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A Comprehensive Framework For Itu Next Generation Pons

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Abstract
Due to the higher number of Optical Network Units (ONU), the power dissipation of Next Generation Passive Optical Network (PON) has gradually risen. Several energy energy-saving schemes have been proposed by the International Telecommunication Union (ITU) such as Cyclic Doze Mode (CDM) and Cyclic Sleep Mode (CSM). The performance of the small capacity devices (nodes) is relying on traffic advent or arrival rate and traffic threshold on which Local Wakeup Indication (LWI) ignited. Thus, an investigative model of ONU to review different CSM / CDM control schemes need extremely important and as well as becoming a hot topic among the scientific community. The state-of-the-art models do not use the sleep buffer parameter that yields lower performance assessment of the CSM process at limited traffic advent rates. They are incapable to acquire the CSM / CDM process at the above traffic rates. The proposed work boosts the current Discrete-Time Markov Chain (DTMC) established power exhibit taking into account a parameter i.e. sleep buffer at each ONU. Additionally, it governs the LWI events at the ONU and as well as Optical Line Terminal (OLT). Furthermore, the suggested exhibit precisely measures the ONU sojourn in every CSM / CDM state, energy savings, and power dissipation of ONU which depends on the advent rate of traffic. According to the recommended model, a CSM / CDM framework is also supplemented to configure all the parameters effectively under the given average delay constraints.

Keywords: Sleep, CSM, CDM, 10G-PON, DTMC

Introduction

Undoubtedly studies of Passive Optical Networks (PONs) become the most challenging and interesting topic in the research community. Thus, energy-efficient solutions for PONs are intended for decreasing ONU power utilization. Therefore, the expansion of PON to yield or implement high-speed broadband connections is extremely valuable. However, it also has a fallout or drawback that is responsible for growing carbon footprints by virtue of increasing power demands [1]. The following-generation PON ONUs are tunable and supportive in more advanced split ratios ranging from acceptable to 256 from a single PON. It enhances their power dissipation. Moreover, the power utilization presence of PON in the information and communication sector is also rising. From the year 2010 to 2015, the power dissipation in the Information and Communication Technology (ICT) network was around 20 GW and was expected to increase further to 1.5 TW by 2025 contributing to 14% of the universal Greenhouse Gas emissions by 2040 [2].

Although PON is relatively energy-effective in comparison to both copper access networks and active optical networks. Though, it's consistently-on-demand by the (ONU) through the synchronous type of ITU PONs. It attracts researchers to reduce power utilization. The power dissipation of an ONU can be classified into different components as displayed in Fig 1. There are the following categories in ONU power dissipation;

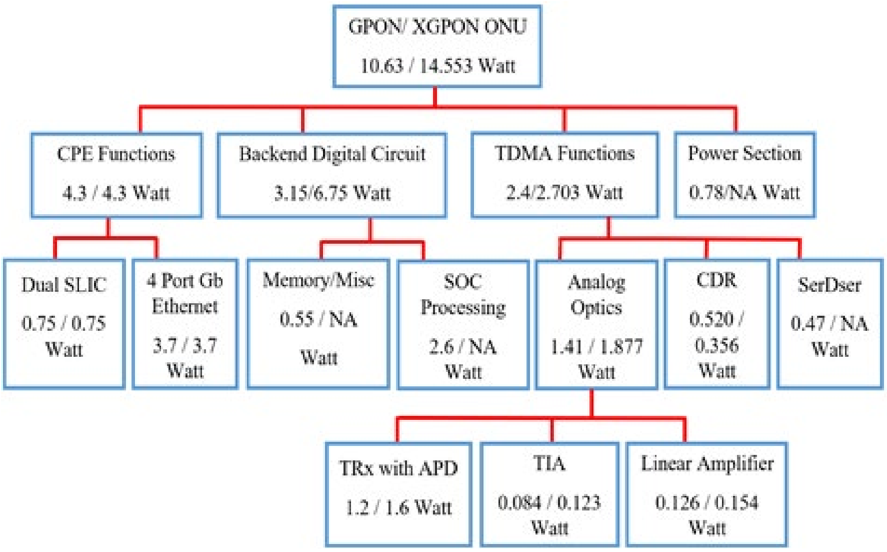

Figure 1: Power Dissipation Breakup of a PON ONU [3].

A power model is developed for an ONU from the studies in [3] to comprehend the power dissipation behavior of an ONU. The ONU power dissipation can be categorized into four parts such as 1) User section (P_{User}), 2) Direct Current to direct current power converter (P_{DC}) 3) TDMA section (P_{TDMA}) 4) Back-end digital circuit (P_{BEDC}). In what follows, the section's details will be discussed.

