1.314-Tbit/s (576 × 380.16-MHz 5G NR OFDM Signals) SDM/WDM/SCM-Based IF-over-Fiber Transmission for Analog Mobile Fronthaul

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Abstract: 576 × 64-QAM 5G NR OFDM signals with a net bit rate of 1.314-Tbit/s are successfully transmitted over a 12.8-km uncoupled 4-core fiber, using subcarrier multiplexing for the 18 OFDM signals and eight wavelength-division multiplexing.

1. Introduction

The demand for high-capacity mobile services has been increasing. In the fifth generation (5G) mobile communication systems, the peak data rate, i.e., the maximum user's throughput, will reach to 10-20 Gbit/s [1]. Various methods for beyond-5G mobile systems have been studied. The target value for the peak data rate would be discussed in future, but taking the evolution for previous generations into account, it is expected to be ten times or more of that in 5G, namely, 100-200 Gbit/s or more. Therefore, the mobile fronthaul (MFH) having 1 Tbit/s-class physical line rate would be required. For high-capacity MFH, analog radio-over-fiber (A-RoF) and intermediate frequency-over-fiber (IFoF), in which analog radio waveforms can be directly transmitted over a fiber by simple intensity modulation and direct detection (IM-DD) scheme, are attractive approaches, since they have potential of small energy consumption, small equipment size and high spectral efficiency, compared to standard digital-RoF transmission based on CPRI or e-CPRI. So far, Orthogonal-frequency-division-multiplexed (OFDM) signals up to 54.7 Gbit/s were successfully transmitted over a fiber by IFoF with subcarrier multiplexing (SCM) [2], [3], [4], and 102.4 Gbit/s [5] and 218.94 Gbit/s [6] IFoF transmissions have been reported together with WDM, respectively. For further increasing the capacity, multi-core fiber (MCF) has been also used for THz-over-fiber systems [7], although it is conventional digital RoF transmission. Multiple-input multiple-output (MIMO) OFDM signals over MCF and bidirectional OFDM signals over MCF were also demonstrated in Refs. [8] and [9], respectively.

We put a target to experimentally verify a mobile fronthaul system based on optical analog transmission scheme exceeding 1-Tbit/s net bit rate with the following approach: (i) Assuming the consecutive evolution from 5G to Beyond 5G, we employ 5G New Radio (NR) signals. (ii) Assuming that plural small cells in a relatively small area are accommodated by a single mobile fronthaul, passive-optical-device-based optical multiplexing techniques such as space-division multiplexing (SDM) and WDM are introduced considering their easiness of installation. (iii) SCM of IFs are also utilized for conveying multiple carrier components to one antenna site, in which each of the IF signals is demultiplexed and converted to the radio frequency (RF) emitted in the air.

In this paper, we experimentally demonstrate IFoF transmission using SCM, WDM, and SDM technologies for high data rate and densely formed small cells accommodated by analog MFH. Five hundred seventy-six (18 IF channels × 8 wavelengths × 4 cores) 5G NR 64-QAM OFDM signals having 380.16-MHz signal bandwidth (BW), which has 400-MHz channel BW including in-band guard bands, are successfully transmitted over a 12.8-km uncoupled 4-core fiber with a standard cladding diameter [10], for the first time. The total net bit rate in the IFoF transmission is estimated to be 1.314 Tbit/s by a spectral efficiency of 6 bit/s/Hz, which is the highest data rate, to our best knowledge, by analog IM-DD scheme for transmitting OFDM signals.

