

# Traffic aware cyclic sleep-based power consumption model for a passive optical network

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## Abstract

For a network, a power consumption model is an important tool to test the performance of a network process for different traffic loads. In a Passive optical network (PON), the optical network unit (ONU) is responsible for the major power consumption of PON. Both IEEE and ITU have standardized a cyclic sleep process (CSP) for ONU energy conservation. In next-generation PON; TWDM and XGS PON, the ONU power contribution has increased further due to higher number of ONUs and ONU being tunable. Therefore, an accurate power consumption model of the CSP process for energy efficiency studies under different traffic conditions is of prime importance. The existing CSP power consumption models do not depict the CSP process accurately especially the inactivity of the ONU in the asleep and sleep aware states are not taken into account which reduce the accuracy of the model. The proposed inactivity aware model (IAM) overcomes these gaps and very accurately models the CSP process, as evident from the results, which are better than earlier model results and quite close to earlier published simulation results. The model is also validated through a simulation-based study and the simulation results are observed to be very close to the model results with only a 5% deviation.

## KEYWORDS

energy efficiency, XGPON, DTMC, green optical networks

## 1 | INTRODUCTION

TO meet the rising bandwidth requirements in the society, the access network has gradually evolved from copper based cable network to optical access networks. The optical access networks also have a promising role in future 5G<sup>1</sup> wireless networks both in the front haul<sup>2</sup> as well as in the backhaul.<sup>3</sup> The true realization of optical access networks is the passive optical network (PON).<sup>4</sup> The expansion of PON is good for globalizing the world but it also has a dark side that it is contributing to the increasing global carbon footprint<sup>5</sup> due to its increasing power requirements. The next-generation PON; TWDM PON and XGS PON ONUs are tunable and support higher user ports, typically up to 256 from a single

PON, which is further increasing their power consumption. Moreover, the PON is being deployed globally and due to these massive deployments, its power consumption contribution in the information and communication (ICT) sector has been increasing. For example from the year 2010 to 2015, the total power requirement of the ICT sector was around 20GW that is now expected to reach to 1.5 TW by 2025<sup>2</sup> which has been estimated to contribute to 14 percent of the global GHG emissions by 2040.<sup>6</sup>

Generally, PON is considered to be a green technology compared to both copper access network as well as the active optical network (AON) technology, however, it is always-ON requirement of optical network unit (ONU) due to the synchronous nature provides a research opportunity to reduce its power consumption. It has been reported that the use of energy conservations schemes is helping to reduce its carbon footprint.<sup>7</sup> Among all the ONU-based energy conservation schemes such as adaptive link rate,<sup>8</sup> bit interleaved PON,<sup>9</sup> processing efficient ONU,<sup>10</sup> the cyclic sleep process (CSP)<sup>11</sup> got wide popularity and has also been adopted as a standard energy conservation scheme for its PON standards by the ITU as well as the IEEE.

The CSP process comprises of four ONU power states; active-held (AH), active-free (AF), sleep-aware (SLA), and asleep (AS). A detailed description of CSP may be referred in reference 12. The performance of CSP depends critically on the traffic arrival rate, configuration of the local wakeup indication (LWI) events and the ONU state timers. Therefore, a comprehensive power model of ONU is of prime importance for such studies for analytical analysis of the CSP schemes as well as for validating the simulation and hardware results of such studies.

The network modeling is an important tool to assess the performance of a network process or network node in the presence of traffic load and the process tuning parameters such as references 13,14. In PON, also many studies have tried to model the power consumption and the traffic arrival process of the ONU using different approaches such as component-based power modeling,<sup>15</sup> queuing theory,<sup>16</sup> discrete-time Markov chain (DTMC),<sup>17,18</sup> and semi-Markov chain.<sup>19</sup> The first approach only considers the power consumption of different ONU components and is not much effective. The later approaches take into account the state powers as well as the traffic arrival process. However, all of the reported models do not consider the ONU inactivity in the AS and SLA states. Since, the power consumption of the AS and SLA state is lesser than the active states and inactivity period of ONU in these states is higher compared to the active states at low and medium traffic loads, therefore, considering these periods is necessary in the ONU power model. Thus, the primary objective of this research was to develop a comprehensive and accurate ITU compliant power model for the ONU CSP process as a function of the traffic arrival process. The secondary objective was (i) To take into account the state transition probabilities of the ONU during CSP process (ii) To take into account the long inactivity period of the ONU in the SLA and AS states in the proposed model.

This study improved the modeling approach of the study reported in reference 17 for an XGPON ONU. This study used DTMC-based modeling but did not exactly model the ITU CSP given in XGPON transmission convergence layer standard G.987.3.<sup>30</sup> They considered an initial SLA state in contrast to the standard CSP process. Moreover, their state transition probabilities are also not accurate and they did not take into account the inactivity of ONU in AS and SLA states. The results of this study also show the inaccuracy of this model as at no traffic load the maximum sojourn of ONU in AS state is only 35% which is not rational and contrast to the simulation results reported in other CSP studies such as references 12,20,21.

