"VERNE": New Packet-Optical Network for Optically Transparent and Lossless Data Centers

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***Abstract*—Further growth of data centers is asking for scalable, low latency and cost efficient interconnection network inside data centers. In this paper, we propose a new packet-optical network called "VERNE", aiming to satisfy the above requirements by exploiting all-optical and "lossless" operation (by "lossless" we mean operation without packet collisions during their transport from source to destination). The VERNE's network and switching node architecture are detailed for the first time, and the numerical evaluation of the VERNE solution w.r.t. traditional data center architectures is provided. The results suggest that VERNE significantly reduces the number of optical transponders required for data center operation.**

***Index Terms*—Packet-optical switching, network and node architecture, data centers, intra-connection, optical network slicing.**

I. INTRODUCTION

Packet-optical networks employing optical grooming and switching of packets in the optical domain (i.e. "optical packet switching" or "optical burst switching" networks) are considered by many to be a viable alternative for data center intra-connection. Indeed, although widely accepted for their high bisection bandwidth and limited latency, the Ethernet based data centers suffer from limited scalability of high-radix electronic switches [1] and from very high power consumption and cost [2]. Future data centers shall be cost efficient, scalable and have guaranteed latency, because of the emerging Internet of Things (IoT) applications, such as autonomous vehicles and medical applications. The strict latency requirements are also driven by the expected performance of 5G network.

There are many optical packet/burst switching technologies, previously considered for the metropolitan and aggregation network segment ([3] provides an overview of such solutions). Optical packet/burst switching has been considered more recently as a candidate for data center solutions, e.g. see [2], [4]- [6]. For data center intra-connection there are also hybrid solutions, for instance those that combine optical packet switching and optical circuit switching [7], [8]. The optical circuits are introduced usually to provide a quick, optical "bypass" between different groups of end hosts, in order to offload large traffic flows from the main switching elements, and consequently to improve the latency and preserve the Quality of Service (QoS) of Ethernet traffic.

The advantage of the previously proposed solutions are usually in their lower cost and/or reduced energy consumption when compared to Ethernet intra-connection based data centers, mainly because costly and energy consuming Optical-Electronic-Optical (OEO) conversion of transit traffic is removed from the network. However, note that most of these solutions still use to a certain extent the OEO conversion of traffic or have a limited scalability [4]. Furthermore, the contention is a very important problem in optical packet switching networks (for instance, see [7], [8]).

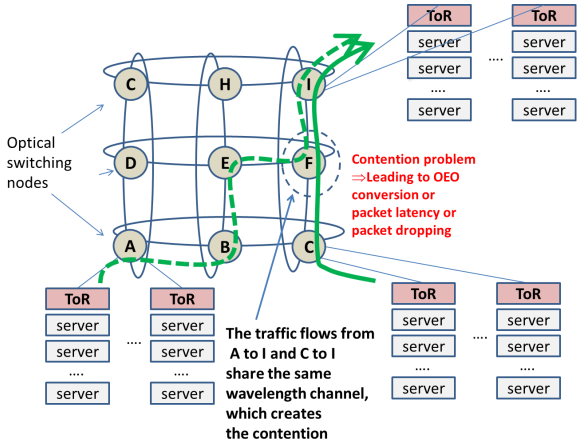

Fig. 1. State of the art: hybrid optical packet/circuit switched network for data centers

Obviously, the technical difficulty is to build the packet-optical network that would fully benefit from: 1) the optically transparent operation (i.e. operation without OEO conversion), 2) easy scalability and 3) absence of packet loss in the transit path due to contention ("lossless" or "contention-less" operation). In attempt to assess the previous technical challenge, the present paper proposes for a first time a new packet-optical network and its corresponding switching node architecture aiming to enable full optical transparency, scalability, low cost, low energy consumption and low latency. The proposed network is called "VERNE" and employs switching of packets in optical domain and optical traffic grooming. VERNE stands for "Virtual, fully transparent, cost and enERgy efficient NEtwork".

