small size. The OLA algorithm simply adds the "tail" caused by the multipath effect in the ZP, to the front part of the received super-block data $\mathbf{r}$ of length SN, so the obtained data $\mathbf{r}' = [r'_0, r'_1, \cdots, r'_{SN-1}]^T$ actually becomes the cyclic

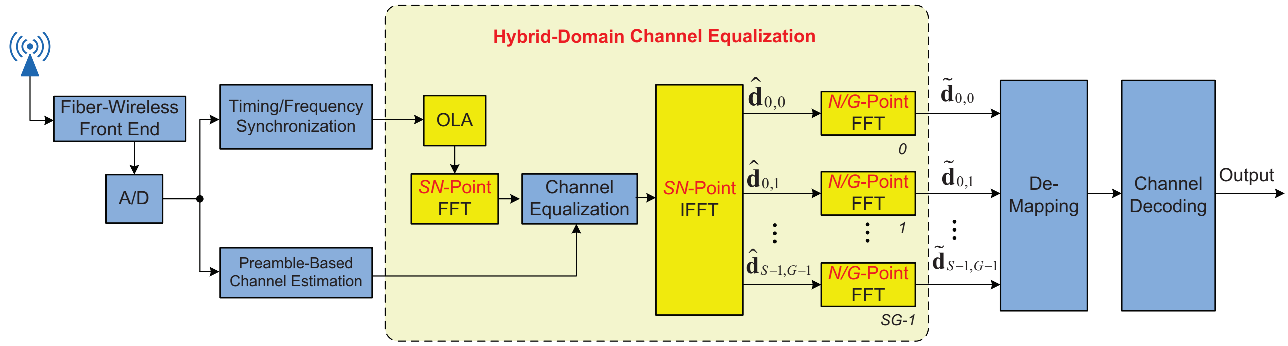

Fig. 5. Receiver architecture of the proposed MB-OFDM scheme with reduced IFFT size and guard interval.

convolution between the transmitted super-block data $\mathbf{d}$ and the CIR $\mathbf{h}$ as

$$\mathbf{r}' = \mathbf{d} \otimes \mathbf{h} + \mathbf{w}, \tag{6}$$

where $\mathbf{w}$ denotes the AWGN vector. Therefore, ZP in the proposed MB-OFDM acts similarly to the CP in conventional OFDM, whereby the cyclicity reconstruction could be achieved by directly removing the CP.

Second, a pair of SN-point FFT/IFFT is used to recover the time-domain transmitted super-block data $\mathbf{d}$ after compensating for the fiber-wireless channel impairments in the frequency domain. The SN-point FFT is applied to the time-domain signal $\mathbf{r}'$ in (6) to produce the frequency-domain signal $\widetilde{\mathbf{r}}'$ as

$$\widetilde{\mathbf{r}}' = \mathbf{F}_{SN}\mathbf{r}' = \mathbf{F}_{SN}\left(\mathbf{d} \otimes \mathbf{h} + \mathbf{w}\right) = \widetilde{\mathbf{d}} \odot \widetilde{\mathbf{h}} + \widetilde{\mathbf{w}}, \tag{7}$$

where $\widetilde{\mathbf{d}} = \mathbf{F}_{SN}\mathbf{d}$ is the FFT output of $\mathbf{d}$ (note that $\widetilde{\mathbf{d}}$ distinguishes the direct stacking of $\{\widetilde{\mathbf{d}}_m\}_{m=0}^{S-1}$ since different IFFT sizes are used), $\widetilde{\mathbf{h}} = \mathbf{F}_{SN}\mathbf{h}$ denotes the channel frequency response (CFR) corresponding to the CIR $\mathbf{h}$, and $\widetilde{\mathbf{w}} = \mathbf{F}_{SN}\mathbf{w}$ denotes the frequency-domain AWGN. Then, the time-domain transmitted super-block data $\mathbf{d}$ could be recovered as

$$\widehat{\mathbf{d}} = \mathbf{F}_{SN}^{H}\widehat{\widetilde{\mathbf{d}}} = \mathbf{F}_{SN}^{H}\widetilde{\mathbf{r}}'/\widehat{\widetilde{\mathbf{h}}}, \tag{8}$$

where $\widehat{\widetilde{\mathbf{h}}}$ is obtained by the preamble-based channel estimation [25]. From (8) we can find that the inter-symbol interference caused by the multipath channel effect over the entire super-block $\mathbf{d}$ has been compensated for.