The first part is $\mathbf{P_{USER}}$, it shows the power dissipation of the user modules and their numerous channels. This part is composed of the Ethernet and Subscriber Line Interface Card (SLIC) modules. The SLIC module gives fundamental facilities for example ringing tone, on-hook and off-hook detections and the Ethernet part gives fast internet facility. The second direct current-direct current power dissipation ($\mathbf{P_{DC}}$) is used by an electronic circuit i.e. need to transform and adjust the input direct current power to the desired voltage levels. The third part is $\mathbf{P_{TDMA}}$ which represents the power dissipation of all the (Time Division Multiple Access) TDMA parts which include trans-impedance amplifier / local amplifier, optical transceivers, clock and data recovery circuit (CDR), and serializer / de-serializer (SerDesr) blocks. Lastly, $\mathbf{P_{BEDC}}$ represents Medium Access Control (MAC) layer processing for arriving frames and buffering in memory storage [3].

Adaptation of such an energy conservation scheme helps to reduce the P_{User}, P_{DC} and P_{TDMA} while the P_{BEDC} cannot be saved as it is required to keep ONU in the ON state, even in the low power state. Thus, it reduces the carbon footprint of ICT. In all the ONU-based energy conservation schemas like adaptive link rate (ALR) bit interleaved Bi-PON effective processing ONU CSM, and CDM became popular and have been considered as standard energy conservation schemes for both the IEEE and ITU compliant PON standards. The dynamic power component of the $\mathbf{P_{TDMA}}$, $\mathbf{P_{USER}}$ and $\mathbf{P_{BEDC}}$ build upon the rate at which data is received at the incoming line [4-8]. Accordingly, the power dissipation of these parts could be decreased by running at lower line rates as in ALR and Bi-PON schemes [9]. The utmost adequate scheme is the CSM / CDM. In this scheme, $\mathbf{P_{TDMA}}$ and $\mathbf{P}$ is decreased by an ONU completely or partially turning off the user channels and the optical transceivers are also closed when there is no traffic.

The idea of CSM / CDM processes is to define four ONU power states; ActiveHeld (AH), ActiveFree (AF), SleepAware (SLA), DozeAware (DA), and Asleep (AS) or Doze. In the first state, the ONU is totally active and waits for the OLT permission to exercise CSM/CDM process. In the second state, the ONU is still active but has gotten permission from OLT so after a pre-defined time it leaves for the SLA state if the upstream (US) and downstream (DS) traffic is under a certain threshold, marked by the LWI events at OLT and ONU. In SLA / DA state, ONU remains active but turns off unnecessary ports and processes and observes LWI events for a certain time. Finally, ONU enters AS / Doze state, which is the least powerful state for the CSM / CDM process. A detailed description of the CSM / CDM process may be referred to in [8]. The performance of these processes depends on the configuration of the LWI events, the rate at which traffic arrives, and ONU state timer values. The power model of ONU is important for analytical analysis as well as the validation of the simulation and hardware analysis yields.

ONU sojourn and the transition probabilities from each power state have not been fixed in the classic CSM / CDM process. Thus, the selection of ONU sojourn in every state and threshold for the triggering of the LWI events critically impacts the performance of a CSM / CDM control scheme. Thus, a power dissipation model for studying the CSM / CDM control schemes is extremely helpful. In literature, numerous ONU power models have been presented in various ways like component-based power modeling queuing theory based power model, DTMC based and semi-Markov chain based power models have been reported [9, 10]. The first method just deals with the power dissipation of the ONU components [11-13]. The other approaches consider the state powers and the transport arrival process. Though, the existing approaches do not deal with the ONU idleness period in AS / Doze and SLA / DA states, and, thus, results in a quick release of ONU from a CSM state on traffic arrival, though authors term them Quick-Release Models (QRM). The results of the QRM approach are irrelevant or inconsequent to the actual simulation results. The authors in used DTMC-based modeling. However, they had not exactly modeled the CDM / CSM process following the 10G-PON (G.987.3) [12]. Further, the authors deal with an initial SLA and DA state as compared to the standard. The state transition probabilities are further inaccurate, and as authors had not considered the ONU idleness time. Their yields showed the imprecision of the exhibit as at no influx or traffic load the maximum sojourn of ONU in AS state is just 35% which is not analytical and in opposition to the simulation yields expressed in various CSM approaches like [8, 14].

Therefore, inspired by prior DTMC-based approach work for LTE networks the work presents a DTMC-based inactivity aware power model (SBM) for 10G-PON, ONU which scrutinize ONU state times, US and DS transport advents, and the ONU idleness time meanwhile low power states [15, 16].

This article is organized into six sections. Section I based on the Introduction, II presents the background or related work. Section III discusses the proposed SBM model. Section IV describes the simulation setup. Section V evaluates the performance of the proposed SBM model and section VI comprises the conclusion.