Thus, inspired from earlier DTMC-based modeling work for Long Term Evolution (LTE) network,<sup>22</sup> this study presents a DTMC-based power model for an XGPON ONU that considers the CSP state times, upstream (US), and downstream (DS) traffic arrivals as well as the ONU inactivity periods during the SLA and AS states. Thus, the proposed model accurately predicts the ONU sojourn in each state at low as well as high traffic loads. The consideration of the inactivity period in each state depicts the ONU sojourn in each state accurately. This results in true power consumption computation of the ONU in each state. Thus, the overall power consumption result of the ONU at a particular traffic load computed from the model are quite closer to the actual values.

The rest of the paper is organized as follows; in the Section 2, a brief overview of the related work will be given, the Section 3 will present the proposed model, the Section 4 will present a numerical analysis of the model, the Section 5 will present a comparison of the model results with the OMNET++-based simulation testbed, and finally the Section 6 will conclude this study.

## 2 | REVIEW OF CLOSELY RELATED WORK

The power consumption modeling of a network component or network process is a commonly used approach for research investigations in the computer and communication networks. For example, the study in reference 23 presents a machine learning-based power consumption model for the data servers in the cloud data centers. Another similar

model has also been presented in reference 24 for the cloud servers. Similarly, the study in reference 25 presents a power consumption model for the multicore processors, that are commonly used in network nodes such as routers using a nonlinear transformation block and a linear estimation block with improved accuracy. The DTMC-based modeling method is also a very attractive modeling approach to model the network communication scenarios, as they are easier to use as they are based only on the discrete events of the process being modeled.

Markov chain-based models have been used in optical core networks to model the spectrum allocation process in a flexi-gird-based DWDM process constrained by different assignment policies and blocking probabilities.<sup>26</sup> In PON, some earlier DTMC-based models have been reported for the CSP modeling. For example, the study in reference 27 presented a generative model to evaluate LDPC code performance for 50G PON Gilbert model due to Frenchman,<sup>28</sup> who proposed the use of partitioned Markov chains to model the error cluster distribution. However, this study did not take into account the ONU power consumption. The study in reference 18 also used the DTMC modeling approach to model the ONU power consumption as a function of ONU buffer size and AS sate time. Results show that 50 ms  $T_s$  and 1 MB Buffer size of ONU is a good choice for minimum US delays, frame losses, and higher savings. However, this study do not model the CSP process as a finite model and is difficult to use and analyze it. The paper also lacks complete model derivation steps and only evaluates the model performance for very low traffic loads. Another study in reference 29 used DTMC to model the ONU power consumption as a function of ONU entropy, state power consumption, and the traffic arrival rate. However, this study only considered the Active and AS states. An empirical model based on the queuing theory to configure the CSP has been presented in reference 12 using which the all the CSP parameters can be configured according to the desired average target US and DS delays. However, using this model the ONU sojourn in each state and the expected power consumption cannot be computed. The closest modeling study to our work has been reported in reference 17 for an XGPON ONU. This study used DTMC-based modeling but did not exactly model the ITU CSP given in XGPON transmission convergence layer recommendations G.987.3.<sup>32</sup> They considered an initial SLA state in contrast to the standard. Moreover, their state transition probabilities are also not accurate and they did not take into account the inactivity of ONU in AS and SLA states. Their results also show the inaccuracy of this model as at no traffic load the maximum sojourn of ONU in AS state is only 35% which is not rational and contradict with the simulation results reported in other CSP studies such as in references 12,20,21. A comparison of the closely related work is given in Table 1.

Therefore, in this work, a DTMC-based model is reported that can be used to model both the CSP as well as the cyclic doze process (CDP) by incorporating the ONU inactivity in SLA and AS states in addition to the state transition probabilities based on the both US and DS traffic arrival rates. The idea of inactivity timer has been taken from the

**TABLE 1** Comparison of earlier ONU power models for PON

Ref No	Modeling approach	Process modeled	ITU compliant process	Considers inactivity periods	LWI trigger method	Shortcoming
18	DTMC	Cyclic Sleep	No	No	Based on traffic buffer overflow	Can only work for low traffic arrival rates.
19,33	Semi-Markov chain	Watchful	Yes	No	Uses a fixed Asleep time approach	Can only work for low traffic arrival rates.
17	DTMC	Cyclic sleep and doze modes	No	No	On a single frame arrival	Inaccurate model. Shows low energy savings at very low traffic loads.
16	Queuing theory	Cyclic sleep	No	No	Not applicable	Only expression for mean packet delay was derived
12	Queuing theory	Cyclic sleep	Yes	No	Sleep buffer approach	No power model has been derived, only framework for Asleep timer values and sleep buffer size was presented.
34	DTMC	Watchful/integrated sleep-doze mode	No	No	Not applicable	The proposed integrated sleep process is not compliant to ITU or IEEE PON standards.

earlier similar modeling approach presented in reference 22 for the LTE network. However, in this work, two sleep states have been used while in the CSP process only single sleep state is used. Moreover, contrary to this work, only Poisson traffic arrival process is used for all the states.

