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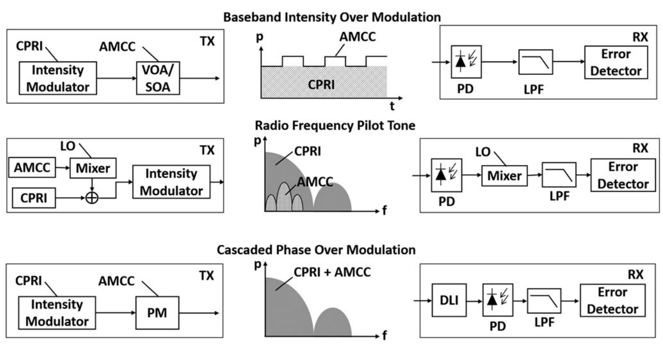

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Cascaded Phase Modulation for AMCC Superimposition Toward MFH Employing CPRI

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Abstract: A cascaded phase modulation is proposed for auxiliary management and control channel (AMCC) superimposition toward mobile fronthaul employing common public radio interface (CPRI). Different from other AMCC implementations, like the baseband intensity overmodulation scheme and the radio frequency pilot-tone scheme, the proposed cascaded phase overmodulation shows negligible impact on CPRI performance. Differential binary phase-shift keying is employed to encode the AMCC message, which is then overmodulated on CPRI via a cascaded phase modulator. Demodulation of AMCC message is achieved by a delay line interferometer, which converts the phase modulation to amplitude modulation. In the proof-of-concept demonstration, a 500-kb/s AMCC data are superimposed on a 10.1376-Gb/s nonreturn to zero signal with CPRI option 8, which is transmitted over 20-km standard-single-mode fiber. A −30-dBm receiver sensitivity is achieved for CPRI, with negligible penalty compared to the AMCC-free transmission of CPRI data.

Index Terms: Mobile front haul, WDM-PON, auxiliary management and control channel.

1. Introduction

In the coming years, a fast evolution of fixed and mobile network is expected due to the spread of cloud and mobile services. Capacity expansion is strongly required in the 5G era, with data rates about 10 times faster than current 4G systems. One of the attractive methods for increasing network capacity is densely deploying many small cells on a macro cell in the urban areas. Accordingly, a centralized radio access network (C-RAN) architecture [1] is proposed to decrease the network costs. The C-RAN architecture improves transmission performance by coordinated transmission and reception among small cells, with centralized baseband units (BBUs) and remote radio heads (RRHs). Common public radio interface (CPRI) [2] is used within the segment between BBUs and RRHs, which is also called the mobile fronthaul (MFH), to send digitalized IQ-sampling data with low latency [3]–[8]. However, CPRI suffers from low spectral efficiency. For a typical LTE channel with 20-MHz bandwidth and 2×2 multiple-input and multiple-output (MIMO), CPRI requires a fronthaul data rate of 2.5-Gbps [9]. Furthermore, many optical fibers are needed

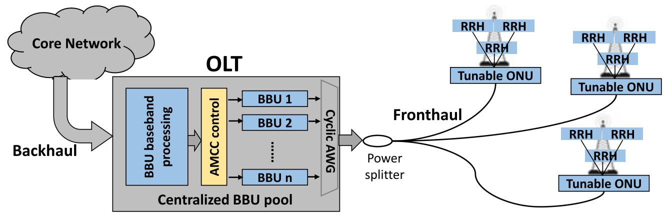

Fig. 1. WDM-PON architecture for connections between BBUs and RRHs.

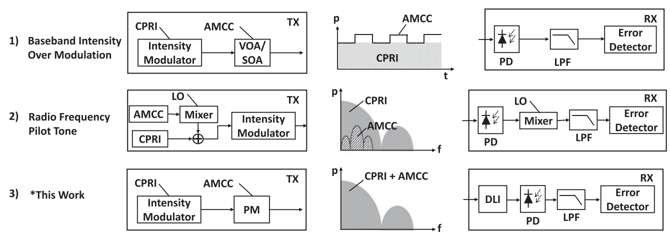

Fig. 2. Operational principle for 1) the baseband intensity over-modulation, 2) RF pilot-tone, and 3) the proposed cascaded phase over-modulation schemes.

to accommodate the small cells, which leads to a significant increase of network costs. Recently, a wavelength-division multiplexed passive optical network (WDM-PON) system has been defined for MFH by the ITU-T to solve the above problems [10]–[13]. System of this type can provide high capacity and low latency, which also reduces the required number of fibers. The wavelengths can be semi-statically assigned to small cells in accordance with mobile traffic load, and it is possible to reduce the number of transceivers via an auxiliary management and control channel (AMCC) [14]. Fig. 1 shows the implementation of WDM-PON architecture for connections between BBUs and RRHs. In the optical line terminal (OLT), wavelengths are assigned to each transceiver, which is connected to each port of the wavelength mux/demux component. And, a tunable transceiver is used at the optical network unit (ONU), where each wavelength is remotely controlled from OLT site by means of AMCC scheme.