Related Work

The DTMC modeling is a commendable way of modeling scenarios in network communication, as it is straightforward to implement and depends only on the discrete acts of the method being modeled. Usually, in PON, few prior DTMC-based approaches have been expressed for CSM / CDM process exhibiting. For instance, in authors, proposed a generative approach to evaluate low-density parity-check (LDPC) code performance for the 50G-PON Gilbert approach because Frenchman in suggested the use of partitioned Markov chains to exhibit error cluster distribution [17, 18]. This work had not considered ONU power dissipation. Similarly in authors used the DTMC approach to exhibit ONU power dissipation depending upon ONU buffer size and AS state time [12]. Yields showed 50ms T_s and 1MB buffer size of ONU is considerable for less upstream delays, frame losses and huge savings. Though, this work does not exhibit CSM process as a finite model and is burdensome to analyze. Additionally, this work is also inadequate in the model derivation steps and alone assess model efficacy for minimum transport loads. Moreover, in authors, used DTMC to model ONU power dissipation depending upon ONU entropy, state power dissipation and rate at which transport arrives. This work just considers the Active and AS states [19]. An analytical model to configure the CSM process has been presented in [7, 11]. The authors considered every CSM parameter which could be tuned based on the mid-value targeted US and DS delays. Adopting this approach for the ONU sojourn in each state and expecting power dissipation are unable to compute. The most relevant modeling work to our proposed model has been expressed in for a 10G-PON ONU. This work exploited DTMC-based approaches but did not precisely model the ITU CSM process mentioned in the 10G-PON transmission convergence layer standard (G.987.3). Authors also examined starting SLA state in comparison to the standard. Additionally, their state transition probabilities are inaccurate. The authors did not deal with the idleness of ONU in AS and SLA states. Though, yields show imprecision of this approach at no transport traffic while the maximum sojourn of ONU in AS state is just 35% i.e. not analytical and contradicted simulation yields which are described in other CSM studies such as [8, 14 and 15].

Here, a DTMC-based approach is noted which could be utilized for modeling CSM and the SDM processes by integrating the ONU idleness in SLA / DA and AS / Doze states. Additionally, the state transition probabilities relied upon US and DS Poisson distribution-based traffic arrival rates.

Sleep Buffer-Based CSM / CDM Model (SBM)

Fig. 2, illustrates the CSM procedure for ITU-compliant PON; GPON, 10G-PON, and TWDM PON. Its DTMC model is shown in Fig. 3. Where in every state, the ONU transition to more states relies on transport advent. Assuming a Poisson transport advent procedure with advent rate λ, the probability of more than N traffic frames advent in time interval T can be expressed as $(1-e^{(-(\lambda T)}\ )^N$, Where N is the traffic verge specified in frames/sec. As a result, the probabilities A, B, and C are calculated, given in (1) to (3). Probability A is denoted as the probability of one or more DS traffic frame advent meanwhile AH state. This refers to OLT permission which is sent using SA (ON) information as shown in Fig 2. Thus, the state transition probability P_{11} is to A (probability). Similarly, it is declared as the probability of N DS or US traffic frame advents. However, in the SLA state, the ONU turns idle for a span of T_{SLA}. The probability of this idleness is calculated as a relative part of ONU sojourn in a particular CSM state. Where T_i is denoted as the total of idleness timers; T_{i1}, T_{i2}, T_{i3}, T_{i4} of AH, AF, SLA / DA, and AS / Doze states. The inactivity of ONU in the meanwhile the AH and AF states is for a small interval of a single 10G-PON frame duration (125µs). Thus it is neglected inthe computation of the relevant state transition probabilities. Thus, the idleness of the ONU is in meanwhile the SLA / DA state is calculated as Z in (4). The state transition probability P_{31} is denoted as a joint probability that SLA / DA state idleness timer has lapsed and there are N frame advents as shown in Fig 3. Consequently, state transition probability P_{34} can be described as the opposite event of the P_{31} and is calculated as (1-W) (1-Z). Similarly, during AS state, ONU turns idle for a period of T_2. Inactivity of ONU in the meanwhile AS state is calculated as Y in (5), and the state transition probabilities P_{44}, P_{43} and P_{34} are calculated as Y, (1-X) (1-Y), and (1-W) (1-Z).

Exploiting the state transition probabilities, transition matrix U can be expressed as described in (6). Let $u=\{u_1,u_2,u_3,u_4\}$ expressed as the probability of staying at the state S_i (i ε {1,2,3,4}) of the DTMC model in steady state for the 4-state CSM / CDM exhibit. By using equation $\sum_{i=1}^{4} u_i$ and the state transition equations; $u_i = \sum_{j=1}^{4} u_i P_{j,i}$, the stationary distribution is formed and obtains the steady-state distribution in (14) to (17).

