Performance Evaluation of Short-Cut Eulerian Routing

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Performance Evaluation of Short-cut Eulerian Routing

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Abstract— **We analyze the performance of a new routing strategy for all-optical packet networks. This strategy improves the Eulerian routing technique, a convergence routing based on a an Eulerian directed cycle. This new technique allows to use shortcuts along the Eulerian cycle. Usual Eulerian routing provides deterministic transport delays but has a very low network utilization. With this new strategy the average transport time is much smaller and we can prove a deterministic upper bound of the transport delay, unlike deflection routing which suffers from livelocks. We study the performance guarantees provided by this new algorithm using graph arguments for the ending property and simulations to give some insights for the performance of the algorithm.**

keywords: optical packet switching, convergence routing, distribution of transport time, throughput, simulation.

I. Introduction

All-optical packets switching represents a challenging and attractive technology to provide a large bandwidth for future networks. Packets are more flexible than circuits and it is assumed that moving from WDM into OPS will help to design high bandwidth multi-service network (see for instance [10]).

But with nowadays optical technology, optical switches do not have large buffers or even buffers at all. Delay loops allow some computation time for the routing algorithms but they are not designed to store a large amount of packets. Therefore routing algorithms are quite different of the algorithms designed for store and forward networks based on electronic buffering. And routing strategies have a large impact on network performance. Most of the routing strategies for all optical packets networks do not allow packets loss as there are no buffer overflow. Packets loss is just the physical loss rate which is very low for optical fibers. However these strategies keep the packets inside the network and reduce the bandwidth. Furthermore, if a packet is delivered before a time-out occur, the packet will be logically lost. It is still in the network but it is considered as lost. The usable bandwidth (i.e., the throughput) and the tail of the distribution for transport delay are therefore two major measures of interest.

In this paper, we study the performance of packet routing strategies without intermediate storage of packets [2, 15] based on convergence routing [3,4,11]. During the ROM [10], we have, in collaboration with Alcatel, designed several topologies and routing strategies. ROMEO is a sequel of this first project with the same research groups devoted to the transition from OEO switches to all-optical ones. Within ROMEO, it is assumed that best-effort traffic will not use electronic memory and store and forward algorithms for routing.

The most studied routing technique for OPS is shortest path deflection routing [1,6,18]. In shortest-path Deflection Routing, switches attempt to forward packets along a shortest path to their destinations. Each link can send a finite number of packets per time-slot (the link capacity). No packet is queued. At each slot, incoming packets have to be sent to their next switch along the path. If the number of packets which require a link is larger than the link capacity, only some of them will go through the link they ask for and the other ones have to be misdirected or deflected. Thus, deflected packets travel on longer paths to their destination. These routing algorithms are known to clearly avoid deadlocks but livelocks could occur (packets move but never reach their destination).

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Simulations and models have shown [1,7] that the throughput is quite good but the number of deflections may be not negligible. We have analyzed by simulation a 11×11 2D-mesh. If the traffic is unbalanced, some simulations on 2-dimensional meshes have shown that the mean number of deflection is small but a large number of packets are heavily deflected. Furthermore, even if the key idea of deflection simple, it does not explain how to select efficiently the packets to be deflected and even what is the minimal number of deflected packets for a set of packets in the router. As the number of deflections has a high impact on the performance [9,19], we must deflect the minimum number of packets. The theoretical problem is not that difficult: the routing is associated to matching in bipartite graph. The maximal matching problem has a polynomial complexity [13] but it is too slow to be used in an optical router. In general, random selection or very simple strategies based on packets age are used [7,19], even if they provoke a relatively large number of deflections. Recently, an optimal selection algorithm has been published [8,14] but one must prove that it is possible to implement it following the time constraints due to optical routing.

In Figure 1 and 2 we present the distribution of the transport delays (i.e., the length of the paths followed by the packets) obtained with this optimal deflection routing strategy. Figure 1 states that most packets will experience a fast transport inside the mesh. The average delay measured during the simulation is 16.6, much smaller than the diameter (the maximal physical distance) which is only 20 in a 11×11 2D-mesh. Thus the average performances sound good. The source of traffic is uniform on the mesh but the destinations follow a skewed distribution based on the superposition of a uniform distribution on the whole mesh for 10% of the traffic and the uniform distribution on a small centered mesh of size 5×5 for the remaining traffic. The link capacity is one and the global arrival rate (for the whole network is 20 packets per time-slot).

