80 Gb/s 2×2 MIMO Fiber–Wireless Integrated System in W Band Using IFoF Transmission

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Abstract— **We present a high-speed integrated fiber–wireless system in the W band for transmission of multiple-input multiple-output (MIMO) radio signals. The proposed system utilizes a wavelength-division multiplexing intermediate frequency-over-fiber system and a remote generation and transmission of local oscillator signals. Satisfactory performance is experimentally confirmed for 2×2 MIMO FBMC/OQAM signal transmission with a total capacity of 80 Gb/s. The system is spectral-efficient and scalable for large-scale MIMO signal transmission and can be a promising solution for future mobile networks.**

Keywords—Seamless fiber–wireless; radio-over-fiber; mobile fronthaul; 5G and beyond

I. Introduction

In 5G and beyond networks, high carrier frequencies and carrier aggregation spanning multiple bands can be potentially used. Frequency bands below 6 GHz will be used for the evolution of long-term evolution-advanced, such as Release 15 and beyond, with enhancements to machine type communication and narrow-band-IoTs. Some pre-5G standards, such as Verizon wireless [1], operate in the 28 GHz band. In other standards, frequencies from 30 to 40 GHz are expected to be mainly utilized. For example, the United States has defined 27.5–28.35 GHz, 38.6–40 GHz, and 37–38.6 GHz bands as their spectrum frontier bands. In Japan, the 27.5–29.5 GHz frequency band has been defined as the candidate for 5G and is planned to provide 5G services during 2020 Tokyo Olympic Games [2]. For radio networks beyond 2020, frequency bands above 100 GHz can be potential candidates for achieving a significant increase in the throughput to end users. In addition, advanced wireless technologies, such as massive multiple-input multiple-output (MIMO) and beamforming, will be employed to overcome high propagation loss of radio signals in high-frequency bands [3].

The evolution of radio access networks in 5G and beyond networks poses significant challenges to transport networks, especially the fronthaul systems for transporting radio signals from a cloud in a center office to antenna sites. Conventional transmission methods using the common public radio interface or next-generation fronthaul interface will face great difficulties when radio carrier frequency increases. The integration of fiber and radio systems, especially wireless systems in high-frequency bands, can be a good solution for future radio access networks. Some fiber–wireless integrated technologies can be considered for radio signal transmission, as shown in Fig. 1. In the first system, shown in Fig. 1(a), a radio-over-fiber (RoF) system for high-frequency radio signal transmission can significantly simplify the system and antenna sites. However, the signal performance can be degraded by fiber dispersion and nonlinear distortions. The system also requires a high-speed and linear optical modulator, which is not available yet or very expensive. An optical self-heterodyne system using an RoF signal generation [4], shown in Fig. 1(b), can be a good choice for ultra high-speed signals at very high-frequency bands. However, it is difficult to apply the system for a point-to-multipoint transmission owing to the difficulty in the generation of multiple RoF signals as well as the low spectral efficiency. An optical heterodyne system [5], shown in Fig. 1(c), can be useful for a point-to-multipoint transmission of high-frequency radio signals. Nevertheless, there is a significant requirement on the linewidth of the used laser diodes (LD) for the generation of low frequency fluctuation radio signal [6]. The large phase noise of the generated radio carrier signal will also cause degradation in the signal performance.

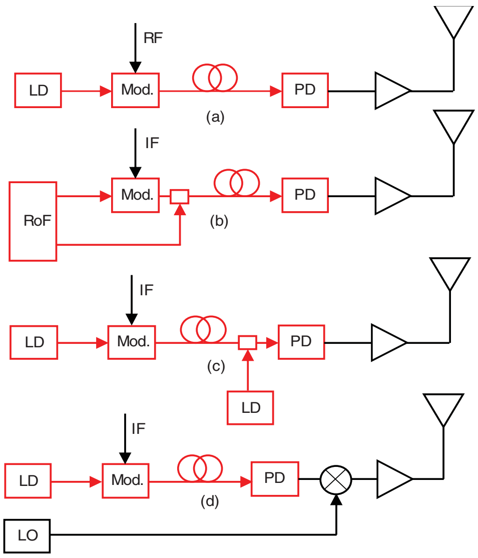

Fig. 1. Fiber transports of broadband mobile signals: (a) RoF; (b) optical self-heterodyne; (c) optical heterodyne; (c) IFoF system. LD: laser diode, Mod: modulator, PD: photodiode, LO: local oscillator, RoF: radio-over-fiber, IFoF: intermediate frequency-over-fiber.