The paper is organized as follows. Section II reviews the related work on optical packet switching networks for data centers. Section III proposes the original VERNE network and node architecture and explains the operation mode of VERNE network. Section IV provides the numerical evaluation of the cost and performance benefits of VERNE network. Finally, Section V draws the main conclusions.

II. RELATED WORK

Data centers proposed in [7] and [8] employ both optical packet and circuit switching. Both solutions allow the collisions of once inserted packets. In another words, the packets that are inserted in the network can be lost.

To illustrate the network behaviour with potential packet losses, in Fig. 1 we illustrate the packet collision scenario for data center networks based on torus interconnection. The network inter-connects the optical switching nodes, and both packet and circuit switching are allowed. We suppose that each optical node (marked with a letter from "A" to "I" in Fig. 1) is connected to a high number of data center end hosts (the servers are connected to optical nodes via Top of Rack, "ToR" switches).

In presented example, the wavelengths and fibers are shared by different traffic flows, and traffic insertion is not synchronized, so the contention is still possible. Contention leads to a bandwidth waste and a perturbation of QoS. For instance, if optical circuit from C to I and packet flow from A to I share the same wavelength on link F to I, the signal contention can occur at node F. The collided optical packets can be rerouted, delayed or even discarded, depending on the situation (e.g. see [7]).

Optical solution proposed in [4] is all-optical and has an efficient centralized scheduler, but it exploits a wavelength based routing, which can potentially limit the maximum network size.

The VERNE solution, as we are going to show, is designed to completely remove the OEO conversion from the network, to minimize the number of transponders (optical interfaces). Indeed, in VERNE network all transponder capacity is used for client traffic insertion/extraction and no transponder capacity is used for transit traffic.

III. ARCHITECTURE OF THE VERNE NETWORK

A VERNE network consists of a set of "VERNE nodes" which are interconnected through a set of disjoint **virtual optical buses** (or rings) in a fully transparent manner. The buses are virtual since they can be reconfigured when needed and can be "virtually" installed over the given physical topology. VERNE nodes belonging to the same virtual bus employ optical packet switching, communicating synchronously over that bus. The idea is that each destination shall be reachable within a single optical hop, from any source. This system reminds to a metro system of a large city, where each destination has a direct line to each other destination. The fact that routing is static differs our solution from those using convergence or Eulerian routing (e.g. see [9]).

In Fig. 2, we illustrate a VERNE network interconnecting 9 nodes, with supposed reach limit of 7 nodes[1] (meaning that in this example optical signals can traverse transparently a maximum of 7 nodes to satisfy the quality of signal requirements at the reception side). The reach limit determines the maximum bus length. Note that reducing the reach limit increases the number of virtual buses required to assure full network connectivity. The virtual buses can be also implemented over a given fiber mesh topology, as illustrated in Fig. 3.

Three versions of VERNE network are possible, w.r.t. the network synchronization choices:

1) **VERNE I** or **"synchronous"**: each virtual bus is synchronous in operation, but different virtual buses are not synchronous between themselves. This variant of the solution allows a cheap, efficient and simple network. The network is lossless in operation and the transponders are dedicated to each bus.
2) **VERNE II** or **"fully synchronous"**: each network bus is synchronous, and all network buses operate synchronously between themselves. In another words, the operation of the entire network (insertion/extraction of optical packets) is synchronous. Thanks to the synchronous operation of the network, the number of needed wavelengths/fibers and transponders in the network can be further reduced, comparing to "synchronous" solution, because different buses can share the same transponders.
3) **VERNE III** or **"asynchronous"**: no synchronization is needed in the network. The network has a centralized dynamic scheduling, and a centralized routing point. Network with centralized routing topology can achieve 100% throughput efficiency, by using e.g., the scheduler similar to those proposed in [4], that is highly efficient in use of transponders.

