132 Gb/s 3×3 Full MIMO Fiber–Wireless Seamless System in W Band Using WDM/PDM RoF Transmission

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Abstract *We demonstrate the first 3×3 full multiple-input multiple-output fiber–wireless seamless system in W band. Satisfactory performance is experimentally confirmed for a total capacity of approximately 119 Gb/s and 132 Gb/s using standard and flexible FBMC/OQAM signals, respectively.*

Introduction

Seamless fiber–wireless system in the high frequency bands is considered a reliable and cost-effective solution for future mobile transport networks. In addition, the seamless system can also play as a new radio access technology in beyond 5G networks where radio access signals in the very high frequency bands are deployed [1]. In these systems, wireless signals play the role of radio access while the fiber links work as mobile fronthaul systems. The seamless system will be very effective to simplify antenna sites, reduce cost, power consumption, and latency for ultra-dense small cell networks. In both use cases, large-scale multiple-input multiple-output (MIMO) fiber–wireless systems will be indispensable to increase the transport capacity and/or to facilitate the transmission of large-scale MIMO radio signals in future mobile networks.

There have been many studies on MIMO fiber–wireless seamless systems in high-frequency bands, including the W band (75 – 110 GHz) [2-8]. A wavelength-division multiplexing (WDM) intermediate frequency-over-fiber (IFoF) system was recently demonstrated for MIMO signal transmission [2, 3]. The system is promising owing to the simplicity in the generation of IFoF signals. However, the system, especially the antenna site, is relatively complex due to the use of electrical signal up-conversion. In addition, the system performance is significantly affected by the signal-to-signal beating interference in the single-sideband and direct-detection IFoF link. For the applications that require simple antenna sites, radio-over-fiber (RoF) based fiber–wireless system should be considered. Nevertheless, in the previous works [4-8], the size of MIMO signals was limited to 2×2 due to the use of optical polarization-division multiplexing (PDM) RoF systems. In the system using an optical heterodyne method [5-8], it is also difficult to increase the scale of a full MIMO fiber–wireless system greater than 2×2. This is because for the large-scale MIMO system, the use of additional WDM RoF channels is indispensable. However, interference and crosstalk between the MIMO signal streams, whose carrier frequency and phase noise are highly and randomly fluctuated, make the MIMO signal synchronization and channel estimation very challenging. The carrier frequency offset estimation and phase tracking also become very difficult due to the interference between the unstable MIMO signals.

In this paper, we propose and demonstrate the first 3×3 full MIMO fiber–wireless seamless system using a combined WDM/PDM RoF system. To reduce the complexity of digital signal processing, we utilize a highly stable RoF system based on a coherent optical self-heterodyne method [9]. The ultralow carrier frequency fluctuation and low phase noise of each MIMO channel in this method make the MIMO signal synchronization and demodulation simple. In addition, different to the previously reported MIMO fiber–wireless systems in high-frequency bands [4-8], we demonstrate a full and flexible end-to-end MIMO system in which a MIMO signal is precoded and decoded before and after the transmission. We successfully transmitted approximately 132 Gb/s 3×3 Filter Bank Multicarrier (FBMC/OQAM) signal over the seamless system in the W band. The system is scalable for transmission of large-scale MIMO radio signals in future mobile networks.

Experimental setup

The experimental setup for the 3×3 MIMO fiber–wireless system using WDM/PDM RoF transmission in the W band is shown in Fig. 1. To generate RoF signals, optical millimeter-wave signals with a frequency spacing of 79.6 GHz are generated using a high-precision optical modulation technology based two-tone optical signal generators [9]. To make use of WDM

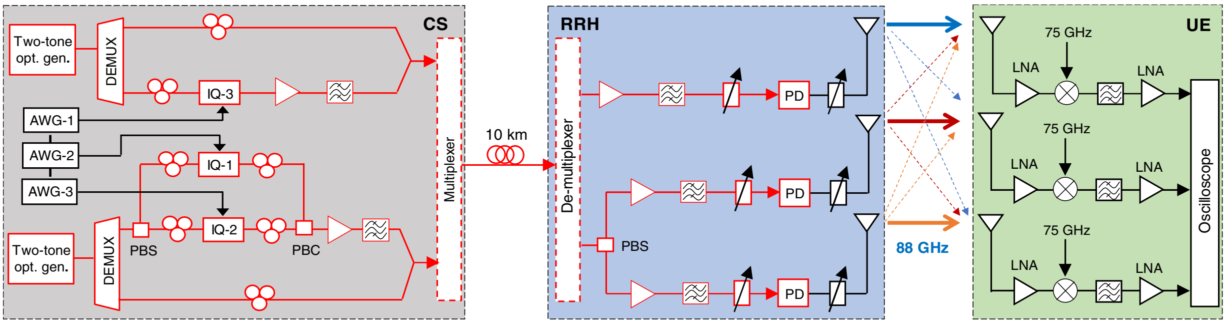

Fig. 1: Experimental setup for 3×3 MIMO seamless fiber–wireless system in the W band.