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

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

$$X = \begin{cases} \left(1 - e^{-(\lambda_u T_{AS})}\right)^N & (In\ case\ of\ CSM) \\ \left(\left(1 - e^{-(\lambda_u+\lambda_u) T_{Doze}}\right)\right)^N & (In\ case\ of\ CDM) \end{cases} \quad (3)$$

$$Z = \frac{T_{i_1}}{T_i} \quad (4)$$

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

$$U=\begin{bmatrix} V & 1-V & 0 & 0 \\ 0 & 0 & 1 & 0 \\ W(1-Z) & 0 & Z & (1-W)(1-Z) \\ X(1-Y) & 0 & (1-X)(1-Y) & Y \end{bmatrix} \quad (6)$$

$$u_1 = u_1V + u_3W(1-Z) + u_4X(1-Y) \quad (7)$$

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

$$u_3 = u_2 + u_3Z + u_4(1-X)(1-Y) \quad (9)$$

$$u_4 = u_3(1-W)(1-E) + u_4D \quad (10)$$

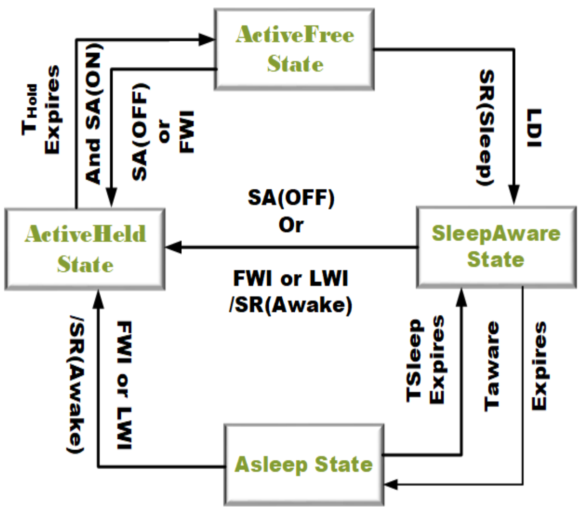

Figure 2: Traffic arrival in ONU Sleep Buffer during CSM [3].

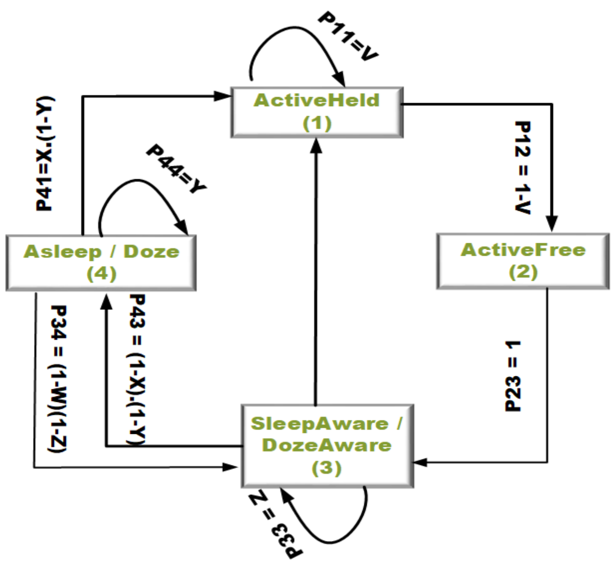

Figure 3: DTMC model for ONU during CSM [3].

$$R = (1-Y)((1-Z)-(1-X)(1-W)(1-Z)) \quad (11)$$

$$S = (1-V)(1-D)((1-E)-(1-X)(1-W)(1-Z)) \quad (12)$$

$$T = (1-V)(1-Y) + (1-W)(1-Z) * (1-V) \quad (13)$$

$$u_1 = \frac{(1-Y)((1-Z)-(1-X)(1-W)*(1-Z))}{R.S.T} \quad (14)$$

$$u_2 = (1-V).u_1 \quad (15)$$

$$u_3 = \frac{u_2}{((1-Z)-(1-X)(1-W)(1-Z))} \quad (16)$$

$$u_4 = \frac{(1-W)*(1-Z)}{(1-Y)} * u_3 \quad (17)$$

In what follows, the section is based on the performance evaluation of the SBM Model.

Performance Evaluation of the SBM Model

Suppose T_{AH}= T_{i1}= 125 µs, T_{AF}= T_{i2}= 525 µs, T_{SA}= T_{i3}= 2 ms and T_{AS}=T_{Doze}= T_{i4}= 20 ms, the average AH state time (T_{AH}%), AF state time (T_{AF}%), AS state time (T_{AS}%), SA state time (SA%), and Power dissipation (P%) can be calculated using (18) to (24) and the results are plotted in Fig 4 to Fig 8 versus λ_D (DS Traffic Arrival). The value of λ_D varies up to 2500 frames per second. For every value of λ_D, the λ_U is (1/4) of λ_D , since the rate of data at the US line is equal to a quarter of the rate of data at the DS line in 10G-PON. Efficacy is calculated for different values of the (DS traffic verge) N with (US traffic verge) M always set to N/4.

