Technical Journal, University of Engineering and Technology (UET) Taxila, Pakistan Vol. 23 No. 2-2018
ISSN:1813-1786 (Print) 2313-7770 (Online)

Receiver ON Time Optimization for Watchful Sleep Mode to Enhance Energy Savings of 10-Gigabit Passive Optical Network

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Abstract-The Passive optical network (PON) has opened new avenues for the provisioning of very high bandwidths per user through a pure optical fiber based Access Network. However, increasing split ratios in PON are leading to higher power consumption of the PON due to 60% of the power being consumed by the optical network units (ONUs). Recently, watchful sleep mode (WSM) has been added to the PON standards that combines both the cyclic doze and sleep techniques in a single operation by periodically turning on the ONU receiver (RX) during the sleep cycle. However, still, the impact of RX on time on the energy-saving performance of WSM has not been studied. Therefore, this study presents a performance evaluation of the WSM in a 10 Gb/s PON (XG-PON) network with varying RX (ON) times. The investigation is performed with a dynamic bandwidth assignment scheme and real traffic data from Broadcom CATV headend. A comprehensive review of the power saving techniques for XGPON is also presented. The results of the simulation study show that the maximum energy savings are achieved if the RX ON and OFF times are set to 100% duty cycle of the Watch state with non-significant increases in upstream and downstream delays and variance.

Keywords-Energy Conservation, Energy Efficient, Passive Optical Network, Watchful, Sleep Mode

I. INTRODUCTION

The last decade has seen an immense revolution in the Access Network where the copper-based infrastructure has been largely replaced with Optical Access Network. The Passive Optical Network (PON) technology is the true fibre to the home (FTTH) technology that brings the high capacity fibre optic link closer to the broadband users. It offers an affordable maintenance cost to the service provider and provides faster and more reliable services compared to copper Access Network. Next generation PON (NG-PON) including the 10-Gb/s capable PON (XG-PON) are the most popular candidate technologies for the FTTH. It is typically deployed in a tree topology as shown in Fig.1 with optical line terminal (OLT) located at the point of presence (POP) while the Optical Network unit (ONU) is present at the home of each subscriber. The OLT acts as a concentrator and connects to voice network, data network cloud as well as the Cable TV headend to provision triple play services to each user as per its subscription. The PON has got wide deployments worldwide [i] and is also being largely deployed in major cities of Pakistan[ii].

Due to an increasing trend of Internet services [iii] and broadband users, the carbon footprint of the Telecommunication sector is also increasing. Although PON is considered to be a green communication technology, but in PON most of the power consumption is in the ONUs which increases the overall power consumption of PON. This is depicted in Fig.2 that from the total power consumption in broadband telecommunication network, the majority contribution is by the ONUs, followed by the IP core devices, Ethernet Aggregators (EA) and OLT [ii]. Therefore, in relation to the worldwide agenda of 'green technology', it is necessary to minimize the power consumption of PON and have an energy-efficient system. Thus, the research for a green PON is crucial and has attracted the attention of the research community at large scale.