Approximatively 2 millions packets have been transported and a significant number of them (more than 7400) have experienced more than 100 deflections. We have also observed some packets which need more than 3000 hops to reach their destination. In Figure 1 and 2 we present the distribution of the transport delays (i.e., the length of the paths followed by the packets) obtained from simulations.

Figure 2 shows the tail of the distribution of packet delays. For the sake of readability we use a logarithmic scale for the probability and we gather the packet delays in intervals of 50 time slots. Almost 2.000 packets need more than 500 time slots to leave the network. This is not consistent with a network protocol, such packets will be considered as lost because they arrive after the transport time-out or they reach their time to live (TTL). The shape of the bar chart also suggests a geometric distribution.

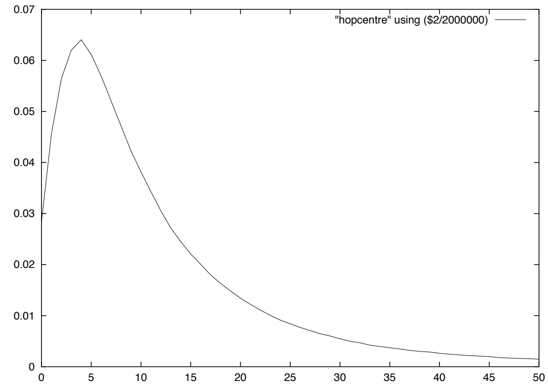

Fig. 1. Head of the distribution of the packet delays on the mesh with non uniform traffic

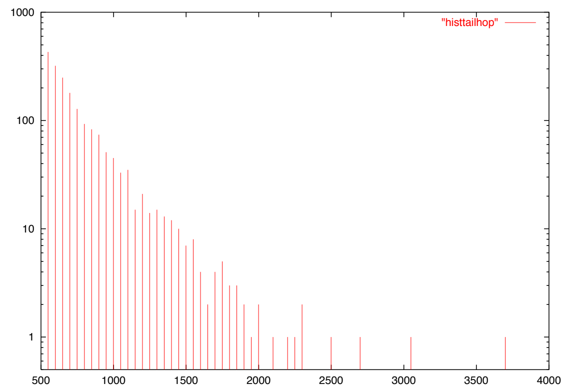

Fig. 2. Tail of the distribution of the packet delays on the mesh with non uniform traffic

Thus we may have for some packets two orders of magnitude between the physical distance that we can obtain and the experienced distance we got because of deflections. And the transport time is not upper bounded. The lack of ending guarantee is a real problem.

Convergence routing has been propose to provide a finite ending guarantee [12,15,20]. In such a routing, packets are routed along a global sense of direction, which gives an ending guarantee. As proposed in various works [12,20], such a global sense of direction can be created by using some decompositions of the target directed graphs (or of a covering sub-digraph of it) into circuits. For instance, some of us have proposed Eulerian routing [4,11] in which packets follow an Eulerian circuit in the network. We model our network by directed graphs $G = (V, E)$. The *vertex* set V represents the set of routers of the network. An arc (u, v) in the *arc* set E

represents a link from router u to router v. An *Eulerian circuit* of a graph $G = (V, E)$ is a closed tour which crosses each arc of G exactly once. Hence, an Eulerian tour is a numbering of the arcs of G modulo m where m is the total number of arcs in G.

Let us consider an Eulerian circuit $\mathcal{C}$. Each emitted packet follows $\mathcal{C}$ and, at each step, has priority on the next arc on this circuit. Hence, a packet emitted by a node u for a final destination v will eventually reach it. Let us denote by $d_{\mathcal{C}}(u, v)$, the maximal number of arcs on $\mathcal{C}$ between one occurrence of the source vertex u and the first following occurrence in $\mathcal{C}$ of the destination vertex v. It represents the longest delay for packet transport from vertex u to vertex v. Thus, we can define the *ending guarantee* of $\mathcal{C}$ by

$$EndG_{\mathcal{C}} = \max_{\substack{u,v \in V \\ u \neq v}} d_{\mathcal{C}}(u, v).$$

where V represents the set of vertices of the network. Clearly, following $\mathcal{C}$, any packet emitted in G reaches its destination in at most $EndG_{\mathcal{C}}$ step and we get the ending guarantee.