VERNE node architecture is illustrated in Fig. 4. The node incorporates a photonic layer and an electronic layer. Basic functionalities of the photonic layer are:

1) The extraction of optical packets that have reached the node at one of its inputs. The optical packets are carried via the virtual buses in the form of the optical data streams. To receive the packets, the optical data streams are directed to the node receivers[2] after a demultiplexing stage.
2) The optional blocking of packets that have already been received by the node. The blocking is achieved by using the packet gates. The transit packets pass through the node in a transparent manner (without the OEO conversion).
3) The establishment of virtual buses, thanks to the node's switching stage. This stage enables the redirection of pre-established optical data streams from the inputs towards the outputs, creating in this way virtual buses between the nodes, through a physical, fixed network. Note that the buses are reconfigurable and can be used to enable the function of the optical network slicing (the "optical network virtualization").
4) The insertion of optical packets, coming from the transmitters, into different virtual buses (optical data streams), prior to the node's multiplexing stage.

The electronic layer is in charge of the optical packet assembly, the optical packet de-assembly, scheduling and medium access control (MAC), the synchronization and control of all node functionalities.

VERNE's configuration is highly generic because VERNE node deals with different kinds of input/output optical medias

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[1] The reach limit of 7 nodes is used as an example, and it is not a general physical limitation of the VERNE technology.

[2] A transponder is a pair of a transmitter and a receiver.

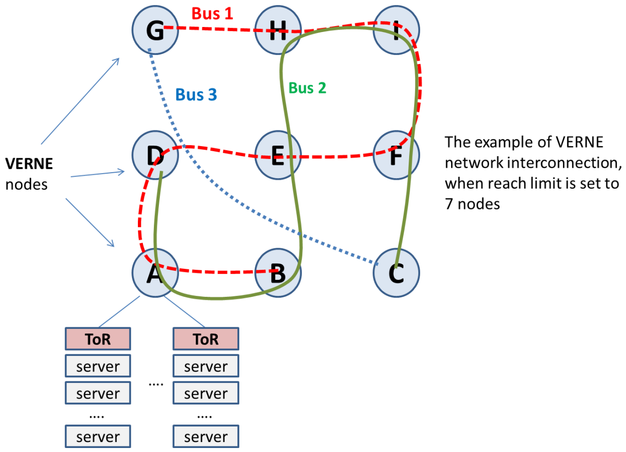

Fig. 2. VERNE Network of 9 nodes, with reach limit set to 7 nodes

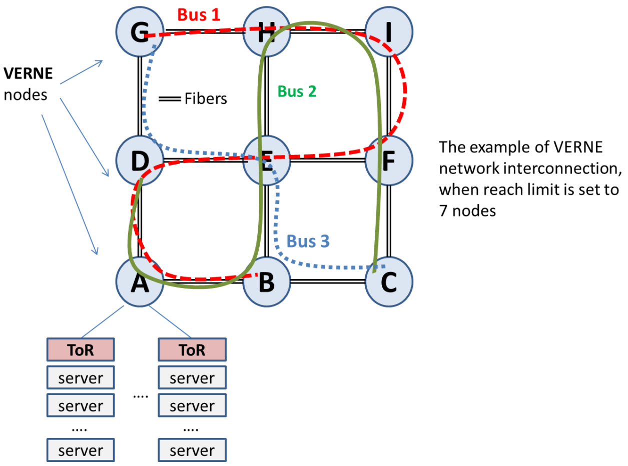

Fig. 3. VERNE Network of 9 nodes, with reach limit set to 7 nodes implemented over a given fiber mesh topology.

(I/O) and different types of virtual buses, for example:

1) If I/O is based on the use of standard Single Mode Fibers (SMF) or standard Multi Mode Fibers (MMF), then a virtual bus corresponds to a particular wavelength or a wavelength group.
2) If I/O is based on the use of multi-core fibers, then a virtual bus corresponds to a core, a wavelength group in a core, etc.
3) If I/O is based on the use of Few-Mode Fibers (FMF), the virtual bus can be a mode, a wavelength group in a mode, etc.
4) Finally, if I/O is based on the use of fiber ribbons, the virtual bus can be a single fiber, a wavelength group in a fiber, etc.

