Preliminary Results of Packet Loss Analysis in Optical Packet-Switched Networks with Limited Deflection Routing*

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Abstract

We present an approximate analytical method for the evaluation of packet loss probability in synchronous optical packet-switched networks which operate under limited deflection routing with the contention resolution method based on priorities. Packets are lost because they experience too many deflections and stay prohibitively long in the network. The presented results are those for the network in the torus topology of a two-dimensional grid, which operates at a steady state with the uniform load u, $u \in \langle 0, 1 \rangle$. *To our knowledge, this is the only article to present such an analysis for networks with nodes of the* 4×4 *type. For the network composed of 100 nodes, we predict the packet loss probability as low as* 10^{-9}, *while our simulator provided results on the order of* 10^{-6}. *We verify our analysis by simulation, when possible.*

1. Introduction

The communication networks currently in operation exploit only a small fraction of the bandwidth available in optical fibers, because of their slow electronic components. The already available technology for transparent optical packet switching (OPS) is faster [6], but several years must elapse before OPS networks start being deployed. One of the reasons for this is that such networks are yet to be designed and evaluated. Our work contributes to the evaluation of the packet loss probability (PLP) in limited deflection routing.

Deflection routing is an attractive routing strategy for OPS networks, because it need not rely on the optical buffering of packets. However, with deflection routing a packet can live in the network for a long time before it eventually arrives at its destination due to a large number of deflections it can experience.

In limited deflection routing the number of a packet's deflections (recorded in the packet header) is limited to the number S, called the threshold. A packet is removed from the network and lost when it experiences the Sth deflection. There are two reasons to employ limited deflection routing. First, packets that travel in the network far too long a period of time can be removed because they will be ignored by real-time applications anyway (such as video conference applications) or considered lost by the TCP protocol (data transfer) and retransmitted. Second, the optical signal quality packets which travel too long is unacceptable due to the noise from optical amplifiers through which the packet has traveled.

Limited deflection routing suffers from packet loss. For a given network topology there are two parameters that influence packet loss: the threshold S, $S = 1, 2, \ldots$, and the network load u, $u \in \langle 0, 1 \rangle$. The parameter u expresses the probability with which a packet arrives along any link at any time slot.

The objective of our work is to find the values of u and S for which a given level of the PLP is not exceeded. The ROM project [5] aimed at the PLP on the order of 10^{-9} for their "Premium" quality service. We provide the values of S and u such that the "Premium" service is of the requested quality.

We obtained our results with mathematical analysis, since the sought PLP is very low, and software simulators are unable to provide the results of the desired precision within a reasonable time limit.

As to previous works, in [3] unlimited deflection routing is examined with Markov chains. In [7] deflection routing is loopless, and for this reason the analysis there does not consider circulating packets. A detailed combinatorial analysis of packet deflection at a node

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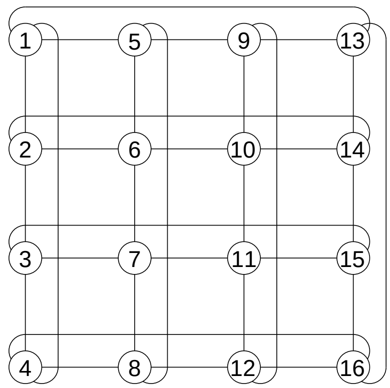


Figure 1. The torus of the two-dimensional grid with 16 nodes.

is conducted in [4], but there the packet loss is caused by buffer overflows, not by limited deflection routing. An analysis of limited deflection routing is presented in [8], which is an adapted analysis of unlimited deflection routing published in [1]. In [10] packet loss analysis is presented for asynchronous OPS networks with unlimited deflection routing. Regular networks built of 2×2 nodes running unlimited deflection routing are analyzed in [2].

2. Network Model

The network works synchronously, i.e. time is the same for every node and is divided into time slots. The network is homogeneous, i.e. every node functions both as a routing node for packets in transit and as an access point where packets can enter or exit the network. At every node packets arrive from the source according to the Poisson process and ask for admission into the network. They are admitted whenever there is an available slot in one of the output fibers. The destination of the packet asking for admission is uniformly distributed among every node in the network except the admitting node.

Nodes are connected with fibers that carry only one wavelength forming a network in the torus topology of the two-dimensional grid. The torus has l rows and l columns, and has $N = l^2$ nodes. A sample network with $N = 16$ nodes is shown in Fig. 1. This topology is regular or, in the graph theory parlance, node symmetric.