### 3 | STATE AND INACTIVITY-BASED CSP MODEL

Figure 1 shows the state diagram for the CSP process for ITU compliant PONs; GPON, XGPON, and time wavelength division multiplexing (TWDM) PON modeled as a DTMC as in reference 17 and is shown in Figure 2. In the AH state, the ONU is fully active and it stays in this state for a time period of  $T_{\text{Hold}}$  and if CSP process permission has been granted by the OLT through sleep aware (SA) ON message it transitions to AF state otherwise restarts the timer again in AH state. The ONU stay in AH state is very short as it only has to check the CSP process permission from the PON vendor indicated by the local sleep indication (LSI) flag. If  $LSI = 1$ , the ONU transitions to SLA state otherwise goes back to AH state. In the SLA state, the ONU sojourn is for a period of  $T_{\text{SLA}}$ . After this time, it transitions to AS state if the traffic buffer is not full at the OLT, indicated by OLT via SA (OFF) message or by setting the forced wakeup flag (FWI) to 1 in the DS frames. In the AS state, the ONU sojourn is for a period of  $T_{\text{AS}}$  after which it goes to SLA state if the local traffic buffer is not full that is indicated by local wakeup indication (LWI) flag. If LWI flag = 1 at the ONU, it goes to the AH state.

Figure 2 explains the CSP process with the help of a flowchart showing all the start and stop conditions for all the state and inactivity timers. From each state, the ONU transition to other state depends upon the traffic arrival. Assuming a Poisson traffic arrival process with arrival rate  $\lambda$ , the probability of more than  $N$  traffic frames arrival during the time  $T$  can be written as  $(1 - e^{-(\lambda T)})^N$ , where  $N$  is the traffic threshold defined in frames per second. Based on this result, the probabilities  $A$ ,  $B$ , and  $C$  are computed and are shown in Equations (1) to (3). The probability  $A$  is defined as the probability of one or more downstream traffic frame arrivals during the AH state. This basically corresponds to the OLT permission that is sent using SA (ON) message. Thus, the state transition probability  $P_{11}$  is simply set to  $A$ . The probability  $B$  is defined as the probability of  $N$  DS or US traffic frame arrivals during  $T_{\text{SLA}}$ . However, During the SLA state the ONU becomes inactive for a time period of  $T_{\text{SLA}}$ . The probability of this inactivity is measured as a relative measure of ONU sojourn in a particular CSP state. Where  $T_i$  is defined as the sum of inactivity timers;  $T_{i1}$ ,  $T_{i2}$ ,  $T_{i3}$ ,  $T_{i4}$  of the AH, AF, SLA, and AS states. The sojourn of ONU during the AH and AF states is for a very short duration of a single XGPON frame duration (125  $\mu\text{s}$ ) and during this time period, the ONU is busy in sending/receiving the traffic frame so its inactivity in these states is negligible. Thus, the probability of the inactivity of the ONU during SLA state is computed as  $E$  in Equation (4). Therefore, the state transition probability  $P_{31}$  can be defined as a joint probability that the SLA state inactivity timer has expired and there are  $N$  frame arrivals as shown in Figure 2. Consequently, the state transition probability  $P_{34}$  can be written as an inverse event of the  $P_{31}$  and is computed as  $(1 - B)(1 - E)$ . Similarly, during the AS state the ONU becomes inactive for a time period of  $T_2$ . Therefore, the probability of inactivity of the ONU during AS state is computed as  $D$  in Equation (5) and the state transition probabilities  $P_{44}$ ,  $P_{43}$ , and  $P_{34}$  are computed as  $D$ ,  $(1 - C)(1 - D)$ , and  $(1 - B)(1 - E)$ , respectively. Using these state transition and inactivity probabilities given, the state

