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Two-level modulation scheme to reduce latency for optical mobile fronthaul networks

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Abstract: A system using optical two-level orthogonal-frequency-division-multiplexing (OFDM) – amplitude-shift-keying (ASK) modulation is proposed and demonstrated to reduce the processing latency for the optical mobile fronthaul networks. At the proposed remote-radio-head (RRH), the high data rate OFDM signal does not need to be processed, but is directly launched into a high speed photodiode (HSPD) and subsequently emitted by an antenna. Only a low bandwidth PD is needed to recover the low data rate ASK control signal. Hence, it is simple and provides low-latency. Furthermore, transporting the proposed system over the already deployed optical-distribution-networks (ODNs) of passive-optical-networks (PONs) is also demonstrated with 256 ODN split-ratios.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications; (060.4080) Modulation.

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1. Introduction

With the popularization of mobile applications, 4G systems such as Long Term Evolution (LTE) and LTE-Advanced may not satisfy the bandwidth demand in the near future; hence the 5G wireless networks are being actively planning. It is expected that 5G networks should support a more unified frame serving various applications, with higher capacity and lower latency [1]. As more and more base stations (BSs) are installed, centralized architectures are proposed and used to simplify the management. For example, in a cloud radio access network (C-RAN) architecture [2], the traditional functions of a BS are separated into a baseband unit (BBU) and a remote radio head (RRH). Each BBU handles most of the processing and several BBUs can be grouped together for resource sharing. As most of the processing is handled in the BBUs, the complexity and the cost of each RRH can be significantly reduced. And the mobile fronthaul network [2–6] is used to connect the centralized BBU pool and the RRHs. Considering the possible high capacity and long transmission ranges for the 5G applications, optical fibers may be chosen as the main transmission media. Cost-effective strategies to obtain optical fibers for the fronthaul networks are hence an important issue.

Common public radio interface (CPRI) is the most general technique for signal transportation in the fronthaul networks [7]. All transported signals are digitized into CPRI frames before their transmission. The digitized signal is more resistant to quality degradation, and the control signal for management purposes can be embedded into CPRI frames directly. However, the spectral-inefficient feature of the digitized signal results in high transmission bandwidth demand. This bandwidth demand is difficult to be met while the data rate of the future wireless systems is increasing rapidly. In [2–6], it is proposed to transport spectral-efficient radio signals in the fronthaul networks; hence relieving the burden of the bandwidth demand. Reference [6] shows the transportation of the control signal using frequency-division multiplexing (FDM). Since additional digital signal processing (DSP) is involved in the remote nodes, the complexity and cost of the RRHs increase. Besides, for the CPRI-based systems and FDM radio-over-fiber (RoF) based systems, high speed digital-to-analog conversion (DAC)/analog-to-digital conversion (ADC) and signal recovery processing are necessary. This will result in excess latency of about several micro-seconds [6–8]. This is disadvantageous for the future 5G wireless systems which may need more signal processing [9].

In this work, a system using optical two-level orthogonal-frequency-division-multiplexing (OFDM) – amplitude-shift-keying (ASK) modulation is proposed and demonstrated. In this scheme, the low data rate control signal and the high data rate payload signal are separately encoded in the ASK and OFDM formats respectively. At the proposed RRH, the high data rate OFDM signal does not need to be signal processed, but is directly launched into a high speed photodiode (HSPD) and subsequently amplified and emitted by an antenna [10–14]. On the other hand, only a low bandwidth PD is needed to recover the low data rate optical ASK control signal. Hence, the proposed RRH is simple and provides low-latency. Furthermore, since passive optical networks (PONs) have been widely deployed in the last decade, re-using the already deployed optical distribution networks (ODNs) of PONs for the fronthaul networks can relieve the burden of deploying massive new optical fibers in the early stage of 5G era. By carefully choosing the transmission wavelengths, the proposed systems can be seamlessly added into the PON ODNs by wavelength division multiplexing (WDM) technique. In our proof-of-concept experiment, 16-quadrature amplitude modulation (QAM)-OFDM-2-ASK wireless signal with 2.18 Gbit/s payload and 3.61 Mbit/s control signal is demonstrated for transmitting over a 40 km single-mode fiber (SMF) and a wireless channel. 256 ODN split-ratio of the remote nodes can be supported, which meets the minimum requirement of NG-PON2.

