# High-Speed Radio-on-Free-Space Optical Mobile Fronthaul System for Ultra-Dense Radio Access Network

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**Abstract:** We present a transmission of radio signals in high-frequency band over a seamless fiber–FSO system for ultra-dense radio access network. We successfully transmitted 80-Gb/s and 40-Gb/s 2×2 MIMO FBMC-OQAM signal in the 90-GHz band over the DL and UL direction.
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## 1. Introduction

Ultra-small cell radio access network (RAN) in high-frequency bands is considered an important technology in 5G and beyond networks. In 5G network, radio frequency up to 40 GHz has been assigned worldwide. For beyond 5G and 6G network, radio frequency up to 100-GHz band will be likely considered to increase significantly throughput to users. The use of radio signals in very high frequency bands will limit the cell size and the number of radio cells will rapidly increase, posing significant challenges to the transport networks. There is a need to deploy fiber cables to ultra-dense small cells, including to those in ultra-dense urban areas. Wireless transport systems in the mmWave and terahertz-wave bands can provide an attractive solution. However, for radio access signals in high-frequency bands, the wireless transport might not be applicable owing to the necessity to have oscillator signal generators at antenna sites for the signal up-conversion. Free-space optical (FSO) system can be a promising alternative for fiber links to facilitate the deployment of ultra-dense small cells. A seamless fiber–FSO system without the necessity to have a signal format conversion at the fiber–FSO interface can serve as an extension of a fiber link for transferring transparently any radio signals, including those in very high-frequency bands and MIMO signals (Fig. 1(a)). On the other hand, ultrahigh-speed indoor communication is an essential element in future beyond 5G and 6G network. Several solutions have been proposed, including light-fidelity (Li-Fi) [1], hybrid Li-Fi and radio network [2], and high-speed optical wireless communication using narrow laser beams [3]. For Li-Fi and hybrid Li-Fi/radio networks, the capacity is limited owing to the bandwidth limitation. For narrow laser beam systems, a very accurate position information and a highly complicated tracking system are indispensable. A cascaded fiber–FSO–mmWave system, as proposed in Fig. 1(b), in which seamless fiber–FSO links work as high-speed and flexible backhaul/fronthaul transmission while mmWave links serve as high-speed indoor radio access, can provide a more attractive solution.

Analog transport over fronthaul system would be promising for ultra-dense network owing to its high spectral efficiency and simplified antenna sites. Radio-over-fiber (RoF), including those using optical heterodyne and self-heterodyne, and intermediate-frequency-over-fiber (IFoF) are the two main methods for the analog mobile transport. RoF method can simplify antenna sites, however, the spectral efficiency is low and the generation of multiple RoF signals is complicated and expensive. IFoF method can improve significantly spectral efficiency and ease the generation of multiple IFoF signals. In this paper, we demonstrate the transmission of high-speed 2×2 radio signal in the 90-GHz band over a seamless fiber–FSO system in both downlink (DL) and uplink (UL) direction using IFoF method. By applying adaptive filter-bank multicarrier (FBMC), we successfully transmitted approximately 80 Gb/s and 40 Gb/s over a seamless end-to-end fiber–FSO–mmWave system in the DL and UL direction, respectively.

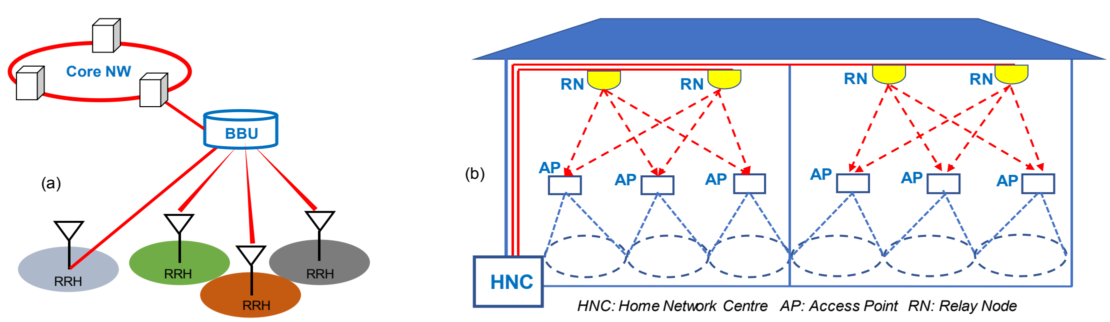


Fig. 1. (a) Seamless fiber–FSO system for mmWave signals; (b) cascaded fiber–FSO–mmWave for ultrahigh-speed access.

