# Performance and energy efficiency analysis in NGREEN optical network

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***Abstract*—We model the end to end delay and energy efficiency in the optical network architecture NGREEN. As the architecture is based on an optical ring, the random part of the delay comes from the random times needed to build an optical container from arriving Data Units and the insertion of the optical container on the ring. We first build a DTMC (Discrete Time Markov Chain) to model the filling of the optical container with Data Units. We take into account a deadline (to have a small latency) and a constraint on a minimal filling of the container (to be energy efficient). We obtain through a numerical analysis using an ad-hoc algorithm we proved, the distribution of the container filling and the distribution of the time needed to build a container. Then, we use this distribution to model the inter arrival of optical containers at a station on the ring. Through simulations and numerical analysis of Markov chains, we obtain the insertion delays and the occupancy of the queue before insertion. The relevance of the paper is to propose a trade-off between energy efficiency and latency for both opportunistic and reservation insertion modes into the ring.**

## I. Introduction

The fifth generation of mobile networks technology represents wireless communication systems related with the enormous growth of data traffic, due to the number of connected devices and the popularity of some applications as video streaming, augmented and virtual reality, cloud gaming, smart homes, connected cars, and remote control of machines [1]. These applications have strict constraints such as ultra-low latency, ultra-high bandwidth, to ensure the delivery of real-time services. These requirements can be met by efficiently integrating heterogeneous wireless and optical network segments and massive computing and storage services, delivered by means of cloud computing.

The C-RAN (Cloud Radio Access Network) has been recently proposed [2]. Because of the stringent requirements (latency in the order of tens of milliseconds) of the several interfaces needed in C-RAN and the maturity and evolution of different optical network technologies, optical networks have been proposed to support interfaces between Remote Radio Head (RRH) and Base-band Units (i.e. BBUs) (front-haul network), among BBUs and between BBUs and their peering point in the mobile core network (back-haul network).

The NGREEN network takes advantages of several improvements of optical technology [3, 4, 5, 6]. First, for metro networks, it is now possible to synchronize entire networks up to nanoseconds. This enables architectures based on Optical Slot Switching (OSS) where packets circulate on specific time slots. Second, the use of WDM (Wavelength Division Multiplexing) packets allows some kind of optical parallelism. The introduction of parallelism in the optical processing has been considered as a powerful approach to reduce cost and energy consumption for optical systems.

The NGREEN project aims to design and validate a versatile network architecture with a scalable capacity, low cost and low energy consumption. For the performance point of view, we expect low latency and high utilization of the optical capacity. In OSS networks, the delay is due to the optical container construction and its insertion into the optical ring. Once the container has been emitted, it is never converted to electronic nor queued until its arrival to destination. The transportation time is only related to the distance (i.e. the length of the optical link) between source and destination.

In this paper, we study two parts of the network. The first one, is the mechanism used to fill the optical container with the electronic packets (i.e. IP or Ethernet) and the second one is the insertion node where the flows of optical containers are queued before being emitted on the ring. Here, we evaluate mathematically both mechanisms and the results from the filling process are used as an input parameter for the analysis of the insertion. Thus we do not need to make the typical assumption about Poisson arrivals of optical containers to the insertion node. The discrete distribution for the inter-arrivals of container is obtained through numerical analysis of the Markov chain and we found that it is quite different from a Poisson process.

The aggregation of several data units into optical container must have a deadline to avoid that some information wait too long during this first step. Adding a deadline which is triggered when the container begins to fill will help to keep the delay shorter. However it makes the container filling incomplete because the PDU (Protocol Data Unit) moves to the insertion node when the deadline occurs. This movement can also be triggered if the filling is larger than a threshold. Thus we have two mechanisms to study the trade-off between latency and energy consumption. Indeed, the energy needed is the same irrespective of the number of SDUs (Service Data Units) carried by the PDU, the optical container has a fixed size and padding is added after the filling to complete the PDU. Thus a shorter deadline and a smaller threshold make the container less energy efficient and reduce the delay. For the insertion of the PDU into the ring we analyze both the opportunistic and reservation mode, in order to compare the delays. In [7], two mathematical models have been proposed to compare these two insertion modes, by considering Poisson arrivals for the PDU. In our paper, we compute the distribution of inter-arrival time of the PDUs obtained from the filling process, in order to evaluate delays for the different insertion modes. We compute both insertion delays and end to end delays from SDU arrival to its depart from the optical ring.

The technical part of the paper is organized as follows. First, in section II, we present the model of a container filling with stationary batch arrivals of service data units which arrive according to a stationary batch process. We derive a Discrete Time Markov Chain (DTMC in the following) to represent the remaining time and the number of service data units still present in the container. We prove that this chain satisfies a property already studied by Robertazzi in [8]. All the directed cycles of the DTMC go through a single state. This property allows to compute the steady-state distribution very efficiently. We obtain the distribution of the PDU size when it is inserted on the ring and the distribution of the delay to fill a container and the delay between the release of two successive containers. Through these models we get the distribution of the delay between two successive arrivals of container at the insertion point on the optical ring which are used in Section III to perform extensive simulations of the ring. We compare distributions of delays for both opportunistic and reservation insertion mode, and we study in section IV the trade off between energy efficiency and delays. At the end, we finish with some remarks.

