

Elastic Optical Transmission of 50 Gb/s/lambda OFDM based Mobile Fronthaul via DSP-aided Sub-band Spreading

You-Wei Chen¹, Peng-Chun Peng², Jhih-Heng Yan³, Shuyi Shen¹, Qi Zhou¹, Long Huang¹, Siming Liu¹, Rui Zhang¹, Kai-Ming Feng³ and Gee-Kung Chang¹

¹*School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30308, USA*

²*Department of Electro-Optical Engineering, National Taipei University of Technology, Taipei 10608, Taiwan.*

³*Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30013, Taiwan.*

*yu-wei.chen@ece.gatech.edu

Abstract: Even suffering from two 20-dB attenuated RF fading notches, a 50-Gpbs sub-band spreading OFDM enhanced intensity-modulation mobile fronthaul is experimentally demonstrated over 25-km fiber transmission with a superior EVM performance over the widely-adapted OFDM signals.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

To date, there are tremendous growth of broadband mobile applications that greatly push the demands of transmission data rate and service-complexity in the mobile fronthaul (FH). Therefore, the next generation FH is expected to meet the soaring data rate and the necessary network flexibility as well as increasing resource utilization [1,2]. This leads us to splicing the FH into two parts by relocating some functionalities [3], known as FH-II and FH-I, connecting from central units (CUs) to distributed units (DUs), and from DUs to remote radio units (RRUs), respectively, as shown in Fig. 1(a). In addition, a CU has ability to support multiple independently located DUs via a remotely-controlled topology for facilitating network virtualization and adaptation as a future-proof FH architecture. A comprehensive comparison of intensity modulation (IM) options with direct-detection for cost-sensitive FH was conducted by Liu [4], including common public radio interface (CPRI), four-level pulse amplitude modulation, and multicarrier data formats, in term of their system complexity and received performance. We focus on a multicarrier scheme because it exhibits a higher spectral efficiency and a higher inter-symbol interference (ISI) robustness [5]. On the other hand, to enable a reconfigurable and elastic FH network, the signal transmitted distance is preferred to be dynamically and remotely-controlled. However, the double-side band nature of an IM signal results a detrimental radio power (RF) fading and thus limits the available transmitted distance and bandwidth, especially for a broadband signal. As shown in Fig. 1(b), even with only 5-km fiber transmission, a RF notch appears at 25 GHz and causes around 20-dB power declination. Since the RF power degradation is spectrally periodic relating to the transmission distance, 1 and 2 frequency null points are observed as the distance increasing to 15-km and 25-km. Each frequency deep attenuates near 20-dB power with around 4 GHz 6-dB down bandwidth and dramatically restrict the available bandwidth for conventional orthogonal frequency division multiplexing (OFDM) to 15 and 12 GHz, respectively.

A straightforward solution to overcome the RF power fading is conducting a single-side band modulation by employing an in- and quadrature-phase (IQ) modulator to achieve a filed modulation [6] or applying an optical tunable filter to sift out the undesired side band [7]; however, both result a complicated, costly and lossy transmitter design. The other approaches were reported by transmitting an IM signal and a phase modulated signal in a parallel manner to enable a broadband RF power fading compensation [8,9]. However, they require either an accurate phase control or a specified signal allocation plan for different fiber lengths. Moreover, above solutions cannot be directly applied in a direct-modulation transmitter. OFDM with sub-band spreading has been proposed to mitigate the RF power fading in our previous works [10]. By dividing OFDM subcarriers into several sub-bands and orthogonally spreading them in the frequency domain, the received signal performance was equalized and enhanced without pre-probing the time-sensitive channel information. Nevertheless, the transmitted bandwidth was limited to 3 GHz due to the employed directly modulation laser diode, and a broadband transmission performance has never been studied, especially when signals suffer from 2 RF power fading null points.

