Efficient, Fault-Tolerant All-Optical Multicast Networks via Network Coding

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Abstract: Network coding, an emerging field of research, provides a means to create efficient all-optical multicast networks that feature hitless reconfiguration. Here a photonic bitwise exclusive-OR hardware element supplies the key enabling functionality.

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1. Introduction

Network coding, a research innovation that dates from the year 2000 [1-5], shows promise of improving network throughput and robustness. Unlike nodes in traditional data network paradigms, the network coding node does not merely forward information. Instead, the network coding node sends out a data stream that may be a complex function of previously received data. This temporal and spatial spreading of information is key to network coding's unique capability to improve throughput and robustness.

For example, a network coding router may calculate a linear combination of multiple packets that were received and stored previously, and as a result of this calculation it may create one or more new packets to be forwarded to adjoining nodes. This is illustrated in Figure 1, where the input packets at a network coding router (color-coded here with red, purple, and green) may result in output packets that differ from the input packets in bit pattern, size, and number (this difference is signified by different colors for the output packets: blue, yellow, and white).

Figure 1 Information processing at a generalized network coding node (left) and a specific realization of such a node in the form of a photonic (or electronic) element that produces the exclusive-OR of two or more bit streams (right)

The network coding node at the recipient's location may then need to gather the data streams from multiple adjoining nodes, and calculate a linear combination of these streams, to recover the data intended for the recipient.

2. Network Coding for All-Optical Multicast Networks

Previous research on network coding assumed that arbitrarily complex data manipulation calculations can be executed at each node to achieve the benefits of the paradigm. In a practical sense, such schemes may apply only to electronic networks because only the electronic domain supports such elaborate calculations.

However, all-optical networks, where we seek to avoid O/E/O conversions and keep the data in the photonic domain, can begin to reap the benefits of network coding with the development of a photonic bitwise exclusive-OR (XOR) hardware element. Such an element would take two or more photonic bit streams (with bit transitions aligned) as input, and produce as its output a single photonic bit stream that is the logical XOR of the input streams. See Figure 1. Ideally, this would be accomplished without O/E/O conversions. However, even if such a device violates the all-optical paradigm by executing O/E/O conversions, the other advantages in Section 3 still pertain.

Using this basic XOR functionality, we can produce the information spreading that can benefit the performance and efficiency of all-optical multicast networks.

3. Robustness and Efficiency Examples

Consider the network examples shown in Figure 2. In Figure 2(a), nodes W and E wish to multicast their data streams to nodes A and B. To protect these data streams at node A from a single-link failure in a conventional hitless[1] tail-end switching scheme, the node in the middle would repeat, in two separate data channels, the W stream and the E stream, sending these redundant streams simultaneously to node A. Likewise for protecting node B.

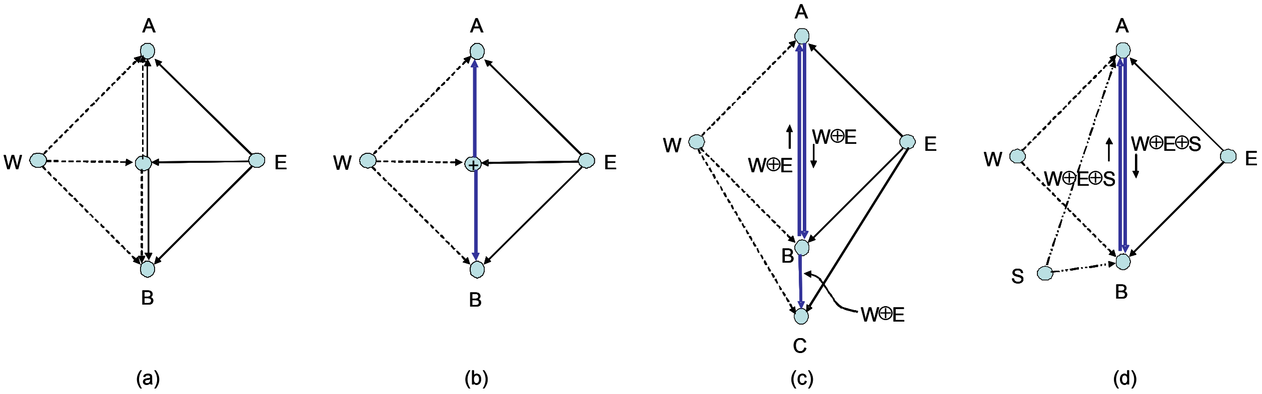

Figure 2 (a) Conventional protection. (b) Network coding protection (c) Network coding protection no central node and a third receiver node, and (d) Network coding protection with third transmitter node.

Now consider the network coding solution shown in Figure (b). Here the middle node performs a bitwise XOR of the two input streams from W and E, and then sends this XOR'd bit stream to both A and B, using a single channel for each. For example, if node A were to lose the direct data stream from E owing to a link failure, then A could still recover the stream from E by XORing (either optically or electronically) the middle node signal with the signal from node W. Of course, variable delay lines would be needed to compensate for the latency differential between the two paths, as would techniques to compensate for thermal drift of that delay.

Whereas the conventional solution in Figure (a) uses 10 transmitter/receiver pairs, the network coding solution in Figure (b) accomplishes the same function with only 8—a 20% saving. Note that one or more additional nodes C, similar to A and B and receiving the multicast from both W and E, could be protected the same way by extending links from W, E, and the middle node to C.