## II. Model for optical container filling

We first model the filling process (Fig. 1) to obtain the distribution of the real number of Service Data Units (SDU in the following) or the number of bytes in a Packet Data Unit (PDU, also denoted as an optical container) and the distribution of time between two successive releases of PDU. We build a PDU by aggregating various SDU like Ethernet frames. As mentioned previously, one must assume that a timer is associated to the filling process to avoid that a SDU waits too much. We also assume that a PDU which is almost full can be sent before the deadline, in order to be inserted in a free slot in the optical ring [6]. The time unit considered in our study is the time slot (see Section III for more details).

### A. Markov Chain model

We consider a discrete time model the time unit of which is the WDM slot duration. We assume that the SDU arrivals follow a stationary batch process called $A$. We also assume independence between the successive batches of arrivals. In Ngreen network [6] specifications, the optical container size is 12500 bytes.

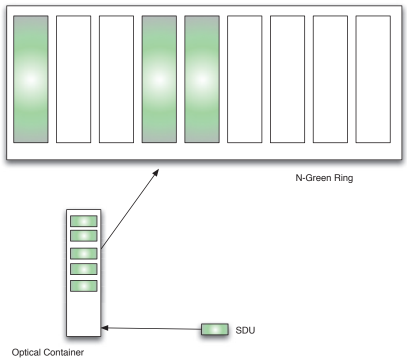


Fig. 1. Container filling and insertion.

The arrivals may represent SDU or chunks with a constant number of bytes depending of the granularity needed by the model. The numerical example presented at the end of this section represents the arrivals of two types of SDU (short SDU of 50 bytes like TCP acknowledgments and larger SDU of 1500 bytes). In that example, we use a chunk of 50 bytes (i.e. the greatest common divisor of the SDU sizes). TCP ack consists in one chunk while a Ethernet MTU (Maximum Transmit Unit) is modeled by 30 chunks.

Let $A_n$ be the number of SDU which arrive at time $n$. We suppose that $A_n$ $(n \geq 0)$ are independent and identically distributed variables following A. The support of $A$ is an upper bounded subset of $\mathbb{N}$, $0 \leq A_n \leq MaxArrival$. This value (i.e. MaxArrival) depends on the number of customers connected to the station and the time slot considered.

Let $X_n$ be the number of SDU in the buffer at time $n$ and let $H_n$ be the value of the timer associated with the SDU in the buffer. The system evolves based of the following events at time $n$:

- a batch of $A_n$ SDU arrives and the chunks are added into the buffer (i.e. $A_n$ may be 0),
- the timer is increased if the number of Data Units in the container is positive,
- if the timer is equal to the deadline, or if the buffer is sufficiently filled, the buffer is released into an optical container to be inserted on the ring. Then, we begin the filling again.

More precisely, the timer is initially equal to 0 and it jumps to 1 when the first SDU arrives in the buffer. It is then increased during each time unit until the buffer is released.

Let $Y$ be the size of the chunk, $Z$ the size of the PDU and $JZ/Y$ be the number of chunks which can be included into the PDU. Let $C$ be the deadline and $Thr$ be the utilization ratio of the buffer which triggers the release of the PDU.

$$\left[\begin{array}{ll} X_{n+1} = min(X_n + A_n, J) & \\ IF \quad X_{n+1} > 0 & H_{n+1} = min(H_n + 1, C) \\ If \ (H_{n+1} = C) & Container \ Ready \\ If \ (X_{n+1} \geq Thr * J) & Container \ Ready \end{array}\right.$$

Once the "Container Ready" event occurs, we make the following transitions at the next step : $X_n = 0$ and $H_n = 0$.

Clearly, due to the independence and stationary assumption, $(X_n, H_n)$ is a discrete time Markov chain. Furthermore the chain is finite. Indeed, we have $0 \leq X_n \leq J$ and $0 \leq H_n \leq C$. Note however that all the nodes in $[0, J] \times [0, C]$ are not reachable. It depends of the arrival process. For instance, state $(5, 0)$ and state $(0, 2)$ are not reachable (impossible to have 5 SDU at time 0 by assumption, or 0 customer at time 2 because the clock jumps out of state 0 only with the first arrival). Thus we will perform a numerical analysis of the chain beginning with the analysis of the reachable states. Let $\mathcal{S}$ be the set of reachable states. The Markov chain is built with the XBorne tool [9], as an example, in Fig. 2 we present the transition graph for $J = 8$, $Thr = 0.75$, $C = 8$ and $0 \leq A_n \leq 3$.