Implementation of AMCC can be done either by the baseband intensity over-modulation scheme or by the radio frequency (RF) pilot-tone scheme [15]–[18]. However, performances of both schemes rely on the modulation depth of AMCC message signal. In this paper, a cascaded phase over-modulation scheme is proposed, in which a cascaded phase modulator is placed directly after the intensity modulator, in order to load the AMCC message onto CPRI data. Differently, such implementation for AMCC superimposition does not decrease the performance of CPRI, because the phase modulation does not change the intensity of optical carrier, which is directly detected by a photo detector for CPRI demodulation. The AMCC message itself is differentially encoded, which is then over-modulated on CPRI via a low-speed phase modulator. Differential binary phase-shift keying (DBPSK) is employed, while demodulation of AMCC message is simply fulfilled by a delay line interferometer (DLI). The DLI is used to converts the phase modulation to amplitude modulation. In the demonstration, a 500-kbps AMCC message is superimposed on a 10.1376-Gbps NRZ signal with CPRI option 8, which is transmitted over 20-km standard single mode fiber (SSMF). A -30 dBm receiver sensitivity is achieved for CPRI, with a negligible penalty compared to the AMCC-free transmission of CPRI data.

2. Principle

Fig. 2 shows the operational principle for AMCC superimposition in MFH employing CPRI, based on 1) the baseband intensity over-modulation, 2) RF pilot-tone, and 3) the proposed cascaded phase over-modulation schemes. The baseband over-modulation of AMCC message is to load an amplitude shift-keying (ASK) signal on the data by controlling the envelope amplitude of CPRI. It is typically fulfilled by a variable optical attenuator (VOA) or a semiconductor optical amplifier (SOA),

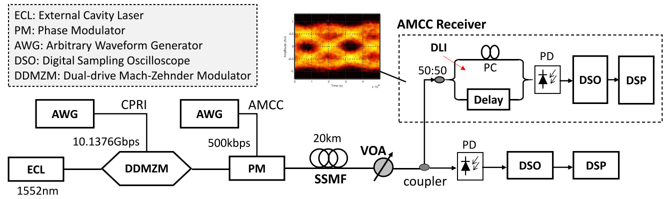

Fig. 3. Experimental setup for the transmission of CPRI data with AMCC superimposition, fulfilled by the proposed cascaded phase modulation.

which is driven by a low-speed message signal [15], [16]. The envelope can be retrieved by a low pass filter (LPF), after the photo detector. In the RF pilot-tone scheme, baseband AMCC signal is first up-converted to a proper RF frequency. Then, it is mixed with the CPRI signal [17], [18]. In the AMCC receiver, RF pilot tone is down-mixed by a local oscillator (LO), then it is low pass filtered. However, in both schemes, the modulation depth of AMCC message decreases the performance of CPRI data. In this work, a cascaded phase over-modulation for AMCC superimposition is proposed, as shown in the bottom of Fig. 2. It is achieved by a phase modulation of CPRI's carrier. The phase modulator (PM) is placed directly after the intensity modulator. The AMCC message is first differentially encoded with DBPSK, then it is over-modulated on CPRI via phase modulation. In the receiver, received signal is split into two parts. One part (for CPRI) is directly detected. While, the other part (for AMCC) is demodulated by a DLI, which converts the phase modulation to amplitude modulation.

