Combating Packet Loss in OPS networks: A Case for Network Coding

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Abstract

Fighting packet loss in optical packet-switched networks has been a priority in the optical research community in recent years. In this short paper, we present a scheme which utilizes both forward error correction at the ingress node and in-network coding at intermediary optical packet switches to reduce packet loss due to contention at the network layer. Initial analysis shows that if used in a smart way, our mechanism can reduce packet loss with multiple orders of magnitude. Coupled with a possible all-optical realization, network coding for contention resolution can be a valuable addition to optical packet switching.

1 Introduction

All-optical networking (AON) is foreseen as the most promising architecture for the future Internet core and metro network [2]. With AON, the use of electronic routing is eliminated by keeping both packet header and payload in the optical domain. Optical Packet Switching (OPS) is an AON architecture enabling statistical multiplexing, thus resembling today's electronic packet switching in the optical domain. There are several technological challenges which need to be resolved in order to deploy OPS, including fast wavelength converters and header processing in the optical domain. However, compared to circuit-switched optical networks, OPS yields better resource utilization resulting in potentially lower costs.

A crucial issue in OPS is packet loss due to contentions. Contentions occur when two or more packets are aligned to the same output wavelength at the same time. Several approaches have been proposed in order to combat such packet loss, e.g., the use of wavelength conversion, fiber-delay line buffering and deflection routing [3]. Orthogonal to these mechanisms, the Network Layer Packet Redundancy Scheme (NLPRS) employs Forward Error Correction (FEC) at an OPS ingress node to create redundancy packets from a set of data packets [1] which largely increases the probability of successful decoding at the respective egress node.

While an efficient technique in its own right, NLPRS treats the operation of OPS network as given, coding is not performed inside the OPS domain. On the other hand, network coding (NC) is a recently proposed mechanism which enables packet routers and switches to combine several incoming packets into outgoing packets [4]. While the original method would have to use O/E/O conversion to

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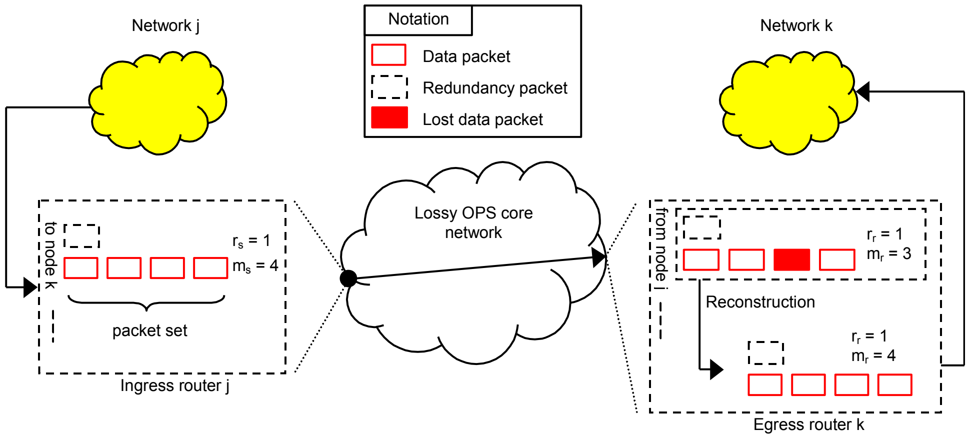

Figure 1: The NLPRS mechanism.

implement network coding [5] in optical networks, simple network codes like XOR can be realized with optical logic, therefore packets can stay in the optical domain [6]. In this paper we propose a joint channel-network coding scheme that extends and improves NLPRS (Section 2). Our initial analysis shows that by using simple XOR network coding instead of random dropping when contention occurs, we can significantly reduce the resulting packet loss (Section 3).

2 Combining FEC and Network Coding

Combining channel coding and physical network coding has been proposed for wireless networks [7], where the broadcast nature of the wireless medium can be exploited to boost throughput. In case of OPS networks on the other hand, the combination of the two coding paradigms can help reduce packet loss.