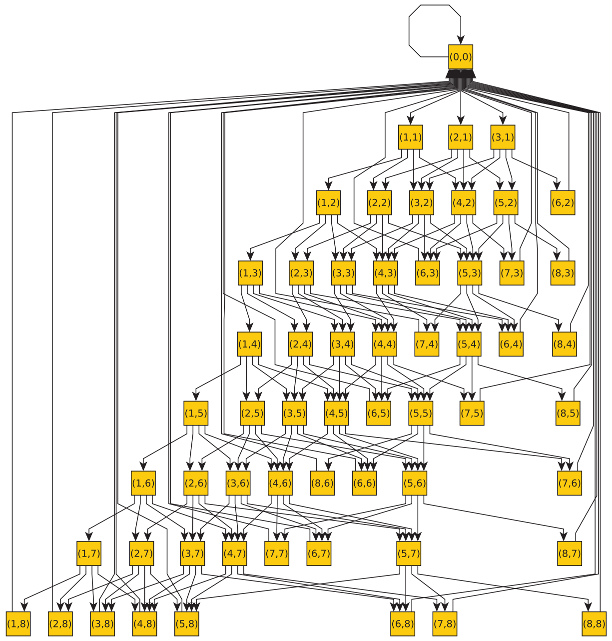


Fig. 2. Transition graph of the Markov chain

### B. Numerical Analysis

One can also state the following properties which are useful for the numerical analysis.

**Property 1.** *Assume that $E[A_n] > 0$ and that $J * Thr + MaxArrival \leq J$, then all the directed cycles of the Markov chain have a unique intersection node at $(0, 0)$. Therefore the matrix of the Markov chain can be decomposed into an upper diagonal matrix plus a matrix whose first column is positive and all the other entries are equal to 0.*

See [10] for the proof of this property.

**Property 2.** *If $Thr \leq \frac{J+1-MaxArrival}{J}$, no SDU are lost. The PDU is released before it is sufficiently filled.*

Indeed, this assumption implies that:

$$J * Thr - 1 + MaxArrival \leq J, \quad (1)$$

and $J * Thr - 1$ is the largest buffer occupancy which does not trigger the emission of PDU.

The first property allows that one can use a very efficient algorithm to compute the steady state distribution of the Markov chain proposed by Robertazzi [8]. Intuitively the chain consists in many directed trees rooted at $(0, 0)$ with back edges from the tree leaves returning to $(0, 0)$. In that case, solving the steady state equation $\pi = \pi P$ where $P$ is the stochastic matrix of the Markov chain can be done as described in Algorithm 1.

**Algorithm 1** Computing the steady state distribution

1: Initialize $\pi(0, 0) = 1$
2: Compute all the values of $\pi(x, y)$ along the trees using the global balance equation (in a tree, a node has only one predecessor, therefore solving the balance equation is trivial)
3: When the probability for all the leaves have been obtained, compute the sum of the probability $S$
4: Normalize: divide each probability by $S$ to obtain a sum equal to 1.0.

Such an algorithm has a complexity which is linear in the number of non zero entries in the Markov chain while the Gaussian elimination for a full matrix has a complexity cubic in the number of states. This allows to solve the steady-state distribution in less than a second.

Once the steady-state distribution is obtained, one can derive the following performance indices:

- Distribution of the timer when the PDU is released. We have two conditions to release a PDU
  - The buffer occupancy $X_n$ is larger than $J * Thr$.
  - The clock $H_n$ is equal to $C$.

  Let $\mathcal{S}1$ be the set of states which satisfy one of these constraints. We first compute the probability of $\mathcal{S}1$

$$Pr(\mathcal{S}1) = \sum_{(X,H) \in \mathcal{S}1} \pi(X, H) \quad (2)$$

  Then, the probabilities are obtained after conditioning.

$$Pr_H(t) = \frac{1}{Pr(\mathcal{S}1)} \sum_{(X,H) \in \mathcal{S}1} Pr(X, H) 1_{H=t} \quad (3)$$

- Distribution of the buffer size when the PDU is released.

$$Pr_X(x) = \frac{1}{Pr(\mathcal{S}1)} \sum_{(X,H) \in \mathcal{S}1} Pr(x, H) 1_{X=x} \quad (4)$$

Let $\mathcal{D}$ be this distribution of time needed for filling a PDU. Note that it has a bounded support: the upper bound is $C$ while the lower bound is $\lfloor J * Thr / MaxArrival \rfloor$.

Once we have obtained the distribution of the timer at release time, we have to add the time period when the buffer is empty. As the arrivals are independent and stationary, the duration of time between the release of the PDU and the arrival of the SDU has a geometric distribution with rate $(1 - Pr(A_n = 0))$. Let $\mathcal{E}$ be the distribution of the empty period.

The time between two successive releases of PDU is the sum of the empty period and the duration to fill a PDU (i.e. $\mathcal{D}$). As the arrivals are independent, the distribution of the timer at release time and the distribution of the empty period for the buffer are also independent. Therefore the distribution of time between successive releases of PDU is the convolution of $\mathcal{D}$ and $\mathcal{E}$. We have to numerically compute a truncation of

$$\mathcal{F} = \mathcal{D} \otimes \mathcal{E}.$$

Note that we must truncate the distribution because the support of $\mathcal{E}$ is not upper bounded. There is a positive probability (extremely small but not 0) that there are no arrivals of SDU during a very long period. Under this assumption, a generation of PDU does not occur as we assume that a PDU cannot be empty. This distribution $\mathcal{F}$ is an input parameter of the simulation of NGREEN optical ring we present in Section III.