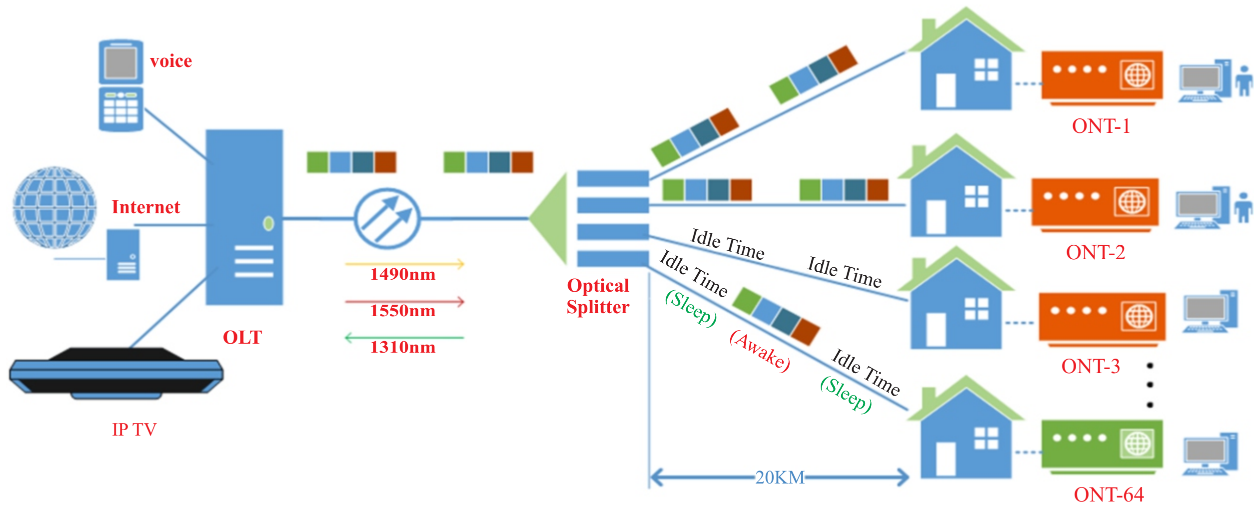

Fig. 1. XG-PON network infrastructure

The International Telecommunication Union (ITU-T) also took various initiatives towards a greener PON and released a comprehensive document under the ITU- G series titled as "GPON power conservation" [iii]. This document describes the power consumption of an ONU and presents three basic power saving methods for the ITU compliant PON standards namely; power shedding, cyclic Listen mode (CDM) and cyclic sleep mode (CSM) [iv]. Power shedding of an ONU is a method to power off the unnecessary functions and related services while maintaining the link as completely operational during the network power failure. Another method is ONU dozing in which an ONU does not observe sleep state completely and retains the ability to transmit upstream which requires the receiver to be continuously ON to receive the downstream (DS) frames. When there are is no upstream traffic arrival, the ONU transmitter can be powering OFF for a certain time termed as Listen state. On the other hand an ONU can be in completeAsleep state which means that both the ONU optical receiver and transmitter are OFF during the whole low power mode of the ONU. The ONU may observe a Fast sleep mode in which it periodically switches between the Active and Asleep states without any external interruption. On the other hand an ONU may observe a deep sleep mode in which it will remain in Asleep state unless there is a traffic arrival. Since, the downstream packet loss is possible in deep sleep, thecyclic sleep is a better mechanism. The sleep schemes are implemented by the OLT and ONU with separate processes and they coordinate with each other using the physical layer operations, administration and maintenance (PLOAM) messages in both the upstream and downstream frames.

The CDM offers lesser energy savings but does not impact the traffic delays much, while the CSM offers very high energy savings but also significantly increases the delays in both directions [v], [vi]. Therefore, a middle approach which is a unification of both CSM and CDM and has been recently added as Watchful Sleep Mode (WSM) by ITU to the transmission convergence layer standards of GPON, XGPON as well as TWDM PON in G.94.3, G.987.3 and G.989.3 respectively. It simplifies the mechanism of CDM and CSM by periodically turn on the receiver periodically to check the DS signal for remote wake up indications at OLT.

The biggest advantage of WSM is that its process can be easily converted to CDM or CSM by defining $T_{watch} = T_{listen}$ & $T_{listen} = 0$ or by only configuring $T_{watch} = T_{sleep}$ respectively. The energy saving (ES) with WSM can be computed by (1). Where, P_{AS}, P_{SA}, P_{Listen} and P_{AF} are the power consumption of the ONU Asleep (AS), Watch Aware (WA), Listen and Active states respectively. Similarly, T_{AS}, T_{WA}, $T_{Rx\text{-}Init}$, T_{Init} and T_{AF} are the ONU sojourn in AS, WA, receiver initialization state, transceiver initialization state and either of the Active Held (AH) or Active Free (AF) states respectively. Since, $P_{Listen} > P_{Sleep}$, therefore, the ES performance of WSM is critically dependent on the $T_{Rx\text{-}Timer}$ value that periodically controls the switching between the AS and Listen states. This impact has not been studied in any of the earlier WSM study. Therefore, in this study the impact of the $T_{Rx\text{-}Timer}$ on the ES performance of WSM is studied and the most suitable choice for the $T_{Rx\text{-}Timer}$ is determined.

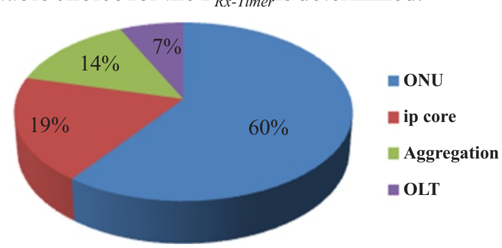

Fig. 2. Power consumption of PON

Rest of the paper follows as; related literature is reviewed in Section II, WSM operation is explained in Section III, the performance evaluation strategy is described in Section IV, the results are discussed and presented in Section V. The final conclusion is made in Section VI.