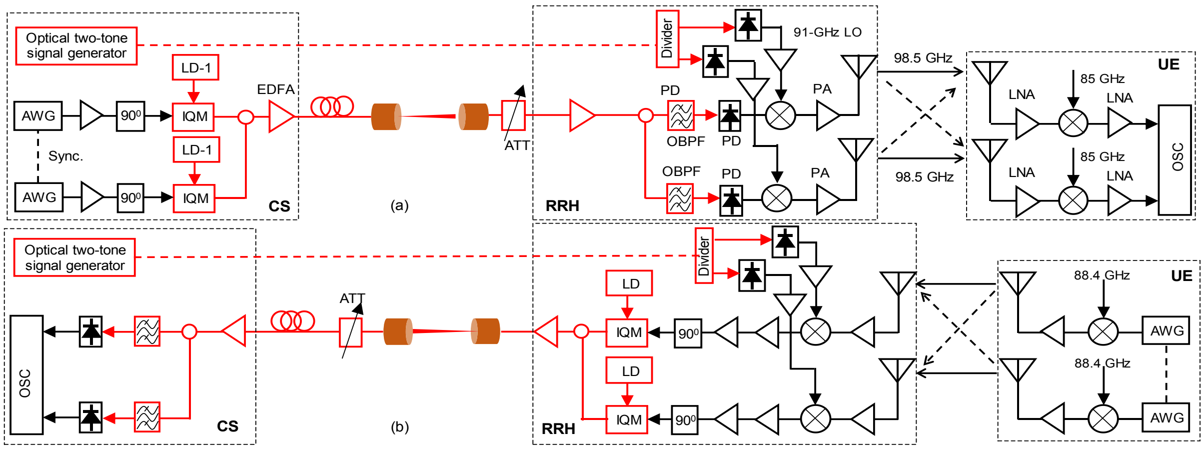


Fig. 2. Experimental setup for 2×2 MIMO mmWave signal transmission over seamless fiber–FSO system: (a) DL, (b) UL.

## 2. Experiment setup

The experimental setup for the transmission of 2×2 MIMO radio signal in the 90-GHz band over a seamless fiber–FSO system in the DL direction using the IFoF method is shown in Fig. 2(a). Two optical signals with a frequency difference of 50 GHz from two laser diodes (LDs) are modulated by 2×2 MIMO FBMC/OQAM signals. The 2×2 MIMO signals having a bandwidth of 12.5 GHz centered at 7.5 GHz are generated offline and downloaded to two synchronized arbitrary waveform generators (AWGs). The number of subcarriers is fixed to 2048, of which 1.5% on each edge of the spectrum are inactive to simplify the 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 [4]. To reduce the effects of fiber dispersion on the transmitted signals, optical single-sideband (SSB) signals are generated using two optical I/Q modulators. The modulated optical signals are combined by a 3-dB optical coupler (OC). The combined signals are amplified using an optical amplifier (EDFA) and transmitted through a single-mode fiber (SMF) having different lengths. After being transmitted over the SMF, the signal is fed directly to an FSO link to transmit to a remote radio head (RRH). In this experiment, we utilized two optical lenses to emulate the FSO link. The distance between the two lenses is approximately 1.5 m and the total loss of link is approximately 10 dB. After being transmitted over the FSO link, the signal is focused directly to another SMF and amplified by an EDFA. To emulate additional loss of the FSO link, we used a variable optical attenuator (ATT). The received optical signals are separated using a 3-dB OC and filtered using optical bandpass filters (OBPFs) 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 can be generated and delivered remotely from the center station (CS) via the same fiber–FSO link with the data signals. In our experiment, an optical LO signal with a frequency separation of 91 GHz is generated using a two-tone optical signal generator [5]. The generated optical LO signal is divided using a 3-dB OC, and input to two high-speed PDs to generate two electrical LO signals at 91 GHz. The up-converted signals are amplified using power amplifiers (PAs) 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 using low-noise amplifiers (LNAs), and down-converted to 12.5 GHz using electrical mixers. The signals are amplified, connected to a real-time oscilloscope (OSC), and finally demodulated offline.

In the UL direction, a 2×2 MIMO signal having a bandwidth of 7 GHz centered at 7 GHz is generated offline and downloaded to two synchronized AWGs. The generated signals are up-converted to 95.4 GHz using electrical mixers. The up-converted signals are amplified by PAs before being transmitted into free space by 23-dBi horn antennas. After transmission over approximately 1-m free-space link, the signals are received using horn antennas, amplified using LNAs, and down-converted to an IF band using electrical mixers. Similar to the DL, the LO signals for the signal down-conversion are generated optically using the two-tone optical signal generator [5]. The signals are amplified before modulating optical signals from two different LDs. The modulated optical signals are combined, amplified using an EDFA, and fed onto an FSO link. The FSO link used for the UL transmission is same as those in the DL direction. After being transmitted over approximately 1.5 m in free space, the signal is focused directly to an SMF. An ATT is inserted to emulate the additional loss in the FSO link. The signal is then transmitted to the CS through another SMF having different lengths. At the CS, the signal is amplified using an EDFA, and separated using a 3-dB OC. The 2×2 MIMO signals are recovered using a pair of OBPFs and PDs. Finally, the recovered signals are sent to the real-time OSC and are demodulated offline.

