Performance Evaluation of the Packet Aggregation Mechanism of an N-GREEN Metro Network Node

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Abstract. Today's telecommunication network infrastructure and services are dramatically changing due partially to the rapid increase in the amount of traffic generation and its transportation. This rapid change is also caused by the increased demand for a high quality of services and the recent interest in green networking strengthened by cutting down carbon emission and operation cost. Access networks generate short electronic packets of different sizes, which are aggregated into larger optical packets at the ingress edge nodes of the optical backbone network. It is transported transparently in the optical domain, reconverted into the electronic domain at the egress edge nodes, and delivered to the destination access networks. Packet aggregation provides many benefits at the level of MAN, and core networks such as, increased spectral efficiency, energy efficiency, optimal resource utilisation, simplified traffic management which significantly reduces protocol and signalling overhead. However, packet aggregation introduces performance bottleneck at the edge node as the packets from the access networks are temporarily stored in the aggregation buffers during the packet aggregation process. In this article, we apply the diffusion approximation model and other stochastic modelling methods to analytically evaluate the performance of a new packet aggregation mechanism which was developed specifically for an N-GREEN (Next Generation of Routers for Energy Efficiency) metro network. We obtain the distribution of the packets' queue in the aggregation buffer, which influences the distribution of the waiting time (delay) experienced by packets in the aggregation buffer. We then, demonstrate the influence of the probability p of successfully inserting the packet data units from the aggregation queue to the optical ring within a defined timeslot Δ. We also discuss the performance evaluation of the complete ring by deriving the utilisation of each link.

1 Introduction

Different access networks such as Digital Subscriber Line (DSL), Ethernet local area networks (LANs), wireless LANs, mobile networks (e.g. 3G, 4G, and 5G), and the Internet of Things (IoT) generate packets of different sizes which are usually aggregated into larger packets. The main objective behind these methods is to leverage on the large optical bandwidth in the core network and to reduce processing overhead. This mechanism is called packet aggregation and it involves the assembly of smaller packets into larger ones. It provides many benefits at the level of core and MAN networks, such as increased spectral efficiency, energy efficiency, optimal resource utilisation [**?**], simplified traffic management, and significantly reduces protocol and signalling overhead. It notably influences the overall performance of the network in terms of packet latency, packet losses, and bandwidth utilisation. Therefore, packet aggregation mechanisms and transmission queue management must be carefully designed and parameterised.

The application of packet aggregation in 5G networks was studied in [**?**], where the short packets from the 5G access networks are aggregated into larger ones before they are inserted into the core network for transportation. Also, the authors in [**?**] applied packet aggregation at the edge router of a software-defined network (SDN) to aggregate smaller packets from IoT networks into larger ones before they are transported in the internet core network to the IoT cloud servers. It is expected that 5G and IoT networks will generate vast amounts of traffic of smaller packet sizes to be transported over IP or optical backbone networks. These packets need to be aggregated to larger IP or optical packets to avoid both increased processing overhead and energy consumption. Packet aggregation was extensively applied in the grooming of electronic packets at the electronic domain of the edge node of optical networks, e.g. optical burst switching (OBS) networks [**?**]. More efficient packet aggregation algorithms have been developed for NGREEN metro networks. An N-GREEN metro network is a cost-effective and energy-efficient optical network which consists of ring typologies of over-dimensioned switches and router nodes. Ring typologies are very common in the Metro networks. They enable the deployment of ring protection mechanisms which ensure the survivability of the core network during failures. Therefore, N-GREEN is an attractive network solution for emerging Metro and core networks, and it is also provided with SDN functionalities [**?**].

To transport electronic packets over optical networks, the smaller electronic packets are aggregated, converted into optical bursts or packets, and then inserted into the core network. The optical signals are then transported transparently from the ingress edge node to the egress edge node, without conversion opto/electro/opto (O/E/O) to perform routing. Therefore, the elimination of O/E/O conversions significantly reduces the energy consumption as the packets are switched in the optical domain, and the optical signals are boosted using optical amplifiers which are relatively energy efficient. In classical IP over optical networks, e.g. OBS networks, smaller packets are collected in aggregation buffers, and the contents of the buffers are framed into lager packets, and then sent to a transmission queue. The most popular packet aggression mechanisms implemented in commercial network nodes are the time-based, the size-based and the hybrid packet aggregation algorithms [**?**].

The drawback of these aggregation mechanisms is that the generated bursts are sometimes of variable sizes which may be very large, resulting in burst dropping at the core network or sometimes small, resulting in poor resource utilisation [?]. Also, under low traffic conditions, the arriving electronic packets may experience longer delays in the aggregation buffer, which are not desirable for real-time traffic. The edge node is therefore, considered to be the performance bottleneck of the network. The performance evaluations of the time-based, size-based, and hybrid packet aggregation mechanisms were studied in [?,?], assuming that the arrival of electronic packets into the buffer follows a Poisson process. The authors in [?] compared the Poisson-based interarrival times distribution with the measured distribution from the Center for Applied Internet Data Analysis (CAIDA) repositories, and realised that even though the Poisson assumption simplifies the performance analysis, it differs from reality. The authors, therefore, used diffusion approximation with CAIDA traffic to evaluate the performance of time-based, size-based, and hybrid packet aggregation mechanisms. In this paper, we propose the use of diffusion approximation to evaluate a novel packet aggregation mechanism that was recently proposed in [?,?]. In this mechanism, smaller electronic packets called service data units (SDU) are continuously collected in an over-dimensioned aggregation buffer. The accumulated packets in the buffer are then framed into fixed-sized larger packet data unit (PDU). The PDUs are then inserted into the metro optical ring using a slot reservation insertion method, timer-based, or an opportunistic insertion method.