The evaluation results of the SBM model show that at no or low traffic load. From the total 75% of the time, the ONU sojourn is in AS / Doze state, subsequent by approximately 25% of its sojourn in the SLA / DA state with zero (0) sojourns in AH and AF states in both CSM and CDM processes for all values of buffer size N. The higher values of N indicate a higher ONU inactivity period. In the case of CDM, as transport load rises the sojourn in Doze and DA states starts falling. Moreover, AH and AF states increase rapidly as load increases while the transition is slower in case CSM process for each value of N. Furthermore, at high transport load, the ONU sojourn is often in an AH state. In the case of CSM, the higher value of N delays the transition from AS and SLA states to AH states. The ONU sojourn in AF mode reduces at greater transport loads as ONU mostly stays in the AH state. These results are rational and in correspondence to Fig. 6 of earlier simulation results which were published in and improved as compared to the earlier similar work [11, 14]. These results are due to inactivity period consideration. The Power dissipation of the ONU also decreases as the load increases which is also rational as ONU mostly stays in AS or Doze state and the Power dissipation of the CSM process is lower as compared to Doze due to the lower power dissipation of AS state compared to Doze.

$$T_{AF}\% = u_1 * 100 \tag{18}$$

$$T_{AF}\% = u_2 * 100 \tag{19}$$

$$T_{SLA}\% = T_{DA} = u_3 * 100 \tag{20}$$

$$T_{AS}\% = \mathrm{T_{Doze}} = u_4 * 100 \tag{21}$$

$$P_{CSM}\% = P_{AH} * u_1 + P_{AF} * u_2 + P_{SLA} * u_3 + P_{AS} * u_4 \tag{22}$$

$$P_{CDM}\% = P_{AH} * u_1 + P_{AF} * u_2 + P_{DA} * u_3 + P_{DozeS} * u_4 \tag{23}$$

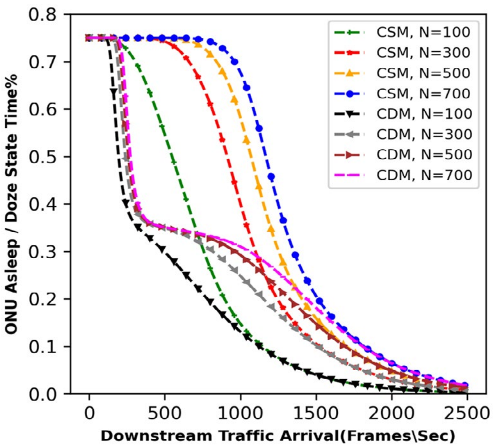

Figure 4: ONU sojourn in Asleep / Doze State.

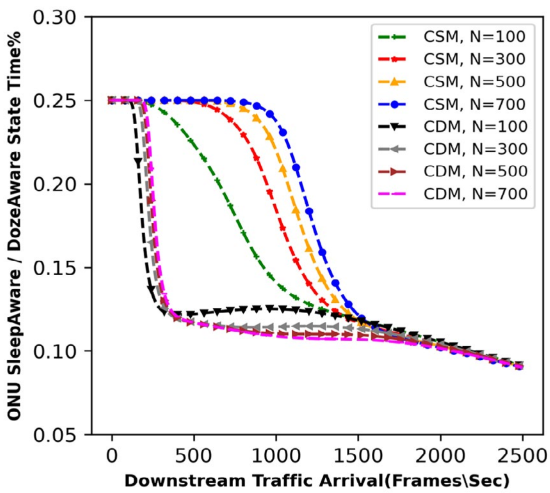

Figure 5: ONU sojourn in SleepAware / DozeAware State.