### C. An example with Ethernet and TCP SDUs

We assume that the SDU sizes are 50 bytes (i.e. TCP acknowledgment plus some extra bytes for the PDU) or 1500 bytes (Ethernet frames). Thus the PDU size expressed in chunks of 50 bytes varies from 0 to $J = 250$ chunks. And we have three possible batches : 1 for the TCP packets, 30 for the Ethernet frames, and 0 for no arrivals. Their respective probabilities are assumed to be 0.4, 0.2 and 0.4.

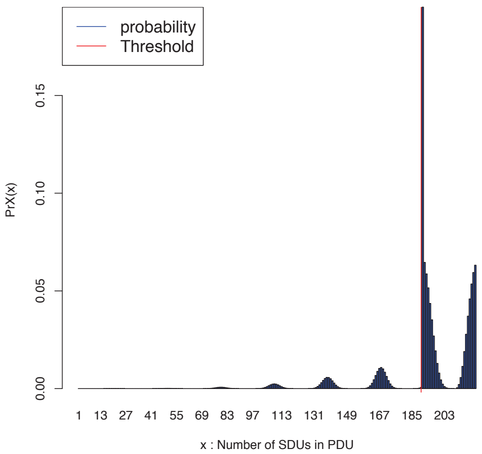


Fig. 3. Distribution of the PDU size at release time.

Thus the average number of bytes arriving per slot is 320 (i.e. 6.4 chunks of 50 bytes). We first chose a deadline equal to 40 and a threshold ratio equal to 75% leading to an integer threshold equal to 190. We obtain a Markov chain with 5200 states and roughly 15000 transitions, the steady-state distribution of which is obtained after $0.01s$ of computation

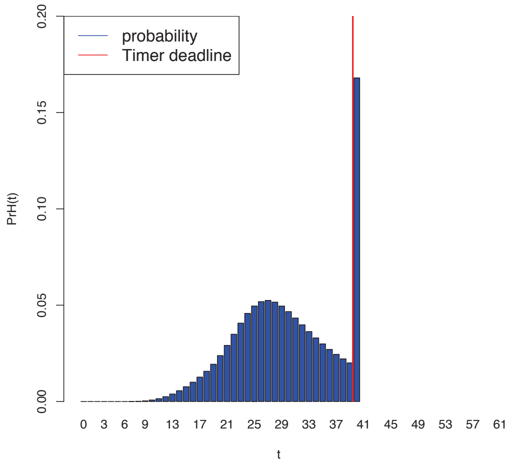


Fig. 4. Distribution of the time to fill a PDU.

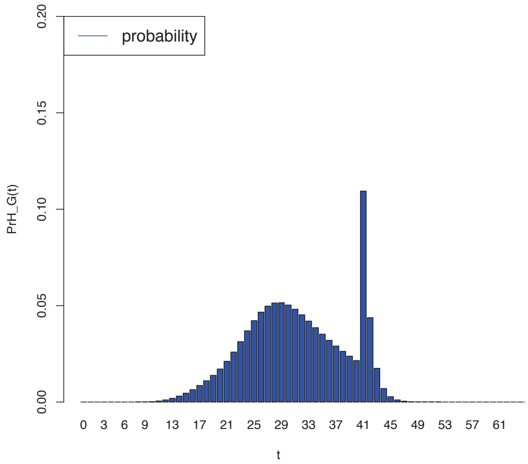


Fig. 5. Distribution of the time between two PDUs.

time. The PDU contains an average payload of 971 bytes (i.e. 194.37 chunks of 50 bytes obtained from the expectation of the distribution depicted in Fig. 3). The average time to fill a container is 29.7 slots (see the distribution in Fig. 4), and the average inter-arrival time 31.3 slots (see the distribution depicted in Fig. 5).

We now study the effect of the deadline and the threshold ratio. In Fig. 6, we present the mean time to fill a container for various threshold ratios $(0.60, 0.70, 0.80, 0.90)$. The analysis shows that the deadline is useful when it is small. After a boundary value depicted by small dots in Fig. 6, the deadline has a weaker impact on the time needed to fill the containers. They are mostly released because they have the minimal size required. Obviously, the mean time to fill a container increases with the threshold ratio.

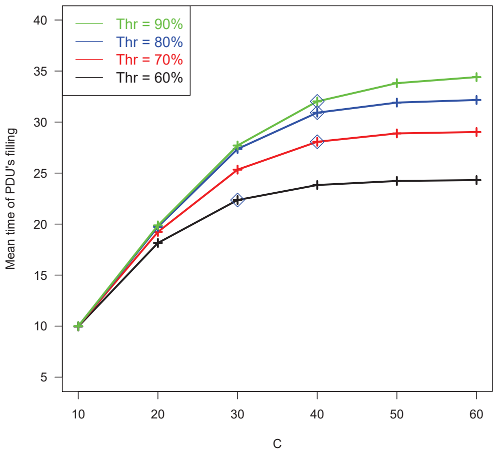


Fig. 6. Mean filling time versus deadline, for different threshold ratios

## III. Modeling the container insertion on the optical ring

We first explain some constraints due to the technology we used to design the NGREEN network. First, the network is an optical ring where optical containers are inserted by stations. The ring network is synchronized and divided into time slots. The communication mode is the so-called Broadcast and Select. Under this mode, the optical container may contain SDU destined to various stations. All the stations copy the container to be converted to electronic packets. The only station which can free the slot on the ring from the container is the sending station. Therefore a container moving on the ring makes one turn and is copied by all the stations.