II. RELATED WORK

The OLT energy conservation has been investigated by only a few studies due to its central and sensitive nature. One such effort is in [x] in which the authors have proposed using two OLTs to work in a master-slave configuration to put one OLT in sleep mode when the traffic load is low. However, this method requires a new investment for a spare OLT and extra arrangement for the master-slave configuration. Another idea investigated in [vii] is of OLT PON port sharing and turning off the unused ports when the traffic load is low. However, this scheme cannot be used with the OLTs having only a single PON port. Overall, the OLT based schemes are not much effective as the OLT only contributes to 7% power consumption in PON.

In the ONU based energy conservation schemes many schemes such as adaptive link rate [xxx], CSM [viii], [ix], CDM [x], [xi], bit interleaved PON (Bi-PON) [xii], buffer-less ONUs [xiii] and processing efficient frame structure [xiv]. As a supplement to all these schemes power shedding may also be used to turn off any unused user ports and relevant software routines. The Bi-PON scheme and buffer-less ONUs schemes need architectural changes in the current ONU hardware design. The ALR scheme requires dual rate transceivers at the ONUs and the OLT. However, the sleep mode schemes such as CSM, DSM, and WSM are medium access layer (MAC) based schemes and can efficiently work with the present as well as the future ONU architectures. Many sleep mode schemes have been presented for PON such as Sleep and Periodic Wake up (SPW) [xv]-[xvii], CSM [xviii], dual phase Listen mode[xiv] and integrated sleep and Listen mode [xx]. However, the WSM scheme being newly introduced by the ITU has got less attention and has only been studied in a few studies [xxi]-[xxvi]. Such a scheme was initially proposed in [xx] and then studied in comparison with CSM in[xxiv], [xxvi]. It was shown in [xxvi] that the energy efficiency of Watchful sleep mode higher than the CSM and CDM with slightly higher values of downstream delay. The impact of T_{sleep} on the ES and delay performance was studied in [xxi]-[xxiii] by modelling the WSM process using discrete time Markov chain. However, only the upstream traffic was considered and a static bandwidth assignment was assumed. The impact of the LWI event at the OLT was neglected which is not a realistic assumption. Therefore, in this work both US and DS traffic is considered and the IACG DBA[xxvii] scheme is used for the US bandwidth management. A detailed recent survey of PON energy conservation schemes may be referred in[iv], [xxviii][xxx].

III. WATCHFUL SLEEP MODE OPERATION

The WSM process is a unification of CSM and CDM schemes. The OLT and the ONU processes for WSM are shown in Fig. 3 and Fig. 4. Unless the WSM process is not allowed by the OLT, the ONU stays in active held (AH) state and keeps on trying to enter active free (AF) state after every T_{Hold} expiry. When an OLT allows ONU to use the WSM mode, it sends a Sleep_Allow (ON) message to ONU. When an ONU receives this message, it sets its local SA (ON) flag and transitions to AF state after the expiry of T_{Hold} timer. This timer is used to keep count of the sojourn in AH state. Then if the upstream and downstream traffic is below a certain threshold indicated by respective local wakeup indications (LWI) events then the ONU will move to WA state for T_{WA} duration. Finally, it enters its Watch. Unlike, Asleep state in CSM, here the ONU periodically keeps on turning ON and OFF its optical receiver while the optical transmitter is kept OFF. However, turning on receiver takes an initialization time T_{Rx_Init}. The ON and OFF timing of the optical receiver are controlled by the T_{Rx_Timer}. However, its value should not exceed the 50% duty cycle of the T_{Watch}. Thus an ONU is in Listen state when the optical receiver is ON and in Asleep state when the optical receiver is OFF. This mechanism enables the ONU to listen to the forced wakeup indication (FWI) events asserted by the OLT in case of downstream traffic LWI event is raised. Thus, the DS delays should significantly reduce with WSM but at a cost of slightly increased power consumption of the ONU due to reduced Asleep state time compared to CSM. Fig. 3 shows the state transition process for WSM. The power levels and states times of all the WSM states are shown in Fig. 4. The choice for T_{WA} and T_{AS} is based on the ONU wakeup time and maximum allowed delay for the upstream and downstream traffic. The choice of the T_{Watch} is not critical as ONU during Watch can wakeup if there is a traffic arrival at the OLT or ONU through local wake up indication (LWI) events.