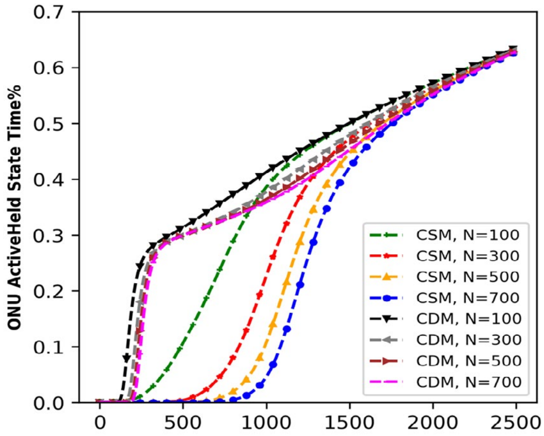

Figure 6: ONU sojourn in Active Held State

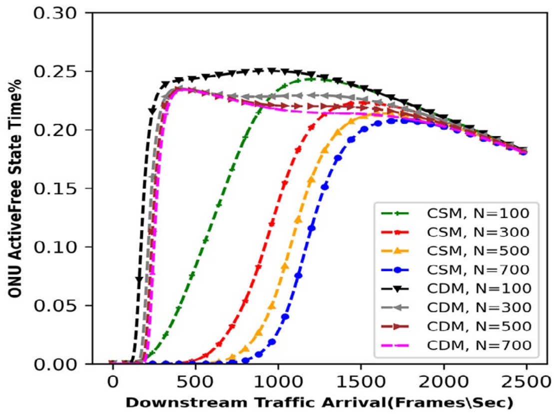

Figure 7: ONU sojourn in Active Free State

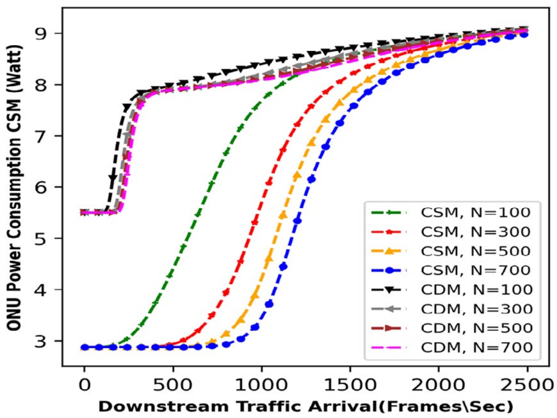

Figure 8: ONU Power dissipation in CSM / CDM.

The QRM model does not have the provision to model for the ONU inactivity, which significantly reduces the ONU sojourn in all the CSM / CDM states as evident from Fig 9 and Fig 10. The inaccurate modeling of the state transition probabilities to and from the AS and SLA states result in an equal ONU sojourn in both states with QRM modeling as evident from Fig 9.

A similar pattern could be observed with the CDM process with a slight pattern difference because of lesser dependence on the DS traffic arrival rate. Due to only depending on the US traffic, the ONU sojourn in the Doze state is higher compared to AS state in the QRM model. In both cases, the ONU sojourn is 30% higher and 25% lower, respectively in the SBM model compared to the QRM model. Thus, the higher ONU sojourn in AS state results in lower power dissipation at a lower traffic arrival rate and higher power dissipation at a higher traffic arrival rate in the SBM model which is analytical or logical. On the contrary, the QRM model shows around 20% higher power dissipation for both CSM and CDM processes compared to the QRM model as obvious from the comparison results in Fig 11. The following section discusses the sleep buffer-based CSM framework.

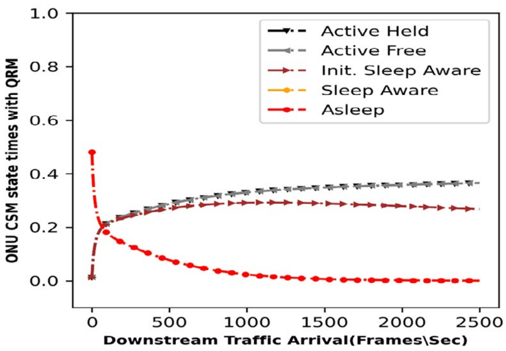

Figure 9: ONU sojourn in CSM states with QRM.

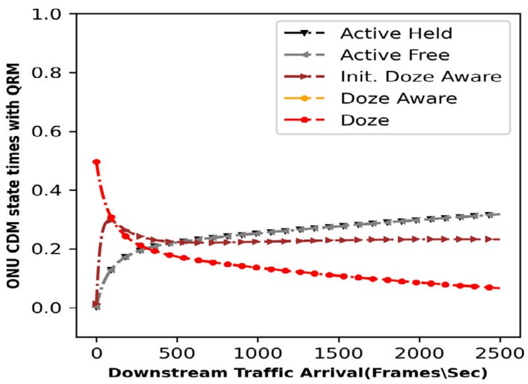

Figure 10: ONU sojourn in CDM states with QRM.

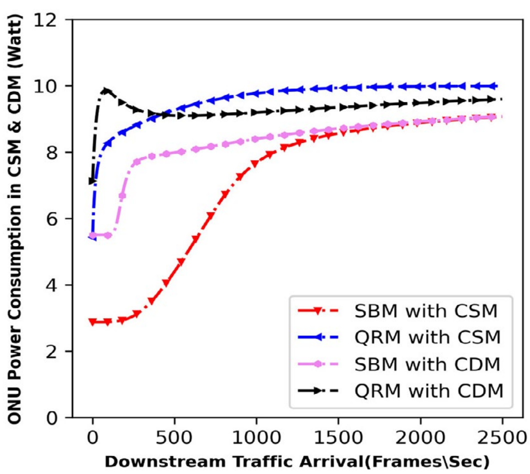

Figure 11: ONU Power dissipation in CSM and CDM modes.