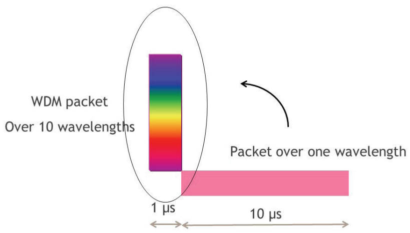


Fig. 7. The optical conversion at the insertion at a NGREEN node (from [3]).

The third important feature already mentioned in the introduction is the use of WDM packets. The NGREEN network is built on slots: 1-$\mu$s long in the time domain and covering 10 WDM channels in the spectral domain. The optical container has 10$\mu$s long time duration (i.e. 12500 bytes, for an emission at 10 Gbs). The container is filled by aggregating different service data units and the optical container is spread over the 10 wavelengths. Thus, the WDM packet has a duration which is 10 times smaller than the optical container previously filled (this is illustrated in Fig. 7).

The slot assignment to containers may be opportunistic or based on a reservation [7]. Next, we analyze these two insertion modes and give numerical results of the delays. The container once it has been released by the filling mechanism waits for an empty slot on the ring. It must also wait 10 slots after the last insertion on the ring. This is a consequence of the conversion of a 10$\mu$s PDU into a WDM packet of 1$\mu$s. Remember that the slot is freed by the node which has used it for emission, after one turn of the ring. A container can be immediately inserted at its arrival if the conditions of insertions are respected. We consider two scenarios which differ by the kind of the insertion mode of the PDU into the ring : opportunistic or slot reservation. We first begin with the opportunistic insertion mode, by a simulation on the ring to find the number of stations which makes the network stable with distribution of PDU inter-arrival time given in Fig.5. The results are depicted in Fig. 8.

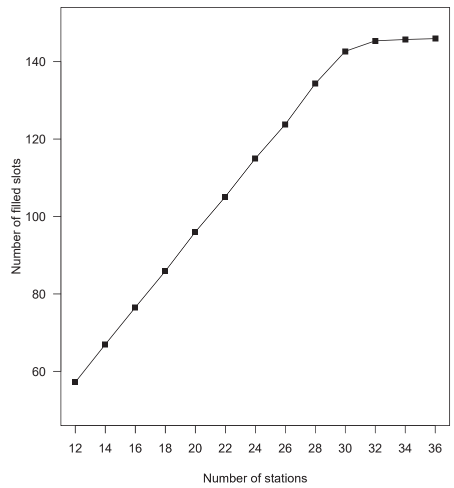


Fig. 8. Average ring occupancy versus number of stations.

We also check with the number of containers waiting for insertion. Clearly, the system is stable up to 30 stations. In the following we will study a network with 22 stations (when the load on the ring is low) and a network with 28 stations which provide a high load to the ring.

### A. Scenario A : latency with opportunistic insertion mode

We build a discrete time simulation engine to study the insertion delay for a container to enter the optical ring. As we model an Optical Slot Switching system, a simulator based on discrete time is easier to build and to use than a continuous event engine. The main loop of the simulator proceeds as described in Algorithm 2.

We assume that all the nodes receive the same traffic which obeys the same model studied in section II-C. We suppose initially that 22 insertion nodes are connected to the ring. The distribution of the time between two arrivals of container is given by the distribution depicted in Fig. 5.

**Algorithm 2** Discrete time simulator

increase the global clock.
make the ring turn for one slot
**for** *all the stations on the ring*
Free the slot in front of the station if it was occupied by the station for a container.
If the slot is empty and if $\Delta = 0$, and if there is a container waiting for insertion, then put the container on the ring, remove the PDU for the queue, perform some statistics on the insertion delay, and let $\Delta = 10$.
If an arrival of a fresh PDU occurs, compute the next arrival instant using an inverse transform method based on the discrete distribution obtained in section II.
Perform some statistics on the queue occupancy
Let $\Delta = \Delta - 1$.
**End for**
Compute some statistics on the ring occupancy

In Fig. 9, we show the distribution of the insertion time in slots for the first station. The number of containers waiting for insertion is extremely small: during the simulation we observe between $0$ and $1$ containers waiting. Note that due to the scheduling used in the simulation a container may be inserted immediately at its arrival. The probability to observe 2 containers waiting is less that $10^{-4}$ with a confidence interval of $95\%$. Thus a very small buffer will be sufficient in the line card. The utilisation of the ring is depicted in Fig. 11. After a small transient period, the ring occupancy has small oscillations around $105$ used slots (remember that the ring contains $150$ optical slots). We remove the first part of the sample path (typically for time smaller than $1000$ slots) to avoid the transient phenomenon. The simulations are long enough to reach steady-state. We propose now to increase the number of insertion nodes to 28, and we see in Fig. 10, the probability distribution reachs higher insertion delays due to a higher load, typically around 135 used slots among 150. For this case, the number of containers waiting is up to 6 and the probability to observe 6 containers waiting is about $10^{-2}$.

