Upcoming Challenges in Signal Processing for Optical Fiber Communications

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Abstract *We discuss upcoming challenges in signal processing for future optical communication systems including coherent transceivers for datacenter interconnects, metro/core, edge and access networks, as well as for continuous-variable quantum key distribution. ©2023 The Authors*

Introduction

Optimized signal processing schemes are essential building blocks of efficient high-performance fiber-optic communication systems. For more than three decades, wavelength-division multiplexed (WDM) optical networks have been the main driver for the development of high-speed optical transceivers, which allow to operate a fiber-optic links at capacities which approach their Shannon limit. However, with the proclaimed ”End of Moore's Law” in sight[1], new challenges are upcoming on the quest to reduce the energy consumption per bit and the cost per bit. In comparison to WDM networks, fiber-optic edge and access networks, which aggregate the data traffic have significantly stronger low-cost requirements, however, they also need to be continuously updated in order to be able to carry the growing amounts of data traffic. This brings new and still unsolved challenges for the transceiver design. Finally, first fiber-optic quantum key distribution (QKD) networks are being installed which promise fundamentally secure communication. They require a redesign of the conventional signal processing schemes.

Coherent Transceivers for DCI and Metro/Core

Digital coherent optical transceivers combining photonic integrated circuits with digital signal processing continue to drive down the cost per bit and the energy per bit of high-capacity datacenter interconnects (DCI) and well as DWDM metro- and core networks. During the first decade after their market introduction, around 2007, significant research and development efforts from industry and academia went into optimizing optical, analog-electronic, and digital signal processing circuits and algorithms[2],[3]. At scientific conferences like ECOC and OFC, novel coherent transceiver concepts and algorithms were discussed in great detail and advanced algorithms like fiber nonlinearity compensation[4] and probabilistic shaping[5] were introduced in order to close the gap to the Shannon limit. At the beginning of their second decade, signal processing schemes for coherent transceivers matured and, as a consequence, the number of scientific papers discussing coherent transceivers architectures and related DSP algorithms slowed down. Moreover, with the 400G-ZR implementation agreement, multi-vendor interoperability is realized[6]. At the same time, significant improvements of key performance metrics such as data rate, cost, power consumption, and footprint were obtained by utilizing increasing integration densities both in CMOS and in photonic integrated circuits. Earlier this year, transceiver manufacturers demonstrated novel coherent transceivers at symbol rates in the order of 138 GBd supporting capacities beyond 1 Tbit/s on a single wavelength[7]. Within the industry, it is expected that the symbol rate can even increased to 200 GBd with future CMOS nodes, but there is skepticism, whether a further increase of symbol rates is possible. Moreover, it is expected that the reductions in power consumption obtained from moving to the next CMOS node will significantly slow down with future CMOS technology nodes. Just before their third decade starting around 2027, coherent optical transceivers therefore face the challenge that the required energy per bit does not scale according to the demands. Possible pathways to overcome this challenge could be new coherent transceiver architectures, in which parts of the DSP functionalities such as polarization demultiplexing or the carrier recovery are moved to the analog electronic domain or the optical domain[8]. Another pathway could be the co-integration of arrays of multiple transceivers, driven from a single optical comb source, which is replacing multiple lasers[9].

Coherent Transceivers for Edge and Access

The network edge, where traffic from radio access and end users like homes, businesses, and factories is aggregated in an optical point-to-multipoint topology, is emerging as a new application arena for coherent transceivers imposing new challenges in terms of signal processing. One approach pushed forward by the Open XR Forum is based on frequency-division multiple access (FDMA) of digitally generated subcarriers which can be flexibly distributed to multiple users[10]. With respect to both power consumption and cost, in particular at the end user side, the laser becomes a key component since it needs to be frequency stable, have low phase noise, and it has to be precisely tunable on a fine frequency grid.

Today, passive optical networks (PONs) based on time-division multiple access (TDMA), allowing dynamic bandwidth allocation on a sub-millisecond timescale, are the preferred solution in access networks[11]. In order to meet the stringent cost requirements in access, PON transceivers are usually based on uncooled lasers whose emission wavelength can vary over several nanometers. While the recently standardized 50-Gbit/s PON standard is still based on intensity modulation and direct detection, system vendors are currently exploring options for coherent transceivers in PONs running at 200 Gbit/s or more[12]. Thereby, a key challenge are again the lasers at the user-ends, which have to match the wavelength of the laser at the central node. We recently demonstrated a novel colorless coherent PON architecture based a frequency comb source in order to overcome this wavelength matching challenge, while still allowing for uncooled lasers at the users[13]. Another upcoming challenge in coherent PONs is the optimization of DSP algorithms for burst-mode operation[14].

Quantum-Key Distribution

Yet another upcoming challenge for signal processing in optical fiber communications arises in the context of QKD, in particular continuous-variable (CV) QKD[15],[16]. An important benefit of CV-QKD systems over their discrete-variable counterparts is that components from conventional coherent transceivers can be reused to a large extent. However, the signal-to-noise ratio of these systems can be as low as -20 dB, far below the region used in conventional optical communication systems. The DSP algortihms for coherent receivers therefore need to be revisited, in particular, timing, polarization, and carrier recovery algorithms[17].

Conclusions

Optical, analog-electronic, and digital signal processing for fiber communications has been a key enabler for capacity-approaching coherent transceivers for DCI and metro/core networks. New challenges arise in scaling the CMOS technology and in the aggregation network as well as in quantum-secure communication.

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