In this paper, we analytically evaluate the performance of the packet aggregation mechanism of an N-GREEN metro network node. We use diffusion approximation model with reflecting barrier to analytically study the dynamic changes in the content of the buffer, as the PDUs are inserted into the optical ring from the aggregation buffer. We obtain the distribution of the content of the queue of SDUs in the aggregation buffer for different values of p (the probability of inserting a PDU into the optical packet within a given timeslot Δ). We also obtained the distribution of the delay experienced by the SDUs within the aggregation buffer and then investigated the influence of p. We discussed the performance evaluation of the complete ring by deriving the link utilisation.

2 Description of the N-GREEN Packet Aggregation Mechanism

The N-GREEN project proposed two technological innovations for optical networks such as the WDM Slotted Add/Drop Multiplexer (WSADM) technology, and a Modular and Self Protected Backplane. It exploits the benefits of WDM or multicoloured optical packets, which enable the use of low cost commercially available components, integration of SDN technology, compliance with 5G performance requirements, and relatively low energy consumption. An N-GREEN metro network ring consists of the optical switch node (also called an electrical bridge) and the bridge nodes as shown in Fig. 1. The optical switch node (node 1 in the figure) aggregates smaller electronic packets from access networks into larger packets which are converted into optical packets and inserted into the metro ring. It also connects the metro ring to other metro rings. The bridge nodes bypass or relays transit optical packets transparently without optical-electrical-optical conversions and add/drop optical packets. The transmission of optical packets between the bridge nodes does not pass through the switch node in order to avoid O/E/O conversions and hence, a relative reduction in energy consumption [**?**]. Capital expenditure (CAPEX) comparisons of WSADM technology with the optical packet switching (OPS) or optical burst switching (OBS) technologies indicate that WSADM could compete favourably with existing technologies in terms of cost, energy consumption and performance [**?**,**?**].

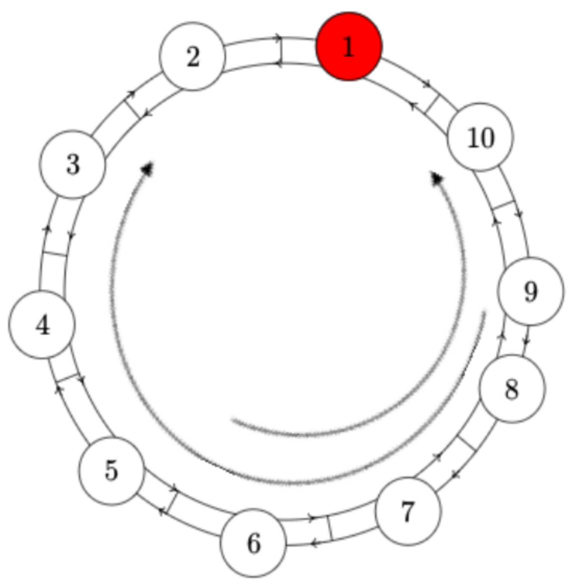

Fig. 1. An N-GREEN optical metro ring [**?**]

In the considered packet aggregation mechanism, multiple electronic packets or service data units (SDUs), e.g. IP packets from various access networks, form a first-in-first-out queue waiting to be inserted into the optical packet at any available timeslot. The size of the optical packet is fixed and equal to L bytes. New optical packets circulating in the ring appear at each constant time interval Δ, but some of them are already occupied and cannot be used, Fig2. Denote by p probability that an optical packet is empty and the content of the queue may be transferred to it. Consider two ways of filling optical packets.

Case 1: Every empty packet is loaded. If the queue is smaller than L bytes, the whole its content is inserted; if the queue is larger then the optical packet, L bytes are inserted, and the rest stays waiting for the next available packet.

Case 2: If the content of the queue is smaller than L, the optical buffer is not filled; otherwise, L bytes are loaded, and the rest is waiting for the next opportunity.

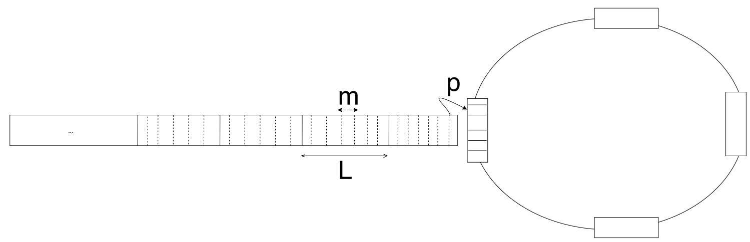

Fig. 2. The N-GREEN packet aggregation system

The optical packets are circulating inside the ring and transport messages among stations. Each station has a similar queue of electronic packets waiting to be transported by the optical ring. First, we will study a single queue, and then we will try to model the queue interactions inside the ring.

3 Diffusion model of the queue

We approximate the size of the content of the buffer by a diffusion process. Diffusion approximation, since its very beginning [?], [?], [?] is applied in queueing problems and performance evaluation, appears also in a patent [?]. The models are often related to G/G/1, G/G/1/N or G/G/m/M+K stations and their networks, cf. [?], it was also used recently for modelling, e.g. energy harvesting sensor nodes [?], Clouds[?] and routers in Software Defined Networks, [?].