We now compute the distribution of the end to end delay. Remember that the duration to fill a PDU is $\mathcal{D}$. As the arrivals of SDU are supposed to be independent, the arrival instants of optical containers are independent. Therefore the distribution of end to end delay for a PDU is the convolution of $\mathcal{D}$, $\mathcal{I}$ (the insertion delay) and $\mathcal{T}$ (the transportation delay on the ring). Transportation delay is upper bounded by the size of the ring as we do not make any assumption on the spatial distribution on insertion stations along the ring (see Fig. 12 and Fig. 13).

$$\mathcal{E}2\mathcal{E} = \mathcal{D} \otimes \mathcal{I} \otimes \mathcal{T}$$

Next, we propose to analyze another insertion mode, allowing a greater stability when the number of insertion nodes increases.

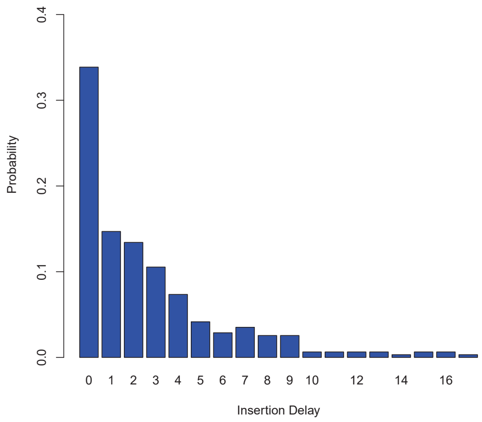


Fig. 9. $\mathcal{I}$: Distribution of the insertion time (in slots) for the first station of 22 stations.

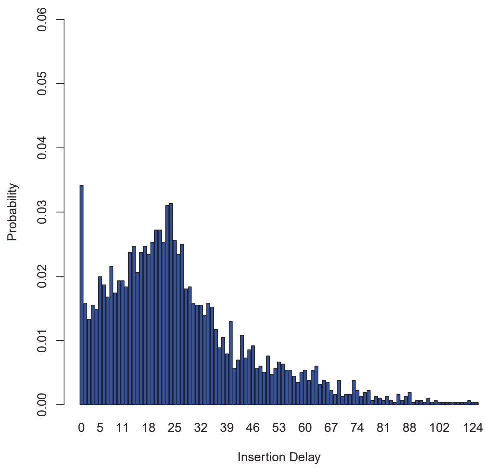


Fig. 10. $\mathcal{I}$: Distribution of the insertion time (in slots) for the first station of 28 stations.

### *B. Scenario B : guarantee latency with slot reservation insertion mode*

We model the slot reservation mode. A station can only use the slots that are periodically reserved for it. We assume that a slot is reserved every $D$ slots on the ring. The arrivals are independent and the inter-arrivals of containers follow the random process, the distribution of which was computed in Section II-C.

We consider a discrete time model, the time unit of which is the WDM slot duration. The model is based on two clocks: $H1$ to model the arrival of a reserved slot on the ring and $H2$ to model the inter-arrival of an optical container. Both clocks are synchronized. However clock $H1$ makes a deterministic

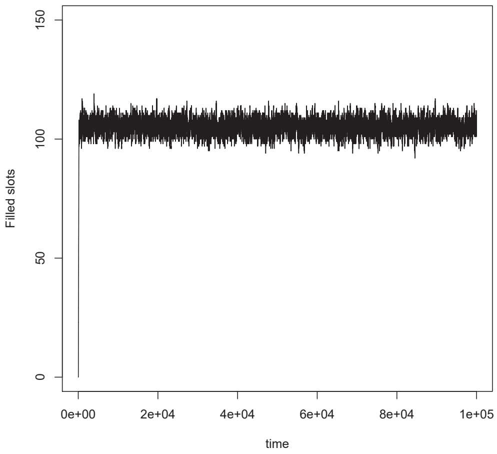


Fig. 11. Ring occupancy versus simulation time.

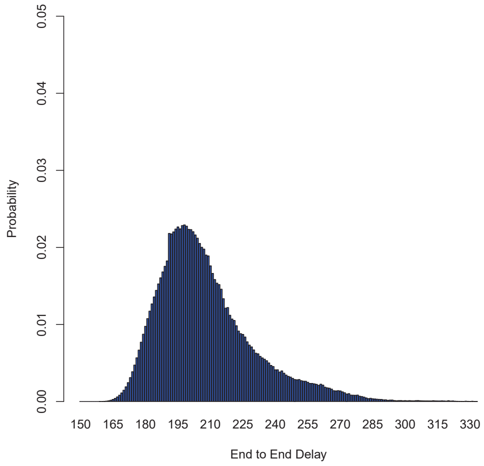


Fig. 13. E2E: distribution of the end to end delay, case of 28 stations.

