Spectrum-Efficient Uplink Transmission for Mobile Fronthaul Based on Coherent Detection

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Abstract *We propose and demonstrate a novel spectrum-efficient radio-over-fiber (RoF) link based on a dual-drive Mach-Zehnder modulator and coherent detection for uplink transmission of mobile fronthaul. Compared with other RoF links, the proposed RoF link offers a two-fold increase in capacity without additional optical transceivers.*

Introduction

With the advent of the 5th Generation era (5G) for mobile networks, there has been an increasing demand for high data rates. 5G mobile communication networks employ a centralized-radio access network (C-RAN) which is composed of a centralized baseband unit (BBU) pool, remote radio heads (RRHs), and a distributed optical transmission network connecting the BBUs and RRHs. Since the fronthaul capacity scales proportionally with the radio bandwidth and number of RRHs, a large number of high-speed optical transceivers are required in the existing CPRI-based fronthaul. To this end, analog radio-over-fiber (RoF) transmission is gaining increasing momentum as a more spectrally efficient transport solution, inherently supporting lower latency and reduced RRH complexity [1]. To extend the capacity of the RoF-based fronthaul and add an additional degree of freedom for multiplexing, slicing or routing, wavelength division multiplexing (WDM) [2, 3], space division multiplexing (SDM) [4], mode division multiplexing (MDM) [5], and polarization division multiplexing (PDM) [6] have been proposed for RoF links. However, all of the previous multiplexing schemes require additional optical transceivers. In this paper, we propose and demonstrate a novel multiplexing scheme to implement uplink transmission for mobile fronthaul without the need of additional optical transceivers. In the remote cell site, two RRHs can be connected to one optical transmitter which includes a dual-drive Mach-Zehnder modulator (DD-MZM). In the BBU pool, an optical receiver based on coherent detection is employed to demultiplex the two uplink signals from the two RRHs. Thanks to the use of coherent detection, this novel transmission link offers a two-fold increase in capacity and at the same time an increase in the receiver sensitivity.

Principle

Fig. 1 shows the schematic diagram of the proposed RoF uplink. At the transmitter, a laser diode (LD) is used to generate an optical carrier which is sent to a DD-MZM via a polarization controller (PC). The DD-MZM has a Mach-Zehnder interferometer (MZI) structure with a phase modulator (PM) in each of the two arms. Two RRHs in the base station (BS) are connected to the two arms of the DD-MZM, so two uplink signals are applied to the DD-MZM and a modulated optical signal is generated at the output of the DD-MZM. The modulated signal is transmitted over a single-mode fiber (SMF) to a coherent receiver at the BBU where coherent detection is performed. To perform coherent detection, a second optical wave generated by a free-running laser source as a local oscillator (LO) light, is also sent to the coherent receiver. After optical-to-electrical conversion, an electrical signal is generated at the output of the coherent receiver. The electrical signal is sampled and processed to demultiplex the two uplink signals.

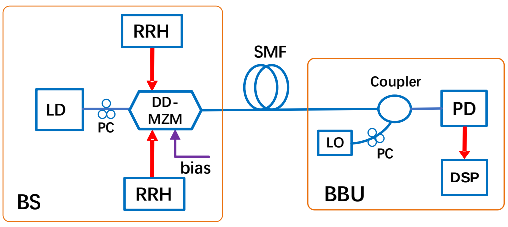

Fig. 1: Schematic diagram of the proposed RoF uplink.

