Performance Evaluation of a Bufferless Packet-Switched Node

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ABSTRACT
In the paper we analyze the steady-state performance of a bufferless optical packet-switched node that works synchronously under the Poisson traffic. Given the admission control and routing algorithms we compute the mean rates at which packets are admitted into the network and probabilities with which packets are lost or leave the nodes along specific outputs. The analysis results differ with simulation results by a small error in the cases that we studied. The analysis is applicable to nodes of any degree and any number of wavelengths.
Keywords: optical packet-switching, performance evaluation, analysis.

1. INTRODUCTION

If optical packet-switched (OPS) networks [1] become commercially viable, software tools would be needed to evaluate their performance as it is the case with the operational wavelength-switched networks, where such tools are already available (SP Guru Transport Planner being one example). General tools for OPS networks would most probably employ simulation. However, for specific cases analysis could be used too, and we consider our work to be a step in this direction. Analysis not only offers more understanding, but if harnessed appropriately, it can yield more accurate and obtained-faster results in comparison with simulation. An important ingredient of the analysis of a network is the analysis of a single node, and this article reports on its probabilistic analytical approach. Performance evaluation of a single node is usually carried out for simple cases of 2x2 or 4x4 nodes with one wavelength, which cripples and limits the analysis to simple and impractical networks [2]. It's not so in this article: we allow the node degree and the number of wavelengths to be any.

We consider two tasks of the analyzed node at the control level which impact the network performance: admission control and routing. The task of admission control is to manage the flow of packets from the access network to the core network, while the routing algorithm tries to make the best use of the scarce OPS resources. Frequently packets ask for the same outputs, and just one of them will get there while others loose the contention. Therefore the routing problem boils down to the algorithm of contention resolution among packets. A loosing packet can be dropped or misrouted to some other output. The process of misrouting packets in order to save them is called deflection. Deflection can be beneficial is salvaging some traffic, and is the necessary evil since there are no buffers in the node. Deflection can improve the performance of the network as reported in [3].

Throughout the article we use the Poisson distribution. While the Poisson distribution is frequently dismissed as simplistic or downright impractical, it's also regarded as suitable for simple and preliminary evaluation. Moreover, recent study suggests that the Poisson traffic can be applicable [4]. If need be, future analysis could take into account other models of traffic [5]. If we assume that the number of packets is given by the Poisson distribution with the mean rate of λ, then the probability that k packets arrive in a time slot is given by equation (1).

$$f(k, \lambda) = \frac{e^{-\lambda} \lambda^k}{k!} \tag{1}$$

Our admission control and routing algorithms are easily implemented in simulation, but analysis is harder. In simulation we examine separate packets, but in analysis we study the mean rate of packets per time slot. In the rest of the article we assume that all the mean rates relate to a time slot, and that they are the mean rates of the Poisson distribution.

2. PROBLEM STATEMENT

The node has input fibers from neighbor core nodes and Z output fibers to neighbor core nodes, each running v_z wavelengths for $z = 1, \ldots, Z$. The node delivers packets from the core network to the access network through the local drop links, and admits packets from the access network to the core network through the local add links. The node is shown in Figure 1.

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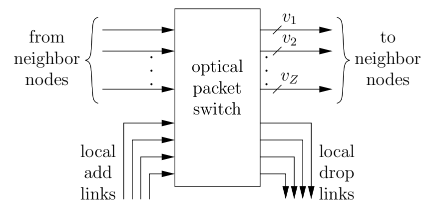

Figure 1. Node model.

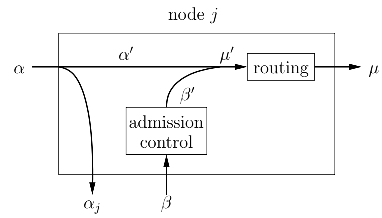

Figure 2. Packet flows and their mean rates.