This guarantee implies that there is no livelock in the network. The ending guarantee is a bound on the transport delay. It does not take into account the waiting time before entering the optical part of the network.

However, this ending guarantee has a cost for networks with many nodes: a significant reduction of the throughput. For various Eulerian directed cycles, we have found by simulation throughput from 3 up to 6 packets per slot for a 10×10 2D-mesh [3]. For similar networks and traffic, deflection routing algorithms provide a throughput of more than 32 packets per slot [3]. This is due to the large average transport delay experienced with Eulerian routing.

Thus, we study the performance of a new routing algorithms which combines the ending guarantee of the Eulerian routing with the throughput efficiency of deflection routing. The rest of the paper is organized as follows. In Section II, we describe the new routing algorithm some of us have designed And in Section III we present the performances of our algorithm using simulations and analysis for a 2D mesh network topology.

II. Design of the routing algorithm

As shown in the previous section, each of the routing strategy has some desirable performances but they do not have all of them. So some of us have designed a new routing strategy: if a message destined to final destination v arrives at vertex w, on arc number i of Eulerian tour $\mathcal{C}$, in the basic Eulerian routing, the message is routed on arc number $i+1 \pmod m$, called the *natural output*. Instead of going in this natural direction, the router could decide to route the message on the shortest portion from w to v. This is what we call a *short cut* and this systematic routing strategy is called the *short cut routing*. To guaranty the ending, the router can decide a short cut if and only if the corresponding link is free; otherwise the message is sent on its natural output.

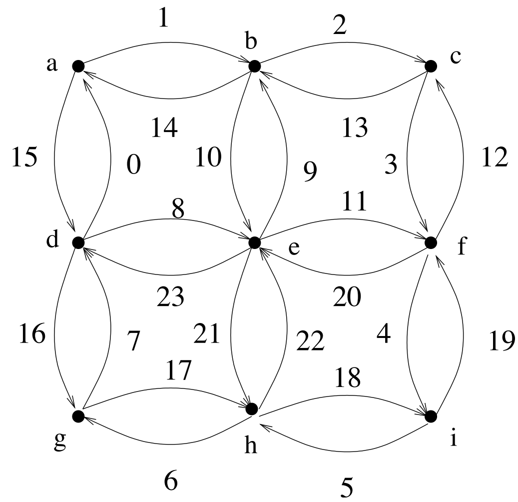

Fig. 3. An Eulerian tour $\mathcal{C}$ of the 3x3 grid, the arcs are labeled according to the ordering along the tour

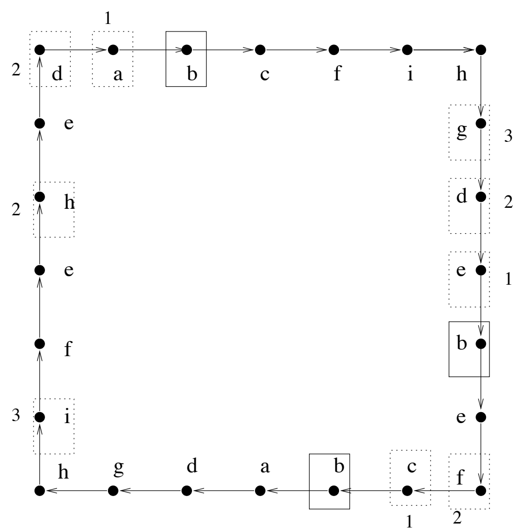

Fig. 4. Results of the computations of $IS_{\mathcal{C}}(u, b)$

Let us give an example, based on figures 3 and 4. Consider the situation where the message is alone in the network and must go from vertex g to vertex c. At the first step, the routing function chooses the shortest portion from g to c, that is the outgoing arc 7 of g. At vertex d, the shortest Eulerian portion to c is $[0, 1, 2]$. The length is 3 that is the distance from d to c in the graph. Now, at each following step the shortest portion will be $[1, 2]$ and $[2]$.