A possible realization of the photonic layer of a VERNE node is shown in Fig. 5. The dropping is performed by optical splitters (this way all signals from each input are dropped and distributed to all receivers (RX) connected to that input). Packet gates can be realized as “packet blockers”, such as those proposed in [10]. Such components perform demultiplexing, packet blocking of any demultiplexed wavelengths and remultiplexing. This device could handle several buses at the same time. Please note that packet blockers are optional for VERNE I and II. They are not used in the variant III of the solution, because the centralized scheduler guarantees the network resource efficiency.

Next, from Fig. 5 we can see that the outputs of packet blockers feed the inputs of a 2x2[3] photonic switch (PS) [11], which has different functionalities : redirecting or switching of any wavelength or any packet of any input towards any output, managing the power of the packet flow in order to guarantee the cascade and preserve the OSNR degradation. Optical splitters are used to add packets from the transmitters (TX) connected to each output (or input of the PS; notice that TXs can be placed before or after the PS).

For receivers and transmitters, both coherent and non-coherent technologies could be used, and also both fast-wavelength tunable and non-tunable transponders can be used.

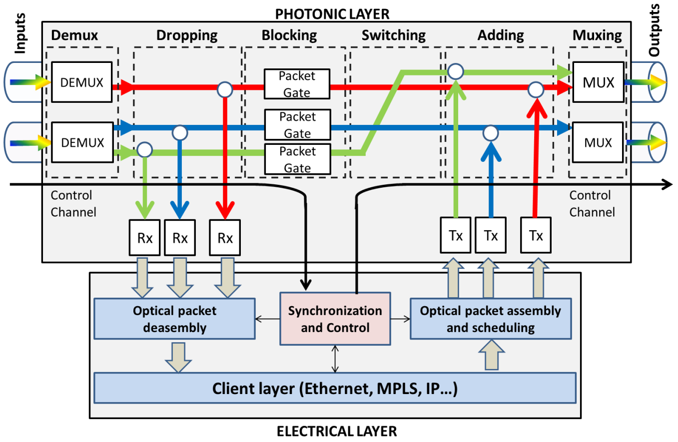

Fig. 4. Architecutre of the VERNE node.

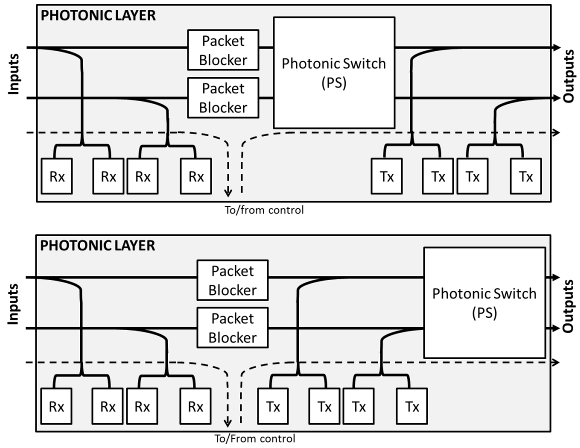

Fig. 5. A possible realization of a VERNE node. Notice TXs can be placed before or after the PXC. Packet blockers are omitted in the asynchronous variant of the solution.

Since each bus is synchronized, in the following we assume that optical packets are assimilated to fixed time slots (typically lasting few μs). If used, the packet blockers allow the time slot reuse on the same bus, by the intermediate nodes between the source and destination.

Each virtual bus has its dedicated control channel, which

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[3] Switch size is $m \times n$ in general case.

provides the information relative to each time slot to enable optical switching operation. In Fig. 5, the control channel could be a dedicated input/output or could be multiplexed within the other inputs/outputs.