Each node is of the 4×4 type, i.e. each has four input and four output fibers. In this node a packet is lost only when its number of deflections has reached S. Contention resolution is based on priorities. More important packets are routed first, while the contention among equally important packets is resolved at random. We try to send a packet along one of its preferred outputs, which we choose at random.

There are four classes of packets: 1st, 2nd, 3rd, and 4th. The 1st class packets are the most important, while the 4th class packets are the least important. A packet is assigned a class depending solely on the number of its preferred outputs. A preferred output is one that follows a shortest path to the packet's destination. For instance, suppose a packet residing at node 11 (Fig. 1) is destined to node 1. At node 11 the packet is of the 4th class with respect to node 1, because each of the four links at node 11 offers a shortest path to node 1. When the same packet arrives later at node 10, it is of the 3rd class with respect to node 1. During its lifetime a packet can be of various classes. The notion of packet class has been taken from [4]. In [3] it is referred to as a packet type.

We note that the KEOPS components [6] can implement our model.

3. Analysis

The goal of the analysis is to obtain the probability distribution of packet loss for an average packet as a function of the number of hops k made by that average packet. The parameters of the analysis are the threshold S and the load u. The analysis is based on the method presented in [8], and concentrates on the tagged packet, which we assume behaves like an average packet. We trace the tagged packet from the time slot it enters the network ($k = 0$), through consecutive time slots ($k = 1, 2, \dots$) up to the time slot when the packet cannot make more hops ($k = K$). The tagged packet makes one hop at a time slot. The value K is the upper bound on the number of hops a packet can make [8]:

$$K = S \cdot (\text{network's diameter}). \qquad (1)$$

Since the network is regular and the traffic is uniform, the tagged packet is traced during its journey to node 1 rather than to every node. In a regular network every node is equivalent to every other node, which together with the assumption of traffic uniformity allows the analysis to be carried out for one node only (e.g. node 1) as the destination.

In the analysis we operate on the probabilities that the tagged packet is present at node n, $n = 1, \dots, N$, after it made k, $k = 1, \dots, K$, hops. For instance, we might investigate the probability with which the tagged packet resides at node $i = 5$ after it made $k = 3$ hops. We also must know the probabilities which correspond to the number s, $s = 0, \dots, S - 1$, of deflections which the packets experiences during its journey. For example, we might investigate the probability that the tagged packet resides at node $n = 5$ after it made $k = 3$ hops and that it has experienced $s = 2$ deflections on the way. We express these probabilities of the packet presence by a polynomial $p_{k,n}(x)$ of the degree at most $S - 1$:

$$p_{k,n}(x) = \sum_{s=0}^{S-1} p_{k,n,s} x^s, \quad (2)$$

where the coefficient $p_{k,n,s}$ expresses the probability with which the tagged packet resides at node n after it made k hops and experienced s deflections.

From the mathematical viewpoint, these polynomials belong to the ring of polynomials modulo x^S over the field of real numbers. This is expressed as the following:

$$p_{k,n}(x) \in R[x]/x^S \quad (3)$$

A polynomial $p_{k,n}(x)$ is a tool to remember the numbers of deflections a packet has experienced and their corresponding probabilities. If we seek only the probability with which the tagged packet resides at node n after k hops, we obtain it by summing the coefficients of the polynomial $p_{k,n}(x)$, which is the same as the evaluation of the polynomial at point $x = 1$: $p_{k,n}(x = 1)$. Using values for x other than 1 has no purpose. We need not treat x as a variable, since it is merely an object on which we perform algebraic manipulations. This polynomial approach is not related to polynomial approximation.

We group polynomials $p_{k,n}(x)$ into vectors P_k of N elements, where each element relates to one node in the network:

$$P_k = (p_{k,1}(x), \ldots, p_{k,n}(x), \ldots, p_{k,N}(x))^T. \quad (4)$$

Vector P_k provides the complete information about the tagged packet presence after it made k hops. Vector P_0 provides the probabilities of packet presence at the moment when it is admitted to the network. The packet is destined to node 1, and starts its journey from every other node with probability $1/(N - 1)$:

$$P_0 = (0, 1/(N-1), \ldots, 1/(N-1))^T. \quad (5)$$

To obtain vectors P_k we employ the following equation:

$$P_k = TP_{k-1}, k = 1, \ldots, K \quad (6)$$

where $T = (t_{i,j}(x))$ is the transition matrix describing the transitions which the tagged packet can make during one hop. The elements $t_{i,j}(x)$ of the matrix are also polynomials. The element $t'_{i,j}(x)$ expresses the probability of the tagged packet transition from node j to node i, provided that the tagged packet resides at node j. As a result of the imposed page limit we are unable to explain the construction of the T matrix here. Please consult [8] for more information on the T matrix.