In case of many messages, the router have to choose a route for each message. The decision will be taken according to the following method (uniformly described here): at each step, for each incoming message, we associate a set of output links weighted by their relative distance (on the Eulerian tour) to the destination. We can model this scheme by a bipartite graph where the two sets of nodes represent the input links and the output links. There exists an edge between an input link and an output link if the message incoming from the input link can use the output link to reach its destination. Each edge is weighted by the relative distance to the destination. We compute a minimum weighted matching, that give an output for each message. Some of us have proved in [11] that these weights imply that a shortcut is accepted if it shorten the distance for all the packets to be routed.

If during the transport, all the shortcuts are refused, then the packets follow the Eulerian cycle and we get the same ending guarantee we have in pure Eulerian routing. Shortcut routing provides an ending guarantee equals to $EndG_{\mathcal{C}}$.

A. Shortcut diameter

Given an Eulerian circuit $\mathcal{C}$ in a target graph G, we have seen that one main characteristic of $\mathcal{C}$ about routing is the stretch related to the end guarantee. Since the routing algorithms we consider here use shortcuts, we have also to consider the theoretical performances of $\mathcal{C}$ about shortcuts, i.e., the maximum length of a path used by a packet in the network if at each step it can use the better shortcut.

The shortcut distance from a vertex u to the vertex v in $\mathcal{C}$ is defined by :

$$Sd_{\mathcal{C}}(u, v) = \begin{cases} 0 & \text{if } u = v, \\ 1 + \min_{w \in Out(u)} Sd_{\mathcal{C}}(w, v) & \text{otherwise} \end{cases}$$

where $Out(u)$ is the set of neighbors of u in the graph. The shortcut diameter $Sd_{\mathcal{C}}$is the maximum measure over all OD-pairs. Given a graph G and an integer k we conjecture that the problem of knowing if there exists an Eulerian circuit $\mathcal{C}$ in G such that $Sd_{\mathcal{C}} \leq k$ is NP-complete. It seems thus difficult to obtain such an Eulerian circuit such that $Sd_{\mathcal{C}} \equiv D(G)$.

Thus, we have mainly focus on the square mesh (see also next paragraph). We have proved in [11] that $Sd_{\mathcal{C}}$ in a square mesh is optimal, i.e. equal to the classical diameter of the graph. Moreover, the average shortcut distance in such a mesh is also closed to the shortest paths as shown on Figure 5. These measures show that if a packet is alone in the network, it can take a shortcut in each router and then it arrives to its destination using a path that is closed to a shortest path.

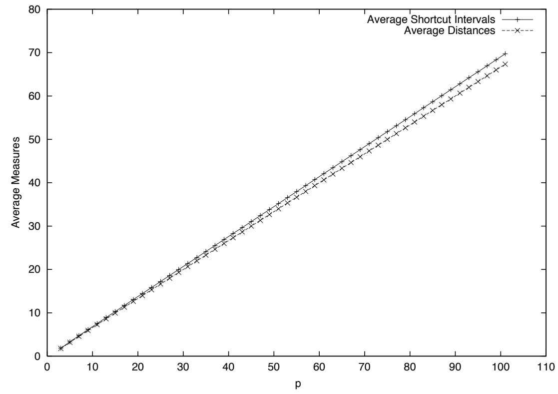

Fig. 5. Comparison of average distance and average short cut distances in $p \times p$ meshes

At end, note that from some theoretical and simulation results we have obtained, it seems to be difficult to obtain in the mesh an Eulerian circuit being (near) optimal both for the ending guarantee and for the shortcut diameter.

B. Application on the 2D-mesh

In the following we consider the square *2D-mesh* $N \times N$ network which seems to be an enough realistic network topology [10]. We also assume that the link capacity is only 1. Of course, real networks will have a much larger link capacity. This restriction is only made to allow the comparison of routing algorithms. Note that this model is also useful for the analysis of networks where wavelength converters are not allowed. It has been proved in [4] that, for a $N \times N$ 2D-mesh the stretch of an Eulerian circuit lies between $2N(N - 1) - 1$ and $4N(N - 1) - 3$.

We now describe the Eulerian circuit we used for our simulations. This Eulerian tour starts from the central vertex X, then goes to part 1, part 2, part 3 and ends using part 4. In each part, the order of edges are shown on figure 6. The generalization of this scheme is easy in every square mesh $N \times N$ with N odd. This Eulerian circuit was studied in [11] and it shows good performances for the *shortcut* Eulerian routing.

