First Demonstration of 4×4 Distributed MIMO Communication with 3GPP-compliant 5G Smartphone utilizing SCM/WDM-Based IF-over-Fiber MFH Link

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Abstract: We successfully demonstrated the real-time bi-directional 5G-compliant 4×4 Distributed-MIMO communication for the first time utilizing SCM/WDM-based IF-over-Fiber mobile fronthaul link architecture and commercially available smartphone for realizing future antenna distribution mobile communication systems. © 2024 The Authors

1. Introduction

Global mobile traffic continues to grow at a rate of more than 1.4 times per year due to the proliferation of mobile devices and diversification of broadband services [1]. In order to accommodate such an increasing traffic, further enhancement of mobile throughput is crucial for the 6th generation (6G) mobile communication system. Distributed multi-input multi-output (D-MIMO) has been considered as one of the key technologies in which a large number of remote antenna units (RAUs) are distributed in a specified area and coordinated using MIMO processing [2]. In a D-MIMO system, the same radio frequency can be reused among the adjacent RAUs because the interference can be cancelled out by MIMO signal processing, resulting in a better frequency utilization and higher throughput across the entire communication area. On the other hand, installing a large number of RAUs leads to the increase in installation and operating costs. One effective way to save these costs is to simplify RAU's configuration as much as possible and to reduce power consumption. Moreover, to perform MIMO processing, it is necessary to transfer radio signals from multiple RAUs to an aggregation point such as a central office (CO), where a MIMO signal processing unit is located. Because the MIMO processing is conducted in a PHY layer of Radio Access Network (RAN) functions, mobile fronthaul (MFH) transmission link between CO and RAUs requires to have enough capacity to carry such large amounts of radio signal information if existing Common Public Radio Interface (CPRI) or eCPRI is considered. Intermediate frequency-over-fiber (IFoF), a type of analog radio over fiber (A-RoF), has been extensively studied as an attractive solution for MFH, because a required optical bandwidth can be drastically reduced by directly transmitting analog waveforms over a fiber without the digitizing processing. In addition, the required structure and functions of the RAU can be simplified by putting all radio signal processing functions in the CO side. Furthermore, IFoF can efficiently accommodate signals from multiple RAUs by utilizing subcarrier multiplexing (SCM) and/or wavelength multiplexing (WDM) [3-5]. The authors have proposed the concepts of a large-scale accommodation of distributed antennas by combining IFoF with SCM and WDM so far with focusing on the high-capacity transmission [3]. Several reports have evaluated the applicability of IFoF technology for real-time mobile communication. In [4] and [5], real-time communication has been demonstrated for single-input single-output systems and centralized MIMO systems by utilizing IFoF technology with SCM and WDM. However, there has been no report on the assessment of real-time communication for D-MIMO systems with IFoF technology, where the interaction among multiple RAUs should be taking into account.

In this paper, we demonstrate an applicability of SCM/WDM-based IFoF MFH links to a D-MIMO application, and bi-directional real-time D-MIMO communications have been successfully demonstrated using a 5G base station (BS) simulator and a commercial smartphone, for the first time. Our developed FPGA-based SCM multiplexer/demultiplexer (MUX/DEMUX) and dense WDM (DWDM) analog IFoF transceivers are utilized for MFH links to convey sub-6GHz (band n77) 5G signals supporting 4×4 MIMO to the four distributed antennas placed in a different location in a shielded room. With these configurations, it is confirmed that a uniform throughput can be obtained across the measurement area and an interference among RAUs can be well suppressed by D-MIMO signal processing even through the IFoF transmission.

2. Experimental Setup

The experimental setup is shown in Fig. 1. The setup was consisted of three main parts; (1) 5G BS simulator, which supply the functions of a next-generation Node-B (gNB) and a 5G core network (5GC), (2) analog IFoF transmission link utilizing SCM/WDM, and (3) over-the-air (OTA) part.

The 5G BS simulator located at the CO side performed real-time signal processing of radio signals. The 5G BS simulator also had the capability of MIMO processing up to four layers and dedicated ports were assigned for downlink (DL) and uplink (UL) signals for each layer. Since the BS simulator operated in non-standalone mode, 4G signals for anchor band were also transmitted and received from the BS simulator, and directly supplied to the antennas using coaxial cables. Four layers of 5G MIMO signals were transferred to the distributed RAUs using SCM and/or WDM-based analog IFoF transmission link. In this experiment, two layers were transmitted through both SCM and WDM MUX/DEMUX with dummy RF signals, while the rest of the layers were input directly to DWDM analog IFoF transceivers with different wavelengths. A center frequency, bandwidth, duplexing scheme, and modulation scheme of the 5G radio signals were 4.05 GHz, 100 MHz, and time division duplex (TDD) 64QAM orthogonal frequency division multiplexing (OFDM), respectively. The overall signal specifications, including signal processing, conform to Release 16 of the 3rd Generation Partnership Project (3GPP).

