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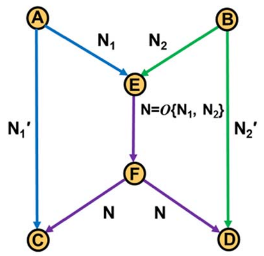
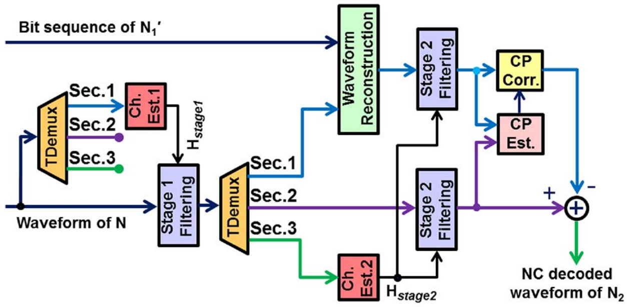


An illustration of an OPNC scenario



Coherent Common-Channel OPNC - the network decoding process

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Abstract: Network coding is a revolutionary technique that can enhance network throughput and protection. This paper introduces optical physical-layer network coding (OPNC) and the recent development of OPNC, with focused discussion on "common-channel" OPNC that can efficiently utilize network resources. It also describes the challenges ahead of OPNC, including incorporating more than two signals for OPNC; circumventing the higher signal processing complexity when higher order modulations are adopted; and exploiting OPNC in more sophisticated multichannel systems.

Index Terms: Fiber optics communications, optical physical-layer network coding, packet-switched networks.

1. Introduction

For many years, we have been enjoying the many-fold increase in fiber capacity that was made possible by two approaches. The first is to simply increase the number of channels per multiplexing dimension, e.g., larger number of wavelength channels or shorter symbol period per unit time. The second approach is to increase the spectral efficiency. This includes exploiting multiple multiplexing dimensions simultaneously (e.g., time-division, wavelength-division, plus polarization-division multiplexing), advanced modulation formats [1], super channel [2], and elastic optical networks [3]. Recently, space-division multiplexing, using multicore fibers and few-mode fibers [4], and orbital angular momentum multiplexing [5] have been demonstrated. By now it seems that almost all possible dimensions in multiplexing have been exploited and we are approaching the fiber "capacity crunch" caused by various effects, including nonlinear optical effects, Shannon limits, fiber fuse and optical amplification/filter bandwidth [6], [7]. Innovative technologies are needed to further improve network efficiency and functionality. Network coding (NC) has been proposed, explored and developed for various applications, including improving network efficiency [8] and security [9]. In particular, NC implemented in the physical layer can boost network throughput significantly [10]. The application and implementation of NC in optical-layer to provide protection of multicast traffic was proposed and investigated in [11]. An optical

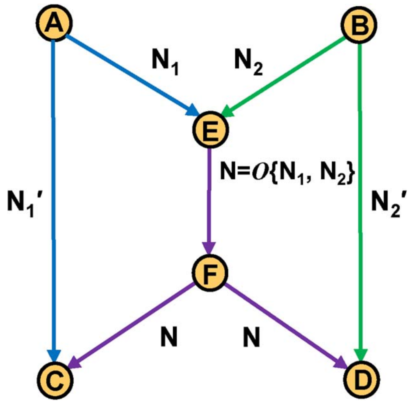


Fig. 1. OPNC scenario.

encoder for NC was first experimentally demonstrated in [12]. Not surprisingly, it was achieved by using a proposed optical XOR gate that mimics the electronic counterparts to achieve the NC functionality. Later optical physical-layer network coding (OPNC) was proposed and experimentally demonstrated with various features, including boosting network efficiency [13], reducing resources needed for network protection [14], and increasing system throughput [15]. Recently, common-channel OPNC (CC-OPNC) was demonstrated for the first time [16], wherein the constituent signal components embedded in the network-coded signal are carried on a common channel (i.e., they occupy the same signal space and cannot be separated by conventional means of demultiplexing). In this paper, based on the discussion in [17], we first describe the concept of OPNC and then present the recent development of OPNC. We also discuss the challenges ahead for OPNC and possible ways to help alleviate some of the problems that lead to "capacity crunch."