The delay line interferometer splits the input optical signal equally into two beams, delays one of the beams by a symbol period. After recombination, the two beams interfere with each other constructively or destructively. The resultant interference intensity is the intensity-keyed signal. The input optical signal can be simply represented as

$$E_{in}(t) = a(t)\, e^{j\varphi(t)} \tag{1}$$

where $a(t)$ is the CPRI data in the intensity domain, and $\varphi(t)$ is the AMCC message in the phase domain. After interference, the output signal can be represented as

$$E_{out}(t) = \frac{1}{2}\Big(E_{in}(t) + E_{in}\big(t-T\big)\Big) \tag{2}$$

and, T is the symbol period of AMCC message. After square-law detection, the output can be represented as

$$E\left(\left|E_{out}(t)\right|^2\right) = \frac{1}{4}\left[a(t)^2 + a(t-T)^2 + 2a(t)\,a(t-T)\cos(\theta)\right] \tag{3}$$

where θ is the phase difference between two consecutive AMCC symbols. Due to the CPRI modulation, $a(t)$ is no longer a constant amplitude, which degrades the performance of AMCC. However, such performance degradation can be minimized by reducing the extinction ratio (ER) of CPRI modulation. Using a low pass filter after the photo detection also helps, since the data rate of AMCC message is much lower than CPRI data. Supposing $a(t)$ equals to $a(t-T)$, the proposed AMCC receiver will output '1', when θ is zero. While, it will output '0', when θ is π.

3. Experimental Setup

Fig. 3 shows the experimental setup for the transmission of CPRI signal with AMCC superimposition, which is fulfilled by proposed cascaded phase modulation. In the transmitter, an external cavity laser (ECL) is used as the optical carrier, which works at around 1552-nm wavelength. A dual-drive Mach-Zehnder modulator (DDMZM) is employed as the intensity modulator, which is biased at the quadrature point to provide linear modulation. The DDMZM is driven by a 10.1376-Gbps NRZ signal (CPRI option 8) with PRBS31, which is generated by an arbitrary waveform generator (AWG). After

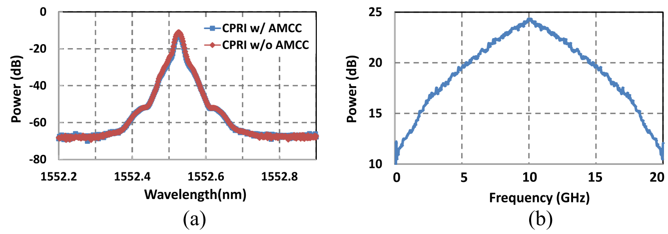

Fig. 4. (a) Optical spectra with and without an AMCC message, (b) electrical spectrum of CPRI signal, after the square law detection.

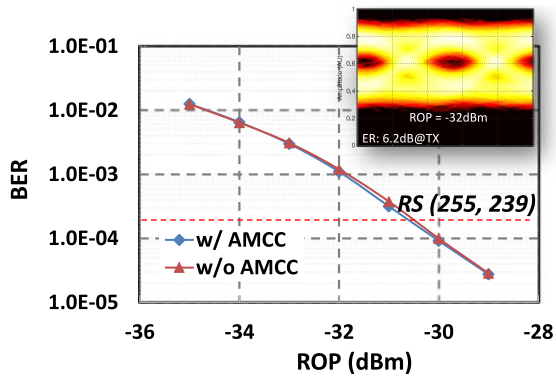

Fig. 5. Measured BER performance of CPRI signal with and without the AMCC message, under different received optical powers.

the intensity modulation, the output of DDMZM is fed into an additional phase modulator (PM), which is driven by a 500-kbps AMCC message. The AMCC message is first generated offline with PRBS7. Then, the AMCC message is differentially encoded and output by an AWG working at 500-kSa/s sampling rate. The optical distribution network (ODN) is composed of 20-km SSMF and a variable optical attenuator (VOA), which is used to emulate the optical power splitter in the passive optical network. In the receiver, signal is first split into two paths. One is fed into the CPRI receiver, while, the other is fed into the AMCC receiver. The CPRI receiver is simply composed of a photo detector (PD), and a digital sampling oscilloscope (DSO). CPRI data is recovered in the offline DSP by simple feed-forward equalization (FFE) and decision. In the AMCC receiver, the received signal is first split equally into two beams, with one beam delayed by an AMCC symbol period. Polarization controller (PC) is used to align the polarization states between the two beams. After interference, a photo detector (PD) is used to convert the optical signal into analog, and the analog signal is sampled by a low-speed DSO. In the offline DSP for AMCC message, a digital LPF is first applied before the clock and data recovery (CDR) and decision. The inset of Fig. 3 also shows the restored eye diagram by the AMCC receiver.

