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10.51-Tbit/s IF-over-Fibre Mobile Fronthaul Link Using SDM/WDM/SCM for Accommodating Ultra High-Density Antennas in Beyond-5G Mobile Communication Systems

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Abstract *4608 × 380.16-MHz 64-QAM OFDM signals are transmitted over a 10.1-km uncoupled 12-core fibre by 16-wavelength-division and 24-subcarrier multiplexing, meeting the error vector magnitude criterion of less than 8%. The highest aggregate capacity of 10.51 Tbit/s in IM-DD-based analog radio-over-fibre transmission is experimentally verified. ©2022 The Author(s)*

Introduction

The fifth-generation (5G) mobile communication services have been launched commercially, and many studies are currently focusing on Beyond 5G. Cell-free (CF) architecture with massive multiple-input multiple-output (MIMO) processing among distributed antennas is in the limelight as one of the key technologies for Beyond-5G mobile communication systems [1]. CF massive MIMO addresses the fundamental idea of cellular architecture by distributing an enormous number of antennas in the field and serving to the users from multiple antennas with collaborating with each other in a centralized radio access network (C-RAN) manner, resulting in the high spectral efficiency in the serving area with eliminating the inter-cell interference or handover issues. At the same time, the peak user data rate of Beyond 5G seems to target more than 100 Gbit/s. It is known that the data rate of mobile fronthaul (MFH) for C-RAN with an intra-PHY functional split becomes several times higher than the mobile user data rate. With those in mind, a large-capacity point-to-multipoint (PtMP) optical access system that efficiently uses an access fibre for accommodating vast numbers of antennas will be required. PtMP analog radio-over-fibre (A-RoF) systems that include intermediate frequency-over-fibre (IFoF) systems are the attractive solution because such systems can transmit analog waveform of the wireless signals with high spectral efficiency to plural antenna sites over an access fibre by simple intensity modulation and direct detection (IM-DD) scheme. For the PtMP IFoF-based MFH, passive optical networks (PONs) and cascaded IFoF links have been studied in Refs [2] and [3], respectively. To enhance the transmission capacity on a fibre, IFoF transmission with subcarrier multiplexing (SCM) and wavelength-division multiplexing (WDM) have been reported in Refs. [4] and [5], respectively. In Ref [5], IFoF transmission with a net bit rate of 218.94 Gbit/s was demonstrated. The authors enhanced the capacity to 1.314 Tbit/s by additionally utilizing space-division multiplexing (SDM) in Ref [6]. A 12.8-km uncoupled 4-core fibre with a standard cladding diameter was used, and 576 × 64-QAM OFDM signals with 380.16-MHz signal bandwidth (BW) were successfully transmitted over the multi-core fibre by 8-WDM and 18-SCM. The data rate is the highest value, to our best knowledge, in IM-DD-based analog RoF transmission. Towards CF massive MIMO architecture for Beyond 5G, however, where a large number of antennas are distributed in the field, larger branching number will be desirable in order to reduce the cost by effectively transmitting multiple radio signals over a single access fibre.

In this paper, the highest aggregate capacity is updated to 10.51 Tbit/s by increasing the multiplicity of SDM, WDM, and SCM. 4608 × 380.16-MHz OFDM signals in 64-QAM format are transmitted over a 10.1-km uncoupled 12-core fibre. Error vector magnitude (EVM) performance of less than 8% for all of the OFDM signals is confirmed after transmission. The number of antenna sites that are accommodated on a single optical fibre increases eight times from 576 in Ref [6] to 4608.

Experimental setup

Figure 1 shows the experimental setup for IFoF transmission using SDM, WDM, and SCM. Sixteen distributed feedback laser diodes (DFB-LDs) with 160-GHz wavelength spacing from 1545.4 nm to 1564.8 nm were used as WDM light sources. The WDM light sources were multiplexed by an arrayed waveguide grating (AWG) and input to a lithium niobate Mach-Zehnder modulator (LN-MZM). The polarisation controllers (PCs) after the DFB-LDs were used for adjusting the input polarisation to the LN-MZM.