It has been previously shown that $EndG_{\mathcal{C}} = 4N(N - 1) - 2N + 1$ for this circuit. The Antenna Eulerian circuit merely reaches the upper bound of the stretch parameter.

III. Performance Evaluation

For the sake of concision, we restrict ourselves here to the presentation of results for two simple traffic matrices,

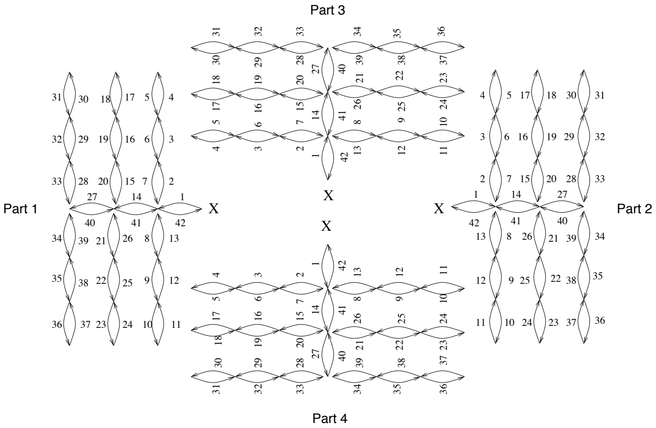

Fig. 6. Antenna Eulerian in a 7×7 square mesh.

even if the simulator design allows much more general traffic description. We always assume Poisson arrivals of packets and an uniform traffic for source among the nodes of the networks. We model uniform traffic (all the destination have the same probability) and the hot stop traffic we have already mentioned in the introduction (90% of the traffic to a set of nodes in the center of the grid and the remaining 10% uniform among the whole set of nodes). In the following, the load will denote the global arrival rate from the outside for the whole set of nodes.

A. Simulator design

We have designed the simulator with QNAP II modeling tool [17]. Objects represented in QNAP are queues and customers. Every switch is modeled by two queues: one for the packets present in the optical part of the network and the other one to store the packets at the interface which wait to enter the optical network. The source, destination, hop count, time and statistics are carried by the customers. The simulator reports statistics about the queue utilization and the customers sample-paths: mean delay to enter the network, switch utilization, distribution of the transport delay. The confidence intervals for the means are computed but they are not depicted in the figures as they are generally smaller than 1 percent. Note that as the destination of the packet is carried by the customer, we can model different types of traffic, even if we do not report all of them here due to the size of the paper.

B. Maximal Throughput

Using Little's formula, we can obtain an upper bound for the average throughput using some simulations. Indeed, let λ be the arrival rate of packets at the interfaces, if the system is stable, λ is also the rate of packets entering the optical part of the net from the interfaces.

Now, let X be the average number of optical packets inside the optical part of the network (we do not take into account the packets waiting at the interfaces), and let T be the average transport time. Little's formula states that : $X = \lambda T$.

As each link has capacity 1, X is smaller than the number of links in the mesh (i.e., $4N(N-1)$). And clearly, the average transportation delay T is a function of λ and other parameters such as the traffic matrix and the Eulerian cycles used in the routing. However, we fix all the parameters except λ to study the upper bound of the throughput for a given matrix traffic and Eulerian cycle. Thus,

$$\lambda \leq \frac{4N(N-1)}{T(\lambda)}.$$

We also assume that function $T(\lambda)$ is non decreasing. Remember that λ is one of the simulation parameters and $T(\lambda)$ is estimated by simulation. When the product $\lambda T(\lambda)$ is larger than $4N(N-1)$, the network is not stable anymore because the offered traffic is larger than the network capacity. This critical value of λ provides an upper bound of the maximal throughput.

But Little's formula also gives some information on the ideal throughput we may obtain on such a grid. Indeed the average transport delay is always larger than the average logical distance using shortest paths. Here, we consider a 2D mesh with N^2 nodes. We assume that the source and the destination are uniformly distributed among the nodes. Under these assumptions, we can easily obtain the average physical distance: $2N/3$. Thus, for uniform traffic and any routing algorithm

$$\lambda \leq \frac{4N(N-1)}{2N/3}.$$

Clearly, this idealistic upper bound for the throughput in a grid for all routing mechanisms and uniform traffic is $6(N-1)$.