Third, as illustrated in Fig. 5, the recovered time-domain super-block data $\widehat{\mathbf{d}}$ is divided into SG length-$\frac{N}{G}$ sub-blocks according to the frame structure at the transmitter, and then SG $\frac{N}{G}$-point FFTs are used to restore the transmitted signal in the frequency domain.

Note that the second step of the proposed hybrid-domain channel equalization is similar to the equalization scheme for single-carrier transmission [17], whereby the multi-carrier "virtual" ZP-OFDM symbol is recovered in the time domain by using the N-point FFT/IFFT first. Then, we use the FFT of smaller size N' to finally recover the multi-carrier signal in the frequency domain in the third step.

IV. Performance Analysis

This section provides the performance analysis of the proposed MB-OFDM transmission scheme in terms of spectral efficiency, PAPR reduction, sensitivity to CFO, and the computational complexity. The potential extensions of the proposed scheme are also discussed.

TABLE I
Comparison of Spectral Efficiency

Number of Data Blocks S	Conventional OFDM	Proposed MB-OFDM
$S = 10$	80.81%	89.89%
$S = 20$	84.66%	94.12%
$S = 40$	86.72%	96.97%

A. Spectral Efficiency

Due to the overhead caused by the preamble, especially the guard intervals, the spectral efficiency of the OFDM-based FiWi networks normalized by the ideal case without any overhead [14] can be expressed in the percentage form as

$$\eta_0 = \frac{SN}{SN + KM + N_p} \times 100\%, \tag{9}$$

where K is the number of guard intervals used in the transmission frame, so $K = S$ for the conventional OFDM scheme while $K = 1$ for the proposed MB-OFDM scheme, N_p denotes the preamble length, and usually $N_p = M + N$ is adopted.

Table I compares the spectral efficiency between the conventional and proposed OFDM schemes for FiWi networks, whereby the typical values $N = 256, M = 32$ are used for both schemes. It is clear that about 10% higher spectral efficiency could be achieved by the proposed scheme due to the removal of $(S-1)$ guard intervals.

B. PAPR Reduction

It is highly desired to reduce the PAPR of OFDM signals in FiWi networks, since PAPR is the main source of nonlinear effect in those systems. The PAPR of the OFDM signal generated by a N-point IFFT (see (1) for example) is defined as

$$\text{PAPR(dB)} = 10\log_{10}\frac{\max\left\{\left|d_{m,n}\right|^2\right\}}{\mathrm{E}\left\{\left|d_{m,n}\right|^2\right\}}. \tag{10}$$

Since the input frequency-domain data $\{\widetilde{d}_{m,k}\}_{k=0}^{N-1}$ are random, the maximal PAPR could be as large as $\text{PAPR}_{\max} = 10\log_{10}N$ in the worst case that all the data $\{\widetilde{d}_{m,k}\}_{k=0}^{N-1}$ are added in phase during the IFFT process to generate the corresponding time-domain signal $\{d_{m,n}\}_{n=0}^{N-1}$. Such extreme case seldom appears in practice, so the widely used metric for evaluating PAPR is the complementary cumulative distribution function (CCDF) $F_c(\alpha)$, which is defined as the probability that the PAPR is larger than a given threshold α. It has been proved that [26]

$$\begin{aligned} F_c(\alpha) &= \Pr(\text{PAPR} > \alpha) = 1 - \Pr(\text{PAPR} \le \alpha) \\ &= 1 - \left(1 - e^{-\alpha}\right)^N, \end{aligned} \tag{11}$$

which indicates that the CCDF is only dependent on the IFFT size N for a given threshold α. Thus, the smaller IFFT size $N' = N/G$ in the proposed MB-OFDM scheme would result in lower CCDF of the PAPR. It is worth noting that the improvement of PAPR by reducing the IFFT size has no penalty of signal distortion or bandwidth extension as the existing PAPR reduction techniques [20], [21].

The PAPR reduction due to smaller IFFT size N' could also be intuitively explained by the fact that the proposed MB-OFDM is essentially a compromise between the multi-carrier and signal-carrier transmission schemes, whereby multi-carrier signal has high PAPR while single-carrier signal enjoys low PARR.