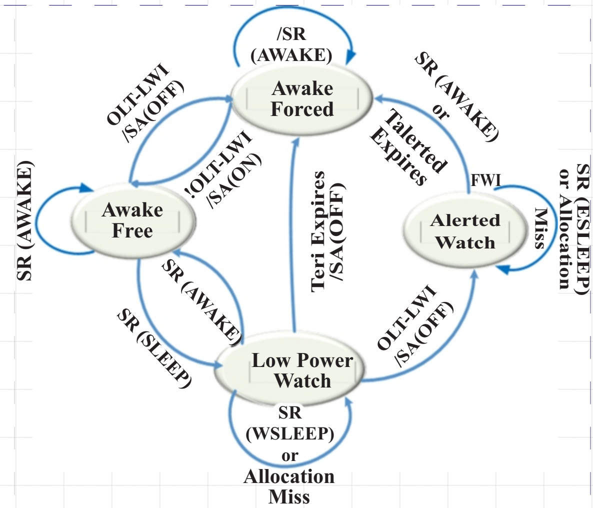

Fig. 3. OLT state diagram for Watchful Sleep Mode

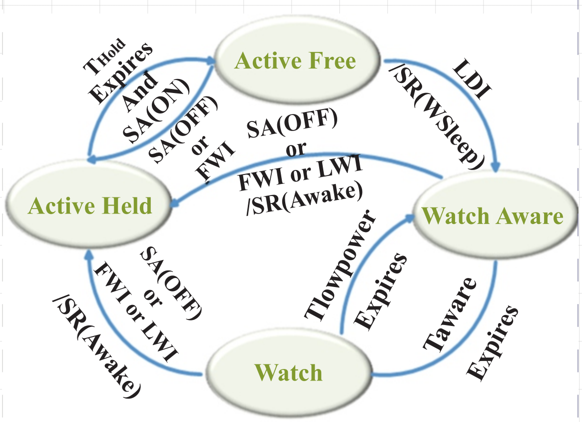

Fig. 4. ONU state diagram for Watchful Sleep Mode

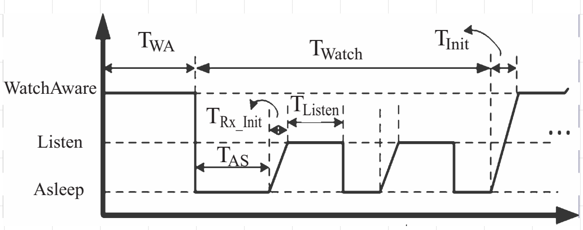

Fig. 5.State transition process of Watchful sleep Mode

IV. Performance Evaluation

In this work an extensive simulation study was performed using OMNET++. The methodology was similar t our earlier PON studies[viii], [xxxi], [xxxii]. A total 16 ONUs were considered, all connected to the OLT through a single power splitter. The ONUs were assumed to be perfectly ranged and be at the maximum distance of 20 Km. For simplicity, only one host and one user was configured per ONU. The downstream network traffic load was varied from 0.1 to 0.7 corresponding to per ONU downstream line rate of 15 Mbps - 550 Mbps similar to the Watchful sleep mode study in[xxvi]. The traffic load was not increased to full capacity as after 70% traffic load, the ONU does not get an opportunity to exercise sleep mode and no significant energy savings are achieved as also in [xxvi]. For traffic frame generation we used the Broadcom CATV upstream and downstream frame distribution of [xxxiii]. The traffic load was equally distributed among the ONUs and a separate traffic generator was configured in each ONU. The duration of each simulation varies as it depends upon the convergence time of λ_{DS}. The simulations are executed with a 95% confidence interval for λ_{DS}.

The details of the simulation parameters for the WSM process and the DBA scheme used are summarized in Table I. The performance of the WSM is studied by varying the duty cycle (DC) of the T_{Rx_Timer} values of 10ms, 30ms and 50ms. The DC is the ratio of the sum of ON and OFF times of the receiver to the Watch state time defined by (1). The DC was set to 20%, 60% and 100%with the Watch state time fixed to 1s. Finally (2) is used to compute the average energy savings (ES%) per ONU.

V. Results and Discussion

From the simulation, the ONU Asleep, Listen and Watch state times, upstream delay and variance of T1 to a T4 traffic class, the downstream delay and variance were recorded for each value network traffic load for all the variation of DC. These results are shown in Fig. 6-20.