2. Proposed architecture

Figure 1 shows the evolution of the wireless access networks, and Fig. 1(a) illustrates the traditional 2G system in which the BS is located close to the antenna to reduce the propagation loss of the RF signal in the electrical cable between the BS and the antennas. In the 3G-4G systems, the BS is separated into BBU and RRH. Hence the expensive BBU can be group together for resource sharing. As most of the processing functions are located in the BBU, the RRH can be much simplified. In a CPRI based fronthaul network, the RRH only needs to handle the DAC and RF conversions, as illustrated in Fig. 1(b). Although the RRH in the 3G-4G systems is much simpler than a BS, the transformation of signals between the digitized CPRI frames and the RF signals results in excess latency. Figure 1(c) illustrates our proposed architecture for the 5G system with reduced latency. In this scheme, the high data rate OFDM signal does not need to be signal processed, but is directly launched into a HSPD and subsequently emitted by an antenna. Only a low bandwidth PD is needed to recover the low data rate ASK control signal.

Apart from the simplification of the RRH and the reduction of the latency, the proposed scheme could facilitate the implementation of coordinated multipoint (CoMP) techniques [3, 4]. The control signal carried by the ASK modulation can contain the CoMP commands. As shown in Fig. 1(c), the signal launching to the RRH is divided into two different paths. One path is connected to the wireless module, which could be composed of a HSPD, a power amplifier, and a beam-forming circuit with an antenna array. The high speed OFDM signal will be directly transmitted via the antenna array without any processing in the RRH as mentioned before. The other path is connected to a low bandwidth PD inside the control module, which will only receive the envelope of the input optical signal (i.e. the ASK signal). The received control signal will be launched into the beam-forming circuit and determine the beam directions of the antennas. As a result, as also shown in Fig. 1(c), the user equipment (UE) can be served by the beam-like RF signals with increase signal-to-interference-and-noise ratio (SINR). The proposed scheme can be applicable for the uplink transmission. However, as the advanced processing, such as CoMP, may not be necessary in the uplink transmission; and usually the uplink transmission has lower data rate than the downlink transmission. Hence, the proposed two-level scheme for the uplink transmission may not be necessary.

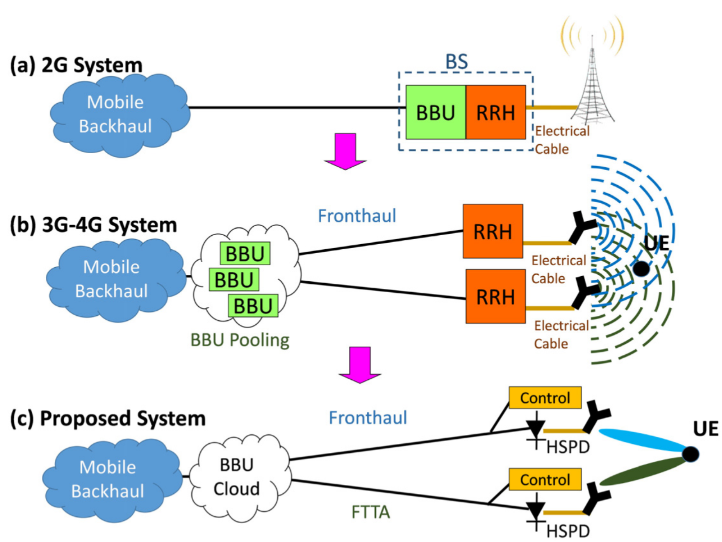

Fig. 1. Evolution of the wireless access networks.