To demultiplex the uplink signals, the DD-MZM should be biased at the quadrature transmission point. Assume the two uplink signals are $s_1(t)$ and $s_2(t)$, under small-signal modulation condition, the optical field at the output of the DD-MZM can be approximately expressed as

$$\begin{aligned} E_S(t) &= \sqrt{P_S}\exp j\left[\omega_c t+\phi_c(t)\right] \\ &\left[\exp j\left(\frac{\pi}{V_\pi}s_1(t)\right)+\exp j\left(\frac{\pi}{V_\pi}s_2(t)+\frac{\pi}{2}\right)\right] \\ &\approx \sqrt{P_S}\exp j\left[\omega_c t+\phi_c(t)\right]\left[1+j\gamma s_1(t)+j-\gamma s_2(t)\right] \end{aligned} \quad (1)$$

where P_S is the optical power at the output of the DD-MZM, ω_c is the angular frequency of the optical wave, $\phi_c(t)$ is the phase noise of the optical wave, V_π is the half-wave voltage of the DD-MZM and $\gamma=\pi/V_\pi$ is the modulation index.

After transmission over the SMF, the modulated optical signal is coherently detected at the BBU. A free-running optical wave generated by the LO light source can be expressed as

$$E_{LO}(t)=\sqrt{P_{LO}}\exp j\left[\omega_{LO}t+\phi_{LO}(t)\right] \quad (2)$$

where P_{LO} is the optical power of the optical wave at the output of the LO laser source, ω_{LO} is the angular frequency of the optical wave, and $\phi_{LO}(t)$ is the phase noise induced by the LO laser source. The received optical signal and the LO signal are combined by an optical coupler, and the combined signal can be given by $E_{PD}(t)=E_S(t)+jE_{LO}(t)$ .After optical-to-electrical conversion at the photodetector (PD), the generated electrical signal is given by

$$\begin{aligned} I_{RF}(t) \propto\; & 2\sqrt{2}\sqrt{P_S P_{LO}}\cos\left[\Delta\omega\cdot t+\phi_p(t)+\pi/4\right] \\ &+2\sqrt{P_S P_{LO}}\gamma s_1(t)\cos\left[\Delta\omega\cdot t+\phi_p(t)\right] \\ &+2\sqrt{P_S P_{LO}}\gamma s_2(t)\sin\left[\Delta\omega\cdot t+\phi_p(t)\right] \end{aligned} \quad (3)$$

where $\Delta\omega = \omega_{LO}-\omega_c$ is the frequency difference between the optical waves from the transmitter laser source and the LO laser source, and $\phi_p(t)=\phi_{LO}(t)-\phi_c(t)$ is the joint phase noise introduced by the two laser sources. As can be seen from Eq. (3), there is a carrier centered at $\Delta\omega$ which can be extracted by a narrow bandpass filter. By introducing a phase shift of +45º or -45º to the carrier, we have

$$I_{c1}(t)=2\sqrt{2}\sqrt{P_S P_{LO}}\cos\left[\Delta\omega\cdot t+\phi_p(t)\right] \quad (4a)$$

$$I_{c2}(t)=-2\sqrt{2}\sqrt{P_S P_{LO}}\sin\left[\Delta\omega\cdot t+\phi_p(t)\right] \quad (4b)$$

If the -45º phase-shifted microwave carrier $I_{c1}(t)$ is used to down-convert the received signal, we can obtain the signal at $\Delta\omega$, given by

$$I_1(t)=2\sqrt{2}P_S P_{LO}\gamma s_1(t) \quad (5)$$

We can see $s_1(t)$ is recovered. On the other hand, if the +45º phase-shifted microwave carrier is used to down-convert the received signal, we can obtain the signal at $\Delta\omega$, given by

$$I_2(t)=-2\sqrt{2}P_S P_{LO}\gamma s_2(t) \quad (6)$$

We can see $s_2(t)$ is recovered. As can be seen from Eqs. (5) and (6), the two signals are demultiplexed and the joint phase noise is eliminated. The demultiplex process is shown in Fig. 2. According to Eq. (3), the phase terms of the two uplink signals are orthogonal while the microwave carrier is shifted by 45º. To recover the two uplink signals, the phase of the microwave carrier is shifted by +45º or -45º and utilized to down-covert the two uplink signals, leading to the demultiplexing of the two signals and at the same time the cancellation of the joint phase noise.