The size of the queue of SDUs in the aggregation buffer is represented by a diffusion process $X(t)$, and its evolution is given by the diffusion equation

$$\frac{\partial f(x,t;x_0)}{\partial t} = \frac{\alpha}{2}\frac{\partial^2 f(x,t;x_0)}{\partial x^2} - \beta\frac{\partial f(x,t;x_0)}{\partial x} \tag{1}$$

where βdt and αdt represent the mean and variance of the changes of the diffusion process at dt. The equation defines the conditional probability density function (pdf) of the diffusion process $X(t)$

$$f(x,t;x_0)dx = P[x \leq X(t) < x + dx \mid X(0) = x_0].$$

The diffusion approximation applied to queueing systems is based on the assumption that the number of arrivals of customers joining the queue during a time T has a distribution which is close to normal and does not depend on the distribution of interarrival times but only on its two first moments. The mean and variance of this normal distribution are λT and $\lambda^3\sigma_A^2 T$ where $1/\lambda$

and σ_A^2, are mean and variance of interarrival times, [?]. Here, the position x of the process $X(t)$ corresponds to the number of bytes currently in the buffer. The number of bytes received at a unit of time is a product of two independent random variables: X – the number of packets and Y – the size of packets. The mean of a product variable XY is $E(XY) = E(X)E(Y)$ and the variance is

$$\begin{aligned} Var(XY) &= E(X^2Y^2) - (E(XY))^2 \\ &= Var(X)Var(Y) + Var(X)(E(Y))^2 \\ &+ Var(Y)(E(X))^2, \end{aligned}$$

the mean number of arrived at a time unit packets is $E(X) = \lambda$ and the variance is $Var(X) = \lambda^3\sigma_A^3$, and we denote by m the mean size of a packet (in bytes) and by σ_m^2 the variance of its size, therefore the mean number of arrived at a time unit bytes is

$$\beta = \lambda m$$

and the variance of number of arrived at a time unit bytes defining α in Eq. (1 is

$$\alpha = \lambda^3\sigma_A^2\sigma_m^2 + \lambda^3\sigma_A^2 m^2 + \sigma_m^2\lambda^2. \tag{2}$$

We consider the unlimited queue; therefore, the diffusion process is limited only by a reflecting barrier at $x = 0$ (the queue is never negative).

Without any barrier, the density of the unrestricted process defined by Eq. (1) and started at x_0 is

$$f(x,t;x_0) = \frac{1}{\sqrt{2\Pi\alpha t}}\exp\left[-\frac{(x-x_0-\beta t)^2}{2\alpha t}\right];$$

with the reflecting barrier at $x = 0$ it becomes, see e.g. [?]

$$f(x,t;x_0) = \frac{1}{\sqrt{2\Pi\alpha t}}\left[a(t) - \exp(2\beta x/\alpha)b(t)\right] \tag{3}$$

where

$$a(t) = \exp\left[-\frac{(x-x_0-\beta t)^2}{2\alpha t}\right]$$

and

$$b(t) = \exp\left[-\frac{(-x-x_0-\beta t)^2}{2\alpha t}\right]$$

.

We may also define the initial condition in a more general way, the starting point is not only at x_0 but it is at any point ξ given by a distribution $\psi(\xi)$, in this case

$$f(x,t;\psi) = \int_0^\infty f(x,t;\xi)\psi(\xi)d\xi. \tag{4}$$

Loading the optical packet with the queue content, i.e. decreasing the queue, corresponds to the jumps back of the process $X(t)$. However, the jumps may occur only at discrete moments, at the end of the interval Δ. Therefore we concentrate on the diffusion description during constant intervals $\varDelta$ and the definition of immediate changes in the process between these intervals.

Two ways of charging the optical packet are considered:

3.1 Case 1

The process is decreased by jumps back occurring with probability p after each fixed time-interval $\varDelta$. If $x \leq L$ jumps are to $x = 0$, the entire content of the queue is loaded to the optical packet, the queue becomes empty, and the filling process is started again when the first electronic packet arrives into the buffer. If $x > L$, the jump is performed to $x = x - L$ (distance L back): the size of the queue is larger than the size of the optical packet and the queue is emptied only partially. Denote by $f^{(i)}(x, \varDelta; \psi^{(i)})$ the pdf of the process during ith interval $\varDelta$. At the beginning of each interval, the time is set to zero, hence always $t \in [0, \varDelta]$. The distribution of the queue at the end of each $\varDelta$, after the jump, if it occurs, defines the initial distribution of the queue for the next time slot. Assume that the initial value of the process is $x_0 = 0$, the queue is empty.

At the end of the first interval, the position of the process, before a possible jump, is given by $f^{(1)}(x, \varDelta; 0)$. The jump occurs with probability p giving the initial distribution for the next interval

$$\psi^{(2)}(0) = \int_m^L f^{(1)}(x, \varDelta; m)dx \tag{5}$$

and for $\xi > 0$

$$\psi^{(2)}(\xi) = f^{(1)}(\xi + L, \varDelta; 0) \tag{6}$$

or with probability $1 - p$ there is no jump and the new initial condition is given by the position of the process at the end of previous time-slot

$$\psi^{(2)}(\xi) = f^{(1)}(\xi, \varDelta; 0). \tag{7}$$

Therefore, the complete initial condition for the second time slot is defined as

$$\begin{aligned} \psi^{(2)}(0) &= p \int_m^L f^{(1)}(x, \varDelta; m)dx, \\ \psi^{(2)}(\xi) &= p f^{(1)}(\xi + L, \varDelta; 0) \\ &\quad + (1-p) f^{(1)}(\xi, \varDelta; 0), \qquad \xi > 0 \end{aligned} \tag{8}$$

and these initial conditions determine the movement of the process during the second time slot and its position at the end of it, $f^{(2)}(\xi, \varDelta; \psi^{(2)})$.