2. OPNC Basic Structure

To illustrate the basic concept of OPNC, one application scenario is shown in Fig. 1. Nodes A and B want to broadcast packets N_1 and N_2 to nodes C and D, respectively. Node A transmits signals containing packet N_1 on both links A–E and A–C. Likewise, node B transmits signals containing packet N_2 on links B–E and B–D. Conventionally, signals N_1 and N_2 will need to occupy two separate channels on link E–F. However, with OPNC, node E will network-code signals N_1 and N_2 to form signal $N = O\{N_1, N_2\}$ (e.g., using an XOR gate or passive signal combiner) for forwarding to nodes C and D. At node C, the bits of packet N_1 can be obtained from the received signal N_1' on link A–C. Then node C can recover packet N_2 from signal N with the help of N_1'. Similarly, at node D, N_1 can be recovered from signal N and the information of N_2' from link B–D. In this way, a channel in link E–F can be saved.

3. OPNC Demonstrations

Several schemes have been proposed to implement OPNC in recent years. Some schemes use more sophisticated optical NC encoder like optical XOR gate [12], [18]. In this way, the corresponding NC decoder can be implemented at the receiver in a simple way. On the other hand, the NC encoder can be implemented by a polarization beam combiner [14], [15] or an optical coupler [13], [16] that combines N_1 and N_2 at node E, thus greatly reducing the NC encoding complexity. However, for this approach the NC decoder at the receiver would be more complicated.

3.1. OPNC Based on All-Optical Logic

OPNC can be realized by all-optical XOR logic gate. NC encoders have been demonstrated for NRZ-OOK signals based on cross-phase modulation and cross-gain modulation in

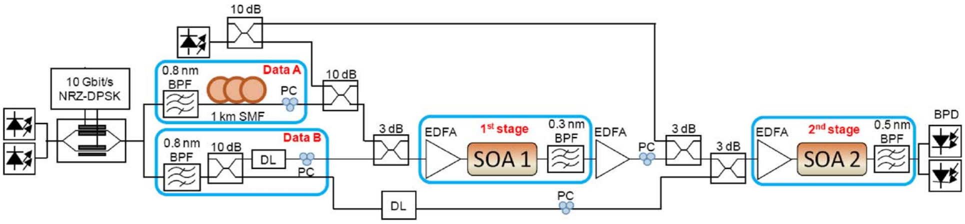


Fig. 2. OPNC based on optical XOR gate. BPF: band-pass filter; DL: delay line; EDFA: erbium-doped fiber amplifier; PC: polarization controller; SOA: semiconductor optical amplifier; BPD: balanced photodetector (reproduced from [12]).

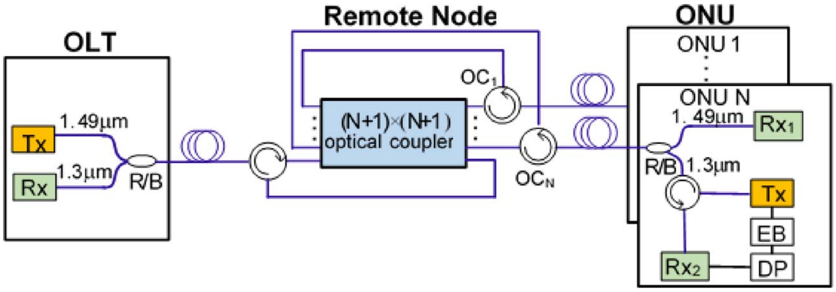


Fig. 3. OPNC based on wavelength division multiplexing. OC: optical circulator; R/B: red/blue coupler; Tx: transmitter; Rx: receiver; EB: electrical buffer; DP: decoding process (reproduced from [13]).

semiconductor optical amplifiers (SOA) [12], as well as for DPSK signals based on four-wave mixing (FWM) in SOA [18]. Various optical XOR schemes have been demonstrated and can serve the purpose [19]. Fig. 2 shows the implementation of the XOR gate in [18] for the DPSK signal. In SOA1, FWM between Data A, Data B and the continuous wave generates new frequency components (idlers). The phases of two of the newly generated components carry the result of XOR operation on Data A and Data B, and can serve as the network-coded signal. For these schemes using optical XOR gate, the symbols of the signals N_1 and N_2 need to be precisely aligned in the time domain. For network decoding, take network decoding N_2 from N and N_1' for example, the bits of N_2 can be recovered by logical XOR operation on the bits of N and N_1'. With reference to Fig. 1, the network-coded signal after the XOR gate has the same power level as the regular signal and yet two bit streams are embedded within the network-coded signal at the same time. This can increase network throughput without increasing signal power, alleviating nonlinear optical effects and the fiber fuse problem.