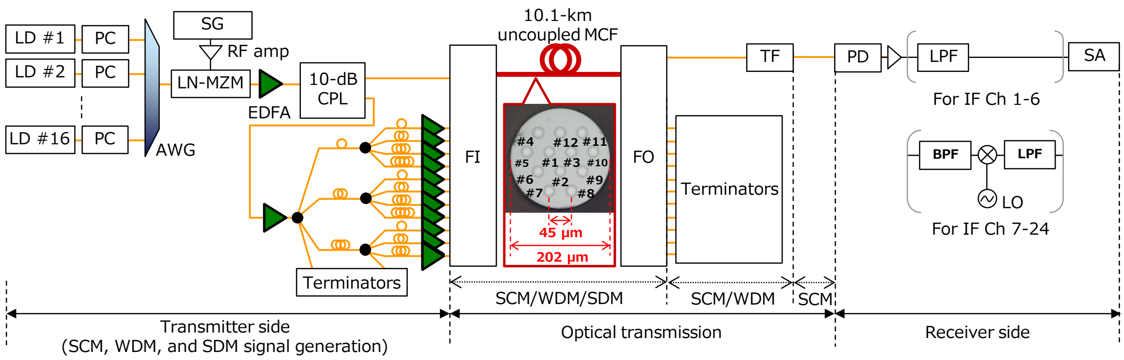

Fig. 1: Experimental setup for IFoF transmission using SDM, WDM, and SCM.

As the input IF signals to the LN-MZM, an SCM signal consisting of 24 64-QAM OFDM signals was generated by a signal generator (SG). The subcarrier spacing and signal bandwidth of each OFDM signal were 120 kHz and 380.16 MHz, respectively. The SCM signal drove the LN-MZM with optimized radio frequency (RF) power. Figure 2 shows the RF spectrum just before the LN-MZM. In this experiment, to flatten the EVM performance among OFDM signals, pre-emphasis was applied to the SCM signal. It should be noted that the wide guard bands at around 3 GHz, 6 GHz, and 9 GHz were used to extract a set of six OFDM channels by analog filters after transmission. The number of the OFDM channels was limited by the bandwidth of the signal analyzer (SA) to measure the EVM performance. The SCM-modulated WDM signals were amplified by an erbium-doped fibre amplifier (EDFA) and divided by a 10-dB coupler (CPL). One signal with a higher power was directly connected to one of the cores of the 10.1-km 12-core fibre through fan-in (FI) as a measurement signal. The other signal with lower power was amplified again by the other EDFAs and split into 11 dummy signals. Fibres of different lengths were inserted for the uncorrelated dummy signals, and then the dummy signals were input to the remaining cores of the 12-core fibre. After the fibre transmission, the measurement signal was extracted via a fan-out (FO). The optical losses of the 12-core fibre including the FI and FO were from the minimum value of 2.9 dB for core #2 to the maximum value of 4.4 dB for core #4. The inter-core crosstalk was also less than -60 dB at 10 km thanks to the trench-assisted core profile and core pitch of 45 µm. Subsequently, each of the wavelengths in the measurement signal was filtered by a tunable filter (TF) and converted to an electric signal using a PIN-PD. The input power to the PIN-PD was adjusted to be 0 dBm by a variable optical attenuator (VOA). The electric signal was amplified by an RF amplifier and filtered by a low pass filter (LPF) or a

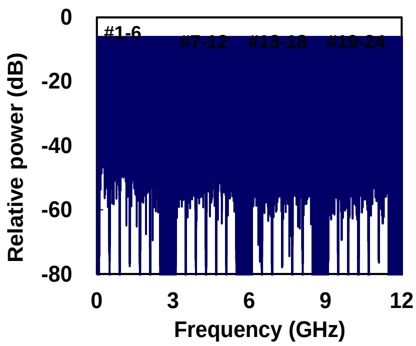

Fig. 2: RF spectrum before the LN-MZM.

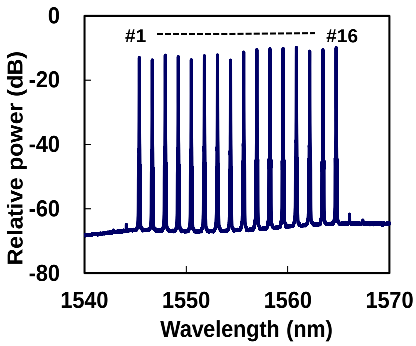

Fig. 3: Optical spectrum before the FI.

bandpass filter (BPF) to extract a set of six OFDM channels. The OFDM channels on the higher frequency side above 3 GHz were down-converted to a lower frequency band by using an analog mixer and a local oscillator (LO). The six OFDM channels were input to an SA, and the EVM performance was measured. All combinations of cores, wavelengths, and OFDM channels were evaluated by changing a transmission core for the measurement signal in turn.