The Network Layer Packet Redundancy Scheme (NLPRS) is a powerful mechanism useful to combat packet loss in OPS due to contention at the network layer [1]. We consider data packets arriving from a legacy network to an ingress node in an OPS network with the same egress node destination. Redundancy packets (r_s) are added to a set of data packets (m_s) at an OPS ingress node j with destination egress node k. Packet loss may occur due to contentions in the OPS core network. However, if the number of successful data and redundancy packet arrivals within a certain packet set is $m_r + r_r \geq m_s$, reconstruction of lost data packets is possible at the OPS egress node using the remaining data and redundancy packets. NLPRS is illustrated in Figure 1.

NLPRS in its original proposal enabled creation and reconstruction of redundancy packets at the network ingress and egress nodes, respectively. However, with in-network coding, NLPRS could be extended to use packet mixing in the network core to further increase its performance, as illustrated in Figure 2. Note, that a simple XOR operation suffices, enabling packets to stay in the optical domain [6]. We refer to this method as NLPRS-NC.

Assume that packets from two sources a and b, (two different ingress nodes) but with the same destination, collide at an OPS core node. Packet a_1 is discarded, however, packet $a_2 \oplus b_2$ is transmitted instead of discarding either a_2 or b_2. Thus, at the OPS egress node, packet b_2 is reconstructed using the remaining packets from sender b, a_2 is reconstructed from b_2 and $a_2 \oplus b_2$, and finally a_1 is reconstructed from

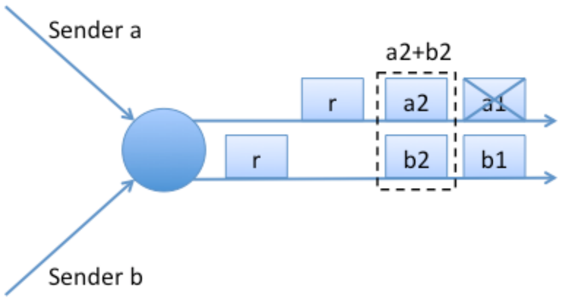

Figure 2: NLPRS extended with network coding. Two packet sets from different ingress nodes collide at an OPS core node.

the packet r in packet set a and the newly reconstructed a_2. Reconstruction would not be possible if a_2 was dropped instead of intercoded with b_2.

Network coding enables redundancy to carry over from one packet set into the other by XORing them together. If the packet loss rate is high and the packet sets themselves are long, e.g., 20 data packets plus 1 redundancy packet, multiple contentions may emerge inside a packet set. In such a scenario, it is always the best to code at the first contention and randomly drop at all the following contentions (which is the default operating mode of an optical packet switch). It is easy to see that one "binding" is enough between the two packet sets, and random dropping from the second contention forward maximizes the available information suitable for decoding at the egress. When considering packet sets traveling across multiple packet switches inside an OPS domain, it is not trivial to ensure an optimal mixture of coding and dropping inside a packet set. Indeed, designing a coordination mechanism among packet switches constitutes important future work.

3 Analysis

Here we derive data packet loss rates (DPLR) for NLPRS and our proposed network coding extension NLPRS-NC analytically. We consider a synchronized, slotted OPS network with fixed size packets to achieve analytical tractability. We assume two flows coming from different ingress nodes, crossing each other at a single optical packet switch, heading towards the same destination egress node. In case of NLPRS-NC, network coding is performed upon contention at the packet switch. Let $p \in \mathbb{R} : p \in [0..1]$ denote wavelength contention probability. The number of source data packets in a packet set is $m \in \mathbb{Z}^+ : m > 0$, while the number of redundancy packets is $r \in \mathbb{N} : r > 0$; the following formulae are valid for any positive integer values for m and r and any positive probability p.