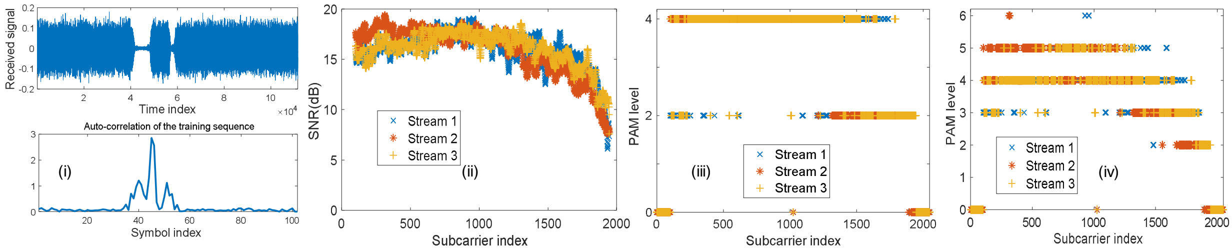

Fig. 2: Received training signal (i); estimated signal-to-noise ratios (ii); estimated modulation level for standard PAM (iii); estimated modulation level for flexible PAM (iv).

transmission of RoF signals over the same single-mode fiber (SMF), optical millimeter-wave signals at different wavelengths should be generated. In our experiment, however, the two-tone optical signal generators operate at the same wavelength, we thus transmit the RoF signals over different SMFs. Nevertheless, the system concept can be easily adapted to a WDM RoF transmission. Similar to the single-input single-output RoF system, in each RoF channel, the two optical sidebands from the RoF signals are separated, and one of them is modulated by one MIMO FBMC/OQAM stream. The other sideband is kept unmodulated to work as a reference signal for the signal up-conversion at antenna site. To realize 3×3 MIMO system, we apply PDM technique in one RoF link. An optical sideband is separated, and its optical polarizations are modulated by different MIMO signal streams. The modulated optical signals are multiplexed using a polarization beam combiner, and consequently combined with the other optical sideband to form a PDM RoF signal.

A 3×3 MIMO FBMC/OQAM signal having a bandwidth of 13 GHz centered at 8 GHz is generated and downloaded to three synchronized arbitrary waveform generators (AWGs). The number of subcarriers is fixed to 2048, of which 10% 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. The real-valued IF signals generated from the AWGs are input to 90-degree hybrid couplers to separate the in-phase and quadrature components before feeding to optical in-phase/quadrature (IQ) modulators. To reduce the effect of fiber dispersion, optical single-sideband signals are generated by controlling the bias of the IQ modulators. The modulated optical signals are combined with the unmodulated sidebands using 3-dB optical couplers and transmitted to the antenna using 10-km SMFs. At the receiver, a polarization beam splitter is used to demultiplex the PDM RoF signals. The received RoF signals are then amplified and filtered to suppress the amplified spontaneous emission noise before being fed to high-speed photomixers. The generated radio signals are emitted into free-space using 23-dBi horn antennas. After transmission over approximately 1-m in free-space, the signals are received by another set of 23-dBi horn antennas. The distance between the transmitter/receiver antennas is approximately 10 cm. The adjacent antenna pairs are placed in different polarizations to reduce the wireless link interference. The received signals are amplified and down-converted to the IF band using electrical mixers. The signals are amplified, sent to a real-time oscilloscope, and demodulated offline. The digital signal processing for the FBMC signal is similar to our previous work [10]. Here, we apply adaptive modulation to effectively exploit the non-uniform received powers and signal-to-noise ratios (SNR) of the subcarriers and signal streams.