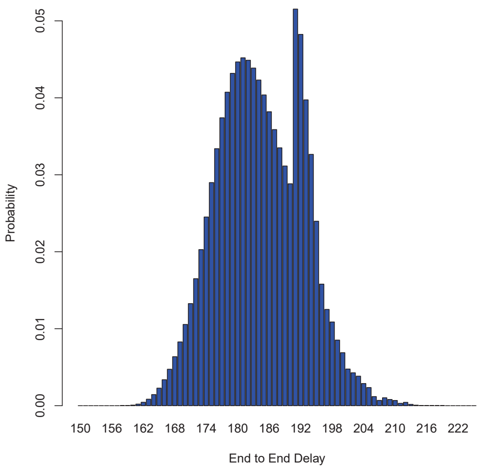


Fig. 12. E2E: distribution of the end to end delay, case of 22 stations.

jump of length $D$ after the arrival of the reserved slot while clock $H2$ makes a random jump after an arrival of a container. The length of the jump is a random variable the distribution of which is given by the steady-state distribution computed in section II-C (Fig. 5).

We also take into account the fact that an arriving container may be inserted immediately if the reserved slot is available. This is modeled by the scheduling used in the dynamics of the clock (i.e. $H2$ first). We assume that the arrival of a container or a slot on the ring are modeled by the transition of the clocks out of 0. The model also contains the population of container waiting for insertion. Let $X$ be this random variable. We assume that the buffer size is $B$. Clearly $(H1, H2, X)_n$ is a Discrete Time Markov Chain. More precisely the dynamics are the following at each time slot.

- First, if Clock $H2$ is positive, then it is decreased, otherwise as it is equal to 0, it jumps to state $K - 1$ while component $X$ is increased if it is not equal to $B$. If an arrival occurs while the buffer size is reached, the incoming customer is lost. This probability will be computed in the following. $K$ is the inter-arrival delay. It is distributed as $\mathcal{F}$.
- Second, if Clock $H1$ is positive, then it is decreased, otherwise it is equal to $0$ and it jumps to state $D - 1$. During the same transition, component $X$ is decreased by $1$ if is not $0$.

The model is generated using XBorne and it is solved numerically using a standard numerical technique (i.e. Sparse version of the Grassman, Taksar and Heyman Algorithm [11]). As the matrix is very sparse, the computations only require a few seconds for a matrix of size 8500. Once we have obtained the steady state probability (say $Pr(H1, H2, X)$), one can numerically compute the following quantity:

- The loss probability for a container :

$$P_{Loss} = \sum_{i} Pr(i, 0, B) \tag{5}$$

- The buffer population :

$$E[X] = \sum_{i} \sum_{j} X \ Pr(i, j, X) \tag{6}$$

- The distribution of the insertion time for an arriving container: when a container arrives at state $(j, 0, Y)$ (with $Y < B$, otherwise it is lost), it has to wait $(Y * D + j)$ time units. Note that we must consider in the distribution the conditional probabilities knowing that a new container arrives :

$$\frac{Pr(j, 0, Y)}{\sum_i \sum_{X<B} Pr(i, 0, X)} \tag{7}$$

The Markov chains are solved for the same traffic assumptions we already use for the simulation. Furthermore the parameter $D$ is supposed to be equal to the number of stations to share equally the bandwidth among the stations. The buffer size is supposed to be small. We consider a buffer which can contain up to 4 containers. The numerical analysis show that this buffer is sufficient to avoid losses (see Tables below, Fig. 14).

| **#Stations** | **22** | **28** |
|---|---|---|
| **Losses** | $10^{-17}$ | $10^{-8}$ |

| **Optical containers** | **0** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|
| **22 Stations** | 0.65 | 0.34 | $10^{-3}$ | $10^{-7}$ | $10^{-12}$ |
| **28 Stations** | 0.46 | 0.50 | 0.03 | $10^{-4}$ | $10^{-5}$ |

Fig. 14. Loss probability & Distribution of the optical containers in the buffer

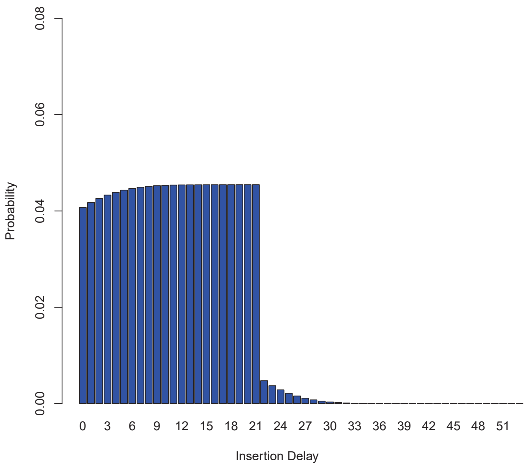


Fig. 15. $\mathcal{I}$: Distribution of the insertion time (in slots) for the first station of 22 stations.

In the case of the slot reservation insertion mode, we can see in Fig.15 (resp. Fig. 16 ), the distribution of the insertion delays of the first station for 22 (resp. 28) nodes. If we compare with the opportunistic insertion mode in Fig. 9 and Fig. 10, we can remark that insertion delays are smaller in the opportunistic insertion mode, for 22 nodes, and higher for 28 nodes. In fact, for 28 stations, the number of containers waiting in the node is up to 6 in the opportunistic insertion mode, against up to 4 in the slot reservation mode. So the slot reservation insertion mode is really interesting when the number of nodes increases.