C. Sensitivity to CFO

It is well known that another main drawback of OFDM is its high sensitivity to CFO [17]. In OFDM-based FiWi systems, the mismatch between either the radio frequency oscillators or optical lasers [11], [18] would cause CFO, and the resulting ICI would deteriorate the overall system performance considerably. Although CFO could be compensated for by using the preamble-based CFO estimate [14], the residual uncompensated CFO is always present in high-speed FiWi networks due to the time-varying nature of CFO [17]. So it is still highly desirable to mitigate the vulnerability of OFDM signals to the residual CFO.

By considering the effect of the residual CFO ω, the nth received time-domain sample r_n should be [17]

$$r_n = e^{j\frac{2\pi}{N}n\omega T}\sum_{l=0}^{L-1} h_l d_{n-l} + w_n, \tag{12}$$

where $2\pi n\omega T/N$ denotes the time-varying effect of the phase rotation caused by the residual CFO ω. Then, the ICI effect on the frequency-domain received signal can be mathematically described by [17]

$$\widetilde{r}_k = \Psi_0 \widetilde{h}_k \widetilde{d}_k + \underbrace{\sum_{l=0,l\neq k}^{L-1} \Psi_{k-l} \widetilde{h}_k \widetilde{d}_k}_{\text{ICI}} + \widetilde{w}_k. \tag{13}$$

The amplitude of the ICI coefficient caused by the residual CFO ω becomes

$$\begin{aligned} |\Psi_{k-l}| &= \left| \frac{1}{N} \sum_{n=0}^{N-1} e^{j\frac{2\pi}{N}n(\omega T-(k-l))} \right| \\ &= \frac{\sin\left(\pi\left(\omega T - (k-l)\right)\right)}{N\sin\left(\frac{\pi}{N}\left(\omega T - (k-l)\right)\right)}. \end{aligned} \tag{14}$$

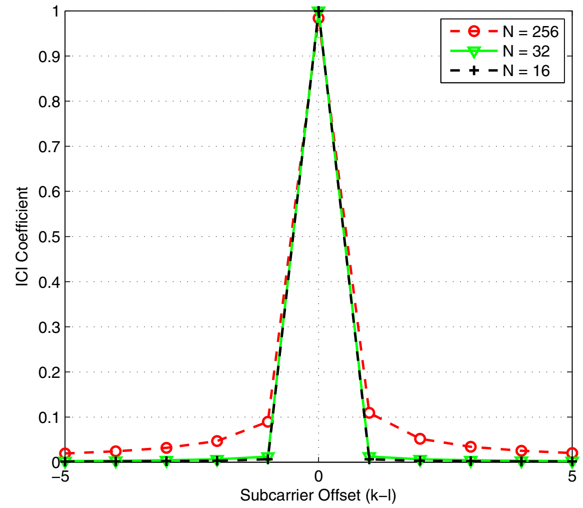

Fig. 6. The amplitude of the ICI coefficients caused by the residual normalized CFO $\omega T = 0.1$ when different IFFT sizes are used.

Fig. 6 depicts the amplitude of the ICI coefficients caused by the residual CFO $\omega T = 0.1$ normalized to the subcarrier spacing $1/T$ when different IFFT sizes are used. It is clear that the obviously decreased ICI effect could be achieved by the reduced IFFT size $N' = N/G$ in the proposed MB-OFDM scheme.

The alleviation of vulnerability to residual CFO due to the reduced IFFT size N' can be also intuitively interpreted by the fact that the proposed MB-OFDM scheme provides a flexible compromise between the multi-carrier and single-carrier transmissions, whereby multi-carrier transmission is very sensitive to CFO while single-carrier transmission is much less sensitive to CFO [17].

D. Computational Complexity

At the transmitter side, Fig. 2 indicates that the proposed scheme utilizes SG $\frac{N}{G}$-point IFFTs instead of S N-point IFFTs to generate the time-domain data. Considering the complexity of a N-point IFFT in terms of the number of multiplications is $\frac{N}{2}\log_2 N$, the proposed MB-OFDM scheme has the complexity of $SG\frac{N}{2G}\log_2(\frac{N}{G}) = \frac{SN}{2}\log_2(\frac{N}{G})$, instead of $\frac{SN}{2}\log_2 N$ for the conventional OFDM scheme. Clearly, a computation reduction of $\frac{SN}{2}\log_2 G$ could be achieved.