Experimental results

To determine respective modulation levels for different subcarriers on each channel, we first transmit a training signal for estimation of SNRs. During the training phase, only a preamble

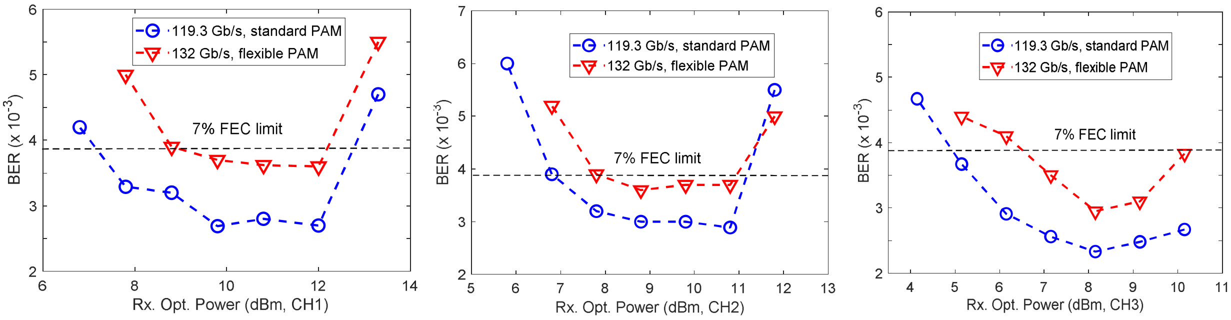

Fig. 3: BER performance of the MIMO FBMC/OQAM signal for different received optical powers in each channel.

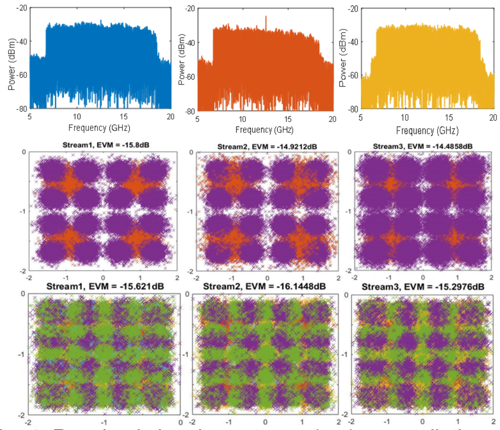

Fig. 4: Received signal spectrums (top); constellations of signals using standard PAM (middle); constellations of signals using flexible PAM (bottom).

composing of pilot symbols was transmitted. The equal modulation level used in the training signal is 4-QAM. Figure 2 (i) and (ii) show the received training signal in the time domain and the estimated SNRs for different subcarriers at different signal streams. We thereafter applied different modulation levels to the subcarriers and transmitted the signals over the system. In OQAM modulations, complex QAM symbols are converted to purely real PAM symbols at the twice faster rate. The real symbols are alternatively made of the real and imaginary parts of the complex symbols [10]. Thus, we can consider that bits are directly mapped to real PAM symbols. Given the value of the $SNR_{m,i}$, the PAM constellation level $M_{m,i}$ of the transmitted symbols (not pilots) assigned to subcarrier m and stream i can be fixed so that a target bit error rate $BER^{target}_{m,i}$ is maintained. The relation of the $BER^{target}_{m,i}$ and the $M_{m,i}$ for a given $SNR_{m,i}$ is written as,

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

The integer values of $M_{m,i}$ can be both powers and not powers of 2, so called standard and flexible PAM [11]. The flexible PAM mapping is possible if bits are mapped to PAM symbols on a block basis, i.e. a group of bits are mapped to a group of PAM symbols. The estimated PAM levels for standard and flexible PAMs are shown in Fig. 2(iii) and (iv), respectively. The total capacity is calculated by summing the number of bits applied to all subcarriers and all the signal streams. We should note that while we changed the modulation level for subcarriers on each channel, the symbol variance remained the same. 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 performance of the signals after transmission over the system is shown in Fig. 3 for different received optical powers in each channel. A total capacity of 119.3 Gb/s and 132 Gb/s could be estimated using standard and flexible PAMs, respectively. Examples of received signal spectrums and signal constellations of the signal streams are shown in Fig. 4. Both transmissions could satisfy 7% FEC limit BER of 3.8×10^{-3}. Notably, compared to the previous 2×2 MIMO systems [5-8], our obtained capacity is lower. Nevertheless, the main target of this work is to study the feasibility of a large scale and flexible end to end MIMO fiber–wireless system, which has not been reported so far. In our experiment, the original real-valued IF signal quality is relatively degraded in the high frequency region due to the limited analog bandwidth of the AWGs. We expect that the system performance and thus capacity will be increased using high performance AWGs and/or multiple AWGs to generate high quality complex baseband signals before the optical modulation.

Conclusion

This paper demonstrates the first 3×3 full MIMO fiber–wireless seamless system in the W band using adaptive FBMC/OQAM modulation. Satisfactory performance is experimentally confirmed for a total capacity of 132 Gb/s with a BER of less than 7% FEC limit. The proposed system can be useful for high capacity fiber–wireless systems and/or for large-scale MIMO radio access signals in high frequency bands.

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