C. Simulation Results of Uniform Traffic

First, let us now consider the evolution of the transportation time when the load increases in the net. Remember that the load is the average number of packets arriving to the whole set of nodes. At very light load, a packet is often alone in a switch. Thus the probability of accepting the shortcut is almost 1 and the packets often use a shortest path. The distribution of distance is very closed to the physical shortest distance (see for instance in Fig 7 the distribution of delay for a 7x7 grid at light load, heavy load and the distribution of physical distance).

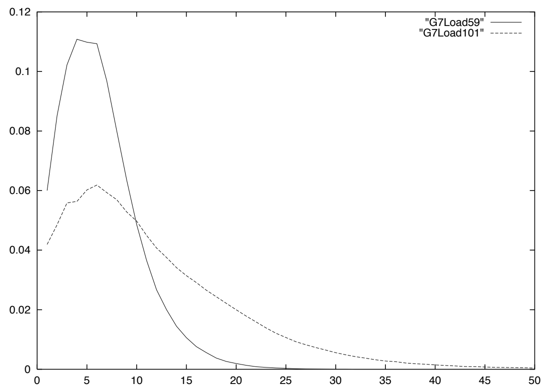

Fig. 7. Distribution of delay for the 7x7 grid with uniform traffic at light load and heavy load and distribution of physical distance

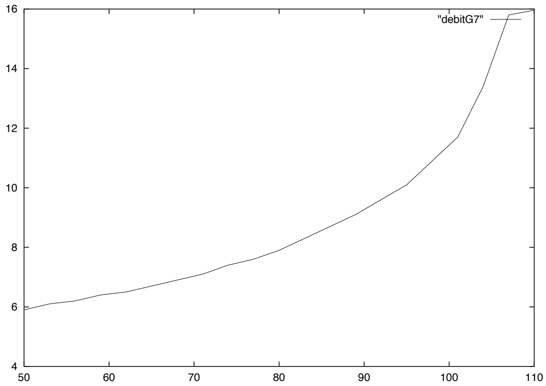

Fig. 8. Delay versus load in a 7×7 square mesh with Shortcut.

When the load increases, this probability of accepting the shortcut decreases. Remember that all the packets must receive a better path to accept a shortcut. If the number of packets is large it is more probable that a packet disagrees on the shortcut and imposes to all the packets to continue on the Eulerian cycle. Thus, as depicted in 8 the transportation delay increases when the load increases. And the distribution of delay changes when we increases the load (see Fig 7). This is a clearly different of pure Eulerian routing. In [3] we have shown that the average transportation delay for pure Eulerian routing does not depend of the load.

When we consider a largest network size (11x11 instead of 7x7), the results look similar. The transportation delay increases when the load increases and the distribution of transport delay evolves from the physical distance distribution to a distribution with a heavier tail. The network saturates when the load reaches 14.4 packets per slot. This is much better than the pure Eulerian routing where we have found a maximal throughput roughly equals to 4 packets per slot [3]. It is also much less than the deflection routing where we can observe

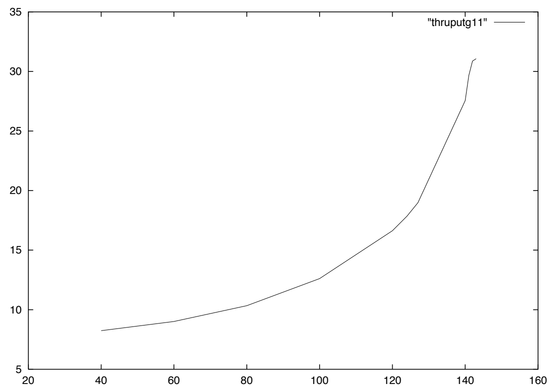

Fig. 9. Delay versus load in a 11×11 square mesh with Shortcut and uniform traffic.

a maximal throughput larger than 32 packets per slot [5]. However, the high throughput for deflection routing disappears when the traffic becomes non uniform.