At the receiver side, the hybrid-domain channel equalization requires a simple addition for OLA-based cyclicity reconstruction, a pair of SN-point FFT/IFFT for single-carrier signal demodulation, and SG $\frac{N}{G}$-point FFTs for multi-carrier signal recovery. By contrast, the conventional OFDM scheme only needs S N-point FFTs to produce the frequency-domain signals for the S length-N IFFT data blocks (note that the preamble-based channel estimate could be used to demodulate all S OFDM symbols). Therefore, the receiver of the proposed MB-OFDM needs $SN \log_2 \frac{SN}{\sqrt{G}}$ more times of multiplications than the conventional OFDM. However, since FFT/IFFT could be efficiently realized by powerful modern digital processors, the increased complexity is affordable, especially for the proposed scheme having higher spectral efficiency, reduced PAPR, and alleviated sensitivity to the residual CFO.

E. Potential Extensions of the Proposed MB-OFDM Scheme

The proposed MB-OFDM scheme, or at least some key components of this scheme, can be directly used or easily extended to other OFDM-based wireless and optical communication systems.

First, the MB-OFDM scheme is also valid when CP instead of ZP is used as the guard interval in fiber/wireless/FiWi networks with the simple modification: replace ZP with CP and put the CP in front of the super-block data. As a result, the cyclicity reconstruction via OLA is not necessary any more, but other procedures at the transmitter and receiver remain unchanged. Thus, higher spectral efficiency, reduced PAPR and mitigated vulnerability to CFO could still be achieved.

Second, single-carrier transmission could also be used for FiWi networks [17], and the proposed MB-OFDM scheme becomes a single-carrier solution when $G = N$ (i.e., $N' = 1$). Thus, the idea of using only one guard interval for multiple data blocks can be also used by single-carrier systems to achieve higher spectral efficiency.

Third, for some applications, especially for wireless communication systems, the channel may change very fast, then it is preferred to reduce the number of data blocks within a super-block to combat the fast channel variation. In the extreme case, $S = 1$ could be configured without improving the spectral efficiency. However, the smaller IFFT size used in the proposed MB-OFDM scheme could still be used to reduce the PAPR and mitigate the sensitivity to the residual CFO.

V. Simulation Results and Discussion

This section provides simulation results to evaluate the performance of the proposed MB-OFDM transmission scheme for future high-speed FiWi networks. In the simulation, we choose the LDPC code [27] due to its low complexity and very low error floor resulted from the absence of 4-cycles in its graph. A 2.5 Gbps random data stream is coded by LDPC, and then 16QAM modulation is adopted for constellation mapping. The constellation signal is used to generate the MB-OFDM transmission frame with the parameters $N = 256, M = N/8 = 32, S = 10, G = 8$. The obtained OFDM signal is up-converted to 5.65 GHz [15], which is then used to modulate the continuous-wave external cavity laser (ELC) with the linewidth of 100 kHz at MZM. After that, the erbium-doped fiber amplifier (EDFA) is used to boost the optical OFDM signal, and the optical filter with 0.8 nm bandwidth is used to filter out the outband noise. After the transmission through a 20 km single-mode fiber (SMF) with the attenuation of 0.2 dB/km, the optical CD of 40 ps/nm/km and the PMD with the mean differential group delay (denoted by $\langle \mathrm{DGD} \rangle$) of 50 ps, a 10 GHz bandwidth photodiode (PD) is used to convert the optical OFDM signal into radio frequency signal. At the wireless receiver which is 5 m away from the wireless transmitter, a 20 dB gain low-noise amplifier (LNA) is followed by a 40 GSa/s analog-to-digital convertor (ADC) to capture the wireless OFDM signal, and then the digital receiver algorithms as detailed in Section III are used for signal recovery. The sum-product algorithm (SPA) for LDPC decoding [27] is adopted for iterative soft-decision decoding with the iteration number of 50. The Indoor A channel model defined by ITU [9] is used to emulate the wireless multipath channel, and the received OSNR is defined with the 0.1 nm noise bandwidth.

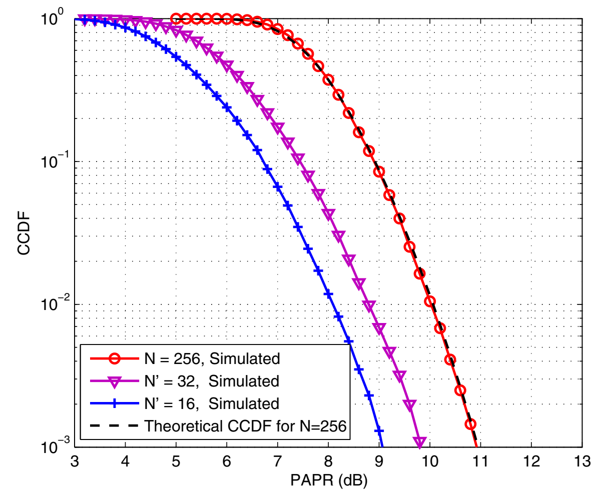

Fig. 7. CCDF of the PAPR when different IFFT sizes are used.