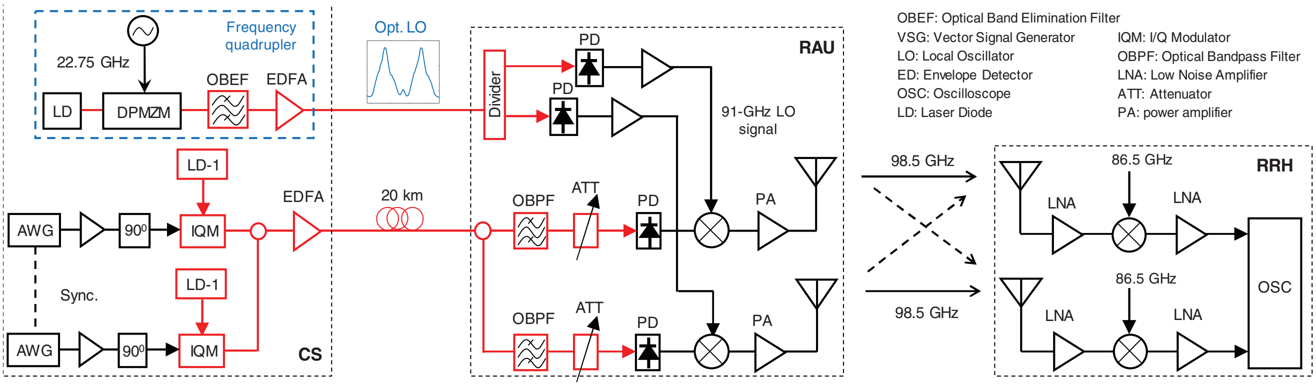

Fig. 2. Experimental setup for the 2 × 2 MIMO fiber–wireless system in the W band using an IFoF transmission.

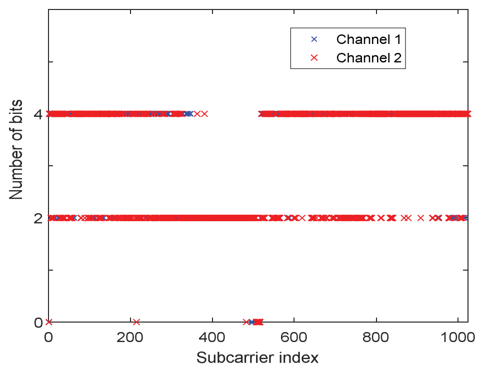

Fig. 3. Bit loading for the 2×2 MIMO signal using 1024 subcarriers.

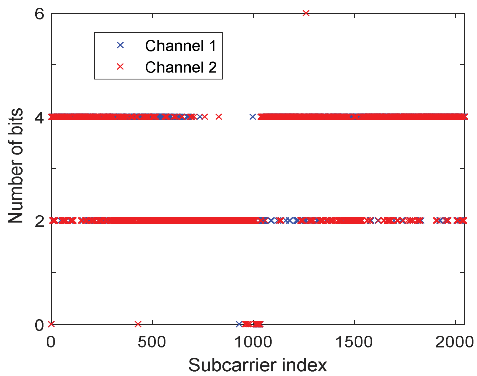

Fig. 4. Bit loading for the 2×2 MIMO signal using 2048 subcarriers.

An intermediate frequency-over-fiber (IFoF) system [7], shown in Fig. 1(d), can be suitable for transmission of radio signals in high frequency bands to multiple antenna sites. In this paper, we present a high-performance IFoF system with a remote delivery of a local oscillator (LO) signal for transmission of ultra high-speed radio signal in the W band. We successfully transmitted more than 80 Gb/s 2×2 MIMO radio Filter Bank Multicarrier (FBMC)/OQAM signals at 98.5 GHz over a fiber system. To the best of our knowledge, this is the highest data rate of an integrated fiber–wireless system using an IFoF transmission.