Sleep Buffer-Based CSM framework

The CSM and CDM processes require the configuration of multiple state timers and the trigger condition for the LWI events at the OLT and the ONU. Specifically, the triggering condition for the LWI events and the sleep buffer size has a critical impact on the efficacy of the CSM / CDM process. Since the expected US delay can be computed by Eq. (18) using the stationary probabilities; u_1, u_2, u_3 and u_4 and CSM state times T_{AH}, T_{AF}, T_{SLA} and T_{AS} respectively.

$$E\,[D] = u_1 . T_{AH} + u_2 . T_{AF} + u_1 . T_{SLA} + u_1 . T_{AS} \qquad (18)$$

Therefore, using Eq. (18) and Eq. (14) to Eq. (17) the expected value of the average delay has been plotted in Fig 12. Using this graph, the suitable value of the US buffer N can be computed for the targeted traffic arrival rate for both CSM as well as CDM processes.

In what follows, Algorithm 1 (SBM Algorithm to configure CSM & CDM) computes the numerical values.

Algorithm 1: *SBM Algorithm to configure CSM & CDM*

Input: D_{US}, D_{DS} λ_{DS} and λ_{US}

Output: Fully configured CSM

1: ***Compute** the N from Fig 3.*

2: ***Set** M = N X 4.*

3: **Divide** *N* between T1, T2 and T3 traffic classes.

$$N_{T1} = N * \frac{ABmin_1}{BW_{ONU}}$$

$$N_{T2} = N * \frac{ABmin_2}{BW_{ONU}}$$

$$N_{T3} = N * \frac{ABmin_3 + ABSur_3}{BW_{ONU}}$$

4: **Set** $N_{T4} = \frac{\mathcal{R} - BW_{US}}{n}$

5: **Configure** all CSM & CDM timers at OLT and ONUs.

Set $T_{AS} = T_{Doze} = 20ms$

Set T_{SLA} = 2ms

Set T_{Hold} = 0.5 ms

Set $T_{Eri} = T_{AS} + T_{init} + \frac{RTT}{2} + SI$

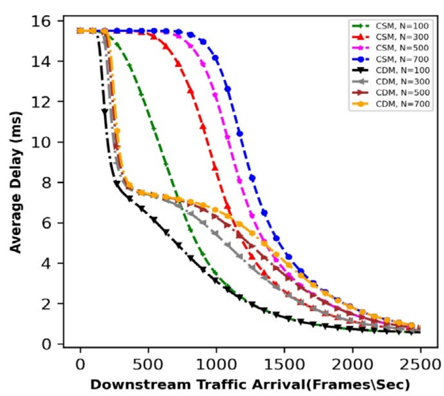

Figure 12: DTMC model for ONU during CSM & CDM

Thus, authors use Algorithm 1 to efficiently configure the CSM process in accordance with given US and DS traffic delays. Initially, the algorithm computes the optimum value of the US sleep buffer N using the graph shown in Fig 11. Secondly, computes the sleep buffer sizes for (Type 1 to Type 3) T1, T2, and T3 traffic classes; N_{T1}, N_{T2} and N_{T3} according to the pre-configured minimum and surplus allocation bytes; $ABmin_1$, $ABmin_2$, $ABmin_3$ and $ABsur_3$ defined by the dynamic bandwidth assignment (DBA) process as in [20]. Whereas the N_T4 is defined on the best effort basis according to the maximum available bandwidth BW_{US} and the traffic load R for total n ONU. Finally, algorithm configures all the CSM / CDM timers according to the chosen values of T_{AS} and T_{SLA}. Generally, T_{AS} is the chosen period between 20ms to 50ms and the T_{SLA} is chosen between 1ms to 2ms. The T_{Eri} and the $T_{Alerted}$ timers are the part of the CSM / CDM process at the OLT and these parameters are configured according to the ITU recommendations G. 989.3 [21].

Conclusion

This article presents a DTMC-based ONU power model that incorporates the ONU inactivity as well as the state transition probabilities for a passive optical network. The incorporation of the inactivity periods yields improving ONU state sojourn times and power dissipation in comparison to previously reported exhibits. The AS / Doze, SLA / DA, AF, AH state sojourn, and ONU power dissipation yields obtained from the proposed SBM model are analytical and in correspondence with simulation yields reported to configure all the parameters efficiently as compared to earlier similar studies.

Declarations

No Ethical Approval is required since the presented results are based on the computer simulation environment, which is harmless.

Authors' Contributions

M.Z.A. and R.A.B. proposed the model, performed the simulations, and analyzed the results; F.A. and QN.N. analyzed the results and conducted proofread as well.