The most significant difference between the results presented here and in [8] is that here we employ 4×4 nodes as opposed to the 2×2 nodes employed in [8]. In our setting the calculation of deflection probabilities is more complicated, because here we must compute the probability of deflection for each of the four packet classes. This computation involves tedious combinatorial analysis, for which a number of ideas have been taken from [4]. We use the brute force approach, where we enumerate all possible combinations of packets, and calculate their corresponding probabilities of deflection.

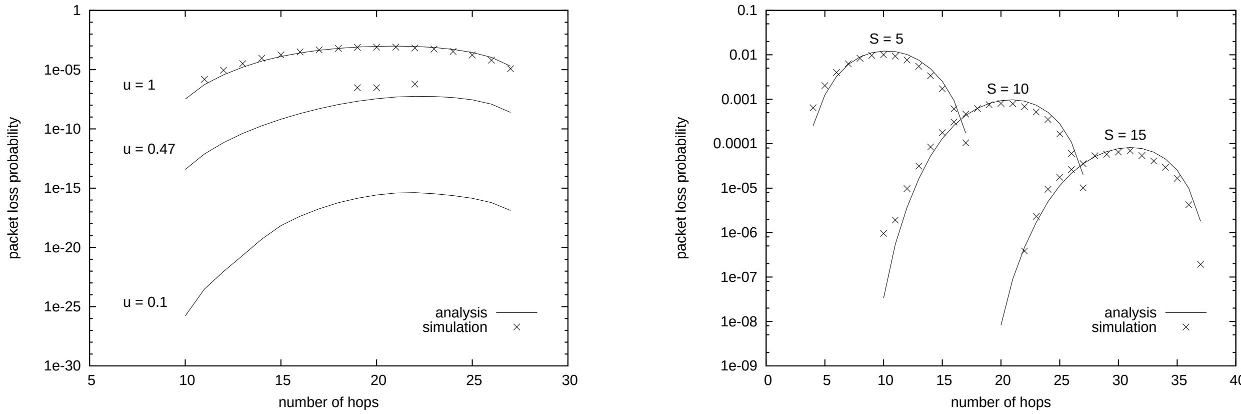
The probabilities of packet loss are derived from vectors P_k. If we investigate the probability that the tagged packet is lost after it makes $k = 2$ hops, we consider vector P_2. Specifically, we sum the coefficients $p_{k,n,S-1}$ for $n = 1, \ldots, N$ which are later multiplied by the corresponding probabilities of deflection.

4. Results

In Fig. 2 presented are the results of the analysis and simulation for the network with 100 nodes. We implemented our simulator in OMNeT++ [9]. The simulation results are represented by crosses, whereas the analysis results by lines.

There are two groups of simulation and analysis results. In the first group the threshold S was fixed at $S = 10$, while the load u varied, $u = 0.1, 0.47, 1.0$. The results are shown in Fig. 2(a). The load u influences only the PLP, not the number of hops at which packets are lost. We note that the results of packet loss presented in Fig. 2(a) for $u = 0.1$ are impractical, since they are very low (10^{-26}) and neither experiments nor simulation could corroborate our findings.

In the other group the load u was fixed at $u = 0.47$, while the threshold S varied, $S = 5, 10, 15$. The results are shown in Fig. 2(b). For different values of the threshold S packets are lost at different numbers of hops. As we increase the value of S, packets are lost later, they are more likely to be delivered to their destinations, and as a result the PLP is smaller.



(a) The PLP as a function of the number of hops for three values of the network load u and the fixed threshold $S = 10$.

(b) The PLP as a function of the number of hops for three values of the threshold S and the fixed load $u = 0.47$.

Figure 2. PLPs obtained by analysis and simulation.

5. Conclusion

We analyzed the PLP in uniformly loaded OPS networks of regular topology with limited deflection routing.

As expected, the greater the load u, the greater the PLP. Moreover, as the threshold S increases, the value of the PLP decreases at the cost of a higher upper bound on the packet delivery time.

Our modeling technique has strong links with discrete time Markov chains and we plan to explore these links in the future.

The presented analytical approach provides results in the important cases for which a software simulator would have to run unacceptably long. The analysis is verified by simulation only for the cases where the simulation provides results. Based on this we believe that our analytical results are correct also for very low PLPs, for which simulations cannot provide results.

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