Latest Advancement in Ultra-Fast Optical Communication

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Abstract— The currently developed high spectral efficiency (SE) and high-baud-rate signal transmission are all based on digital coherent optical communications and digital signal processing (DSP). DSP make simpler the capture of advanced modulation formats and also enables the major electrical and optical impairments to be processed and compensated in the digital domain, at the transmitter or receiver side. In this paper, we summarize the research progress on high-speed signal generation and detection and also show the progress on DSP for high-speed signal detection. We also report the latest progress on multi-core and multi-mode multiplexing.

Key words: Optical Communication

I. Introduction

The rapidly increasing data traffic nowadays has aroused urgent demands for higher spectral efficiency (SE), higher speed and higher capacity in optical communication systems [1–37]. To further improve the transmission speed and system capacity, researchers have proposed approaches concerning multi-level modulation formats and various multiplexing techniques, including frequency-division multiplexing (FDM) [5,6], time-division multiplexing (TDM) [7–11], polarization-division multiplexing (PDM) and spatial-division multiplexing (SDM) [25–37]. Recently, 100 G based on coherent detection is being widely deployed. 400 G or 1 T per channel on a single optical carrier is an attractive solution in future networks, since it can reduce the complexity and cost of the transmitter and receiver, pushing the boundaries of opto-electronic devices and modules [1–11]. It is usually the optimal scheme by utilizing the highest feasible electronic multiplexing rates with the lowest possible number of subcarriers, since optical modules typically dominate transponder costs [6–11]. Two viable options for high baud rate signal generation are always considered, one is based on FDM [5,6], and the other on TDM [7– 11]. For the FDM method, the baud rates of OFDM signals generated by electrical methods are restricted by the processing speed of electrical devices, such as the digital to analog converter (DAC). Recently, OFDM with high-order modulation formats and high baud rates has been widely investigated, using all-optical OFDM signal generation [5]. As reported in [5], a 26 Tb/s line-rate super channel based on an all-optical OFDM has been demonstrated using 16QAM and coherent detection. To generate the high-baudrate signals, a multiple spectral slices synthesis multiplexing technique is also recently proposed based on the transmitter side digital signal processing (DSP) [6]. However, it requires complex DSP operations for spectral slices operation and baseband down conversions. TDM is another effective method for high-baud-rate signal generation, and it can be divided into two major categories, Electrical-TDM (ETDM) [7–11] and all-Optical TDM (all-OTDM) [12–18]. As reported in [7–11], single-wavelength all-ETDM 107- GBaud and 110-GBaud signals are successfully generated and transmitted as the highest ETDM baud rates. The ETDM signals at these high symbol rates show considerable implementation penalties due to electro-optical bandwidth limitations of the multiplexer and optical modulator [7–11]. Optical TDM, on the other hand, based on much lower speed optical transmitters, relaxes the bandwidth requirement of each electrical/optical device [12–18]. It is worth noting that the aforementioned high SE and highbaud-rate signal transmissions are all based on digital coherent optical communications and DSP, which has been proved to be a great success in the last decade [1–18]. The most interesting thing is that coherent optical communication itself is not a new technology, and people have already made the research since 40 years ago [19–22]. The early stage of the work is not accepted by the industry due to the complexity of phase, frequency and polarization tracking requirements. Nowadays, with the appearance of high speed DSP devices, it has revolutionized the optical communication for high speed, high capacity and long-distance transmission after a long stagnation during the time of intensity modulation and direct detection (IM/DD). DSP for a high speed optical signal becomes possible due to the development and maturation of high speed DAC, analog to digital converter (ADC) and application specific integrated circuits (ASIC), which moves the complexity of phase, frequency and polarization tracking into the digital domain using different algorithms [20,21]. Therefore, it simplifies the reception of advanced modulation formats (i.e., QPSK, 16QAM and 64QAM so on) and also enables the major electrical and optical impairments (bandwidth limitation, chromatic dispersion, polarization mode dispersion, and fiber nonlinear impairments) to be processed and compensated for in the digital domain, at the transmitter or receiver side. Recently, the DSP based coherent optical communication system has become one of the most active research topics, and it is a promising technology for future high SE and high speed transmission. On the other hand, multiplexing techniques including Wavelength Division Multiplexing (WDM), PDM, TDM, and Spatial Division Multiplexing (SDM) methods, such as Mode Division Multiplexing (MDM), multi-core fiber multiplexing and Laguerre-Gaussian (LG) beam carrying Orbital Angular Momentum (OAM) modes, are also considered as promising solutions to improve the capacity and SE further .