4. Results and Discussions

Firstly, the CPRI performance is investigated using proposed cascaded phase over-modulation scheme. Fig. 4(a) shows the optical spectra, both with and without an AMCC message. Fig. 4(b) shows the electrical spectrum of CPRI signal, after the square law detection. Since the AMCC message is modulated only on the phase of CPRI's carrier, and the square law detection removes the phase information. No difference is observed for the received CPRI signal after photo detection, both with or without an AMCC message.

The extinction ratio (ER) is defined as the power ratio between '1' and '0' levels in the eye diagram. A typical ER in the experiment is around 6 dB. However, the ER can be adjusted by the driving voltage and the bias current of DDMZM. Fig. 5 shows the measured BER performance of CPRI

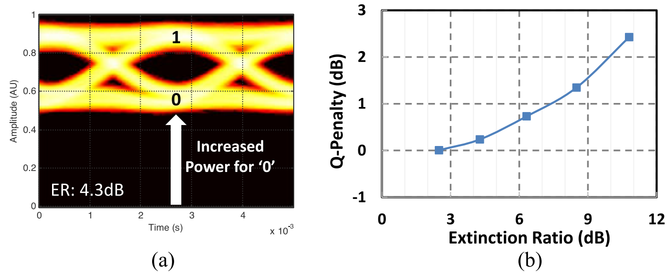

Fig. 6. (a) Eyediagram of CPRI signal at an ER of around 4.3 dB, (b) measured curve of Q-factor penalty versus ER of CPRI signal.

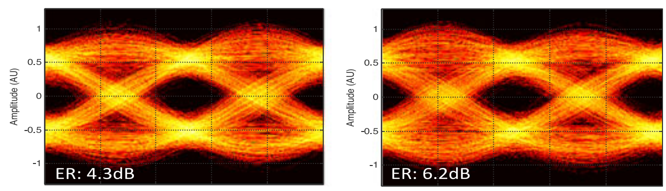

Fig. 7. Restored eyediagrams for AMCC message signal.

signal with and without an AMCC message, under different received optical powers (ROPs). The ER is set to 6.2 dB at the transmitter. Result shows that the AMCC message has negligible impact on the performance of CPRI signal. The minimum achievable ROP is around −30 dBm, using the hard-decision Reed Solomon FEC (RS255/239), with a BER limit of around 2×10^{-4}. If 0-dBm launch power is assumed, the system power budget should be 30 dB, which means at least 1:256 power splitting ratio (24-dB insertion loss) can be supported after transmission over 20-km SSMF. The inset of Fig. 5 also shows the received eyediagram at the corresponding received optical power.

Although the AMCC message shows little impact on the performance of CPRI signal, the ER of CPRI signal indeed affects the performance of AMCC, as mentioned in Equation (3). Fig. 6(a) shows the eyediagram of CPRI signal at an ER of around 4.3 dB. Since lower ER makes higher power for the '0' levels, it reduces the difference between $a(t)$ and $a(t - T)$, thus, increasing the output signal Q factor from the delay line interferometer. Fig. 6(b) shows the measured curve of Q-factor penalty versus ER of CPRI signal. Within 1-dB Q penalty is found for the AMCC message signal, when the ER of CPRI signal is less than 7 dB.

Fig. 7 shows the restored eyediagrams for AMCC message, corresponding to a CPRI signal extinction ratio of 4.3 dB and 6.2 dB, respectively. The eyediagrams in Fig. 7 are measured at a ROP of −32 dBm. A BER less than 1×10^{-5} is achieved for the AMCC message under both ERs, which is far below the FEC limit of 2×10^{-4}. The outperformance of AMCC message is mainly due to the much lower baud rate, compared to the CPRI signal. Thus, around −30 dBm receiver sensitivity can be achieved for the transmission of 10.1376-Gbps CPRI signal with AMCC over 20-km SSMF.

5. Conclusion

A cascaded phase over-modulation method was proposed for AMCC superimposition in a MFH WDM-PON architecture. DBPSK was employed as the modulation format, and demodulation was done via a DLI. The implementation was simple and thought to be cost effective. Different from the baseband intensity over-modulation and the RF pilot-tone scheme, the proposed cascaded phase over-modulation shows negligible impact on CPRI performance. Within 1-dB Q penalty is found for the AMCC message signal, when the ER of CPRI signal is less than 7 dB. Around −30 dBm receiver sensitivity can be achieved by 10.1376-Gbps NRZ transmission with CPRI option 8, with no penalty compared to the AMCC-free transmission.

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