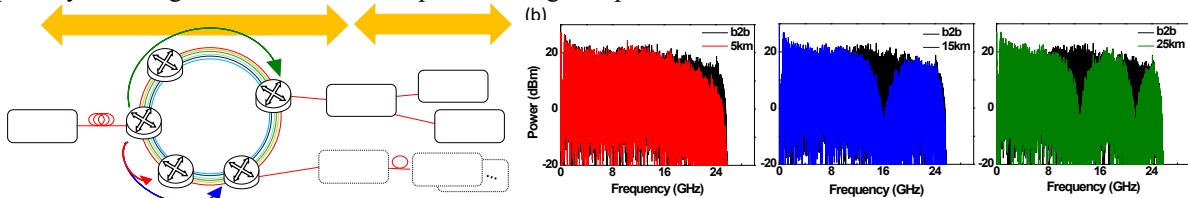


Fig. 1 (a) Conceptual diagram of two tiers adaptive mobile fronthaul. (b) Measured frequency spectra of different transmission distances.

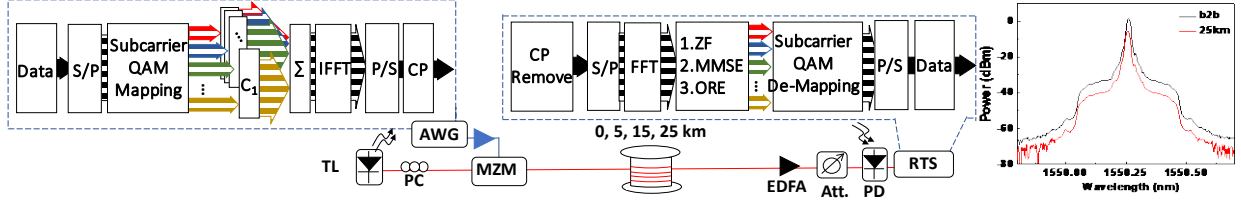


Fig. 2. Experimental setup of the proposed sub-band spreading-aided OFDM.

In this work, a single wavelength 50-Gb/s OFDM based FH is implemented with the digital signal process (DSP) aided sub-band spreading to mitigating the RF power fading degradation. The error vector magnitude (EVM) of the proposed scheme outperform the ordinary OFDM by 1.3-%, 4.27-%, and 4.59-% for 5-, 15- and 25-km transmission as well as the bit-error-rate (BER) can be enhanced via post-DSP implemented in the receiver to support a high data throughput and a flexible transmission distance for future elastic FH network requirements.

2. Operation principles and experimental setup

The experimental setup of the proposed sub-band spreading DSP-aided OFDM based FH is illustrated in Fig. 2. In the offline DSP, the binary data stream is first serial-to-parallel (S/P) converted into multiple narrow bandwidth subcarriers carrying 4-QAM signals. To perform sub-band spreading, we employ an orthogonal variable spreading factor (OVSF) code [11] for each sub-band with 16 code length before conducting the inverse fast Fourier transform (IFFT). 400 subcarriers are actively deployed over 1024 FFT size, and each sub-band has 25 ($=400/16$) subcarriers. The sub-band spreading processing is based on the OFDM frequency grids implying the natural benefits of OFDM are preserved, including high spectral efficiency and higher ISI tolerance. After sub-band spreading into the whole transmitted bandwidth, all encoded channel data can be summed up as the IFFT input. The rest of DSPs are identical to the ordinary OFDM scheme, including IFFT, P/S, and cyclic prefix (CP). To directly modulate the complex-value OFDM signals, the DSP encoded signals are offline frequency up-converted to 13.03 GHz. After sampling via an arbitrary waveform generator (AWG) with 64 GSa/s, the sub-band spreading OFDM occupies about 25 GHz and achieves 50 Gb/s row data. A tunable laser source at 1550.26 nm wavelength with 11.5 dBm output power is applied for linearly modulating the offline encoded sub-band spreading OFDM data, which is pre-amplified via a wideband amplifier with 30 dB gain to achieve the optimized optical SNR by fulfilling the linear region of the applied Mach-Zehnder modulator. The optical spectra of the back-to-back (b2b) and after 25-km transmission are also inset in Fig. 2. At the receiver front-end, an Erbium-doped fiber amplifier (EDFA) cascading a variable optical attenuator (Att) is applied to boost the received optical power. After down-conversion by a photodetector (PD), the received signal is then sampled via a real-time scope (RTS) with an 80 GSa/s sampling rate and a 25-GHz bandwidth.