The analog IFoF transmission link consisted of SCM and/or WDM MUX/DEMUX functions and analog IFoF transceivers. The SCM MUX/DEMUX was composed of one FPGA board and radio frequency (RF) components such as RF amplifiers and filters. Up to eight IF signals could be multiplexed and demultiplexed in real-time by utilizing RF SoC equipped with analog-to-digital converters (ADC) and digital-to-analog converters (DAC) on the FPGA board. An analog IFoF transceiver was consisted of electro-absorption modulated lasers (EMLs) and PIN photodiodes (PDs). For the CO side, eight IFoF transceivers with different TX/RX wavelengths were equipped in a single rackmount chassis. On the other hand, eight sets of IFoF transceivers operating at different TX/RX wavelengths were prepared and installed at different locations of RAUs. The wavelength assignment of each EML in both UL and DL directions are shown in the inset of Fig.1 (a), and the optical spectrum is shown in Fig.1 (b). The transmission flows of each RF signal were as follows: Two of the four layers of 5G signals were connected to the ports no.1 (IN #1) and no.5 (IN #5) of SCM MUX/DEMUX. Dummy RF signals with the same center frequency, bandwidth and amplitude as the 5G signal were input to the remaining ports (IN #2-4,6-8) to generate an eight-channel multiplexed signal with the frequency assignment shown in the inset of Fig.1 (a). The multiplexed signal and the rest of two layers of 5G signals were converted to optical analog signals using IFoF transceivers of a fifth (DL λ_5) and first and third (DL $\lambda_{1,3}$) wavelengths at the CO side, respectively. Note that the IFoF transceiver was originally developed to carry IF signals below 6 GHz, however, the center frequency of the RF signal in this

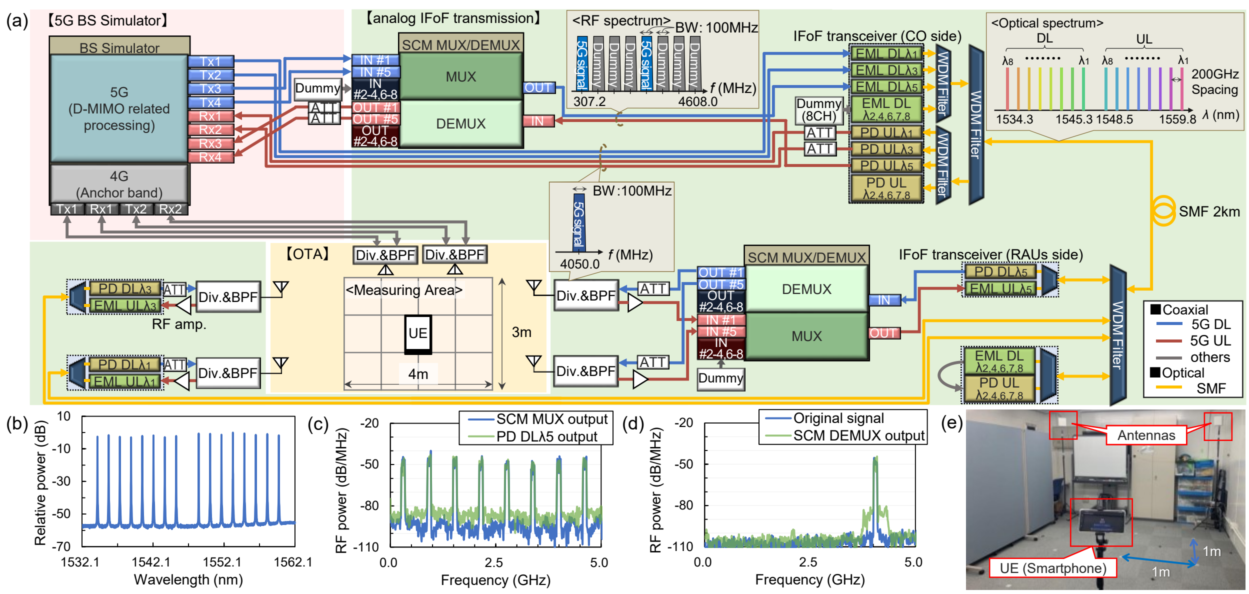

Fig.1 Experimental setup. (a) Block diagram, (b) Optical spectrum, (c) RF Spectrum of SCM MUX and PD DL λ_5 outputs, (d) RF spectrum of original signal input to IN #1 and SCM DEMUX output, and (e) Photograph of the OTA part in the shielded room.