In the same way for the next slots,

$$\begin{aligned} \psi^{(n+1)}(0) &= p \int_0^L f^{(n)}(x, \varDelta; \psi^{(n)})dx, \\ \psi^{(n+1)}(\xi) &= p f^{(n)}(\xi + L, \varDelta; \psi^{(n)}) \\ &\quad + (1-p) f^{(n)}(\xi, \varDelta; \psi^{(n)}), \qquad \xi > 0 \end{aligned} \tag{9}$$

until the convergence, when $\psi^{(n+1)}(\xi) = \psi^{(n+1)}(\xi)$ and $f^{(n+1)}(x,t;\psi^{(n+1)}) \approx f^{(n)}(x,t;\psi^{(n)})$. This convergence is illustrated later in Figs. 3-6 for various valuess of p.

3.2 Case 2

In this case, we try to fill the optical packet at the end of Δ only if the queue size is greater than L. The equations of Case 1 are adapted in the following way. As previously, at the end of the first interval Δ the queue distribution has density $f^{(1)}(x,\Delta;0)$. and for any slot $n \geq 1$

$$\begin{aligned}\psi^{(n+1)}(\xi) &= f^{(n)}(\xi,\Delta;\psi^{(n)}), \quad \xi < L,\\ \psi^{(n+1)}(\xi) &= pf^{(n)}(\xi+L,\Delta;\psi^{(n)}),\\ &\quad + (1-p)f^{(n)}(\xi,\Delta;\psi^{(n)}), \quad \xi \geq L.\end{aligned} \tag{10}$$

When the steady state is reached, the initial distribution $\psi = \lim_{n\to\infty}\psi^{(n)}$ and the state of the queue at the end of Δ is the same $f(x,\Delta;\psi) = \psi(x)$.

In both cases, the manner how the optical packets are filled causes that their volume L is not used in 100%. The packet is filled entirely with the probability that the size of the queue at the end of the interval is equal or higher than L, i.e. $\int_L^\infty f(x,\Delta;\psi)dx$. The partial filling of the optical packet (probability of loading x bytes) is given by $f(x,\Delta;\psi)$, $x < L$. The mean effective size of the packet is

$$L_{\mathit{eff}} = L\int_L^\infty f(x,\Delta;\psi)dx + \int_0^L f(x,\Delta;\psi)xdx. \tag{11}$$

4 Queueing delays

A packet coming at $t \in (t,\Delta)$ sees the queue distribution $f(x,t;\psi)$. With the probability

$$p_1 = \int_0^L f(x,t,\psi)dx$$

the queue is smaller than L, and therefore the packet will be loaded during the nearest filling of the optical packet (this is an approximation as we do not consider the size of the incoming packet). Its waiting time will be therefore $\Delta - t$ with probability p or $\Delta - t + \Delta$ with probability $(1-p)p$, or $\Delta - t + 2\Delta$ with probability $(1-p)^2p$, $\ldots\ \Delta - t + n\Delta$ with probability $(1-p)^n p$ depending when the first empty slot will be available. Denote its distribution density function as

$$\begin{aligned}f_{W1}(w,t) = p\delta\left(w-(\Delta-t)\right) &+ (1-p)p\delta(w-(2\Delta-t))\\ &+(1-p)^2p\delta(w-(3\Delta-t)) + \ldots\\ &+(1-p)^n p\delta(w-((n+1)\Delta-t)) + \ldots\end{aligned} \tag{12}$$

where $\delta(x)$ is Dirac delta function. Assuming that the packet arrival may happen at any moment t of the time slot with the same density $1/\Delta$, we determine $f_{W1}(w)$ as

$$f_{W1}(w) = \int_0^{\Delta} \frac{1}{\Delta} f_{W1}(w,t)dt. \qquad (13)$$

Similarily, if the queue size is between L and $2L$ which will happen with probability

$$p_2 = \int_L^{2L} f(x,t;\psi)dx$$

then we should have two empty optical packets to put the packet inside. It means that we add the delay of waiting for the second empty optical packet to the waiting time defined above, This delay is equal Δ with probability p if just the next optical packet is empty, 2Δ if the next packet is occupied but the one after it is empty – with probability $(1-p)p$, etc. The distribution of this additional delay $f_{\Delta}(w)$ is

$$\begin{aligned} f_{\Delta}(w) = p\delta(w-\Delta) &+ (1-p)p\delta(w-2\Delta) + \\ &+(1-p)^2 p\delta(w-3\Delta) + \ldots \\ &+(1-p)^n p\delta(w-(n+1)\Delta) + \ldots \end{aligned} \qquad (14)$$

Therefore the waiting time for a packet arriving at time t and seeing the queue size between L and $2L$ is determined by the convolution

$$f_{W2}(w) = f_{W1}(w) * f_{\Delta}(w)$$

and the waiting time for the arriving packet seeing the queue size between $2L$ and $3L$ is determined by

$$f_{W3}(w) = f_{W1}(w) * f_{\Delta}(w) * f_{\Delta}(w)$$

and the unconditional waiting time distribution $f_W(w,t)$ for a packet coming at a time t is

$$f_W(w) = \sum_{n=1}^{\infty} p_n f_{Wn}(w) \qquad (15)$$

where

$$p_n = \int_{(n-1)L}^{nL} f(x,t;\psi)dx \qquad (16)$$

and

$$f_{Wn}(w) = f_{W1}(w) * f_{\Delta}(w)^{*(n-1)} \qquad (17)$$

Eq. (15) presents the probability distribution function of the delay introduced by the aggregation queue.