## IV. Energy efficiency and latency analysis

We consider a scenario with 10 stations, with the opportunistic insertion mode into the ring, and we try to analyze

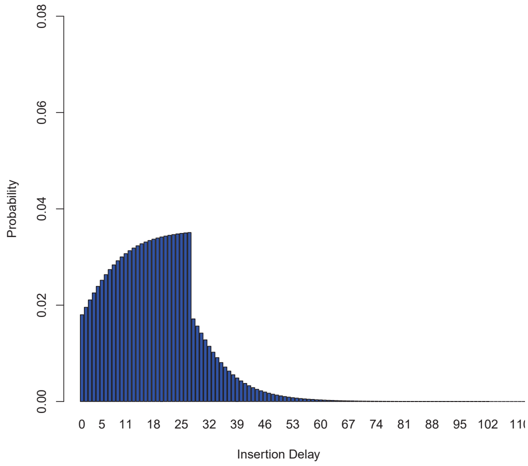


Fig. 16. $\mathcal{I}$: Distribution of the insertion time (in slots) for the first station of 28 stations.

both end to end delays, and energy efficiency. In the NGREEN project, the energy efficiency computed with respect to the different equipment crossed is 0.8 nJoule/bit. For an optical packet of 12500 bytes, the energy consumption is $12500{*}8{*}0.8$ nJoules, so the energy efficiency represents the ratio between 80 $\mu$Joule and the payload of the PDU which depends on the filling. In Fig. 17, we have represented energy efficiency for different filling ratios and deadlines. Obviously, the larger the thresholds and the deadlines, the larger the payload, then the smaller (and better) the energy efficiency. We have also represented in Fig. 18, the end to end delays according to the deadlines and the thresholds ratios, in order to analyze the impact of the traffic aggregation on the end to end performances. So we can see that the higher threshold ratio (0.90) gives the higher end to end delay due to the high delays to fill the PDU (as shown in Fig.6), but the lowest and the best energy efficiency. These results are obtained for the opportunistic insertion mode, and allow to provide the thresholds and the deadlines which guarantee both energy efficiency and end to end delays. In the case of the slot reservation insertion mode, the energy efficiency will be the same as it depends essentially on the parameters of the filling process (threshold and deadline). The insertion delays will be higher as the number of stations is small.

## V. Concluding Remarks

With the deployment of new services related to the Internet of Things (IoT), a large quantities of data will be generated and processed in real time. All optical networks will represent the most efficient solution for high speed transmission in communication networks. NGREEN solution is based on a ring topology and new advances on optical technology which allows to design OSS. Thus the routing problem does not

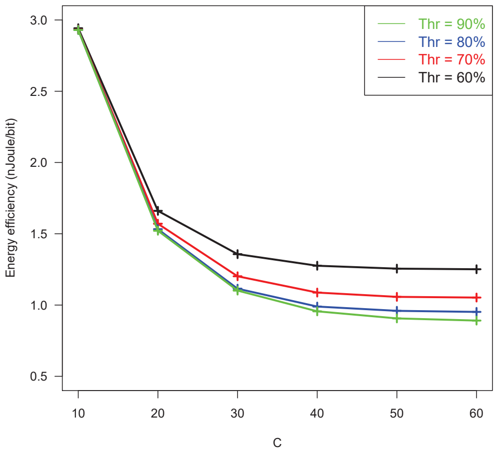


Fig. 17. Energy efficiency versus deadline.

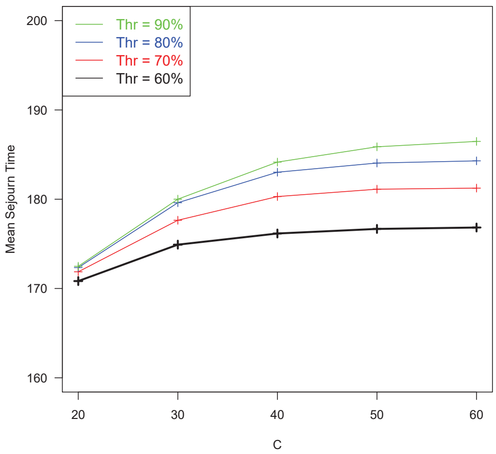


Fig. 18. End to end delays versus deadline.

exist anymore and we only have to deal with the access to the ring, by the filling of the optical container and the insertion mode (opportunistic or slot reservation). The aim of this paper is to develop mathematical models in order to analyze aggregation efficiency and end to end delays taking into account aggregation and insertion delays. The goal is to propose a trade-off between energy efficiency and delays.

We propose a discrete-time Markov chain to model the packet aggregation in the optical container. This model is efficiently solved by a numerical algorithm based on the structure of the chain. From the resolution of this Markov chain, we compute the inter-arrival PDUs which are used for insertion delay analysis in both opportunistic and reservation slot modes.

Another important contribution of this paper is to propose efficient mathematical methods to decide which values of parameters (thresholds, parameters) and insertion modes to choose in order to guarantee both energy efficiency and delays.

All optical networks introduce new problems for stochastic modeling. We hope that the algorithms we have designed will help to solve the questions relative to the filling of the container. Note that the generalization to more sophisticated strategies for the release of the optical container is straightforward.

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