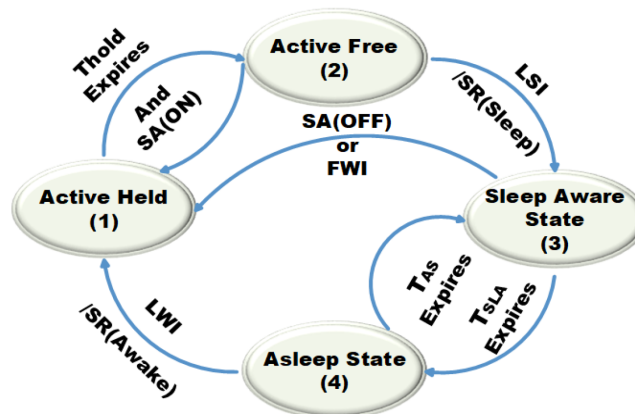


FIGURE 1 Traffic arrival in ONU Sleep Buffer during CSP

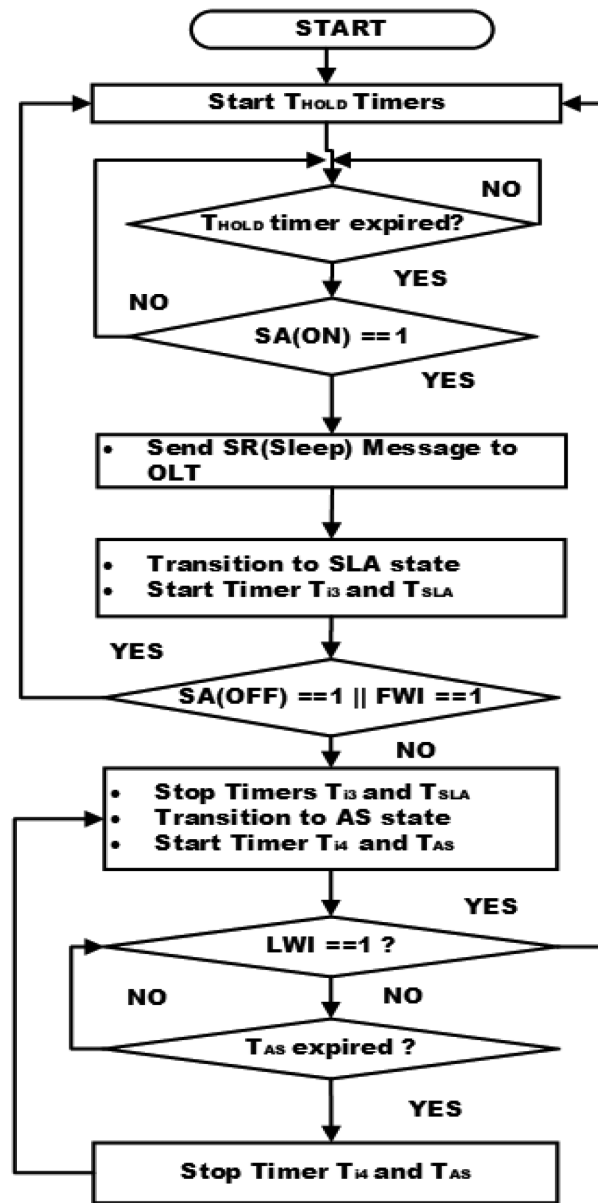


FIGURE 2 CSP process with Inactivity Timers

transition matrix  $M$  can be written as shown in Equation (6). These transition probabilities are a function of  $\lambda_D$  and  $\lambda_U$  with a traffic buffer size of  $N$  as well as the ONU inactivity during these states. Therefore, the stationary probabilities of the DTMC model of the CSP can be computed in  $M$  matrix.

$$A = 1 - e^{-\lambda_D T_{AH}} \quad (1)$$

$$B = \left(1 - e^{-(\lambda_D + \lambda_U) T_{SLA}}\right)^N \quad (2)$$

$$C = \left(1 - e^{-(\lambda_U T_{AS})}\right)^N \quad (3)$$

$$E = \frac{T_i}{T_i} \quad (4)$$

$$D = \frac{T_{i_2}}{T_i} \quad (5)$$

$$M = \begin{bmatrix} A & 1-A & 0 & 0 \\ 0 & 0 & 1 & 0 \\ B(1-E) & 0 & E & (1-B)(1-E) \\ C(1-D) & 0 & (1-C)(1-D) & D \end{bmatrix} \quad (6)$$

Let  $u = \{u_1, u_2, u_3, u_4\}$  denote the probability of staying at state  $S_i$  ( $i \in \{1, 2, 3, 4\}$ ) of the DTMC model in steady state for the 4-state CSP model. Then we can write the initial state probabilities in terms of the state transition probabilities as follows from Equations (7) to (10) using the fact that  $u_i = \sum_{j=1}^4 u_j P_{ji}$ .

$$u_1 = u_1 A + u_3 B(1-E) + u_4 C(1-D) \quad (7)$$

$$u_2 = u_1(1-A) \quad (8)$$

$$u_3 = u_2 + u_3 E + u_4(1-C)(1-D) \quad (9)$$

$$u_4 = u_3(1-B)(1-E) + u_4 D \quad (10)$$

Using the stationary distribution given in Equations (7) to (10) and the fact that  $\sum_{i=1}^4 u_i$  is always 1 the system of equation is solved to obtain the steady-state probability distribution for each state in Equations (11) to (14).

$$u_1 = \frac{(1-D)((1-E) - (1-C)(1-B) * (1-E))}{X.Y.Z} \quad (11)$$

$$u_2 = (1-A).u_1 \quad (12)$$

$$u_3 = \frac{u_2}{((1-E) - (1-C)(1-B)(1-E))} \quad (13)$$

$$u_4 = \frac{(1-B) * (1-E)}{(1-D) * u_3} \quad (14)$$

where the denominators  $X$ ,  $Y$ , and  $Z$  are defined in Equations (15) to (17). They have been used for the ease of representation of the steady-state probabilities.