For the sub-band spreading OFDM signal, the corresponding received DSPs are mainly a reverse processing of the encoder. After CP removing, S/P converting, and FFT transferring, the received signal is equalized via three different equalizing processes, which are one-tap zero-forcing (ZF) with an inner product manipulation, minimum mean squared error (MMSE) and MMSE based coding channel orthogonality restoring (OR). Due to its simple implementation, the ZF is widely applied in the OFDM scheme; however, under such severe RF power fading, the noise enhanced property of ZF dramatically declines the received BER performance. On the other hand, frequency domain MMSE equalizer could mitigate this degradation, but the 20-dB attenuated OFDM subcarriers are still unable to be retrieved. Thus, an OR among the spreading code channels is applied to further enhance the received performance. By re-constructing the interference among the coding sub-band through the first stage of the MMSE result, we can restore the orthogonality among them by subtracting the unwanted interference from the received signal. Since the spreading sub-band number is controlled to 16, and only one time of subtraction processing is employed, the DSP complexity should be tolerable in DUs.

3. Experimental results and conclusions

A comparison of ordinary OFDM and sub-band spreading OFDM is conducted via their EVM performance under the same transmitted bandwidth, QAM level and received optical power over distinct fiber transmissions as shown in Fig. 3(a). In general, the average EVM is gradually degraded by the RF power fading. While such degradation could be mitigated via the proposed sub-band spreading OFDM. In the b2b scheme, both signals with OR equalizer have very similar EVMs; however, the proposed DSP-aided sub-band spreading OFDM outperforms the ordinary OFDM after 5-km, 15-km, and 25-km fiber transmission with 1.3-%, 4.27-%, and 4.59-% EVM enhancements.

Figure 3(b-c) exhibits the received SNRs among the subcarriers of OFDM and the proposed sub-band spreading OFDM under 6-dBm received power. As one can note that, the SNRs of the conventional OFDM are strongly related to the frequency response presented in the Fig. 1(b). The required SNR of 4-QAM signal to satisfy the

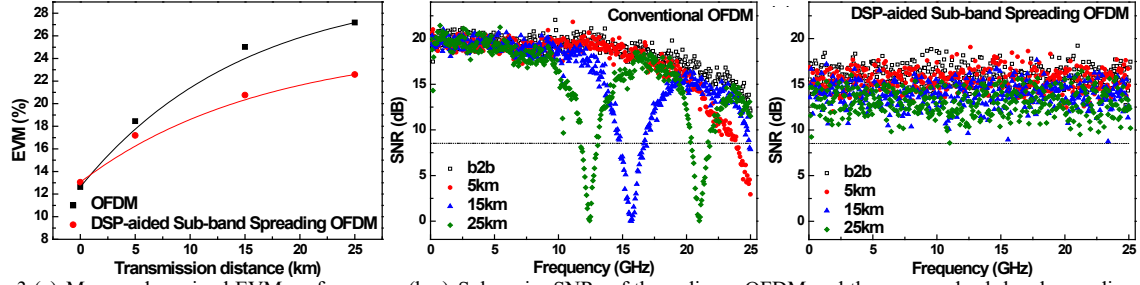


Fig. 3 (a) Measured received EVM performance. (b-c) Subcarrier SNRs of the ordinary OFDM and the proposed sub-band spreading DSP-assisted OFDM over different distances.

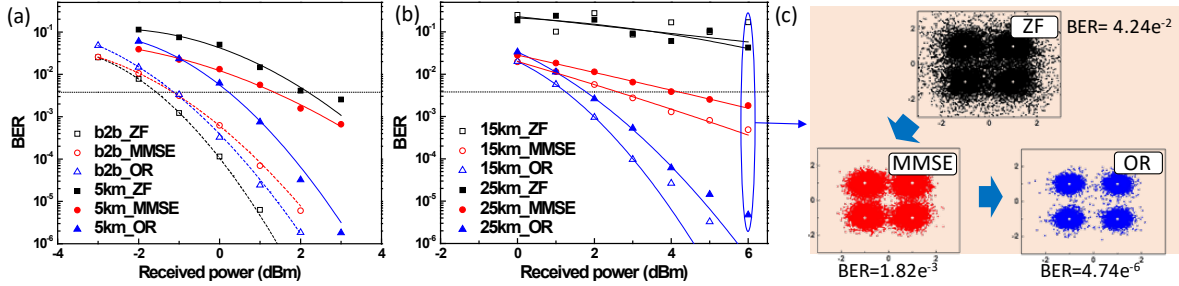


Fig. 4 (a) Measured BER versus received power in b2b and over 5-km transmission. (b) Measured BER versus received power over 15- and 25-km transmission. (c) Constellation diagrams of different equalizer schemes after 25-km fiber transmission at 6 dBm received power.