Table 1. Throughput when changing MIMO layer.

No. of layer	Throughput (Mbps)
1 (Activated Tx/Rx #1)	142.9
2 (Activated Tx/Rx #1, 2)	287.0
4 (Activated all Tx/Rx)	396.2

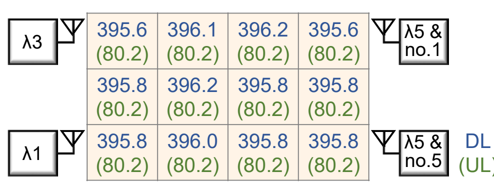

Fig. 2 DL (UL) throughput at each position (Mbps).

experiment was already below 6 GHz; therefore, the IFoF transceiver could be considered as an analog RoF transceiver. The remaining five wavelengths of IFoF transceivers (DL $\lambda_{2,4,6,7,8}$) were input to RF dummy signals with the same amplitudes and frequency assignments as the eight-channel multiplexed signal to generate dummy SCM signals. These eight optical analog signals were multiplexed by WDM filters and transmitted over a 2 km single-mode fiber (SMF) link. At the RAU sides, the DL WDM signals were separated into each wavelength by another WDM filter and transferred to the IFoF transceivers on each RAU site. For DL λ_5, the signal output from PIN-PD was input to SCM DEMUX, and the 5G signals were extracted from the output ports no.1 (OUT #1) and no.5 (OUT #5). For DL $\lambda_{1,3}$, 5G signals were directly output from PIN-PDs and supplied to each distributed antenna. The power levels of RF signals were equalized using an attenuator (ATT), and DL/UL signals were combined using a divider (Div.) and a bandpass filter (BPF) and supplied to an antenna. The remaining dummy signals output from PIN-PDs of DL $\lambda_{2,4,6,7,8}$ were reused as the UL dummy signals and directly input to EMLs for UL via coaxial cable. On the other hand, the system setup for the UL direction was the reverse of the DL direction, except that a RF amplifier (RF amp.) for amplifying the UL signal was input after the divider and an ATT was inserted before the BS simulator to match gains of the DL and UL directions. Note that the end-to-end signal-to-noise ratio (SNR) of all transmission paths, including DL and UL, used to transmit 5G signals in this experiment was confirmed to be more than 30 dB with optimum input signal power, as shown for an example of RF spectrum at each point in Fig.1 (c) and (d).

In the OTA part, D-MIMO signals were transmitted and received with distributed RAUs as shown in the photo of the shielded room in Fig.1(e). Each 5G signal combined by the divider and the BPF was supplied via a coaxial cable to a fixed directional pattern planar antenna, placed at a height of 2 m from the ground. These signals were radiated together with 4G signals in an area of 4 m in length and 3 m in width inside the shielded room and received by a user equipment (UE). In this experiment, a commercial 5G-capable smartphone was used as the UE, fixed at a height of 1.2 m from the ground. The average throughput per minute of the 5G signal was measured using iPerf.

3. Results and Discussion

First, we measured DL throughput with increasing the numbers of MIMO layers to 1, 2 and 4. We fixed the position of the UE at the center of the room, equidistant from all distributed RAUs. Table 1 shows the results, and it was confirmed that the throughput was improved with increasing the number of layers. The results show that our developed SCM MUX/DEMUX and analog IFoF transceiver can successfully transfer the 3GPP-complant TDD 5G signals including higher layer protocols, and also the MIMO process worked properly even antennas are distributed at different sites.

In order to confirm the effect of D-MIMO processing among distributed RAUs, the entire measurement area was divided by an 1 m × 1 m square grid, and throughputs were measured at the center of each grid. All four MIMO layers were activated in this experiment. Fig. 2 shows the measured throughput at each location, corresponding to the 3 m × 4 m grid within Fig. 1(a). Almost uniform throughputs were obtained across the whole area in both UL and DL, and the values were within 99% of the maximum value. It can be said from the result that the interference between different RAUs was properly cancelled out by the MIMO processing, and D-MIMO architecture was successfully configured with proposed IFoF transmission links including SCM and WDM MUX/DEMUX.

4. Conclusion

We demonstrated the applicability of IFoF-based transmission technology utilizing SCM and/or WDM MUX/DEMUX and DWDM IFoF transceivers as the MFH link of D-MIMO application. Through the bi-directional and real-time D-MIMO experiments using 3GPP-complient 5G signals, we have successfully confirmed that D-MIMO worked properly with our proposed SCM/WDM-based IFoF transmission MFH links.

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