$$X = (1-D)((1-E) - (1-C)(1-B)(1-E)) \quad (15)$$

$$Y = (1-A)(1-D)((1-E) - (1-C)(1-B)(1-E)) \quad (16)$$

$$Z = (1-A)(1-D) + (1-B)(1-E) * (1-A) \quad (17)$$

#### 4 | PERFORMANCE EVALUATION OF THE MODEL

Assuming  $T_{AH} = 125 \mu\text{s}$ ,  $T_{AF} = 525 \mu\text{s}$ ,  $T_{SA} = T_{i_3} = 2 \text{ ms}$ , and  $T_{AS} = T_{i_3} = 50 \text{ ms}$ , the average AH state time ( $T_{AH}\%$ ), AF state time ( $T_{AF}\%$ ), AS state time ( $T_{AS}\%$ ), SA state time ( $SA\%$ ), power consumption ( $P\%$ ), and energy savings ( $S\%$ ) can be computed using Equations (18) to (23) and the results are plotted in Figures 3, 4, 5, 6, 7, and 8, respectively, as a

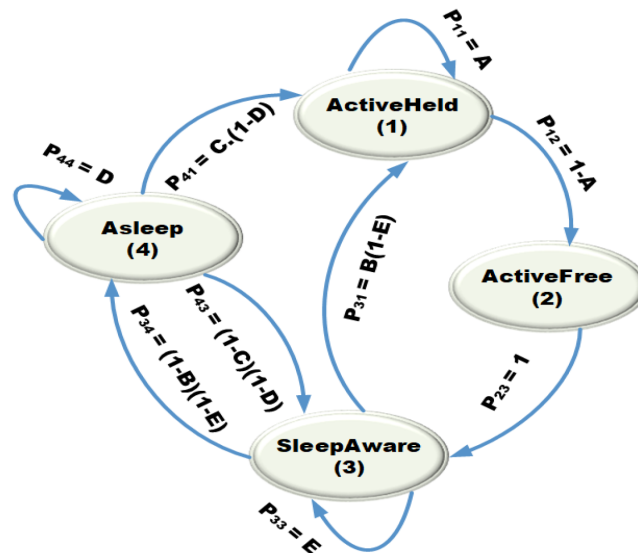


FIGURE 3 DTMC model for ONU during CSP

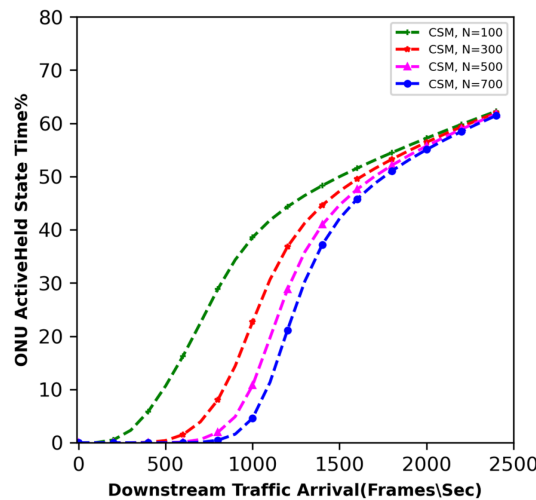


FIGURE 4 ONU sojourn in active held state

function of  $\lambda_D$ . The value of  $\lambda_D$  is varied from 0 to 2500 frames/sec. For each value of  $\lambda_D$ , the  $\lambda_U$  is set to one-fourth of  $\lambda_D$  rate because the US line rate is also one-fourth of the DS line rate in XG-PON. The performance is evaluated for different values of the traffic threshold  $N$ .

The results show that 75% of the time, the ONU sojourn is in AS state at no or very low traffic loads, followed by around 25% of its sojourn in SLA state with zero sojourn in AH and AF states as evident from the results in Figure 4–7. As the traffic load increases the sojourn in AS and SLA states start decreasing and in AH and AF states increases. At a very high traffic load, the ONU sojourn is mostly in AH state. The ONU sojourn in AF also decreases at higher traffic loads. These results are very rational and in line with ONU AS state time results presented figure 6 of earlier simulation results published in reference 20. This is because this study used a fixed size AS state buffer approach to delay the ONU sojourn in AS state which accounts for the ONU inactivity during the AS state time. However, this study was only simulation based and no ONU power model was presented.

As evident from Figures 8 and 9, the ONU exhibits low power consumption and higher energy savings at even quite higher traffic arrival rate of 1000 frames/sec. This is because of the inclusion of the probability of ONU inactivity in the AS and SLA states and due to the traffic buffer-based approach. After the traffic arrival rate of 1000 frames/sec, the