Fig. 7 shows the CCDF of the PAPR when different IFFT sizes are used. When $N = 256$, the IFFT size in conventional OFDM transmission scheme is 256. However, the proposed MB-OFDM scheme could adopt obviously reduced IFFT size $N' = N/G$ to generate the corresponding sub-blocks of length N' as shown in Figs. 2 and 3. The theoretical CCDF (11) is also included in Fig. 7 as the benchmark for comparison. It is clear that the reduced IFFT size N' could lead to the PAPR reduction, e.g., for the clipping ratio of 0.01, the PAPR is reduced by 1.2 dB and 1.9 dB when $N' = 32$ and $N' = 16$ (such IFFT sizes have also been used in [28]), respectively. We could also observe that the simulated CCDF coincides with the theoretical result (11).

Fig. 8 compares the robustness to the residual CFO of the proposed MB-OFDM and the conventional OFDM systems in terms of LDPC coded bit error rate (BER) when a relatively large residual CFO 0.05 is present. For comparison, the BER performance without residual CFO is included as the benchmark for comparison. We could observe that the conventional OFDM system is sensitive to large residual CFO, e.g., the OSNR penalty is about 0.8 dB when the target BER of 10^{-4} is required. However, only negligible OSNR loss (less than 0.1 dB) is imposed on the proposed MB-OFDM scheme, which shows its robustness to CFO due to the reduced IFFT size. In addition, when no residual CFO is present, the proposed MB-OFDM scheme outperforms the conventional OFDM system by the OSNR gain of about 0.51 dB because

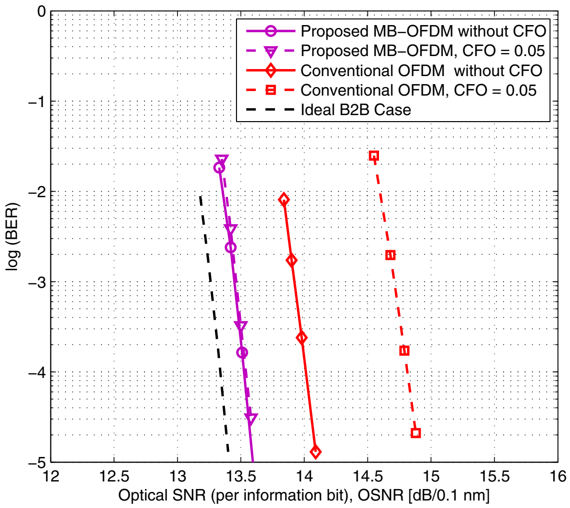

Fig. 8. LDPC coded BER performance with and without residual CFO.

the transmit power originally assigned to the CPs could be added to the useful data parts in MB-OFDM, which leads to the increased equivalent OSNR at the receiver. Note that the proposed scheme also has the BER performance close to the ideal back-to-back (B2B) case.

VI. Conclusions

In this paper, the multi-block OFDM (MB-OFDM) transmission scheme is proposed for high-speed FiWi networks to simultaneously achieve improved spectral efficiency, reduced PAPR and mitigated sensitivity to CFO. One key idea is that the slow time-varying property of the fiber-wireless channel can be utilized to improve the spectral efficiency, which is achieved by sharing one guard interval among multiple data blocks. The other key point is that the OFDM signal generated by smaller size FFT has lower PAPR and alleviated vulnerability to CFO. The above merits, which have been demonstrated by the simulation results, are achieved at the cost of increased yet affordable receiver complexity. The proposed scheme could also be easily extended to other fiber/wireless/FiWi networks. The future work is to incorporate the proposed scheme with wireless multiple-input multiple-output (MIMO) and optical polarization division multiplexing (PDM) techniques [14] to further improve the system capacity and reliability.

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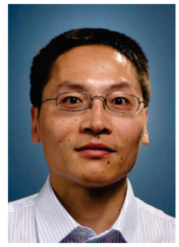

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