The node works synchronously and so during every time slot it receives packets from neighbor core nodes. These packets are either routed to other core nodes or are sent to the access network if the node is their destination. During the same time slot some packets arrive from the access network and ask for admission to the core network. We assume that packet arrivals are independent from each other. The number of packets that are sent along the node's output links is not greater then the node's output capacity v, $v = v_1 + \ldots + v_Z$, and these are admitted packets and *packets in transit*, i.e. the packets received from neighbor nodes which are not destined to the analyzed node.

There are N nodes in the network, and the analyzed node has number j. For the purpose of the analysis we divide packets into $N - 1$ groups depending on their destination nodes. There are $N - 1$ possible destinations since there is no packet for which the analyzed node is both the source and the destination. Each packet group is assigned a number n to which we refer as the group n.

The analyzed node receives packets from its neighbor nodes at the mean rate α, $\alpha = \alpha_1 + \ldots + \alpha_N$, of which α_j are sent to the local drop, and $\alpha' = \alpha - \alpha_j$ are packets in transit. Moreover, the analyzed node receives packets from the access network at the mean rate β, $\beta = \beta_1 + \ldots + \beta_N$, where β_n are given by the traffic matrix. Since the analyzed node is not going to send packets to itself, then $\beta_j = 0$. Packets are admitted at the mean rate β', $\beta' = \beta'_1 + \ldots + \beta'_N$, and then together with the packets in transit α' they are routed. The routing algorithm sends out packets at the mean rate μ, $\mu = \mu_1 + \ldots + \mu_N$. Packet flows and their mean rates are shown in Fig. 2.

Our objective in admission control is to admit as many packets as possible, but not more than the node can accommodate. Therefore in every time slot we admit at most as many packets as there are output slots left, which equals to the difference of the output capacity and the number of packets in transit. The admitted packets are chosen at random from the waiting packets.

At the analyzed node each packet group n is assigned an integer class number from 1 to Z, where Z is the number of the output links. The class number equals to the number of preferred outputs. We define a preferred output as one that yields the distance to the destination at most twice as high as the shortest distance to the destination.

The routing algorithm first routes packets of the better classes (1^{st} class is the best) before lower classes, which is called the priority-based routing. If there are two or more packets of the same class, then the one with the shortest distance to its destination is routed first, which is called the distance-based routing. Therefore the analyzed routing algorithm is based on priority and distance.

3. ANALYSIS OF ADMISSION CONTROL

The analysis is going to tell us the mean rates β'_n of packets admitted for destination node n. What's more, our results show that the distribution of the number of admitted packets can be approximated accurately by the Poisson distribution.

The average number of all packets in transit is α' and the average number of all packets asking for admission is β, but the exact numbers of packets during a time slot are random variables that we approximate by the Poisson distribution. A packet arrival scenario is denoted by a pair of two integer random variables (a_e, b_e), where a_e is the number of packets in transit and b_e the number of packets asking for admission. Since these two random variables are independent, the probability of the (a_e, b_e) scenario is $P_{adm}(e) = f(a_e, \alpha')f(b_e, \beta)$, where f is given by equation (1). The index $e = 1$ denotes the most probable scenario, $e = 2$ the second most probable scenario and so on. Therefore $P_{adm}(e)$ can only decrease as e increases. Listing scenarios (a_e, b_e) involves finding the sequence of the most probable numbers of the Poisson distributions, and then combining them in pairs to create the most probable scenarios.

For the scenario number e the remaining output capacity equals $max(v - a_e, 0)$, the number of admitted packets equals $b'_e = min(max(v - a_e, 0), b_e)$, and the probability that a packet is admitted equals b'_e / b_e. We obtain the average probability of admitting packets by calculating a weighted average for a sequence of scenarios as given by equation (2). The index of the last considered scenario is E_a, which is the largest integer that satisfies $P_{adm}(E_a)$ / $P_{adm}(1) > \varepsilon_a$. The parameter ε_a helps us influence the precision of the admission analysis.

$$\rho = \sum_{e=1}^{E_a} P_{adm}(e) \frac{b'_e}{b_e} \quad (2)$$

Since the probability of admitting packets is ρ, then $\beta'_n = \rho\beta_n$, and $\beta' = \rho\beta$. We assume that the distribution of the number of admitted packets is Poisson which is a good assumption as we'll see in the sample results below.