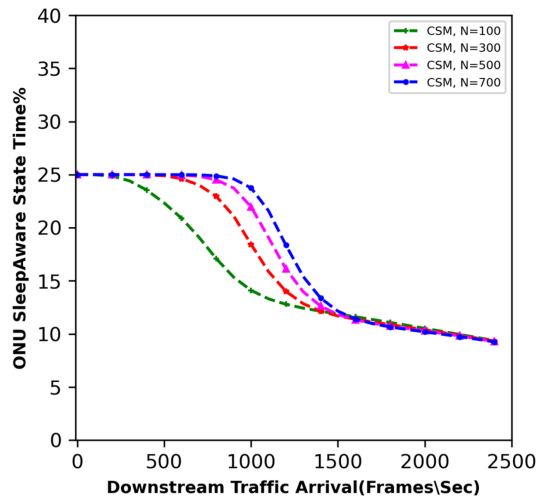


FIGURE 5 ONU sojourn in active free state

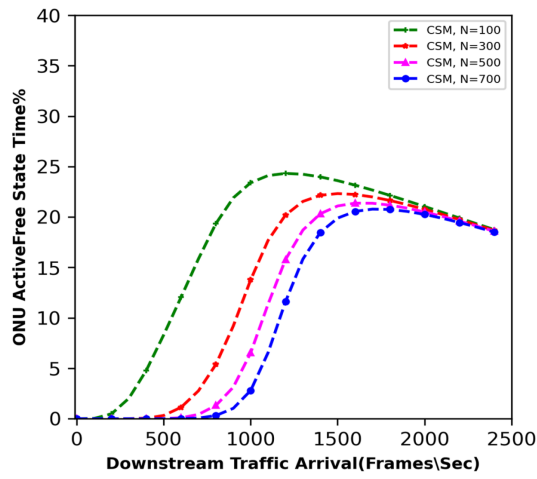


FIGURE 6 ONU sojourn in active free state

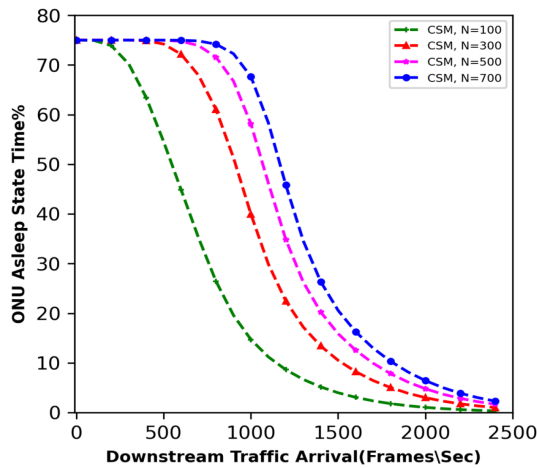


FIGURE 7 ONU sojourn in asleep state

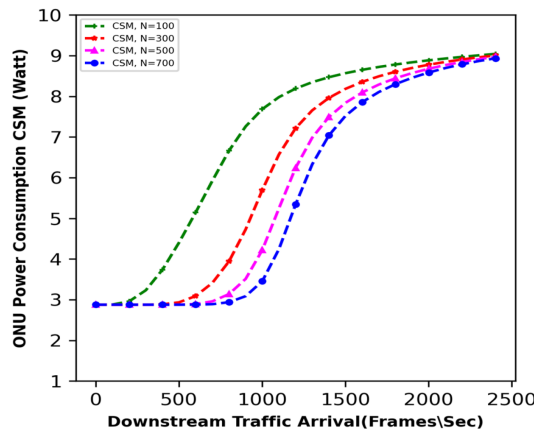


FIGURE 8 Average ONU power consumption

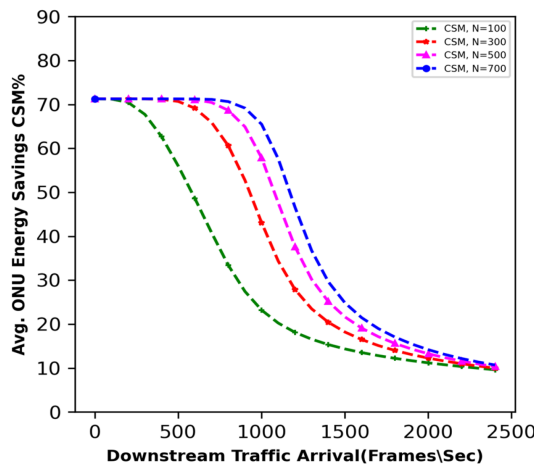


FIGURE 9 Average ONU energy savings

ONU power consumption starts increasing exponentially due to reduction of ONU sojourn in AS and SLA state. Lack of these considerations in the CSP model, as in the earlier similar study,<sup>17</sup> fail to achieve such ONU performance at even a very low traffic arrival rate of 3 frames/sec. They only achieve ONU AS state time of less than 5% even at a traffic arrival rate of 1 frame/sec.

$$T_{AF}\% = u_1 \times 100 \quad (18)$$

$$T_{AF}\% = u_2 \times 100 \quad (19)$$

$$T_{SLA}\% = u_3 \times 100 \quad (20)$$

$$T_{AS}\% = u_4 \times 100 \quad (21)$$

$$P\% = (P_{AH} \times u_1 + P_{AF} \times u_2 + P_{SLA} \times u_3 + P_{AS} \times u_4 + P_{SLA} \times u_5) \times 100 \quad (22)$$