The encoding and decoding flows of the two-level OFDM-ASK signal are shown in Fig. 2. These flows are also used and verified in the proof-of-concept experiment in Section 3. In the BBU, the data payload is encoded as typical OFDM symbols, which includes the gray color functional blocks of Fig. 2(a). The data payload will be serial-to-parallel converted. After the symbol mapping, pilot insertion, inverse fast Fourier transform (IFFT) and cyclic prefix (CP) insertion processes, two additional processing blocks (orange color) are proposed and deployed for the two-level OFDM-ASK generation. The root-mean-square (RMS) power of each OFDM symbol will be normalized to be unity as shown in inset (i) of Fig. 2. Then the control signal will further modulate each OFDM symbol. The final time trace of the two-level OFDM-ASK signal will look like inset (ii) of Fig. 3.

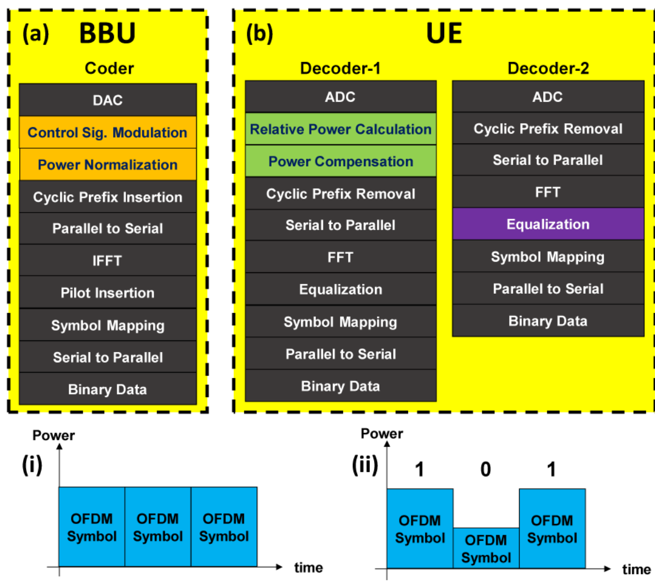

Fig. 2. Encoder and decoder of two-level OFDM-ASK. (a) The encoder in the BBU. (b) The decoder in the UE. Inset: time traces of OFDM-ASK signal: (i) after power normalization; (ii) after control signal modulation.

There may be several choices for decoding the OFDM-ASK signal. It is assumed that the transmitter module in the RRH will only introduce a scaling to the emitted OFDM-ASK signal. Then in the UE, the signal can be decoded by two different schemes. As shown in Decoder-1 of Fig. 2(b), the RMS power of each OFDM-ASK symbol will be recovered into unity according to the received envelop (performed in the green color blocks). After the RMS power recovery, the OFDM signal can be directly recovered according to traditional OFDM decoding processes, including CP removal, FFT, symbol mapping, parallel-to-serial conversion. However, since the RMS power recovery may involve a feedback process after the envelope of the OFDM symbol is received, additional latency will be introduced. Since the equalization (purple color block) processes are conventionally used for decoding the OFDM signals, the RMS power recovery may be directly integrated into the equalization block as shown in Decoder-2 of Fig. 2(b). Some pilot tones are pre-inserted into each OFDM-ASK symbols, such that the RMS power of each OFDM symbol can be directly calculated by the pilot tones rather than the envelope. Decoder-2 can perform better at the expense of wasting some bandwidth.

3. Experimental demonstration

Figure 3 shows the setup of our proof-of-concept experiment. In the central office (CO), a laser at 1550 nm wavelength with spectrum as inset (i) was launched into a Mach-Zehnder