5 Numerical examples

In numerical examples we use PDUs of length $L = 12.5$ KB (12500 bytes) and the time slots $\Delta = 10$ μsec at 10 Gb/sec, the same realistic parameters as considered in [**?**,**?**].

The interarrival times have a general distribution with mean $1/\lambda$, variance σ_A^2, and the size of electronic packets is determined by a general distribution having density with mean m and variance σ_m^2.

Assume $\lambda = 1$ packet/μsec, the average packet size $m = 700$ bytes, squared coefficients of variation $C_A^2 = \sigma_A^2 \lambda^2 = 1$ and $C_m^2 = \sigma_m^2/m^2 = 1$.

It means that the parameters of the diffusion equation are: arrival rate $\beta = \lambda m = 0.7$ kB/μsec and $\alpha = 1.47$, as defined by Eq. (2)

Naturally, the variances C_A^2, C_m^2 may be different and represent any distribution, that is the advantage of diffusion approximation. Note that the squared coefficient of variation close to one does not mean necessarily that a distribution is resembling the exponential one. When analysing the distributions of packet sizes and times between packets given by CAIDA (Center for Applied Internet Data Analysis) repositories, we met distributions which are far away from exponential ones, but with $C^2 \approx 1$.

The PDUs are uploaded following Case 1 procedure.

Figs. 3-6 illustrate the convergence of the solution formulated in Eq. (10) for various values of p, it is visible that at each case, 25 iterations give satisfactory results. Fig. 7 presents the impact of probability p on the final distribution $f(x,t;\psi)$ of the queue length in bytes.

p_n	$p = 0.25$	$p = 0.5$	$p = 0.75$	$p = 1$
$n = 1$	0.000422	0.011993	0.085542	0.5581957
$n = 2$	0.004069	0.066236	0.287785	0.430287
$n = 3$	0.016506	0.130243	0.276826	0.011427
$n = 4$	0.049166	0.183986	0.185722	$8.86 * 10^{-5}$
$n = 5$	0.119076	0.210541	0.100210	$3.66 * 10^{-7}$

Table 1. Probabilities p_n, $n = 1, \ldots, 5$ that arriving electronic packet sees queue size $x \in [(n-1)L, nL]$, as in Eq. (16)

The Table 1 presents probabilities p_n that n empty optical packets will be needed to allow the transport of a packet joining the queue.

Figs. 8 - 10 refer to the waiting time distributions. Fig. 8 presents $f_{Wn}(w)$ as defined in Eq. (17), we see he waiting time depends on the number n of empty slots needed to evacuate the queue before the considered packet may be sent.

Fig. 9 displays $f_{W5}(w)$ and illustrates how the probability p of an empty optical packet changes, for a fixed $n = 5$, the waiting time distribution.

Fig. 10 gives the unconditional waiting time probability density distribution $f_W(w)$ following Eq. (15).

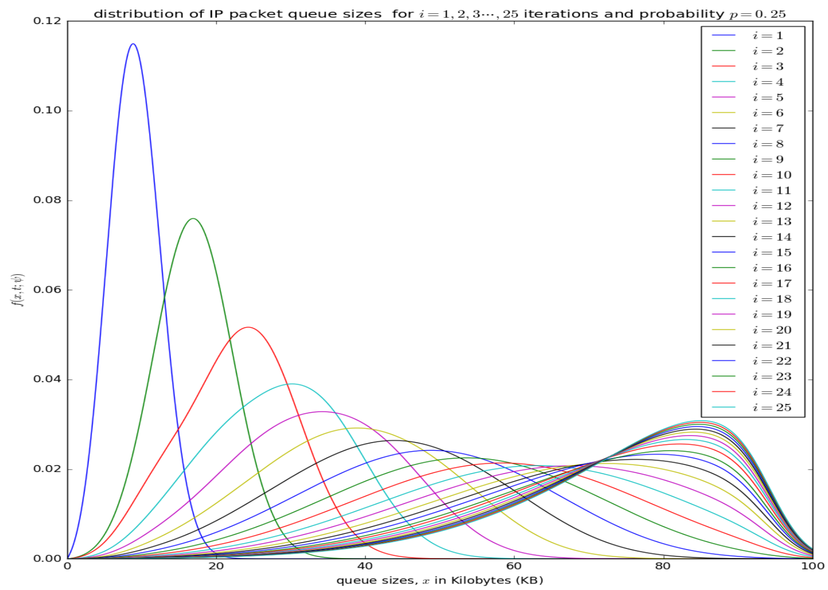

Fig. 3. The distribution of the aggregation queue size, $f(x, t; \psi)$ if $p = 0.25$ for consecutive iterations as in Eq. (10) $i = 1 \dots 25$

6 The ring performance

Let us evaluate the performance of the whole ring having n stations. Assume that each of the stations is delivering a flow of the same intensity λ of packets or $m\lambda$ of bytes. Assume also that the ring has n stations, the destination of flows is equiprobable, the traffic is one-way and the station receiving its flow after making a round deletes it.