II. High-speed signal generation & detection

Fig. 1 shows two options for high-baud-rate signal generation, one is based on FDM [5,6], and the other is based on TDM [7–11]. The FDM method includes the recently reported all-optical OFDM and multiple spectral slices synthesis multiplexing technique. TDM is another effective method for high-baud-rate signal generation, which is divided into two major categories, ETDM or allOTDM [7–18]. In this section, we will present the recent progress on high-baud-rate signal generation based on the ETDM and OTDM methods.

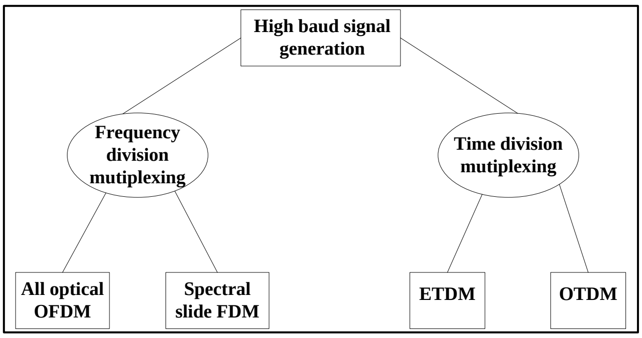

Fig. 1: High-baud-rate signal generation by frequency-division or time-division multiplexing methods reported in previous works.

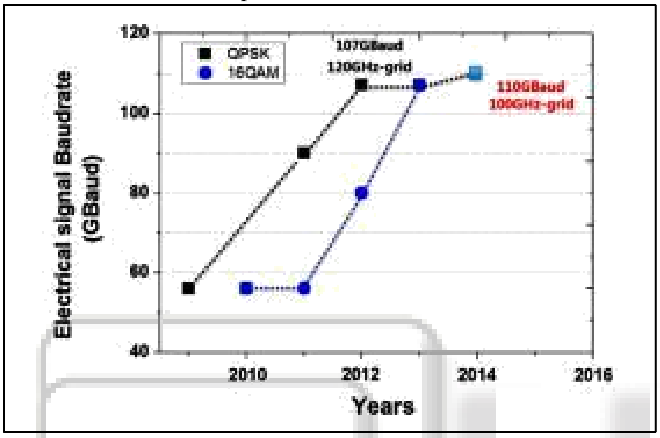

Fig. 2: The electrical signal symbol rate reported based on ETDM method reported in recent years [10].

Fig. 2 shows the electrical signal symbol rate reported based on the ETDM method used in the recent years. Our recent experimental demonstration of the coherent transmission system, with a high symbol rate using up to 110-GBaud PDM-QPSK signals on a 100 GHz grid, reported in 2014 [10], is still among the top records. In our work, the single channel bandwidth is suppressed by using the super-Nyquist-filtering technology on a 100-GHz optical grid. The 100-GHz-grid, 20 channels single-carrier 440-Gb/s super-Nyquist 9-QAM-like signals are successfully transmitted over a 3600- km Ultra-Large effective-Area Fiber (ULAF) with a high net SE of 4 b/s/Hz (after excluding the 7% hard-decision FEC overhead). Experimental results demonstrate the high filtering-tolerant performance of the 9-QAM-like super-Nyquist signal. In this work, 10 channels 440-Gb/s signals are successfully transmitted over 3000- km ULAF and 10 cascaded ROADMs with 100-GHz-grid based on the single-carrier ETDM 110-GBaud QPSK. A real-time oscilloscope at 160-GSa/s sampling rate with 65-GHz bandwidth is used for the coherent detection of 110-GBaud PDM-QPSK. Multi-modulus equalizations are used in the receiver side DSP [38–44].