3.1 Sample results

For the sample results we had the output capacity $v = 16$ and traffic in transit $\alpha' = 10$. There are five demands with rates $\beta_1 = 1.0$, $\beta_2 = 0.5$, $\beta_3 = 2.0$, $\beta_4 = 2.5$, $\beta_5 = 3.0$, and so $\beta = 9$. We assumed $\varepsilon_a = 10^{-5}$.

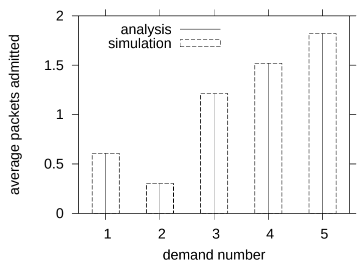

Figure 3. Mean rates of admitted packets per demand.

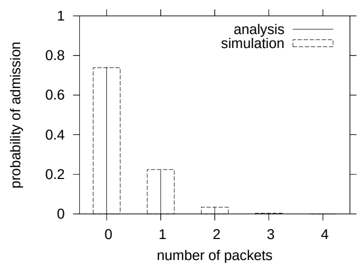

Figure 4. Admission distribution for demand #2.

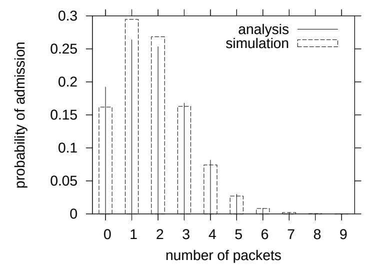

Figure 5. Admission distribution for demand #5.

The average probability of admission ρ for analysis was 0.607 and 0.608 for simulation. Fig. 3 shows the mean rates of admitted packets for each of the five demands, where the spikes represent the analytical results and the boxes represent the simulation results. The analysis gave us $\beta'_1 = 0.61$, $\beta'_2 = 0.30$, $\beta'_3 = 1.22$, $\beta'_4 = 1.52$, $\beta'_5 = 1.82$, and so $\beta' = 5.47$. These results agreed with simulation with the error of less than 0.1%.

Fig. 4 shows the number of admitted packets for the second demand and their corresponding probabilities. The spikes show the Poisson distribution with the mean rate of 0.3. We can see that the analytical and simulative distributions agree quite well, but this agreement is less pronounced for the fifth demand as shown in Fig. 5. Nonetheless, the simulation corroborated the analysis results and showed that indeed the admitted traffic can be approximated by the Poisson distribution.

4. ANALYSIS OF ROUTING

In this section we derive the mean probabilities $\varphi_{n,z}$ of sending the packets destined to node n through the output link z. Having $\varphi_{n,z}$ we can compute the mean number μ of sent packets, $\mu = \mu_1 + \ldots + \mu_N$, where $\mu_n = (\varphi_{n,1} + \ldots + \varphi_{n,Z})\mu'_n$ for each packet group n. The probability of dropping a packet destined to node n equals $1 - (\varphi_{n,1} + \ldots + \varphi_{n,Z})$.

We employ the same approach as in the analysis of admission control: we enumerate the most probable scenarios of receiving packets for routing; then for each scenario we calculate its probability and the probabilities of routing its packets along specific outputs; finally, we calculate the average probabilities over considered scenarios.