It means that the whole flow λ packets generated by a station i is transmitted entirely between i and $i+1$, at $i+1$ station a $1/(n-1)$ part of it is subtracted and the rest, i.e. $(n-2)/(n-1)\lambda$ is sent further, on the next station again $1/(n-1)$ part of the original traffic is deleted, etc. and there is no traffic at all between station $i-1$ and i. If the traffic of each station is behaving in the same way, the total traffic between stations is $\lambda_{tot} = \lambda n/2$.

The total capacity of the ring assured by optical packets is L/Δ, but packets are not filled entirely, the effective mean content of a packet is L_{eff}, eq. (11), hence the real capacity is $\mu = L_{eff}/\Delta$.

Let us define the utilisation factor of the link as

$$\varrho = \lambda_{tot} m/\mu = \frac{\lambda_{tot} m \Delta}{L_{eff}} \tag{18}$$

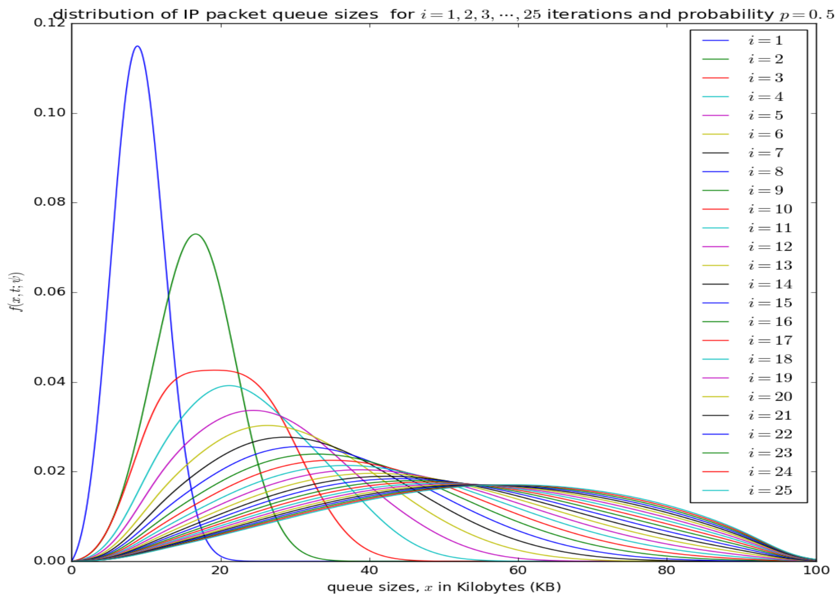

Fig. 4. The distribution of the aggregation queue size, $f(x,t;\psi)$ if $p = 0.5$ for consecutive iterations as in Eq. (10) $i = 1 \ldots 25$

and take it as an estimation of the probability that an optical packet is occupied $\varrho = (1 - p)$.

In the multicasting mode, where the traffic generated by a station i makes nearly the entire loop and is deleted only by the station $i - 1$, the ring traffic is $\lambda_{tot} = n\lambda$, the rest of the reasoning remains the same.

The evaluation of p, in Eq. (18) is based on L_{eff} in Eq. (11) which in turn is given by the diffusion model where p is a parameter. Therefore we should use iteratively the diffusion model and equation (18) looking for convergence of p for a given λ.

7 Conclusion

We have applied diffusion approximation modelling to analytically evaluate the performance of the packet aggregation mechanism of an N-GREEN metro network node. We compared the distribution of the queue size of SDUs in the aggregation buffer (distribution of the content of the buffer) for different values of p (the probability of loading a PDU into the optical packet within a given timeslot $\varDelta$ or the probability that an empty optical packet is available within the timeslot $\varDelta$) as shown in Fig. 7 . For large values of p, the queue size of SDUs

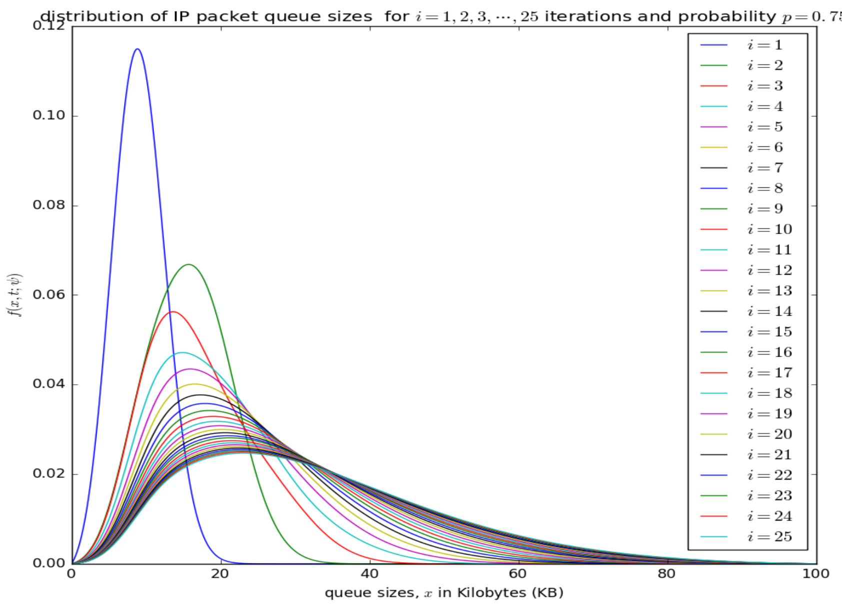

Fig. 5. The distribution of the aggregation queue size, $f(f(x,t;\psi))$ if $p = 0.75$ for consecutive iterations as in Eq. (10) $i = 1 \ldots 25$