TABLE I
Simulation Parameters

Parameter	Values / Details
P_{WA}, P_{AH}, P_{AF},	100%
Line Rate (ONU to OLT)	200 Mbps
P_W	5%
RTT	200 us
US / DS Line Rates	2.5Gbps / 10Gbps
λ_{DS}	Variable from 15 Mbps - 550 Mbps (per ONU).
λ_{US}	λ_{DS} /4
T_{watch}	1s
T_{WA}	5 ms
T_{Init}	3ms
T_{Hold}	500us
T_{ERI}	5ms
T_{Rx_Init}	2ms
$T_{ALERTED}$	5ms

Bandwidth for T1 traffic class	AB_{min} = 1575 bytes with SI_{max} = 5 (equivalent to 20 Mbps)
Bandwidth for T2 traffic class	AB_{min} = 7020 bytes with SI_{max} = 5 (equivalent to 90 Mbps)
Bandwidth for T3 traffic class	$AB_{min} = AB_{sur}$ = 3510 bytes with $SI_{max} = SI_{min}$ 5 (equivalent to 45 Mbps assured & non-assured bandwidth reservation for T3)
Bandwidth for T4 traffic class	AB_{sur} = 7812 bytes with SI_{min} = 5 (equivalent to 100 Mbps bandwidth assignment on best effort basis)

From Fig. 6, Fig.7 and Fig. 8, it is evident that by increasing the receiver ON time, the ONU AS state time increases, while the Listen state time decreases but the Watch state time remains almost the same which is certainly logical. This happens because the delayed release (DR) approach used to control the LWI events delays the current state of ONU in case of a frame arrival during the Watch state. So when T_{Rx_Timer} has higher value, the ONU sojourn in AS state increases and consequently the sojourn in Listen state proportionally decreases. It can be seen in Fig. 6 that at 100% DC, an ONU does not get the chance to observe Listen state at higher traffic loads. This because, in Watch state the ONU, always starts with AS state first and due to its longer time it always gets interrupted before completing it successfully and, thus starting over with Watch state again next sleep cycle. Obviously, with increasein traffic load the sojourn in Asleep, Listen and Watch states decreases.

$$DC = \frac{2 * T_{Rx\_Timer}}{T_{Watch}} \quad (1)$$

$$ES\% = \left(1 - \left(\frac{T_{AS}*P_{AS}+T_{Listen}*P_{Listen}+T_{WA}*P_{WA}+T_{Rx\_Init}*P_{Listen}+T_{Init}*P_{AF}+T_{AF}*P_{AF}}{T_{Sim}*P_{AF}}\right)\right) * 100 \quad (2)$$

Due to increase in Asleep state time and consequently reduced ONU Listen state time for higher values of DC, the energy savings (ES %) also increase as evident from Fig. 8.

