Optical Physical-Layer Network Coding – another dimension to increase network capacity?

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Abstract: Network coding is a revolutionary technique that can enhance network throughput and protection. This presentation introduces optical physical-layer network coding (OPNC), focusing on "common-channel" OPNC that can fully utilize network resources.
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I. INTRODUCTION

Record-breaking demonstrations of high capacity optical transport networks have taken the center stage of optical communications conferences for many years. The many-fold increase in capacity was enabled mainly by two approaches. The first is to increase the number of channels per multiplexing dimension and/or the number of multiplexing dimensions, e.g. TDM, WDM, and polarization-division multiplexing. Recently space-division multiplexing, using multicore fibers and few-mode fibers [1], and orbital angular momentum multiplexing [2] have been demonstrated. The second is to increase the spectral efficiency by, for instance, advanced modulation formats [3], super channel [4], and elastic optical networks [5]. By now it seems that almost all possible dimensions in multiplexing have been exploited and we are approaching the fiber "capacity crunch", caused by 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]. Especially, NC implemented in the physical layer can boost network throughput significantly [10]. The first deployment of NC concept in optical domain was demonstrated in [11], and not surprisingly, it was achieved by using optical XOR gates that mimic the electronic counter parts to achieve the NC functionality. Later optical physical-layer network coding (OPNC) was proposed and demonstrated with various features, including boosting network efficiency [12], reducing resources needed for network protection [13], and increasing system throughput [14]. Recently common-channel OPNC (CC-OPNC) was demonstrated [15], 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). This paper explains how the extra capacity is extracted by OPNC and how it may help remove or bypass some of the aforementioned road blocks that lead to "capacity crunch".

Fig. 1 illustrates one application scenario of OPNC. 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 the signals N_1 and N_2, e.g. by an XOR gate or passive signal combiner, into a new signal N, and forward signal N to nodes C and D. At node C, packet N_1 can be obtained from the received signal N_1' on link A-C. Signal N_1' differs from signal N_1 because they undergo different transmission conditions in the paths A-C and A-E-F-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 from B-D link. In this way a channel in link E-F can be saved.

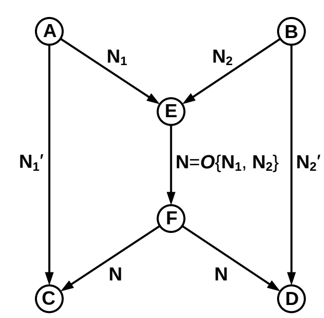

Fig. 1.An illustration of a network coding scenario

II. OPTICAL PNC SCHEMES

A. Optical PNC based on all-optical logic

Optical PNC can be realized by all-optical XOR logic gate. It has been demonstrated for NRZ-OOK signals based on XPM and XGM in SOA [11], as well as for DPSK signals based on FWM in SOA [16]. 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 increases network capacity without increasing signal power, alleviating nonlinear optical effects and the fiber fuse problem.

B. Optical PNC based on wavelength division multiplexing

For optical PNC, the exact symbol-level alignment between N_1 and N_2 can be relaxed if the network decoding is realized by waveform subtraction instead of logical XOR operation. An optical PNC scheme based on combing the NRZ-OOK signals N_1 and N_2 with a coupler was proposed in [12]. 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. Network decoding N_2 from N and N_1' can be realized by subtracting the waveform of N_1 from that of N in the analog domain.

C. Optical PNC 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 [13][14]. 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 [13] and OFDM signals [14].

D. Coherent common-channel optical PNC

For optical PNC schemes based on multiplexing (i.e., methods *B* and *C* above), the signal components of N_1 and N_2 in the network-coded signal N can also be obtained by demultiplexing. To fully utilize network resources, CC-OPNC for PM-DQPSK signals was proposed [15]. Each of N_1 and N_2 exploits polarization-multiplexing for its own signal (i.e., each of them uses both polarizations). Furthermore, 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.

For CC-OPNC, a major challenge in network decoding N_2 from N and N_1' (which carries the same information as N_1) is estimating the carrier phase of the signal component N_1 embedded in N. The estimation difficulty arises from that, within N, the signal component N_1 is interfered by the other signal component N_2. The property that equalized and polarization-demultiplexed DQPSK signal has constant amplitude at sampling time can be utilized to circumvent the difficulty [15]. In particular, the carrier phase of the signal component of N_1 can be estimated as the phase that minimizes the moving sum of the squared error in the network-decoded signal [15].

III. SUMMARY

We have presented the recent development of OPNC and its applications. We posit that OPNC is a promising scheme to fully utilize network resources and to circumvent the optical power limit that hinders further increase in network capacity. In particular, CC-OPNC is shown to reduce the number of channels used as two signals are in the same signal space. There are still many challenges ahead for OPNC, including 1) how to incorporate more than two signals on a common channel; 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. This project is supported in part by the University Grants Committee, Hong Kong SAR, under Project AoE/E-02/08.

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