II. Experimental Setup

The experimental setup of the transmission of a 2×2 MIMO radio signal in the W band over a fiber system using an IFoF transmission is shown in Fig. 2. Two optical signals with a frequency difference of 50 GHz from two LDs are modulated by 2×2 MIMO FBMC/OQAM signals. The 2×2 MIMO signals at 7.5 GHz and having a bandwidth of 12.5 GHz are generated offline and downloaded to two synchronized arbitrary waveform generators. The number of subcarriers is fixed to 1024 and 2048, of which 1.5% on each edge of the spectrum are inactive to simplify digital-to-analog conversion. A preamble of 5 symbols was added to the data symbol frame for the channel estimation and synchronization at the receiver [8]. To reduce the effects of fiber dispersion on the transmitted IF signals, two optical I/Q modulators are used to generate optical single-sideband (SSB) signals. The modulated optical signals are combined by a 3-dB optical coupler (OC). The combined signals are amplified by an EDFA and transmitted to a remote antenna unit (RAU) via a 20-km single-mode fiber (SMF). The received optical signals are separated using another 3-dB OC and filtered using optical bandpass filters to recover the transmitted IFoF signals. After being converted to electrical signals using photodetectors (PDs), the signals are up-converted to 98.5 GHz using electronic mixers. The LO signals for the signal up-conversion are generated and delivered remotely from the center. In our experiment, an optical LO signal with a frequency separation of 91 GHz is generated using a two-tone optical signal generator [9]. In this method, two sidebands of the generated optical LO signal are completely phase- and frequency-stabilized; thus, stable and low-phase-noise LO signals can be generated at the RAU. The generated optical LO signal is transmitted over an SMF, divided by a 3-dB OC, and input to two high-speed PDs to generate two electrical LO signals at 91 GHz. The LO signals are amplified to a sufficiently high power to drive the mixers. The up-converted signals are filtered using bandpass filters to suppress the carrier and lower sideband signals, amplified using power amplifiers before being emitted into free space by 23-dBi horn antennas. After being transmitted over approximately 1 m in free space, the signals are received, amplified by low-noise amplifiers, and down-converted to 12 GHz using electrical mixers. The signals are amplified, connected to a real-time oscilloscope (OSC), and finally demodulated offline. The digital signal processing for the FBMC signal generation and demodulation is similar to our previous work [10]. In this paper, however, we apply an adaptive modulation to better utilize the signal-to-noise ratios (SNR) of subcarriers on each channel.

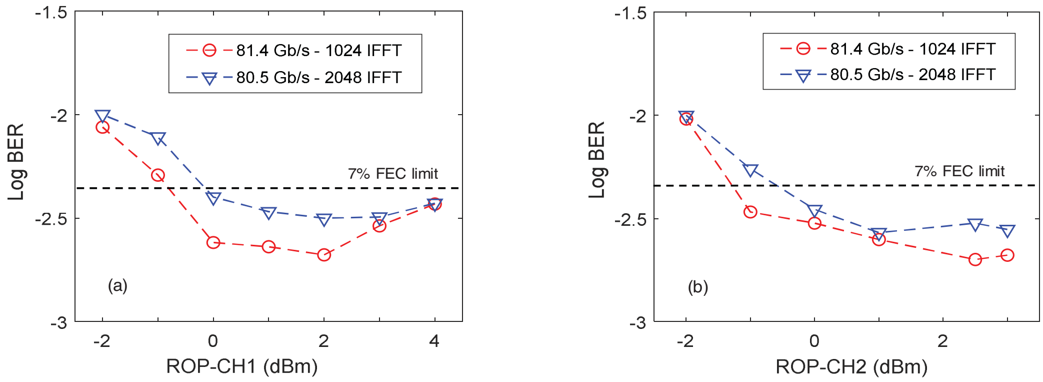

Fig. 5. Performance of the 2×2 MIMO fiber–wireless system: (a) versus received optical power in channel 1; (b) versus received optical power in channel 2.

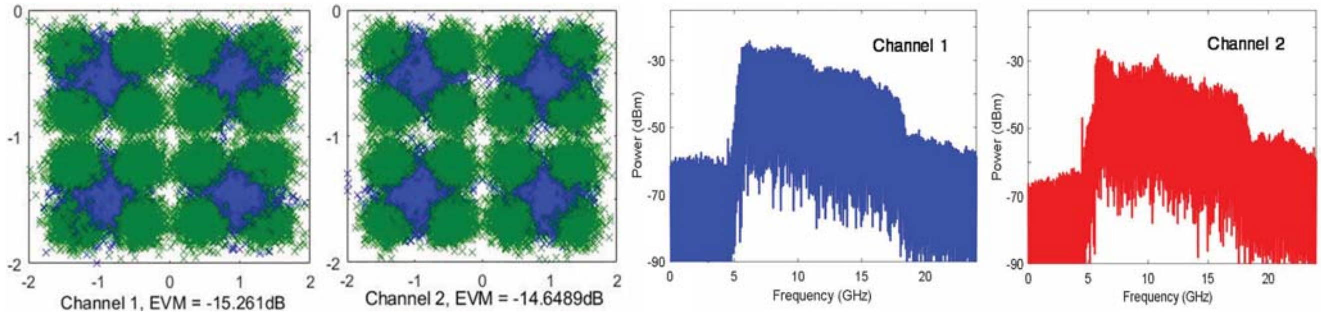

Fig. 6. Examples of received constellations and spectrums of the 81.4 Gb/s signal using 1024 subcarriers.