III. DIGITAL SIGNAL PROCESSING AT THE RECEIVER-SIDE

As we mentioned above, the high SE and high baud rate signal processing requires an advanced DSP. In this section, we present the recent progress in DSPs in digital coherent communication systems. Fig. 3 shows the typical digital coherent receiver with a DSP for signal equalization and recovery [20,21]. The optical signal is coherently detected by a polarization and phase diverse hybrid with a local oscillator, which converts the optical signals into electrical signals with both in-phase and quadrature (I/Q) signals in the X and Y polarizations after the balanced photo-detectors. The electrical signals after the PDs are then sampled and digitized by the ADCs and then processed by the DSP as shown in Fig. 8. Generally, the DSP at the receiver side is divided into several subsystems or sub-units, and each of them is applied to handle one specific impairment in the transmission link and transponders.

Ideally, the I and Q signals should be orthogonal to each other. However, in practical systems, the I/Q signals are not orthogonal to each other due to the imbalance between these two components. These imbalances can be caused by bias drift, device defects of modulators and PDs or power differences after the drivers. In order to properly uncover the signals, I/Q imbalance compensation should be applied first to the digitized signals. This process can be done by the Gram–Schmidt Orthogonalization Process (GSOP) algorithm [22]. The GSOP creates a set of mutually orthogonal vectors, taking the first vector as a reference against which all subsequent vectors are orthogonalized [20]. After that, the signals are then processed by the linear signal process to electrically compensate for the Chromatic Dispersion (CD). CD compensation is realized at the receiver side in the frequency-domain or time domain [20,21]. In the time-domain, the required filter coefficients for the FIR can be obtained by the fiber CD transfer function using either the frequency-domain truncation method or the time domain truncation method [21]. For short-distances, the time-domain method shows less complexity, however, for long-haul transmission (over 1000 km), and Frequency-Domain Equalization (FDE) based on Fast Fourier Transform shows less computation complexity.

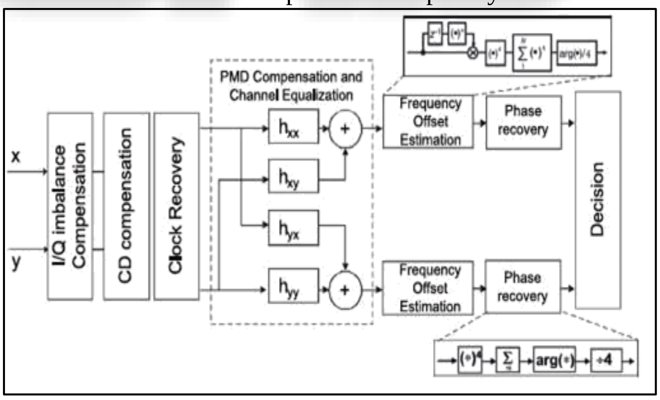

Fig. 3: Typical digital signal processing at the receiver-side for coherent optical communication.

IV. DIGITAL SIGNAL PROCESSING AT THE TRANSMITTER-SIDE

With the advancement of ultra speed DACs, digital to analog converter has become a well accepted and most efficient technique for signal generation. It has the benefits of a much simple configuration and flexible signal generation ability, and has drawn a great pact of interest in recent times. DAC for signal production also provides the capability of Software-Defined Optics (SDO) with random waveform generation. Consequently, it can be utilized for signal modulation formats software switch. Additionally, pre-compensation based on the DSP at the transmitter side further enhance the system performance.

V. Conclusions

We have reviewed the current advancement in high-speed optical transmission with rational recognition of DSPs. The trend for bit rate per channel is from 100 G to 400 G and even higher. 100 G per channel is widely deployed, and 400 G or 1 T is a hot research topic. Using advanced DSPs can greatly improve the signal performance and spectral efficiency, and reduce the time consumption for signal procession. Using multi-core and multi-level multiplexing technologies can greatly increase the system capacity.

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