in the aggregation buffer is small. However, for small values of p, the queue size of SDUs in the aggregation buffer is significantly large. Even though we have assumed that the aggregation buffer is over-dimensioned to ensure that it does not overflow, it can overflow if the value of p is low and the arrival of packets into the aggregation buffer is fast. We also investigate the influence of p on the distribution of the waiting time (delay) experienced by the SDUs in the aggregation buffer, as shown in Fig. 9. The higher the value of p, the smaller the delay, but the smaller the value of p, the longer the delay.

Therefore, we have demonstrated the influence of the probability of successfully inserting the aggregated packets from the aggregation buffer to the optical transmission ring on the distribution of the queue size in the aggregation buffer and on the distribution of the delay experienced by the SDUs in the aggregation buffer. We have also discussed the performance evaluation of the complete ring by deriving the link utilisation. The designer can optimise the throughput and delay by tunning the design parameters such as the size of the aggregated packet (PDU) L, the timeslot Δ and the probability p of successfully inserting the packet.

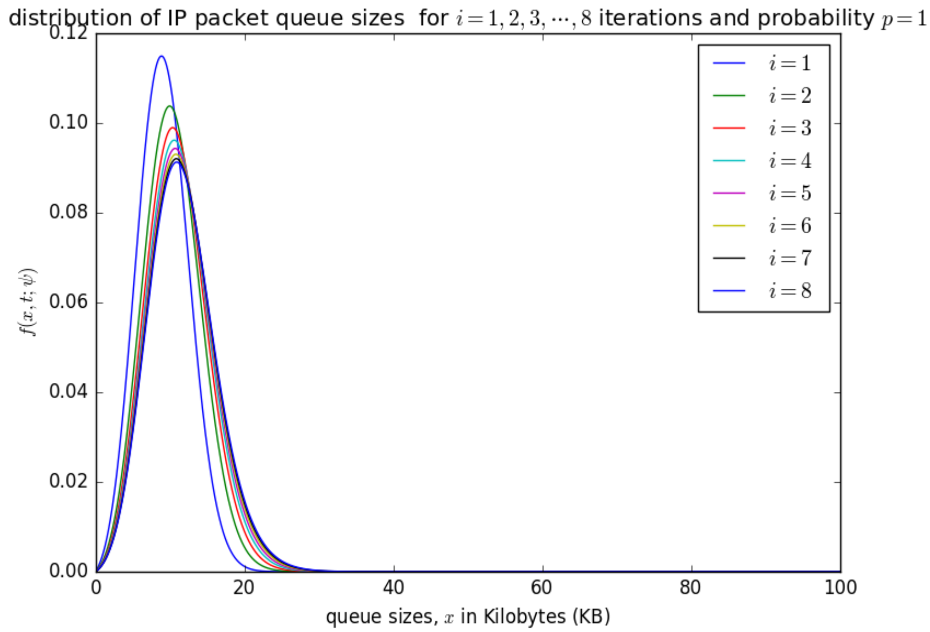

Fig. 6. The distribution of the aggregation queue size, $f(x,t;\psi)$ if $p=1$ for consecutive iterations as in Eq. (10) $i=1\ldots 25$

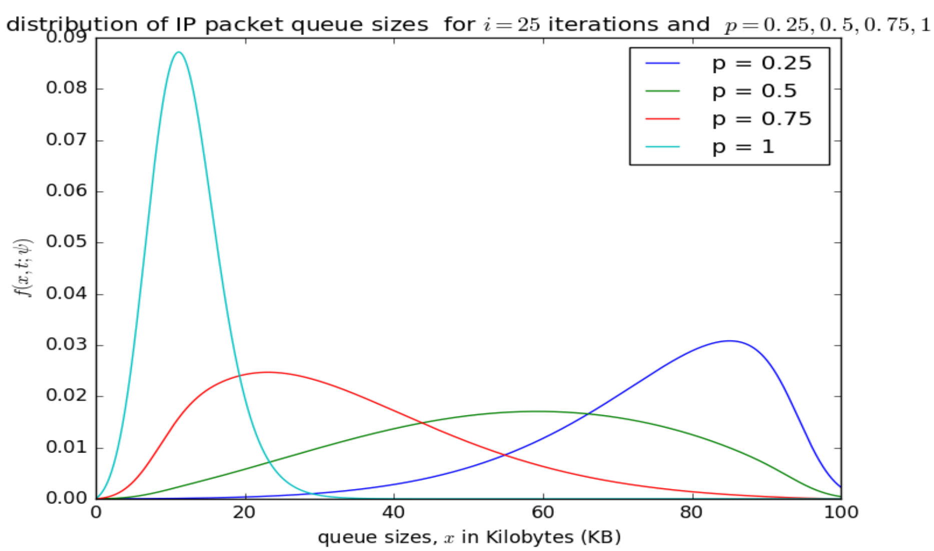

Fig. 7. The distribution of the aggregation queue size, $f(x,t;\psi)$ for the $i=25$ iterations and different values p