Each scenario of packet arrivals is denoted by index e and described fully by a tuple $(x_{1,e}, \ldots, x_{N,e})$, where $x_{n,e}$ is the number of packets destined to node n in scenario e. The value of $x_{n,e}$ is given by the Poisson distribution. Since $x_{n,e}$ are independent random variables, the probability of obtaining scenario e equals $P_{rou}(e)$ as given by equation (3).

$$P_{rou}(e) = \prod_{n=1}^{N} f(x_{n,e}, \mu_n) \quad (3)$$

The probability that packets destined to node n are sent to the output z for scenario e is expressed by $\varphi_{n,z,e}$, and its value is the ratio of $x_{n,e}$ to the available capacity in the packet's preferred output links. Therefore the probability $\varphi_{n,z}$ is the weighted average of $\varphi_{n,z,e}$ over considered scenarios as expressed by equation (4). The index of the last considered scenario is E_r, which is the largest integer that satisfies $P_{rou}(E_r)$ / $P_{rou}(1) > \varepsilon_r$. The parameter ε_r helps us influence the precision of the routing analysis.

$$\varphi_{n,z} = \sum_{e=1}^{E_r} P_{rou}(e)\varphi_{n,z,e} \quad (4)$$

4.1 Sample results

We analyzed and simulated the routing algorithm for the node #5 shown in Fig. 6, where the numbers over the links represent the number of wavelengths. Node #5 sends packets (these are the demands) to the neighbour nodes #1, #2, #3 and #4 with the requested rates $\mu'_1 = 20.4$, $\mu'_2 = 5.1$, $\mu'_3 = 10.2$ and $\mu'_4 = 0.5$. Tables 1 lists the properties of the demands. Table 2 reports the routing probabilities calculated by the analysis (the first number) and the simulation (the second number), and we can see that these numbers agree quite well.

Table 1. Properties of demands.

Demand #	Destination node #	Class	Distance to destination [km]	Preferred output links #
1	1	1	100	1
2	2	2	300	1, 2
3	3	2	500	1, 3
4	4	3	700	1, 2, 4

Table 2. Routing probabilities.

	Link #1	*Link #2*	*Link #3*	*Link #4*
Destination #1	*0.767, 0.798*	*0.204, 0.181*	*0.023, 0.017*	*0.002, 0.001*
Destination #2	*0.003, 0.001*	*0.556, 0.593*	*0.261, 0.247*	*0.045, 0.040*
Destination #3	*0.029, 0.030*	*0.078, 0.078*	*0.216, 0.241*	*0.061, 0.064*
Destination #4	*0.003, 0.001*	*0.013, 0.003*	*0.0, 0.0*	*0.088, 0.039*

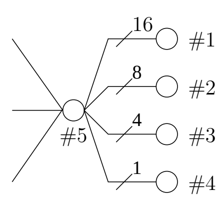

Figure 6. Connections between node #5.

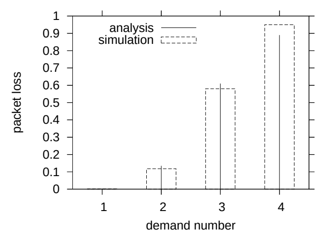

Figure 7. Packet losses for all four demands.

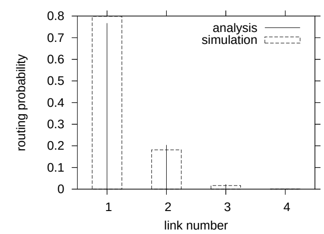

Figure 8. Routing probabilities for the demand #1.

Fig. 7 shows packet losses for the four demands as calculated by the analysis and simulation. Fig. 8 shows the routing probabilities for the demand #1, which is the plot of the data presented in Table 2 for demand #1 only.

5. CONCLUSIONS

The analysis was developed for specific admission control and routing algorithms, but using a similar approach we can develop analysis for other algorithms. We used the deflection routing, but its use is not required. Our analysis is quite simple and agrees well with the simulation results. Since the analysis applies to nodes of a large node degree and a large number of wavelengths, it can be used in analyzing networks of real-world properties.

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