IV. BENEFITS OF VERNE DATA CENTERS

In the following we discuss and evaluate the advantages of data centers using VERNE technology.

A. Low network cost

Thanks to its full optical transparency, VERNE efficiently uses the network resource, e.g. the transponders (TRX). Indeed, in VERNE, a direct optical bus exists between any node pair, and OEO conversion is eliminated from the network. Since transit traffic is never converted to electronic domain, the number of electronic buffers, electronic switching matrices and transmitters is minimized. We consider two scenarios for evaluating the transponder savings.

1) Scenario 1: We calculate the number of TRX for VERNE and Ethernet Fat-Tree data center, operating without the oversubscription. The total number of servers $SERV_{total}$ is given, each of which is equipped with $C_S = 10$ Gbit/s interface (when comparing different technologies, the server interfaces are not accounted for). With $SERV_{node}$ we note the number of servers per single VERNE node, which is also a given parameter.

For Ethernet we suppose that switch interfaces have data rate of 100 Gbit/s. For simplicity, we suppose that the switch ports used at client side are connected to 10 servers of rate C_S. Let k be the number of switch ports in Ethernet Fat-Tree (see [12]). Then, total number of connected servers $k^3/4$ is equal to $\lceil n_{ser}/10 \rceil$ and for such k, the total number of interfaces in the network is: $TRX_{ETH} = k^3 - k^2$.

For VERNE network, we suppose that each bus has its dedicated transponders, that are either:

- standard 100 Gbit/s transponders, like in Ethernet Fat-Tree network;
- elastic transponders [6], operating at rates in set $\{100, 150, 200, 250, 300\}$ Gbit/s, that are achievable with reach limit of $\{145, 62, 50, 20, 9\}$ optical nodes, respectively. The reach limit of the transponders comes mainly from the optical filtering [5]. Let V be the time-averaged data rate of such elastic transponder. For each destination of a given TRX at source, the maximum available rate is used, during a period of time adjusted to provide the same average rate received at each destination. It can be easily shown that the resulting time-averaged rate sent by a TRX is then:
$$V = \frac{\sum_i N_r(i)}{\sum_i N_r(i)/B_r(i)}, \tag{1}$$
where $N_r(i)$ is the number of nodes of group i, such that the nodes belonging to the group i can be reached with the same data rate $B_r(i)$.

Let S the total number of VERNE nodes in the network. Obviously: $S = \left\lceil \frac{SERV_{total}}{SERV_{node}} \right\rceil$.

Let L be the virtual bus length (i.e. the number of destinations that can be reached by a bus). Let N_{bus} be the number of buses leaving from each VERNE node (we suppose a symmetric solution, where N_{bus} is the same for all VERNE nodes). For each bus, VERNE node is connected to L destinations. In order to reach its $S - 1$ destinations, it must be: $L * N_{bus} \geq S - 1$. Since $L \leq S - 1$, we have: $N_{bus} = \left\lceil \frac{S-1}{L} \right\rceil$.

The total traffic sent by a single node is $SERV_{node}C_S$, resulting in the total needed number of transponders per single node: $N_{bus} \left\lceil \frac{SERV_{node}C_S}{N_{bus}C_{trx}} \right\rceil$, where C_{trx}, the "transponder capacity", is the "time-averaged" TRX capacity V (as previously defined). The total number of transponders in VERNE network is[4]:

$$TRX_{VERNE} = SN_{bus} \left\lceil \frac{SERV_{node}C_S}{N_{bus}C_{trx}} \right\rceil. \tag{2}$$

For VERNE we suppose $L = 20$ resulting in $C_{trx} = V \approx 270$ Gbit/s and $SERV_{node} = 1000$.

The comparison results are summarized in Fig. 6, for different values of total server number, $SERV_{total}$. This figure shows that the number of TRX in VERNE is up to 10 times smaller than in an Ethernet Fat-Tree data center. The savings are greater when elastic TRX are used. For 100 Gbit/s transponders, the savings of the VERNE network go up to 4 times in number of interfaces.