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modulator (MZM). The MZM was driven by a 30 GHz sine wave and biased at null. Two optical tones separated by 60 GHz were generated as shown in inset (ii) of Fig. 3. An interleaver was used to further suppress the trivial tones as shown in inset (iii). After this, the signal was amplified and modulated by another MZM. The MZM was driven by the OFDM-ASK signal generated by an arbitrary waveform generator (AWG). The signal processing was described in Section 2, with FFT size of 512, and CP of 1/32. The OFDM signal was over-sampled by a factor of 6 and the AWG sampling rate was 12 GS/s. After the modulation, the optical signal was amplified by an erbium-doped fiber amplifier (EDFA). Inset (vi) shows the optical spectrum of the EDFA amplified signal after 40 km transmission. The relatively enhanced harmonic signals besides the two main optical signals could be due to the four-wave mixing (FWM) effect in the fiber. After the fiber, a tunable attenuator was used to emulate the power splitter at the remote node (RN) in PON. In the proposed RRH, a tunable band-pass filter (TBF) was used to select the corresponding optical wavelength. The OFDM-ASK signal was launched into a 10 GHz PD and a 60 GHz HSPD for retrieving the ASK control signal and the OFDM payload data respectively. A 933 MHz electrical low-pass filter was connected after the 10 GHz PD; and a real-time sampling scope with 10 GS/s sampling rate was used to receive the control signal. After the 60 GHz HSPD, the wireless signal was transmitted for about 42 cm wireless distance in this proof-of-concept demonstration. Longer transmission distance can be achieved if higher power RF amplifier is used after the HSPD. In the UE, an envelope detector was used after the antenna. The envelope of the wireless signal was then recorded by the 10 GS/s real-time sampling scope and offline decoded. The spectra at the corresponding ports of the system are shown in insets of Fig. 3.

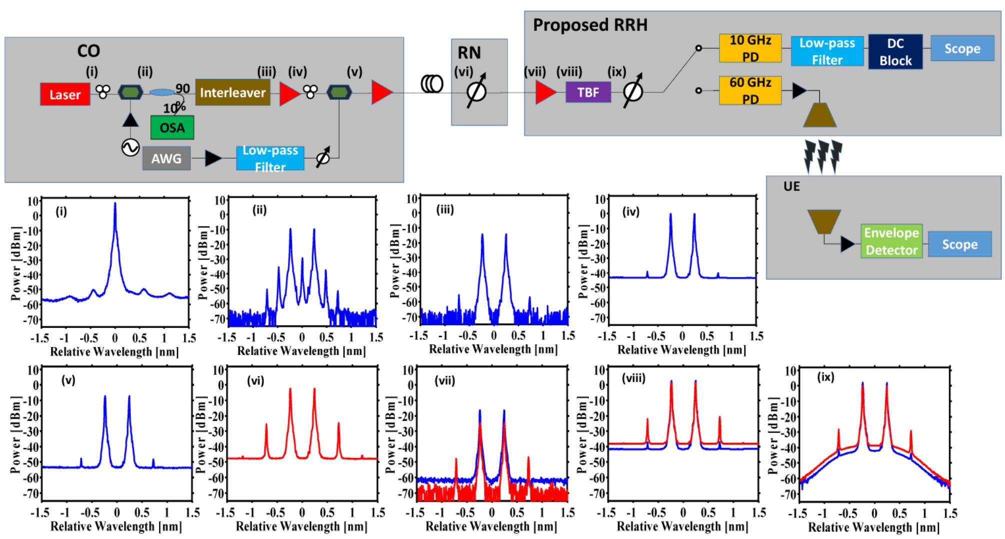

Fig. 3. Proof-of-concept experimental setup with Inset (i) to (ix): corresponding optical spectrum at different ports. Black curve: back-to-back; gray curve: 40 km. CO: central office; RN: remote node; OSA: optical spectrum analyzer; AWG: arbitrary waveform generator; TBF: tunable band-pass filter.

4. Results and discussion

In order to determine the modulation ratio of the control signal, the signal performance was analyzed after 40 km fiber and 256 split ratio as a minimum requirement of NG-PON2. Figure 4 shows the signal performance of the control signal and the wireless payload. The blue curve is the bit error rate (BER) performance of the OFDM signal modulated by 2-ASK signal with different modulation depths. 80% zero level denotes the “0” logic of the 2-ASK signal has 80% of the RMS power of the “1” logic. The red curve is the Q value of the 2-ASK signal with different modulation depths. The dash-line is the forward error correction (FEC) threshold level with BER 3.8 x 10^{-3} for the QAM symbols and the threshold of Q value corresponding to BER 10^{-12} for noise with Gaussian behavior. 80% zero level is chosen in the remaining experiment since 2-ASK signal with BER lower than 10^{-12} and OFDM signal with BER lower than FEC threshold can be achieved simultaneously.