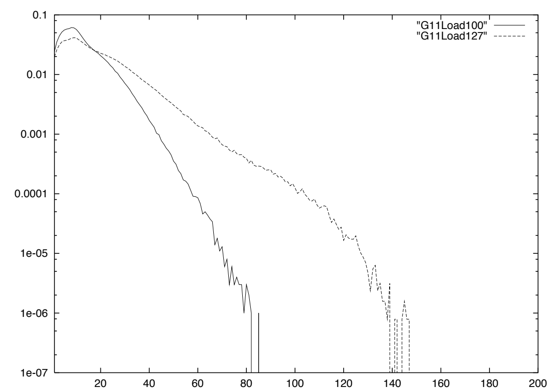

Fig. 10. Distribution of delay for the 11x11 grid with uniform traffic with light and heady load, log-scale

Finally we must remark that even if the guarantee is roughly $4N^2$ the largest delay experienced by the packets during simulation is much smaller than the theoretical guarantee (roughly $4N^2$). Of course, we may expect that packets with significant larger delays are quite rare but it also suggests that it may be possible to improve the theoretical deterministic guarantee or to give a stochastic guarantee (see for instance [16] to show how the stochastic bounds can be more accurate than usual Network Calculus deterministic bounds when we analyze waiting times with Fair Queuing disciplines).

D. Non Uniform Traffic

We now consider another traffic matrix we have already mentioned in the introduction. The source are uniform but the destinations follow a a "hot spot" distribution: 90% of the traffic are destinated to a set of nodes at the center of the grid and the remaining 10% are uniformly distributed among all the nodes of the grid. The size of the "hot spot" set depends of the size of the network. For a 7x7 grid, we consider a 3x3 square while for a 11x11 grid the hot spot size is 5x5.

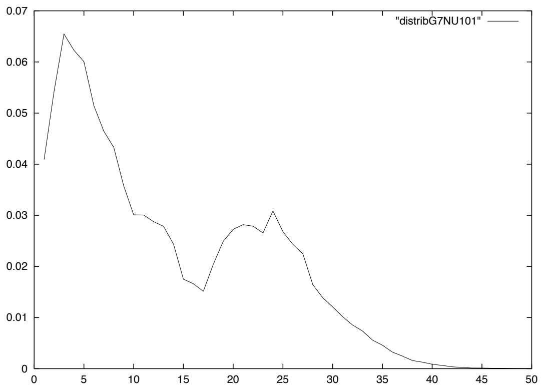

Fig. 11. Head of the delay distribution for the 7x7 grid with non uniform traffic, Heavy load

For every example, we give the head and the tail of the transportation time distribution in two figures to provides more information.

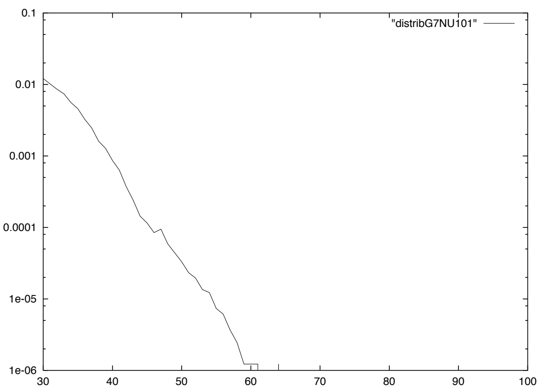

Fig. 12. Tail of the delay distribution for the 7x7 grid with non uniform traffic, Heavy load, Log-scale

First we consider a $7x7$ grid in figures 11 and 12. The network is heavily loaded (an average of 10.1 packets per slot for the whole set of 49 nodes). It is worthy to remark that the distribution has two modes and is clearly different for the distribution depicted in figure 7 for the same load and an uniform traffic. It is also very interesting to note that the largest delay experienced by a packet is smaller when the traffic is not uniform. Of course the guarantee is the same for all types of traffic and simulation results about the tail of a distribution are not very accurate but again this suggests that we may obtain tighter bounds using stochastic bound techniques.