2) Scenario 2: In this scenario, we compare VERNE with data center based on electronic packet switched 2D torus, e.g. employing the Ethernet switching. Torus data centers are typically used for High-Performance Computing (HPC) applications. The 2D torus that is observed is composed of the unidirectional rings and is "symmetric" (as in Fig. 1), meaning that the number of switching nodes in horizontal and vertical dimension of torus is equal and noted with N. We suppose an uniform and a symmetric traffic matrix, where each node sends the same amount of traffic (noted with a) to any other node.

Next, in the electronic 2D torus, the shortest path routing is adopted. When changing the ring, each traffic flow travels via a horizontal ring (Fig. 1) until it reaches the destination belonging to the vertical ring of its destination. This way of routing minimizes the number of OEO conversions in torus. By accounting for all connections of a single torus switch (in transit, sent and received), it can be shown that each electronic switch sends the traffic of $\frac{N^2}{2}(N-1)a$ on a horizontal ring, and the same amount of traffic on a vertical ring. The total number of TRX required by N^2 nodes in electronic switched torus is then: $TRX_{torus} = 2N^2 \left\lceil \frac{N^2(N-1)a}{2C_{trx}} \right\rceil$.

For VERNE network, the total traffic sent by a single node is $(N^2 - 1)a$, resulting in the total number of TRX in VERNE

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[4] Note that $\left\lceil \frac{SERV_{node}C_S}{N_{bus}C_{trx}} \right\rceil$ in eq. (2) is equal to the number of transmitters needed per bus and per node in VERNE network. The number of receivers per bus and per node is equal to $\left\lceil \frac{SERV_{node}C_S}{N_{bus}LC_{trx}} \right\rceil$. Since number of TRX is equal to the maximum number of its transmitting or receiving parts, and the latter expression is smaller than the former expression, we use the former expression for the eq. (2).

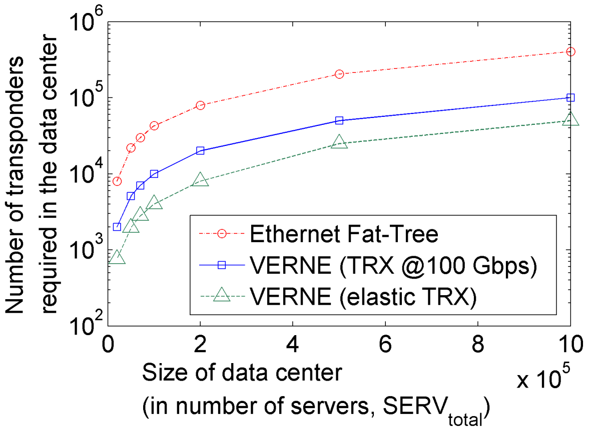

Fig. 6. The number of transponders in the VERNE network compared with the Ethernet Fat-Tree

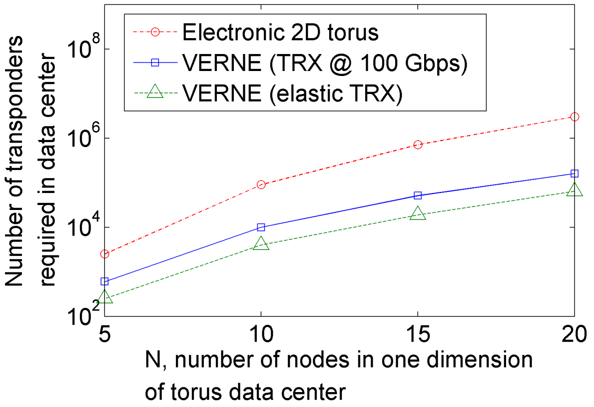

Fig. 7. The number of transponders in the VERNE network compared with the Electronic 2D torus

network of: $TRX_{VERNE} = N^2 N_{bus} \left\lceil \frac{(N^2-1)a}{N_{bus} C_{trx}} \right\rceil$.