First, we derive the DPLR for NLPRS. As we know from basic coding theory, packet loss will occur if more packets are lost than redundancy is provided ($i > r$). Also, the maximum number of data packets lost between two packets sets is m, as at every contention event, exactly one of the colliding packets will be dropped. We utilize the binomial distribution to calculate the probability of i contentions inside a single packet set, and also to determine the average number of data packets lost at such an event. After some calculation we get:

$$DPLR_{\text{NLPRS}} = \frac{\sum_{i=r+1}^{m+r} p^i (1-p)^{m+r-i} \sum_{j=i-r}^{\min(m,i)} j \binom{m}{j} \binom{r}{i-j}}{2m}. \tag{1}$$

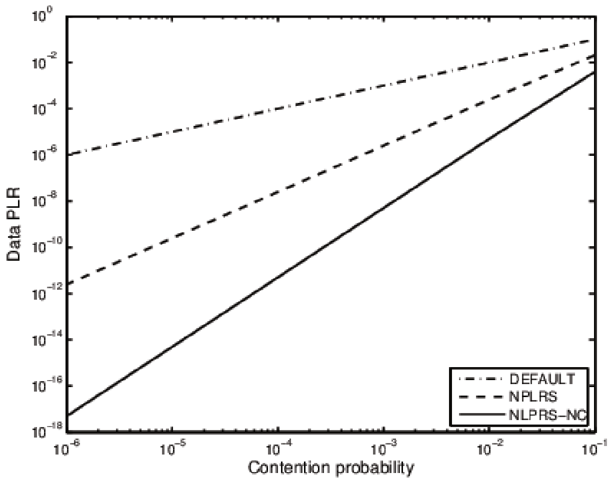

Figure 3: Packet loss rates using the analytical model, $m = 5$ and $r = 1$.

Second, we consider NLPRS-NC. As demonstrated in Figure 2, network coding can alleviate one more packet loss per packet set. Therefore loss occurs only if the number of contentions inside a packet set is $i > r + 1$. Also in this case, an extra packet is lost since the XORed packet cannot be decoded (two lost packets at one contention event). Note, that this extra packet loss is far more unlikely to happen than adequate decoding, since $p^r >> p^{r+1}$ with a small p. Factoring in these observations, after some calculation we get:

$$DPLR_{\text{NLPRS-NC}} = \frac{\sum\limits_{i=r+2}^{m+r} \frac{m+r}{i} p^i (1-p)^{m+r-i} \sum\limits_{j=i-r-1}^{\min(m-1,i-1)} (j+2)\binom{m-1}{j}\binom{r}{i-j-1}}{2m}. \quad (2)$$

The resulting packet loss rates under various contention probabilities are shown in Figure 3. Default OPS operation (without FEC or network coding) is plotted as a baseline. Notice the significant improvement from baseline through NLPRS to NLPRS-NC. Take the case of $p = 10^{-2}$ for example: the baseline data packet loss rate is DPLR= 10^{-2}, NPLRS can improve this value to $\text{DPLR}_{\text{NLPRS}} = 2.45 \cdot 10^{-4}$, finally, NLPRS-NC reduces it to $\text{DPLR}_{\text{NLPRS-NC}} = 4.92 \cdot 10^{-6}$. As it can be seen in the log-log plot this trend is consistent across different contention probabilities, as our combined channel-and-network coding scheme reduces the packet loss rate with several orders of magnitude. We have also developed a simulator using Simula/DEMOS for validating the analytical formulae. Mean values for simulation results are near-identical (given a sufficiently large number of data packets) to analytical results depicted in Figure 3.

4 Conclusion and Future Work

In this short paper we have barely scratched the potential of combining channel and in-network coding to alleviate packet losses in optical packet switched networks. Our preliminary analysis shows that combined channel and network coding indeed has potential in reducing data packet loss rate. Important future work includes studying realistic networks with relevant real-world topologies, multiple packet switches, a large number of flows and no flow synchronization using simulation. Furthermore, performance and cost comparison with the numerous existing contention resolution schemes should also be addressed.

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