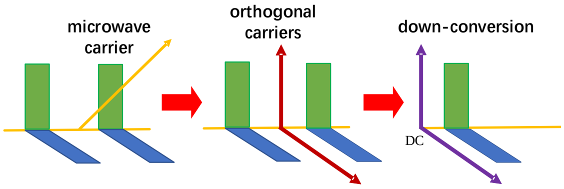

Fig. 2: Diagram to show the demultiplexing process.

Experimental results

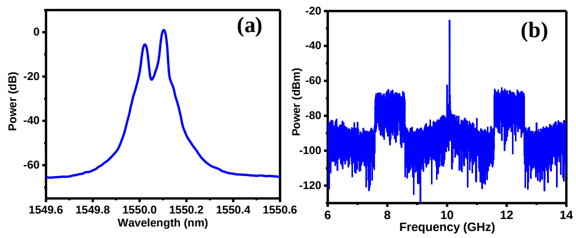

Fig. 3: (a) Measured optical spectrum before the PD, (b) Measured spectrum of the generated electrical signal at the output of the PD.

An experiment based on the setup shown in Fig. 1 is performed. A continuous-wave (CW) optical wave at 1550 nm with a linewidth of 100 kHz is generated and is sent to a DD-MZM which has a half-wave voltage of 4 V and a 3-dB bandwidth of 10 GHz. Two independent OFDM signals centered at 2 GHz with a bandwidth of 1 GHz are generated by an arbitrary waveform generator (AWG) and applied to the two arms of the DD-MZM. The bias of the DD-MZM is adjusted to allow the DD-MZM operate at the quadrature transmission point. A modulated optical signal is generated at the output of the DD-MZM and transmitted to the BBU over a 25 km SMF. In the BBU, a CW optical wave at 1550.08 nm with a linewidth of 100 kHz is used as the LO. The power of the LO signal is set to be 9 dBm. The received optical signal and the LO signal are combined by a 50:50 optical coupler and sent a PD with a bandwidth of 30 GHz and a photo responsivity of 0.8 A/W. In the experiment, the polarization of the light from the LO is adjusted by a polarization controller to be aligned with the light from the transmitter. In practice, a polarization diversity configuration can be used. After optical-to-electrical conversion at the PD, the detected electrical signal is sampled by a digital storage oscilloscope (Agilent DSO-X 93204A) with a sampling rate of 80 GHz and a bandwidth of 32 GHz. The sampled signal is sent to a digital signal processing (DSP) unit to demodulate the two uplink signals. The optical spectrums of the combined received signal and the LO signal are measured and are shown in Fig. 3(a). The high power of the LO signal leads an enhanced sensitivity of the receiver, thus making the overall transmission uplink have an increased sensitivity [7]. Fig. 3(b) shows the measured spectrum of the generated electrical signal. Since the wavelength difference between the received optical signal and the LO is about 0.8 nm, a microwave signal at about 10 GHz is generated. The microwave carrier is extracted and phase-shifted to down-convert the two OFDM signals.