The total number of transponders, needed by considered technologies is compared in Fig. 7, for $a = 100$ Gbit/s and $L = 20$. Both electronic 2D torus and VERNE use the same types of transponders as in Scenario 1. Fig. 7 shows that VERNE achieves significant TRX savings, going up to 2 orders of magnitude.

Since the TRX cost represents the important part of total network cost, in the following we are interested in the evolution of TRX cost savings for different network sizes. We take the results from the previous comparisons but only for non-elastic transponders operating at 100 Gbit/s, in order to get a fair cost comparison. Next, we define the cost saving ratio α as the ratio between the TRX number in Ethernet (or 2D torus) and in VERNE, i.e. $\alpha = TRX_{ETH}/TRX_{VERNE}$ (or $\alpha = TRX_{torus}/TRX_{VERNE}$).

The results for α are given in Fig. 8. Thanks to the all-optical operation of VERNE network, the amount of transported network traffic is reduced, which results in the lower cost of transponders. When VERNE is compared with Fat-Tree, the cost savings are independent of the network size, and are around 4 times. When compared with electronic 2D torus, the cost savings increase with the network size and go up to several orders of magnitude.

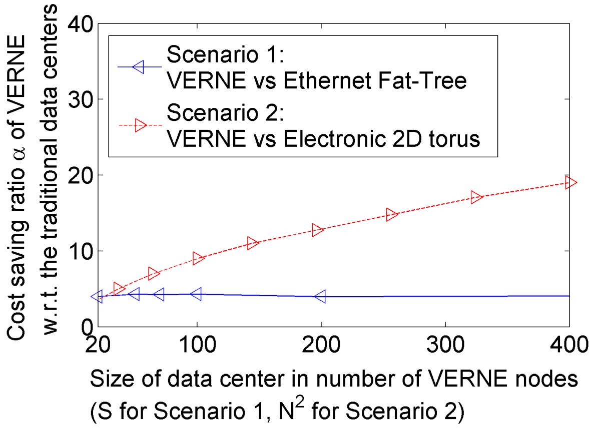

Fig. 8. The TRX cost savings of VERNE network

TABLE I
SOURCES OF LATENCY AND JITTER

	Ethernet	**VERNE I, II, III**
TRAFFIC INSERTION	YES	YES
TRAFFIC EXTRACTION	YES	YES
TRAFFIC TRANSIT (Eth.)	YES	n.a.
TRAFFIC TRANSIT OVER THE SAME BUS/RING	n.a.	NO
TRAFFIC TRANSIT WHEN CHANGING THE BUS/RING	n.a.	NO

B. Low energy consumption

To illustrate the savings in number of OEO conversions achieved by VERNE, let us consider the number of OEO conversions in the electronic 2D torus (for symmetric $N \times N$ torus). The number of OEO conversions (per traffic connection) in such a torus is as large as $N^2 \cdot (N^2 - 1) \cdot N$, where the formula is given in format: *number of sources*number of destinations reached with OEO conversion*average number of OEO conversions per source-destination pair.*

VERNE achieves a much better result by completely eliminating the OEO conversion, and has a significant potential for the energy consumption reduction. Indeed, by decreasing the needed network capacity, the size and the hardware requirements thanks to an all-optical operation, our solution is efficiently reducing the energy consumption in the network.

C. Low network latency and simple scheduling

Since the transit traffic is never queued in our solution, the end-to-end latency of the VERNE network originates from the insertion and extraction process, but not from the queueing and reinserting of the traffic at intermediate nodes. The main sources of latency and jitter of VERNE and Ethernet Fat-Tree are compared in Tab. I[5].