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References

1. Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G., & Friday, A. (2020). The climate impact of ICT: A review of estimates, trends and regulations. arXiv preprint arXiv:2102.02622.
2. Abdollahbeigi, B., & Salehi, F. (2020). The role of information and communication industry (ICT) in the reduction of greenhouse gas emissions in Canada. International Research Journal of Business Studies, 13(3), 307-315.
3. Butt, R. A., Idrus, S. M., Qureshi, K. N., Shah, P. M. A., & Zulkifli, N. (2018). An energy efficient cyclic sleep control framework for ITU PONs. Optical Switching and Networking, 27, 7-17.
4. Miśkiewicz, R. (2021). The impact of innovation and information technology on greenhouse gas emissions: A case of the visegrád countries. Journal of Risk and Financial Management, 14(2), 59.
5. Takahashi, Y., & Harai, H. (2012, May). Energy-efficient PON system with a 1Gbps/10Gbps independent and adaptive link rate control. In The 10th International Conference on Optical Internet (COIN2012) (pp. 44-45).
6. Ayhan, T., Suvakovic, D., Chow, H., & Kazovsky, L. G. (2015). Energy-efficient cascaded bit-interleaved converged optical access/in-building network protocol. Journal of Optical Communications and Networking, 7(8), 785-796.
7. Butt, R. A., Ashraf, M. W., Faheem, M., & Idrus, S. M. (2018). Processing efficient frame structure for passive optical network (PON). Optical Switching and Networking, 30, 85-92.
8. Butt, R. A., Idrus, S. M., Qureshi, K. N., Shah, P. M. A., & Zulkifli, N. (2018). An energy efficient cyclic sleep control framework for ITU PONs. Optical Switching and Networking, 27, 7-17.
9. Hagstrom, R. O., Drummond, A. C., & Faria, H. (2020, July). Passive optical and BaseT local area networks power consumption comparative study. In 2020 22nd International Conference on Transparent Optical Networks (ICTON) (pp. 1-4). IEEE.
10. Bokhari, M., Sohail, M., Kasi, J. K., & Kasi, A. K. (2016). Performance analysis of passive optical networks with energy saving through the integrated sleep mode. Optical Switching and Networking, 21, 16-30.
11. Sarigiannidis, P., Louta, M., Papadimitriou, G., & Theologou, M. (2016). Analysing the optical network unit power consumption in the 10 GB-capable passive optical network systems. IET Networks, 5(3), 71-79.
12. Bang, H., Kim, J., Shin, Y., & Park, C. S. (2012, December). Analysis of ONT buffer and power management performances for XG-PON cyclic sleep mode. In 2012 IEEE Global Communications Conference (GLOBECOM) (pp. 3116-3121).
13. Zhu, M., Zeng, X., Lin, Y., & Sun, X. (2016, September). Modeling and analysis for watchful sleep mode in PON power management. In 2016 15th International Conference on Optical Communications and Networks (ICOCN) (pp. 1-3).
14. Butt, R. A., Faheem, M., Ashraf, M. W., & Idrus, S. M. (2018). Sleep assistive dynamic bandwidth assignment scheme for passive optical network (PON). Photonic Network Communications, 36(3), 289-300.
15. Hirafuji, R. O., da Cunha, K. B., Campelo, D. R., Dhaini, A. R., & Khotimsky, D. A. (2015). The watchful sleep mode: a new standard for energy efficiency in future access networks. IEEE Communications Magazine, 53(8), 150-157.
16. Fowler, S., Shahidullah, A. O., Osman, M., Karlsson, J. M., & Yuan, D. (2015). Analytical evaluation of extended DRX with additional active cycles for light traffic. Computer Networks, 77, 90-102.
17. Mahadevan, A., van Veen, D., Kaneda, N., Duque, A., van Wijngaarden, A. D. L., & Houtsma, V. (2021). Hard-input FEC evaluation using Markov models for equalization-induced correlated errors in 50G PON. Journal of Optical Communications and Networking, 13(1), A100-A110.
18. Fritchman, B. (1967). A binary channel characterization us-

ing partitioned Markov chains. IEEE transactions on Information Theory, 13(2), 221-227.
19. Rayapati, B. R., & Rangaswamy, N. (2021). Bridging electrical power and entropy of ONU in EPON. Optoelectronics Letters, 17(2), 102-106.
20. Butt, R. A., Faheem, M., & Ashraf, M. W. (2020). Efficient upstream bandwidth utilization with minimum bandwidth waste for time and wavelength division passive optical network. Optical and Quantum Electronics, 52(1), 1-26.
21. Ahmed, F., Arfeen, M. Z., Butt, R. A., & Nguyen, Q. N. (2022). Sleep Buffer-based Cyclic Sleep/Doze model & framework for ITU Next Generation PONs.