2. Experimental setup

Figure 1 shows the experimental setup. On the transmitter side, eight distributed feedback laser diodes (DFB-LDs) were used as the optical light source. The wavelengths of LD #1 to LD #8 were from 1546.8 nm to 1558.1 nm with 200-GHz wavelength spacing. The four odd channels and the four even channels were wavelength multiplexed using different arrayed waveguide gratings (AWGs), respectively. Each WDM signal was input to a lithium niobate Mach-Zehnder modulator (LN-MZM) and intensity modulated with subcarrier-multiplexed 5G-NR OFDM signals generated by a signal generator (SG). Polarization controllers (PCs) were put after the LDs for the polarization adjustment to the LN-MZM. The reason of using independent LN-MZMs and SGs for the odd and even WDM channels was to decrease the correlation between adjacent WDM channels. The SCM OFDM signal consists of 18 5G-NR OFDM channels. Each OFDM channel has the bandwidth of 380.16 MHz and multiplexed with channel spacing of 400 MHz. The subcarrier modulation, the signal bandwidth, the subcarrier spacing and the number of subcarriers of 5G-NR OFDM signal were 64 QAM, 380.16 MHz, 120 kHz, and 3168, respectively. Due to the bandwidth limitation of the signal analyzer (SA) at the receiver side, 18 IF channels were not able to be input to the SA, simultaneously. In order to avoid the constraints, the channel spacing between channel 6 and 7, and channel 12 and 13 were set to 1 GHz for the ease of analog signal filtering at the receiver side. Figure 2 depicts an example of the electrical signal spectrum just before the LN-MZM. Note that pre-emphasis was applied to level the RF power of the IF signals. The input electrical power to each of the LN-MZM was optimized by electrical amplifier and attenuator to obtain the lowest error vector magnitude (EVM) performance. The modulated odd and even WDM signals were amplified using erbium-doped fiber amplifiers (EDFAs) and combined by a 1×2 coupler (CPL) for generating 8 WDM/SCM signals. The total input power to the EDFAs were +5.2 dBm and +4.7 dBm for odd and even IF channels, respectively. The combined signals were duplicated with a 1×4 CPL and input to 4-core MCF. Just before a fan-in (FI), short fibers were used to remove the correlation among four of the optical signals. The total optical power input to the FI were +18.3 dBm. Figure 3 depicts the optical signal spectrum before the FI and MCF transmission. After the transmission over a 12.8-km uncoupled 4-core MCF, each WDM/SCM signal was output from a fan-out (FO). The output optical power ranged from +13.8 dBm to 14.5 dBm. From each of the four FO output signals, one of the eight wavelengths was extracted with an optical tunable filter (TF) in turn. The extracted optical signal was detected by a PIN-PD with the received optical power of 0 dBm. The OFDM signals from channel 1 to 6 were extracted using a low pass filter (LPF). The OFDM signals from channel 7 to 12, and channel 13 to 18 were extracted using a bandpass filter (BPF), a mixer, and a LPF. A local oscillator (LO) of 3-GHz and 6-GHz were used to down-convert the frequency of the signals input to the SA. The EVM values were measured for all OFDM channels of SDM/WDM/SCM transmitted signals.

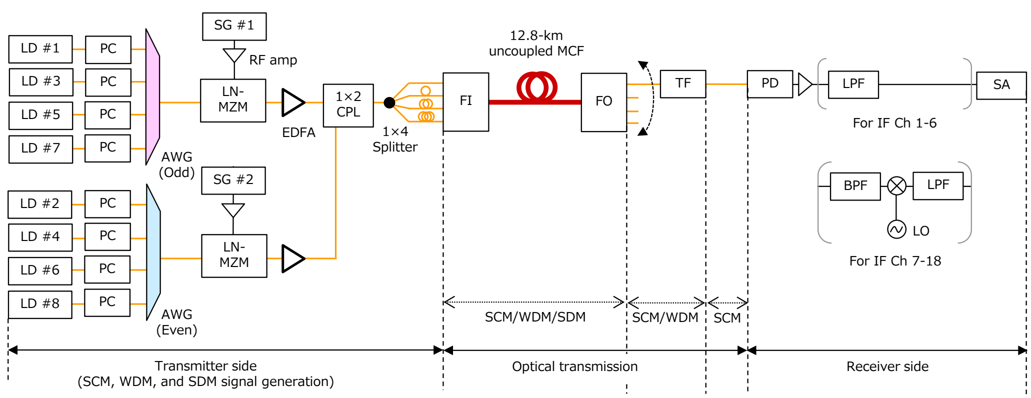

Fig. 1. Experimental setup.

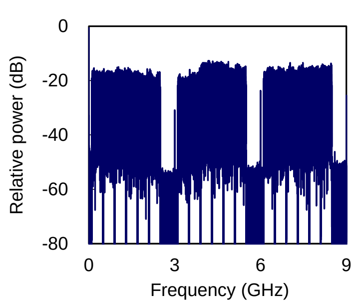

Fig. 2. RF spectrum before the LN-MZM.