3.2. OPNC Based on Wavelength Division Multiplexing

For OPNC, the exact symbol-level alignment between N_1 and N_2 can be relaxed if the network coding and decoding are realized by simple power summation and waveform subtraction, respectively, instead of logical XOR operation. An OPNC scheme based on combining the NRZ-OOK signals N_1 and N_2 with a coupler was proposed in [13] to support inter-ONU communications (IOCs) in passive optical networks (PONs), as shown in Fig. 3. Two IOC signals are generated by the transmitters (Tx) at two ONUs and are forwarded to the remote node coupler. The combined IOC signal $(N = N_1 + N_2)$ is broadcasted to the two ONUs, filtered by an R/B filter, and detected by the Rx_2 in each ONU. Take network decoding N_2 from N for example, N_2 can be derived by subtracting the locally buffered N_1 from the detected combined signal N. The center wavelengths of N_1 and N_2 need to be sufficiently different to preserve the linear relationship between the network-coded signal N and the signals N_1 and N_2 in direct detection.

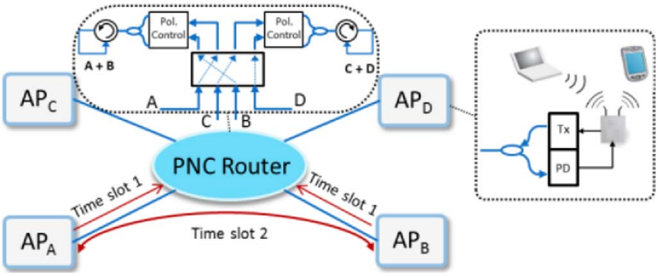


Fig. 4. OPNC based on polarization multiplexing (reproduced from [15]).

3.3. OPNC Based on Polarization Multiplexing

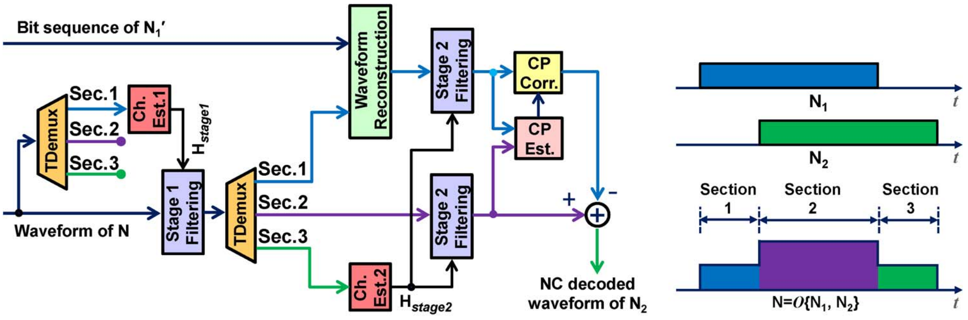
Another way to preserve the linear relationship in direct detection is to combine N_1 and N_2 through polarization multiplexing. When the center wavelengths of N_1 and N_2 are exactly the same, the orthogonality between the signal components N_1 and N_2 in the network-coded signal N is maintained during transmission. After direct detection the electrical waveform of N is the addition of those of N_1 and N_2. The corresponding network decoding has been successfully demonstrated for NRZ-OOK signals [14] and OFDM signals [15]. Fig. 4 shows the system architecture for OPNC over fiber-wireless proposed in [15]. Inside the PNC router, signals N_1 from AP_A and N_2 from AP_B are combined by polarization multiplexing and the composite signal N is transmitted back to AP_A and AP_B for direct detection, without polarization demultiplexing. For network decoding N_2 from N, the waveform of N_1 is subtracted from that of N in the digital domain.

3.4. Coherent CC-OPNC

For OPNC schemes that use multiplexing (i.e., methods 3.2 and 3.3 above) to implement network coding, the signal components of N_1 and N_2 in the network-coded signal N can be obtained by demultiplexing. To fully utilize network resources, CC-OPNC for PM-DQPSK signals was proposed [16]. Each of N_1 and N_2 exploits polarization-multiplexing for its own signal (i.e., each of them uses both polarizations) and both N_1 and N_2 are carried on the same wavelength. After network coding, the signal components of N_1 and N_2 in N cannot be separated by means of demultiplexing. The linear relationship is preserved by coherent detection.