Figure 3 describes the optical spectrum for the measurement signal before the FI. The maximum power difference among wavelengths was 3.9 dB. The input power to the FI was adjusted by the EDFA to obtain an input power of 0 dBm at the PD. Due to the limitation in the available EDFAs,

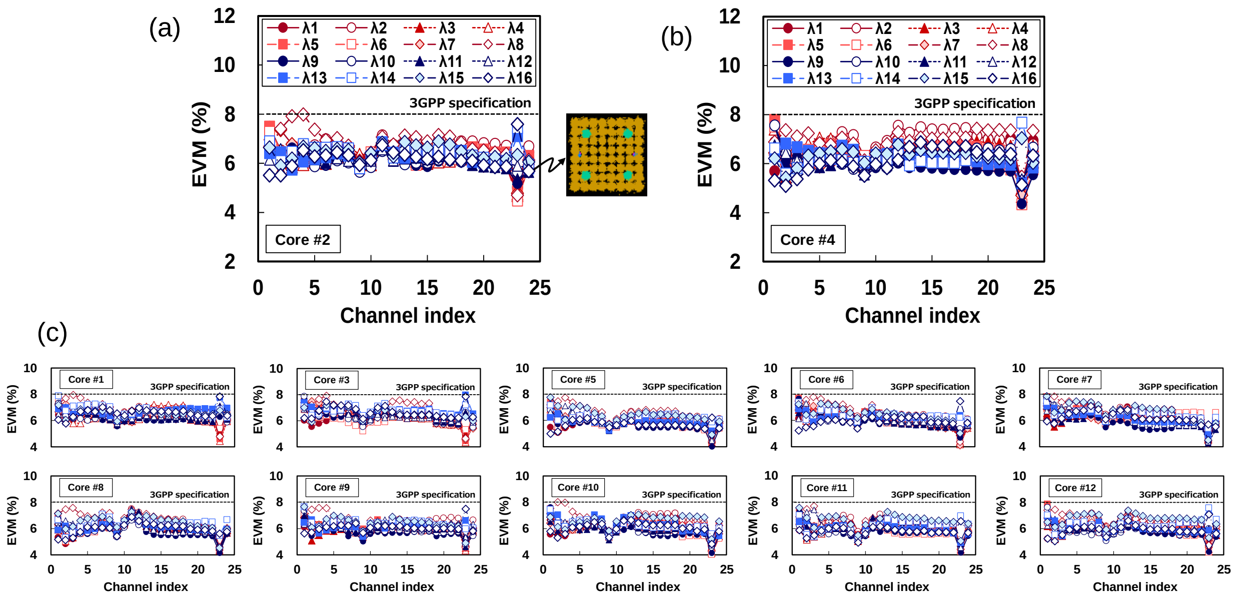

Fig. 4: EVM values after the 12-core fibre transmission (a) for the second core, (b) for the fourth core, and (c) for the other cores.

the input power levels of the dummy signals to the measurement signal level were not completely aligned. We firstly checked the impact of the power difference using core #2 by measuring the EVM values for all OFDM channels of all wavelength after the transmission. The EVM values were compared in two cases where the input power levels of the dummy signals for the adjacent cores were equal or about 3-dB lower to that of the measurement signal. The average of the EVM differences and the standard deviation were around 0.1 percentage point and 0.1, respectively. This was partially because the 12-core fiber had ultra-low inter-core crosstalk. Thus, the 3-dB smaller power for the dummy signals was not significant. Therefore, the input power of the dummy signals to the FI for the adjacent cores were set to 3-dB smaller than one of the measurement signal.

Results and discussion

Figure 4 (a) and (b) plot the EVM values after the fibre transmission for core #2 with the minimum loss and #4 with the maximum loss, respectively. The inset describes an example of a 64-QAM constellation diagram. The EVM values that depend on the IF channel index are similar to each other between the two cases. Lower-frequency IF channels have wider EVM ranges, compared to the other channels. This may be because unwanted components occurred in such frequencies due to the nonlinear effect from the high-power EDFA and degraded the EVM performance. Additionally, the occurrence of stimulated Brillouin scattering (SBS) and the reflected signal may have deteriorated IF Channel #23 in some wavelengths. Even though such degradation was taken into account, all of the EVM values were less than 8% which is a criterion for 64-QAM OFDM signals in 3GPP [7]. Figure 4 (c) describes the EVM values for the other ten cores. From these results, it was confirmed that all of the OFDM signals that were transmitted over the 12-core fibre met the EVM criterion. The total capacity per fibre in this experiment was 10.51 Tbit/s calculated from 12 cores × 16 wavelength/core × 24 OFDM channels/wavelength × 380.16 MHz/ch × 6 bit/s/Hz.

Conclusions

4608 × 380.16-MHz OFDM signals in 64-QAM format have been successfully transmitted over a 10.1-km 12-core fibre by SDM, WDM, and SCM. The aggregated capacity corresponds to 10.51 Tbit/s which is the highest in analog RoF transmission. Additionally, up to 4608 antenna sites could be accommodated over a single access fibre. These results show the potential of the IFoF transmission technology for supporting the high aggregated capacity and high-density antenna allocation in Beyond-5G mobile communication systems.

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