The latency due to the insertion process in VERNE can be efficiently limited by a proper network dimensioning. In addition, the scheduling is very simple when all the destinations on a VERNE bus share the available resources (e.g. wavelengths). In such cases, scheduling can be modeled by a simple First In First Out (FIFO) queueing process.

As an example, we consider the time-slotted VERNE network in a form of ring of size R. We suppose that the VERNE ring is equipped with single TRX per source, and

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[5] Optical fiber propagation latency is not considered.

TABLE II
USE OF PACKET BLOCKERS

	VERNE I	VERNE II	VERNE III
YES			
NO			X
OPTIONAL	X	X	

has $n = 4$ wavelength channels, shared at the reception by all destinations[6]. The packet insertion process can be modeled with FIFO queues. For simplicity, we suppose that the packet arrivals and the service times follow the Bernoulli's process, leading to the Geo/Geo/1 queueing model of the system (this assumption is true if traffic is not too bursty). Let λ be the probability of traffic arrival, and μ, t the probabilities of single wavelength availability (occupancy, respectively) in a time slot. Then, the average insertion latency δ (in number of time slots) in VERNE network is provided by the expression:

$$\delta = \frac{1-\lambda}{\mu-\lambda} = \frac{1-\lambda}{1-(t/n)^n-\lambda}, \tag{3}$$

under assumption that the TRX source performs load-balancing of (equally splits) the traffic over all the wavelength channels (leading to $\mu = 1-(t/n)^n$). For an uniform and a symmetric traffic matrix of amplitude a (a normalized to single channel capacity), we get: $t = \frac{(R-1)(R-2)a}{2}$. The results for average insertion latency are summarized in Fig.9, in function of the traffic intensity per source, $\rho = \lambda/\mu$. We see that the average insertion latency is limited to few time slots, even when the size of the ring (R) is 3 times greater than the number of available wavelength channels in the ring (n). The scheduling in VERNE in this example is simple and based on a simple FIFO queueing mechanism.

Note that the previous results can be applied to solutions VERNE I and II, which support distributed scheduling operation.

D. High network scalability and lossless operation

Since VERNE efficiently uses the network resources (as previously discussed) and is not restricted by a predefined topology or type of optical resources used for virtual buses, it can be highly scalable. Furthermore, the use of packet blockers in our solution is optional or not needed (Tab. II), which also simplifies the network and increases its scalability.

Finally, thanks to the physical separation of optical buses and use of the appropriate scheduling, the contention due to a simultaneous use of network resources does not exist in our solution, and the network is lossless in operation.

V. CONCLUSION

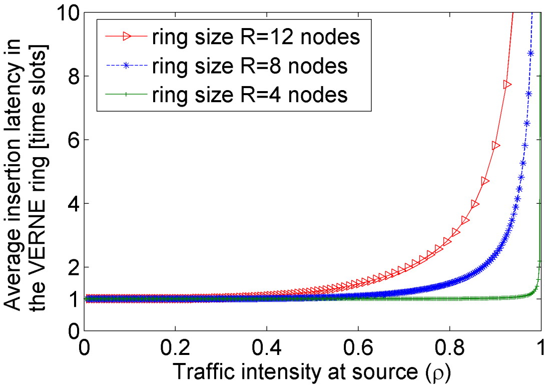

Fig. 9. Average insertion latency in VERNE ring in function of traffic intensity.

We propose VERNE, novel packet-optical data center that is scalable, and has a potential for enabling low cost, low energy consumption and low latency. The network comes in three flavors depending on how the network synchronization is handled. VERNE reduces the cost of transponders for approximately 4 times or for several orders of magnitude, when compared with a data center based on Ethernet Fat-Tree or electronic packet 2D torus, respectively. Because of its simple scheduling and synchronization, VERNE I is the most efficient option of VERNE solution. A more detailed cost and performance evaluation of the VERNE network are left for a future study.

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[6] Such receivers are called "WDM-receivers" and are studied e.g. in the ECOFRAME project (2007-2010) [13].