$$S\% = 1 - P\% \quad (23)$$

## 5 | VALIDATION OF THE MODEL THROUGH SIMULATION

For the validation of the model a simulation study was conducted in the OMNET++ with our existing simulation testbed for PON 3031. This simulation testbed comprises of 16 ONUs with a single user are connected to OLT through an optical power splitter. The US and DS processes for the ONU, OLT and Splitter are coded in C++ using a discrete event driven approach. The optical channel with a length of 20 km is used. An XGPON frame is used with an US line rate of 2.5 Gbps and DS line rate of 10 Gbps. The line from user to ONU is set to 156.25 Mbps All the type 1 (T1) to type 4 (T4) traffic classes are considered in each ONU. The bandwidth assignments for these traffic classes are set as; 10% bandwidth is reserved for T1 traffic class by setting the minimum bandwidth parameter  $ABmin_1 = 1575$  bytes with a service interval (SI) of 5. Rest of the bandwidth is equally divided between T2 and T3 by setting the  $ABmin_2 = 7020$  bytes with SI = 5 which is equivalent to 90 Mbps and  $ABmin_3 = ABSur(3) = 3510$  bytes with an SI value of 5. This results in 45 Mbps assured and 45 Mbps nonassured bandwidth assignment to T3. For T4 traffic,  $ABsur_4$  is set to 7812 bytes with an SI value of 5, which is equivalent to 100 Mbps bandwidth assignment on best effort basis. The buffer size for each traffic class in both upstream and downstream traffic for each ONU is set to 1 MB as in references 31,32. The US and DS traffic generators are configured using Poisson batch arrival process. The  $\lambda_D$  is varied from 1 to 2400 frames/sec per ONU with  $\lambda_U$  always being one-fourth of DS, as in reference 21. The arriving frames are distributed as 10% to T1, 30% to each of T2, T3, and T4. The frame size is chosen according to a uniform distribution with an average frame size  $\mathcal{F}_{avg}$  computed as 729. Each simulation is run unless the mean of recorded values of  $\lambda_{DS}$  converges to a value within 95% confidence interval of  $\lambda_{DS}$ . The comparison is performed for a fixed value of  $N = 100$ . Table 2 shows the additional simulation parameters configuration for the CSP process in the simulation.

Figures 10–13 show the simulation results in comparison with the proposed inactivity aware model (IAM) for ONU sojourn in the AH, AF, SLA, AS states. The simulation results for all the states are observed to be quite close to the model results with the only difference that they are not smooth. This is due to several reasons. The first reason is the imperfection of the traffic generation such as the 5% variation in the expected traffic load due to 95% confidence interval used. Moreover, the CSP is managed by the OLT with the help of PLOAM messages that also take time as the messages can only be sent in the US or DS traffic frames after every 125  $\mu$ s. The ONU sojourn at the higher traffic arrival for the values greater than 1500 frames per second the ONU sojourn in the AS state is almost zero and is mostly in the AH state due to which the simulation results and the model results match very closely for both these states.

Similar to the ONU state sojourn results the power consumption and the ONU average energy savings results computed from the simulation results are also observed to be very close to the simulation results and only observed to vary within 5% confidence interval as evident from Figures 14 and 15, respectively. The variation of results in simulation is due to the frame loss, which is not considered in the proposed IAM model.

TABLE 2 Additional simulation parameters

Parameter	Values/details
$P_{AH}, P_{AF}, P_{SLA}$	100%
$P_{AS}$	5%
RTT	200 $\mu$ s
US and DS line rates	2.5 Gbps/10 Gbps
$\lambda_{DS}$	Varied from 7500 to 112 000 frame/sec corresponding to a load variation from 15 to 550 Mbps per ONU.
Frame size	Chosen from triangular distribution with 20%, 20%, and 60% probability of 64, 1500, and 500 Bytes.
$T_{Aware}$	2 ms
$T_{AS}$	50 ms
$T_{init}$	125 $\mu$ s (time taken by ONU in switching from AS state to AF or SA state.
$T_{Hold}$	0.525 ms as in reference 33
$T_{ERI}$	$T_{AS} + T_{init} + SI + RTT = 55 \text{ ms}^{34}$
$T_{ALERTED}$	Should be $\geq (T_{AS} + T_{aware} + T_{init}) = 60 \text{ ms}$