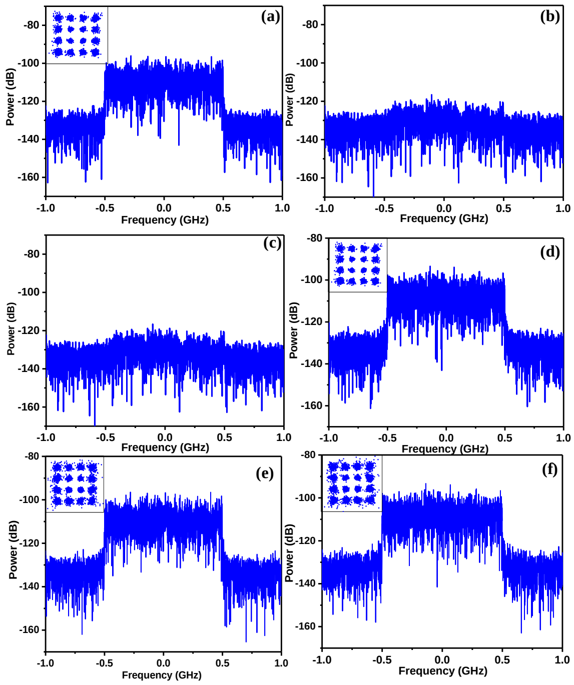

Fig. 4: Experimental results. One uplink signal is applied to the DD-MZM, (a) spectrum of the down-converted signal by the -45º phase-shifted microwave carrier, (b) spectrum of the down-converted signal by the 45º phase-shifted microwave carrier. Only the other uplink signal is applied to the DD-MZM, (c, d) spectra of down-converted signals by -45º and 45º phase-shifted carriers. (e, f) Spectra of down-converted signals when both uplink signals are applied.

Firstly, we only apply one OFDM signal to the DD-MZM, then the down-converted spectrum by the orthogonal phase-shifted microwave carriers is shown in Fig. 4(a) and (b). As can be seen, the -45º-shifted carrier can be used to down-convert the applied OFDM signal while the 45º-shifted carrier cannot. The error vector magnitude (EVM) of the applied OFDM signal is 9.54%. Then, we only apply the other OFDM signal to the other arm of the DD-MZM and the spectrum of down-conversion is shown in Fig. 4(c) and (d). In this case, the 45º shifted carrier can down-convert the OFDM signal applied to the other arm of the DD-MZM while the -45º shifted carrier cannot. The measured EVM of the other OFDM signal is 9.59%. Finally, both OFDM signals are applied to the DD-MZM, and the down-conversion results are shown in Fig. 4(e) and (f). The EVMs of two uplink signals are 12.12% and 12.51%, which is a little worse due to cross talk between the two signals.

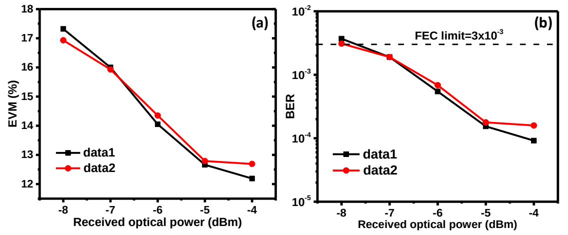

Fig. 5: Measured EVMs and BERs at different received optical power levels for the two uplink signals.

To further evaluate the performance of the RoF link, the EVMs at different received optical power levels are measured, which are given in Fig. 5(a). The BERs are calculated from the EVMs, and the results are shown in Fig. 5(b). As can be seen, when the received optical power is -8 dBm, the EVMs for the two recovered OFDM signals are 17.32% and 16.93%, and the corresponding BERs are 3.7×10^{-3} and 3.1×10^{-3}, which are beyond the FEC limit. When the optical power is increased to -4 dBm, the BERs are measured to be 9.16×10^{-4} and 1.59×10^{-3}, which are well within the FEC limit. By employing a state-of-the-art FEC technique, a raw BER of up to 3×10^{-3} can be improved to an effective BER of 1×10^{-15} at the expense of a 6.7% overhead [8], and error-free transmission can be achieved.

Conclusion

We have proposed a novel technique to implement a spectrum-efficient RoF link based on a DD-MZM and coherent detection to achieve uplink transmission for mobile fronthaul. At the transmitter, two uplink OFDM signals from two RRHs were modulated on an optical carrier by applying them to the DD-MZM via the two arms. After transmission over a 25 km SMF, the optical signal consisting of the two OFDM signals were detected based on coherent detection in the BBU and recovered at a DSP unit free from the joint phase noise. The RoF uplink offers a two-fold increase in capacity without additional optical transceivers. In the experiment demonstration, two OFDM signals with a bandwidth of 1 GHz were transmitted and error free receiving was achieved if FEC was employed.

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