forward error correction (FEC) threshold ($\text{BER} = 3.8 \times 10^{-3}$) [12] is 8.52 dB. Therefore, there are 4.5%, 8%, and 11% irretrievable data losses as we apply 25-GHz broadband signal with a 4-QAM OFDM in an FDM manipulation. On the other hand, the subcarrier SNRs perform uniform in the proposed DSP-aided sub-band spreading OFDM scheme, and all subcarriers are guaranteed to satisfy the FEC criterion.

Figure 4(a) exhibits the received performance of the proposed sub-band spreading OFDM scheme in b2b and after 5-km SMF transmission. Since the frequency response is relatively flat in the b2b scenario, one-tap ZF can estimate and compensate it. Weighting operation of MMSE [10], on the other hand, reduces the orthogonality among coding channels and causes a slight performance degradation. The received sensitivity, defined as the received power at the specified FEC threshold, is around -1.3 dBm. However, when RF power fading happens, the BER performance is dominated by the impairments of RF attenuated frequencies. The ZF equalized data can barely be retrieved under the FEC criterion at high received power case. The BERs with MMSE and OR equalizers are enhanced with the corresponding received sensitivities of 1.3 and 0.2 dBm. Due to the frequency diversity of the proposed scheme, a nearly 1-dB DSP gain, defined as the received sensitivity deviation of MMSE and OR, is achieved. The power penalty between b2b and 5-km transmission with OR equalizer of the 25-GHz broadband signal is only 1.5 dB. The BER versus received power are also measured after 15-km and 25-km fiber links, as shown in Fig. 4(b). Since the frequency notches are totally interweaved into the desired signals, ZF is no longer to serve as an available equalizer. On the other hand, MMSE still works, but the ability of signal retrieval is limited. BERs could be further enhanced via OR, and DSP gains between MMSE and OR are 1.3 dB and 2.3 dB, while power penalties respecting to b2b are 2.5 and 3 dB after 15-km and 25-km transmission, respectively. The corresponding constellation diagrams of three different equalizers after 25-km fiber link are presented in Fig. 4(c). The zero point of ZF constellation is ruined, while in MMSE case, the received data spillover the hard decision level, and causes decision error. On the other hand, OR scheme achieves a more concentrated constellation.

In conclusion, a 50 Gbps FH network is achieved with proposed DSP-aided sub-band spreading OFDM over 25-km fiber link, and only 3 dB power penalty is observed even signals suffering from 2×20 -dB attenuated RF power fading null points as well as it exhibits a superior performance over wide-adapted OFDM in EVM and equalized SNRs among subcarriers.

4. References

- [1] 3GPP TR 38.913 V14.3.0 (2017).
- [2] B. A. Nunes et al., *Commun. Surv. Tutor.* **16**, pp. 1617 (2014).
- [3] C.-L. I et al., *J. Lightw. Technol.* **36**, pp. 541 (2018).
- [4] X. Liu and F. Effenberger, *J. Opt. Commun. Netw.* **8**, pp. B70 (2017).
- [5] W.-R. Peng et al., *J. Lightw. Technol.* **27**, pp. 5723 (2009).
- [7] J.-H. Yan et al., in *Proc. OFC*, paper Tu3J.7 (2018).
- [8] Y. Cui et al., *Photon. Technol. Lett.* **24**, pp. 1173 (2012).
- [9] S. Ishimura et al., *J. Lightw. Technol.* **36**, pp. 1478 (2018).
- [10] Y.-W. Chen et al., *J. Lightw. Technol.* **35**, pp. 2646 (2017).
- [11] F. Adachi et al., *Commun. Mag.* **36**, pp. 56 (1998).

[6] Y.-W. Chen et al., Opt. Exp. **23**, pp. 18525 (2015).

[12] ITU-T Recommendation G.975.1, Appendix I.9 (2004).