Conventional protection techniques may achieve the same savings in links (transmitter, fiber or wavelength channel and receiver) that we obtain with network coding, but at a cost. For example, a conventional line switching technique could share the single channel between the middle node and A (or B) for protection purposes, but at the cost of a complicated distributed switching protocol; moreover, the switchover would not be hitless. Consider also the case when the data streams from W and E underutilized a channel to the extent that the two of them could be combined onto a single channel. If this were true, then only one channel would be needed between the middle node and A (or B), again matching (for this special case) the savings we obtain with network coding. However, the middle node would then require buffering for contention resolution, and attaining the significant amount of buffering needed for reliable contention resolution in all-photonic networks is a notoriously difficult and unsolved research problem. Moreover, this solution introduces potential queuing delays in the backup path that are beneficially absent in the network coding solution. Consider the further examples of fault-tolerant network coding solutions shown in Figure 2. Figure 2(c) shows how the middle node from Figure (a) can be eliminated. Now nodes A and B protect each other, using network coding. Moreover, node B also protects a third receiving node, C. Such protection can be extended to any number of additional receiving nodes. Here we use 9 links, as opposed to 12 for a conventional hitless design (25% savings). Figure 2(d) shows how an additional multicast transmitter S can be added to the network. Protection is achieved with only 8 links, versus 12 for a conventional design (33% saving).

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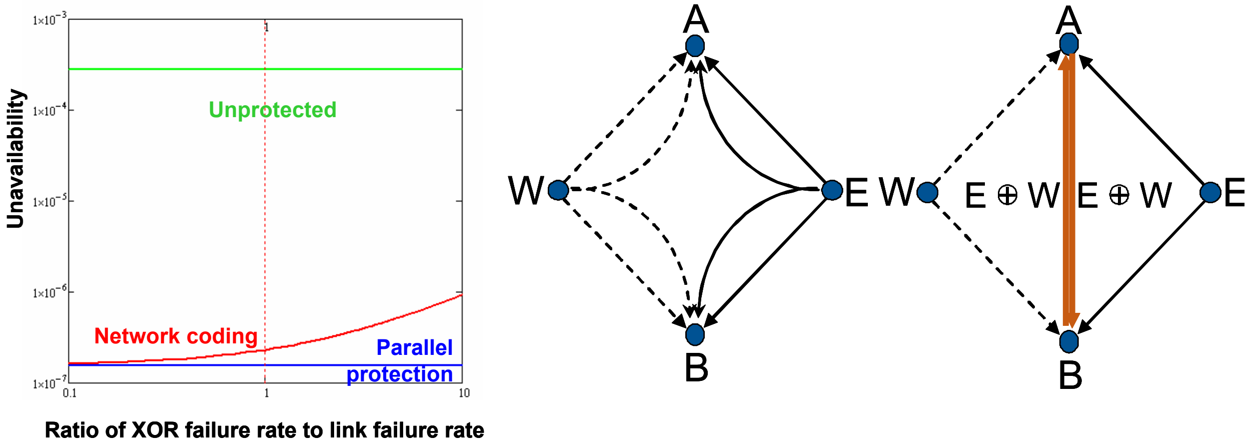
[1] We use the term "hitless" figuratively. Tail-end switching may involve a data hit, but generally less than that from typical line switching.

The purpose of providing protection is to reduce service unavailability. The facilities efficiencies gained by using network coded protection for multicast services come at the cost of additional complexity at the network coding nodes (no longer simple repeater/forwarding elements) which may impact overall service unavailability. The chart in Figure 3(a) provides an unavailability comparison of a conventional parallel protection scheme, Figure 3(b), and one based on network coding, Figure 3(c). Unavailability is determined from the failure and repair rates of network elements. In this unavailability calculation for these simple test cases, we assume that link failures are dominated by fiber failures and that all fiber links are 200 km in length. The mean-time-to-failure (MTTF) for fiber is calculated assuming 240 FITS/km (FITS=failures in 10^9 hours). In all cases, a mean-time-to-repair (MTTR) of 5.6 hours was assumed. The reliability of the XOR functionality itself is an unknown factor. Accordingly, in Figure 3(a), the unavailability of one of the two multicast services at either node A or node B is plotted versus the ratio of the XOR failure rate to the link failure rate. In this log-log plot, this ratio is varied from 0.1 to 10, meaning the XOR functionality is 10 times more (or less) reliable than the fiber link, respectively. The uppermost and lowermost curves indicate the unavailability for an unprotected link and a parallel protected link (~2.8e-4 and ~1.55e-7, respectively), and both are independent of the XOR failure rate. As shown, the unavailability of the network coding protection scheme depends rather weakly on the XOR failure rate in this range. Provided the XOR failure rate is as good as, or better than, the fiber failure rate, the increase in unavailability is modest.



(a) (b) (c)

Figure 3. (a) Unavailability comparison for a conventional parallel protected multicast network (b) and a network coding protected network (c).

4. Concluding Remarks

Network coding techniques based on a simple photonic bitwise XOR element provide efficient, fault-tolerant all-optical multicast networks without the need for complicated line-switching protocols or optical buffering. Our examples showed savings of up to 33% in links, compared to conventional tail-end switching protection techniques. For a simple network example, the availability penalties of network coding designs compared to conventional fault-tolerant network designs are shown to be modest, provided the XOR reliability is comparable to that of fiber links.

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