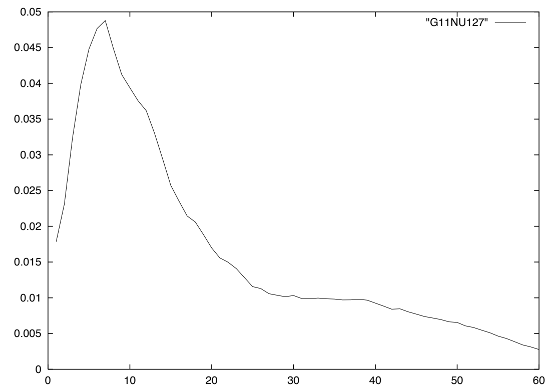

Fig. 13. Head of the delay distribution for the 11x11 grid with non uniform traffic, Heavy load

Then, we present the results for a larger network (a 11x11 mesh) for two arrival rates: 12.7 (heavy load) and 14.0 (the network is saturated).

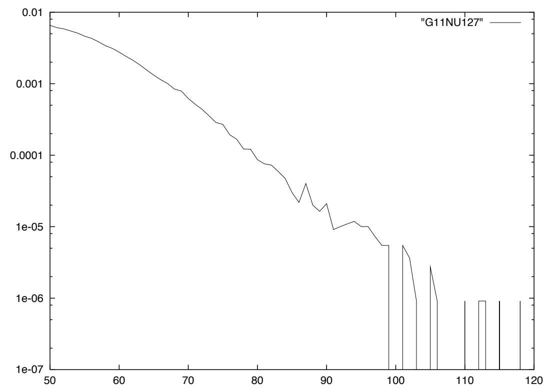

Fig. 14. Tail of the delay distribution for the 11x11 grid with non uniform traffic, Heavy load, Log-scale

In both cases, we observe that the maximum delay is again much smaller than the guarantee (419 hops for a 11x11 mesh with Antenna).

And the network is saturated for a load of 14 packets per slot. This maximal throughput for the non uniform matrix is roughly the same we have found for uniform traffic. Unlike deflection routing, the Eulerian with shortcut routing provides almost the same throughput when the traffic becomes non uniform. At least the experiments we have done have shown that the variation of the throughput is very small.

IV. Conclusion

In this paper, we have studied the performance of a recently proposed routing algorithm for optical packet switching. It is based on an Eulerian tour where packets can use shortcuts when all of packets in the switch

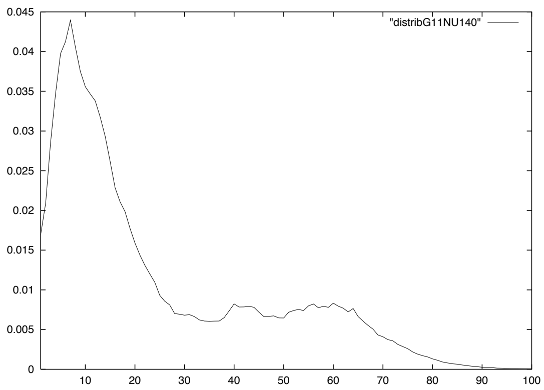

Fig. 15. Head of the delay distribution for the 11x11 grid with non uniform traffic, Saturation

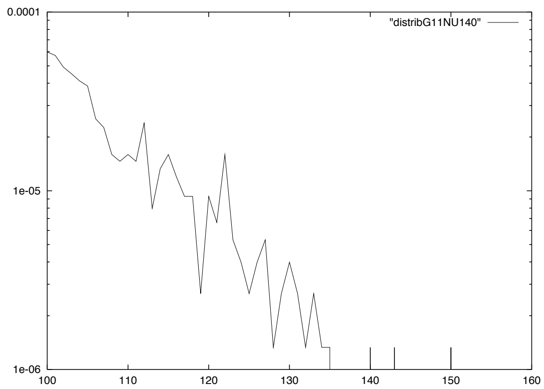

Fig. 16. Tail of the delay distribution for the 11x11 grid with non uniform traffic, Saturation, Log-scale

agree. This new algorithm provides a larger throughput than pure Eulerian routing and the same ending guarantee, a very important feature which is not achieved by deflection routing. The packets with a significant number of deflections are a real problem because they are considered as lost due to large delay and they increase significantly the loss rates at heavy load with unbalanced traffic.

Unlike Deflection routing, shortcut routing looks to provide the same throughput for uniform and non uniform traffic, again a very nice property. Further studies are still necessary to prove better performance guarantee.

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