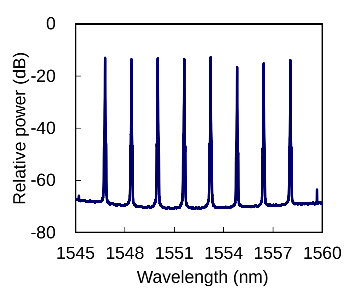

Fig. 3. Optical spectrum before the FI.

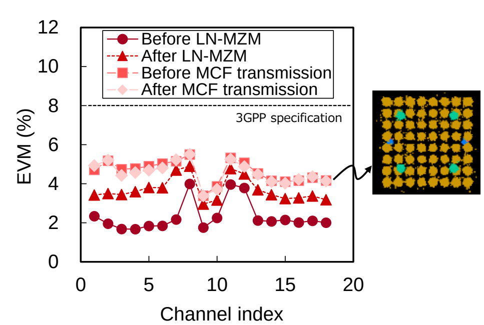

Fig. 4. EVM values for the first wavelength on the first core.

3. Results and discussion

Figure 4 shows the measured EVM values for all of the IF signals only in the first wavelength at several measurement points and an example of the measured constellation. The minimum and maximum EVM values before the LN-MZM were 1.7% and 4.0%, respectively. The eighth, eleventh, and twelfth IF channels, which were down-converted by 3-GHZ LO, had around 4.0% EVM values. Undesired distortion components may have occurred at the frequencies for the IF channels in the mixing process and deteriorated the EVM performance. Except for such IF channels, EVM values were around 2% and almost equal. After the LN-MZM, the EVM values ware measured to be 3.0% to 4.9%. The average EVM degradation was also found to be 1.4%. Before and after the FI and multi-core fiber transmission, EVM values were 3.4% to 5.5%. As expected, almost no EVM degradation was found after the multi-core fiber transmission in all of the IF channels. Figures 5(a), (b), (c), and (d) plot measured EVM values for all of the IF channels after 12.8-km 4-core fiber transmission including the optical tunable filter, for the first core, for the second core, for the third core, and for the fourth core, respectively. The EVM values of below 8%, which is an EVM criterion from 3GPP [11], are confirmed for all of the 576 OFDM signals, although the maximum EVM difference among wavelengths in a core and an IF was found to be 1.2%. From these results, the total net bit rate of 1.314 Tbit/s (18 IF channels × 8 wavelengths × 4 cores × 380.16 MHz × 6 bit/s/Hz) was achieved.

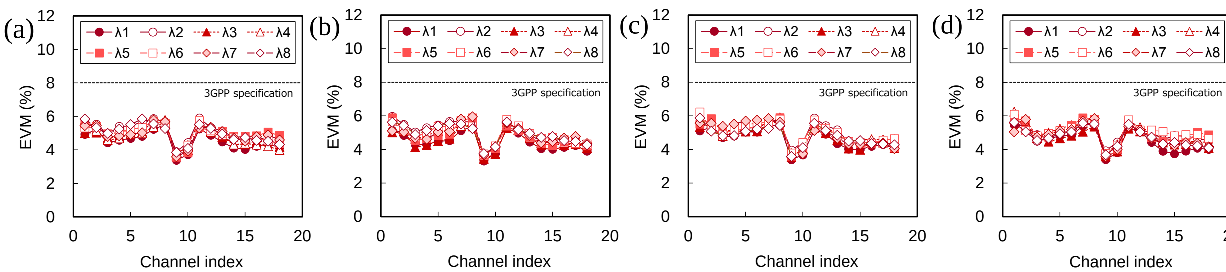

Fig. 5. Measured EVM values after the 12.8-km MCF transmission (a) on the first core, (b) on the second core, (c) on the third core, and (d) on the fourth core.

4. Conclusions

Five hundred seventy-six 380.16-MHz 5G NR 64-QAM OFDM signals with corresponding net bit rate as high as 1.314-Tbit/s have been successfully transmitted over a 12.8-km uncoupled 4-core fiber with a standard cladding diameter by SCM, WDM, and SDM. This result verifies the possibility of SDM/WDM/SCM-based IFoF transmission systems for efficiently transmitting a large number of radio signals over an access fiber to accommodate densely-allocated small cells in Beyond-5G analog MFH systems.

5. Acknowledgement

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