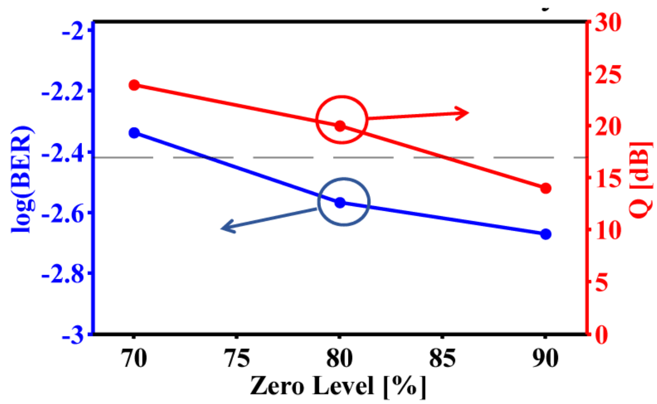

Fig. 4. Measured result of system performance versus the modulation depths of the 2-ASK signals. Blue line: the log(BER) value of the OFDM signal; red line: the Q value of the 2-ASK signal.

The experimental signal performance is shown in Fig. 5. Figure 5(a) shows the performance of the ASK control signal evaluated at the proposed RRH. The dash line of Fig. 5(a) is the Q. value corresponding to BER 10^{-12} for noises with Gaussian behavior. The control signal has identical performance at all split ratios. This may cause by its relative slow speed. Figure 5(b) shows the performance of the OFDM payload signal evaluated at the UE. Although the signals after 40 km SMF transmission show error floors at high RRH Rx power, FEC limit can be satisfied in all the signals. The error floors may come from the impairment induced by the nonlinear interaction in the fiber. While the receiving power become lower, nonlinear distortion from fiber transmission will not dominate the signal performance; hence, the power penalty induced from the fiber transmission becomes insignificant. About 1 dB power penalty is observed between the 80% and 100% 2-ASK zero level. 40 km fiber transmission and 256 split ratio which are the minimum requirement of the ODN of NG-PON2 are supported by the proposed system

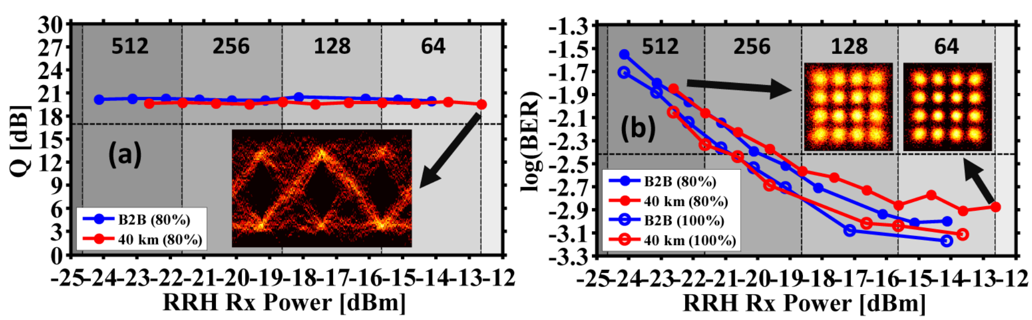

Fig. 5. Signal performance versus received power at RRH. (a) Control signal. (b) Wireless payload signal.

5. Conclusion

A system using optical two-level OFDM-ASK modulation is proposed and demonstrated. At the proposed RRH, the high data rate OFDM signal does not need to be signal processed, but is directly launched into a HSPD and subsequently emitted by an antenna. On the other hand, only a low bandwidth PD is needed to recover the low data rate ASK control signal. Hence, the proposed RRH is simple and provides low-latency. In order to maintain the signal performance of the control and payload signals, modulation ratio of the control signal is defined first. In our proof-of-concept experiment, wireless signal with 2.18 Gbit/s payload and 3.61 Mbit/s control signal is demonstrated and transmitted over 40 km SMF and a wireless channel with 256 ODN split-ratios. The proposed system can thus be operated over the ODN of the NG-PON2 systems. The deployment cost can thus be relieved.

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