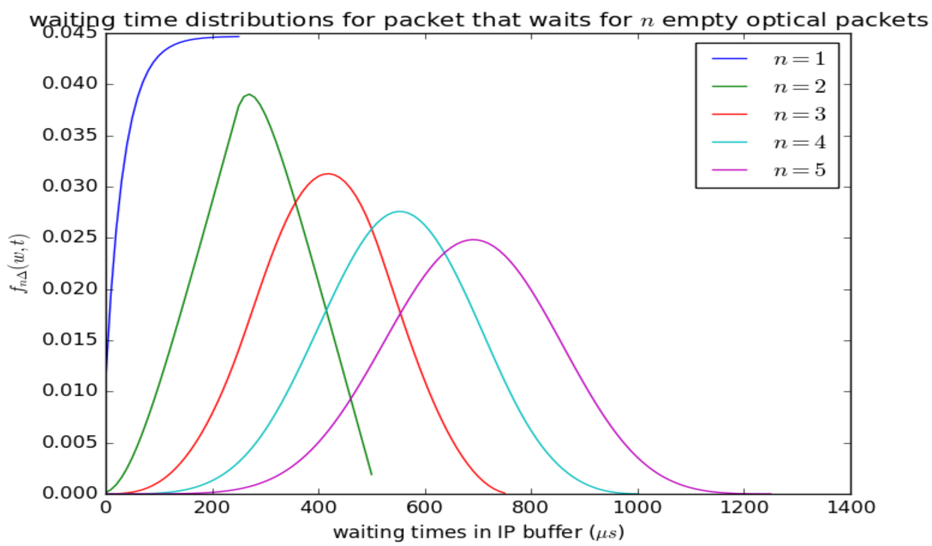

Fig. 8. $f_{Wn}(w)$ as defined in Eq. (17) – the influence of the number of empty optical packets n needed to complete the transfer on the waiting time distribution, $p = 0.25$

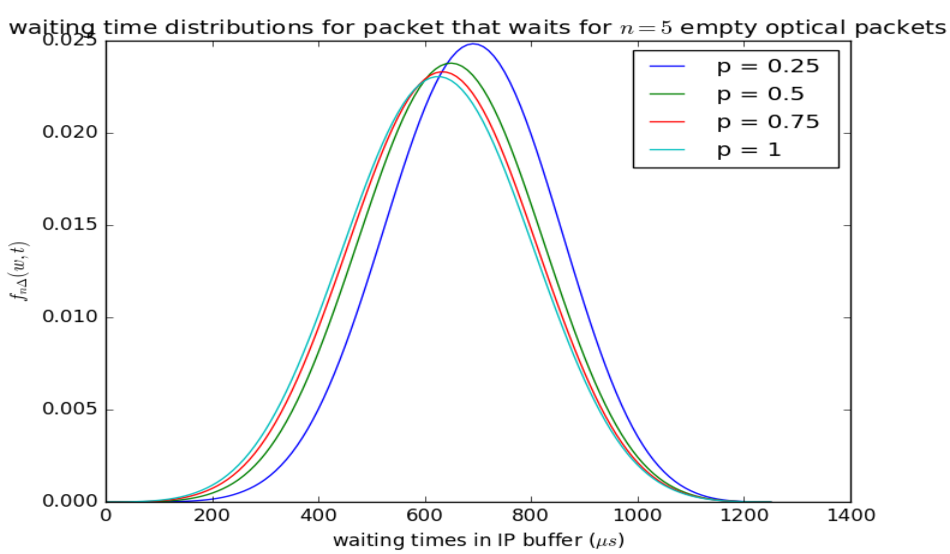

Fig. 9. $f_{W5}(w)$ as defined in Eq. (17) – the influence of the probability p of the empty optical packet on the distribution of waiting time if $n = 5$.

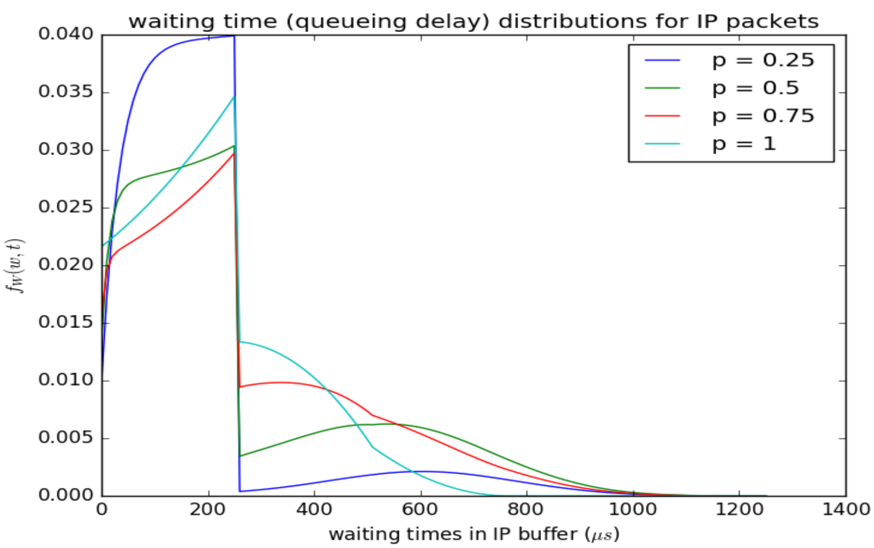

Fig. 10. The unconditional waiting time (queueing delay) density function $f_W(w)$ as in Eq. 13; $p = 0.25, 0.50, 0.75, 1$