CC-OPNC can efficiently utilize fiber resources by saving multiplexing dimensions for further expansion in network capacity. However, this does not come for free, as separating the waveforms of N_1 and N_2 from that of N can be very challenging. One of the two major tasks in NC decoding for CC-OPNC is to precisely reconstruct the waveform of N_1 from its bit sequence (decoded from N_1' in Fig. 1). Due to inter-symbol interference (ISI) and inter-polarization interference (IPI), the waveform of N_1 depends not only on the current symbol in the current polarization, but also on adjacent symbols and symbols in the other polarization. Therefore, before waveform reconstruction, we first filter the waveform of N [stage 1 filtering in Fig. 5(a)] to minimize the ISI and IPI in the signal component of N_1 embedded in N, and the waveform of N_1 can be conveniently reconstructed, e.g. with a lookup table (LUT). We adopt offset arrangement in time domain for N_1 and N_2 [shown in Fig. 5(b)], such that the channel characteristic of the traverse paths of N_1 and N_2 can be derived from N in Sections 1 and 3, respectively, for channel estimators (Ch. Est.1 and Ch. Est.2).

The other major task is carrier phase (CP) estimation for the reconstructed waveform of N_1 embedded in Section 2 of the waveform of N, because it is interfered by the other signal component of N_2. We can utilize the property that PM-DQPSK signal has constant modulus at sampling point after it is equalized and polarization demultiplexed. That is, we use this property to evaluate the quality of the signal that is network-decoded with assumed carrier phase for the reconstructed N_1. Since the signal components N_1 and N_2 have passed through different links and thus different channel characteristics, another filtering stage [stage 2 filtering in Fig. 5(a)] is used to minimize the ISI and IPI in the signal component of N_2 embedded in N. By subtracting



(a) (b)

Fig. 5. Coherent CC-OPNC. (a) Network decoding process. (b) Two packets before and after OPNC.

the waveform of reconstructed N_1 after CP correction from that of N at the output of stage 2 filtering, N_2 in Section 2 can be extracted.

4. Other Applications of OPNC in Optical Networks

Other investigations related to NC in optical networks have also been reported recently. A three-input optical XOR gate that also provides simultaneous multichannel wavelength multicasting for NRZ-DPSK channels was discussed and experimentally demonstrated in [20]. The device may be useful for implementing multichannel OPNC. Optical multicast protection using NC has been intensively studied. In [21], some enabling technologies to support NC-based protection were discussed. The aforementioned demonstration of OPNC for inter-ONU communications in PON [13] was for single optical-line-terminal (OLT) case. In [22], a flexible and efficient software defined PON with multi-OLT using NC was proposed. Other than optical wireline applications, NC has also been investigated for free space optical (FSO) communication systems and a two-way, single-relay, network-coded FSO system was proposed [23].

5. Discussions

We mentioned that nonlinear effects coupled with the Shannon limit and other factors determine fiber capacity. To achieve higher capacity or longer transmission reach over a single fiber link, various mitigation methods to combat nonlinear impairments, such as digital or optical signal processing, special coding methods, and multi-core fibers, have been proposed. Some mitigation methods, like forward error correction, consume additional bits or bandwidth, and thus, system overhead is increased. Those methods may not be able to solve the “capacity crunch” problem when the system is scaled up to fully utilize the available optical bandwidth. Further studies are needed to evaluate the tradeoffs. On the other hand, NC can improve network throughput, though only applicable to certain types of networks. Optical implementation of NC still requires further improvement. For the schemes using optical XOR gate, it would be desirable to reduce the power penalty induced by the XOR gate and to alleviate the requirement of bit synchronization of the two channels. For CC-OPNC, it is important to reduce the implementation complexity of the waveform reconstruction and CP estimation in network decoding. It is also desirable if the percentages of sections 1 and 3 can be reduced to further increase the network efficiency with NC.

There are still challenges ahead for OPNC, including 1) how to incorporate more than two signals for OPNC to further increase its gain; 2) how to circumvent the higher signal processing complexity when higher-order modulations are adopted; and 3) how to exploit OPNC in more sophisticated multi-channel systems.

6. Conclusion

We have presented the recent development of OPNC and its applications. In particular, CC-OPNC can reduce the number of channels used, since the signals being multiplexed are in the same signal space, thanks to the use of network coding. We posit that OPNC is a promising scheme to fully utilize network resources and to circumvent the optical power limit that hinders a further increase in network capacity.

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