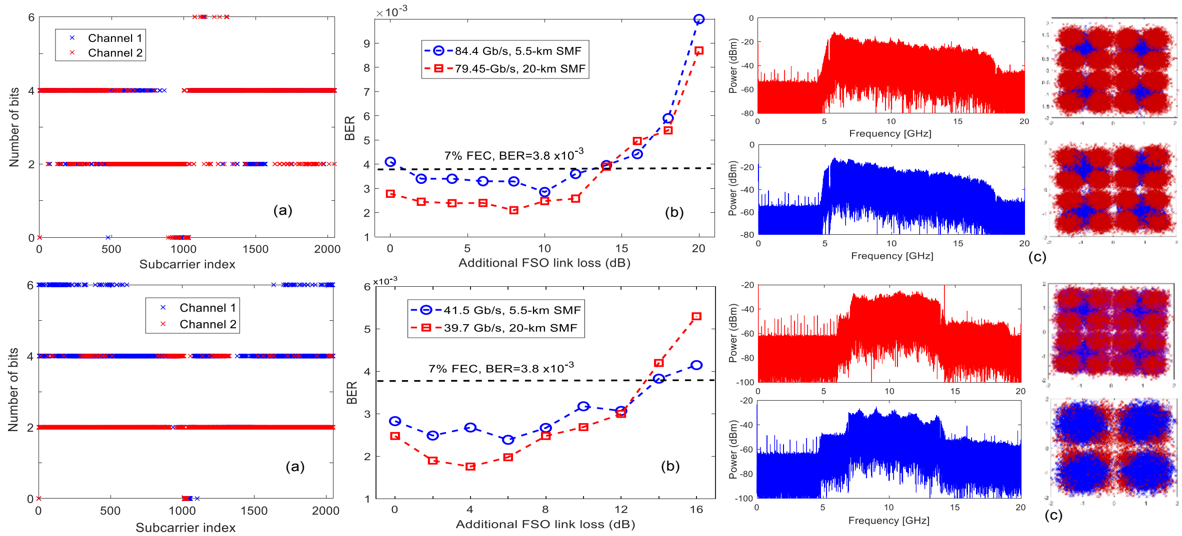


Fig. 3. Performance of 2×2 MIMO signal over the seamless fiber–FSO system in the DL (upper) and UL (lower).

## 3. Experimental results

Figure 3 (upper) and (lower) shows the performance of the signal transmission over the DL and UL direction, respectively. First, for estimation of signal-to-noise ratios and respective QAM levels for subcarriers on each channel, we transmitted a training signal over the system. During the training phase, only a preamble composing of pilot symbols was transmitted [4]. We should note that while we changed the modulation level for subcarriers on each channel, the symbol variance remained the same. 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 [6]. The estimated number of bits loaded to the subcarriers for the case of applying 2048 subcarriers on each channel are shown in Figs. 3(a) (upper) and (lower) for the DL and UL system, 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 signal transmission over the seamless fiber–FSO–mmWave system in the DL and the mmWave–FSO–fiber system in the UL direction is shown in Figs. 3(b) (upper) and (lower), respectively. A signal with a total capacity of approximately 80 Gb/s and 40 Gb/s was successfully transmitted over the DL and UL system, respectively, with a bit error rate below the soft-decision 7% FEC overhead of $3.8\times10^{-3}$. In the figures, we compared the performance for two cases: using a 5.5-km and 20-km SMF together with the FSO link for connection of the CS and RRH. Figure 3(c) shows examples of constellations and spectrums of the received signals in the DL and UL directions. The frequency responses are different on each channel because the devices used in different channels have different performance characteristics. The satisfactory performance could be maintained even when the additional loss of the FSO link increases to approximately 12 dB. This estimated additional loss is equivalent to the transmission loss of an FSO link over several hundred of meters in an outdoor environment [8], which is sufficient for many application cases of mobile fronthaul for ultra-dense small cell networks. The use of an EDFA after the FSO link helps to compensate for the losses on the FSO link. It can also help mitigate the power fading induced from the atmospheric turbulence on the FSO link [7]. However, during strong atmospheric turbulent conditions, such as in hot summer days and/or sunrise/sunset times, a seamless fiber–FSO system using a fine tracking technique should be applied to suppress strong scintillations and angle-of-arrival fluctuations due to random change in the incoming beam direction [8].

## 4. Conclusion

This paper proposes and demonstrates a high-speed radio-on-free-space optical system for flexible mobile fronthaul for ultra-dense RAN. Satisfactory performance is experimentally confirmed for the transmission of 2×2 MIMO FBMC/OQAM signals over a seamless fiber–FSO–mmWave system in the 90-GHz band with a total capacity of approximately 80 Gb/s and 40 Gb/s over the DL and UL system, respectively. The proposed system will be very useful for transmission of large-scale MIMO mobile signals in high carrier frequencies in future mobile networks.

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