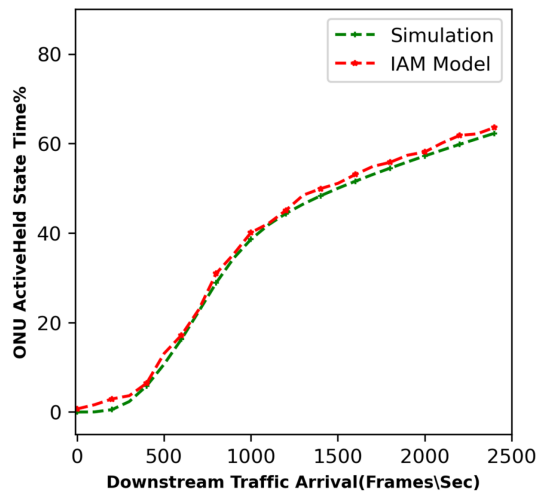


FIGURE 10 ONU sojourn in active held state

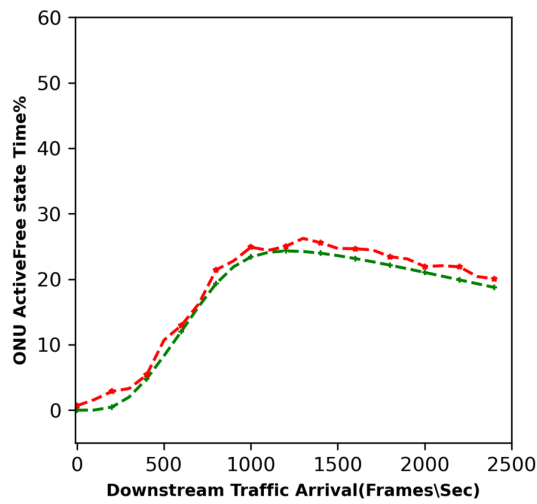


FIGURE 11 ONU sojourn in active free state

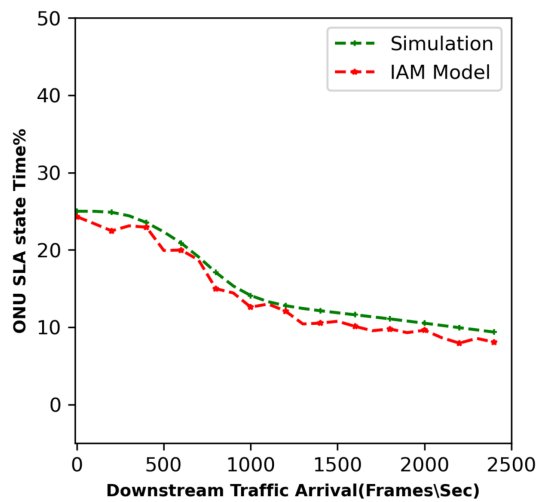


FIGURE 12 ONU sojourn in SLA state

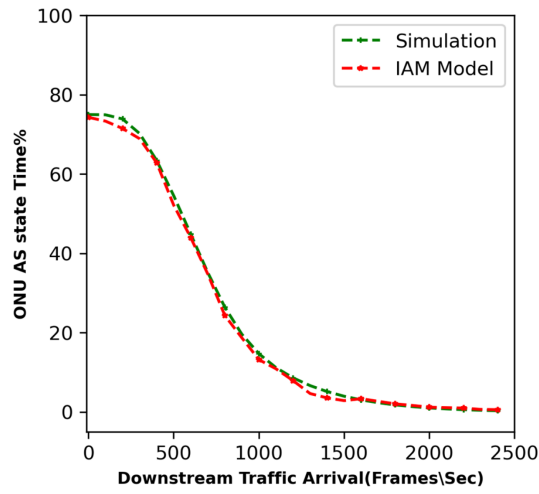


FIGURE 13 ONU sojourn in AS state

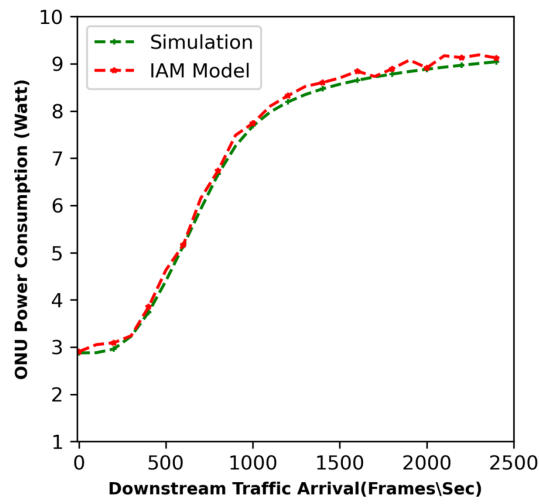


FIGURE 14 ONU average power consumption

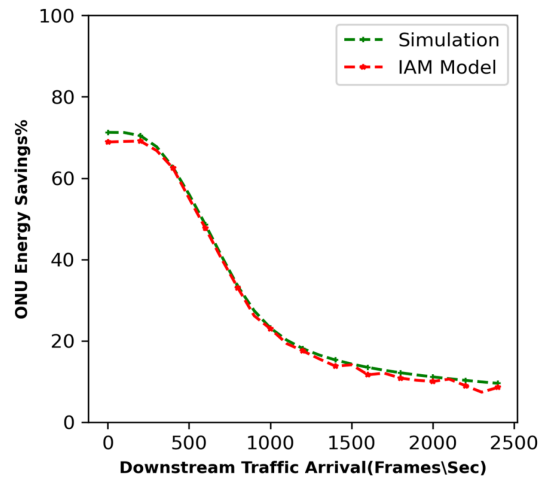


FIGURE 15 ONU average energy savings

## 6 | CONCLUSION

This study presented an improved CSP model using DTMC approach. The proposed model shows much better results compared to earlier similar models. The AS, SLA, AF, AH state sojourn results and the ONU power consumption results are very rational and in-line with simulation results of earlier published work. Moreover, the model validation through simulations also shows the accuracy of the model as the simulation and model results perform very closely within a 95% confidence interval. This model will also be useful for the front haul studies of 5G. In our future studies, we will improve our model to incorporate the cyclic doze process (CDP), CSP and watchful sleep process (WSP) in a single model

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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