III. Experimental Results

We first transmitted a training signal for estimation of SNRs and respective QAM levels for subcarriers on each channel. During the training phase, only a preamble composing of pilot symbols was transmitted. Using the training signal, the SNRs, denoted by $SNR_{m,i}$ for subcarrier *m* on channel *i*, were estimated at the receiver. The *SNRs* do not depend on the modulation parameters, but on the channel parameters, noise variance, and symbol variance. Given the value of the $SNR_{m,i}$, the QAM constellation level $M_{m,i}$ can be assigned to subcarrier *m* on channel *i* so that a target bit error rate $BER^{target}{}_{m,i}$ is maintained, i.e.,

$$BER_{m,i}^{target} \geq \frac{1}{log_2\left(\sqrt{M_{m,i}}\right)} . \frac{\sqrt{M_{m,i}}-1}{\sqrt{M_{m,i}}} . erfc\left(\sqrt{\frac{3SNR_{m,i}}{2\left(M_{m,i}-1\right)}}\right).$$

We should note that while we changed the modulation level for subcarriers on each channel, the symbol variance remained the same. In other words, no power loading was applied. After the bit loading, the modulation levels are different on different subcarriers and channels. However, the rest of the FBMC/OQAM transceiver chain is the same as in the case of using fixed modulation, including preamble design, synchronization, equalization, channel estimation, and phase tracking.

The estimated number of bits loaded to the subcarriers for the case of applying 1024 and 2048 subcarriers is shown in Figs. 3 and 4, respectively. We thereafter applied the estimated modulation levels to the subcarriers on each channel and transmitted the signals over the system. The total capacity is calculated by summing the number of bits applied to all subcarriers. The performance of the signals after being transmitted over the seamless fiber–wireless system is shown in Figs. 5(a) and (b) for different received optical powers (ROP) in channel 1 and channel 2, respectively. More than 80-Gb/s signal was successfully transmitted over the system with a bit error rate (BER) below the soft-decision 7% FEC overhead of 3.8×10^{-3}. In the figures, we compare the performance for two cases: using 1024 subcarriers with a total capacity of 81.4 Gb/s and 2048 subcarriers with a total capacity of 80.5 Gb/s. The performance for the case of using 1024 subcarriers is better. This could be because the use of 1024 subcarrier better balances the trade-off between phase noise and channel frequency response of each subcarrier. Figure 6 shows examples of constellations and spectrums of the received signals for the case of using 1024 subcarriers. The frequency responses are different on each channel because the devices used in different channels have different performance characteristics.

We should note that the signal-signal beat interference (SSBI) by the optical SSB modulation and direct detection at the RAU can cause degradation in the performance. Some SSBI-cancellation techniques, such as those proposed in [11], can help improve the performance. However, the complexity of the wireless receivers will prohibitively increase, resulting in high cost and power consumption. This can be acceptable for point-to-point systems, such as those for mobile backhaul/fronthaul transmission. Nevertheless, when the integrated fiber–wireless system is used as the access network to end users, it is not appropriate to increase the complexity of the receiver as it is located at the users' terminals. Increasing the carriers of the IF signals before being transmitted over the systems can help overcome the effects of SSBI. However, it is difficult to generate such broadband IF signals owing to the limitation in the bandwidth and sampling rate of digital-to-analog converters. Applying an appropriate joint bit and power loading scheme would be a good solution to overcome the effects of SSBI and non-flat channel frequency response and to maximize the throughput of the system. In our experiment, we did not apply any power loading scheme. We expect that the total capacity of the system will be further increased by applying an appropriate joint bit and power loading.

IV. Conclusion

This paper proposes and demonstrates an integrated fiber–wireless system in the W-band for transmission of 2×2 MIMO signals using an IFoF transmission. The system is scalable to large-scale MIMO signals and is spectral-efficiency owing to the use of a WDM IFoF system in the optical link. We successfully transmitted 2×2 MIMO FBMC signal using adaptive modulation with a total capacity of more than 80 Gb/s. Satisfactory performance is experimentally confirmed with a BER of less than 7% FEC overhead limit of 3.8×10^{-3}. The proposed system can be very useful for increasing the capacity of fiber–wireless systems and for the transmission of large-scale MIMO mobile signals in high-frequency bands in 5G and beyond mobile networks.

Acknowledgment

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