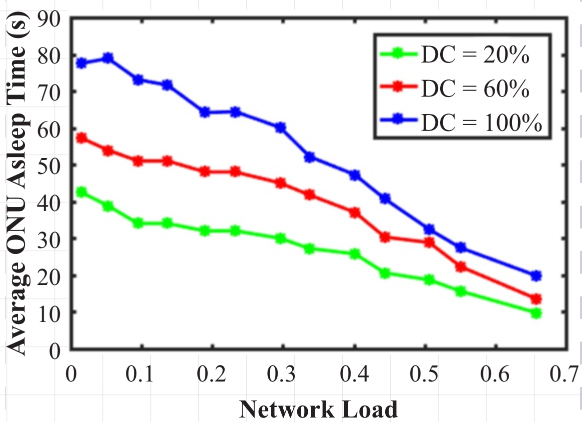

Fig. 6. Percentage of ONU sojourn in Asleep State

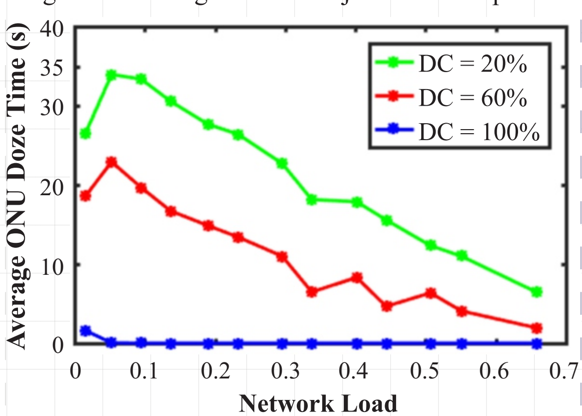

Fig. 7. Average ONU Listen State time

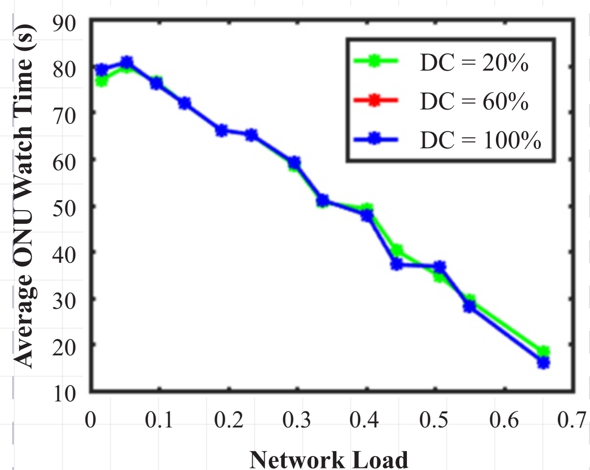

Fig. 8. ONU Watch State time in percent of total time

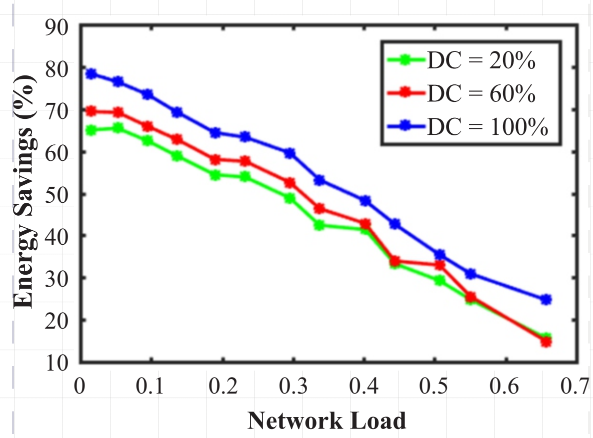

Fig. 9. Percentage of Energy savings per ONU

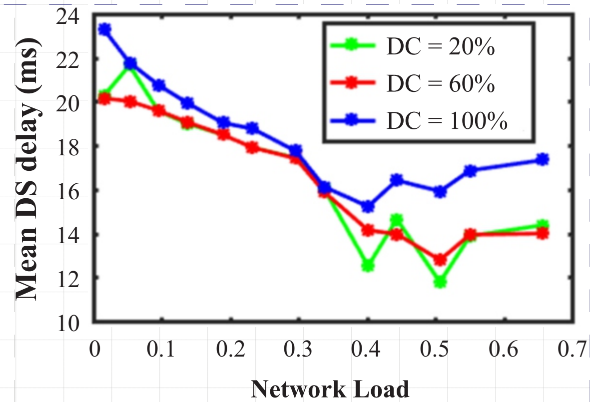

Fig. 10. Average downstream delay per ONU

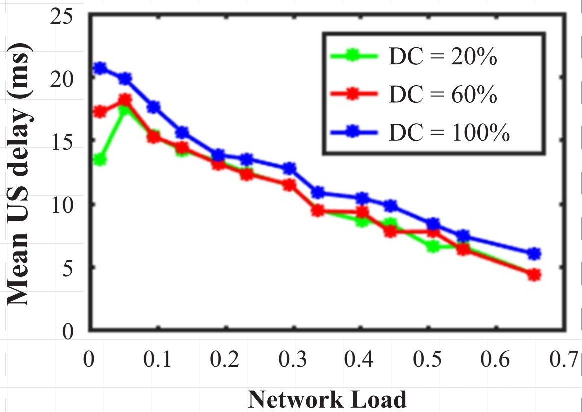

Fig. 11. Average upstream delay per ONU

Although with increase in Asleep state, the upstream and downstream delays also slightly increase but this increase is not substantial as evident from Fig. 9 to Fig 14. Compared to DC value of 20%, the US delays for DC =60% and DC=100% increase by at maximum 6ms, 8ms. 9ms and 10ms for T1 to T4 traffic classes respectively but overall all the delays remain below 22ms which is fairly acceptable value. However, the downstream delays are recorded slightly higher but do not exceeded 24ms at maximum. The rationale behind this is that the OLT is actually not aware of the Listen state of the ONUs and actually queues the traffic until the Watch state is over after the Watch $T_{Lowpower}$ expires or the LWI event at OLT is raised. With increase in network traffic load, the delays decrease due to reduced ONU sojourn. From these results it can be fairly concluded that a higher value for the T_{Rx_Timer} is suitable for the Watchful sleep process. The best performance is achieved by setting the DC to 100% which allows the ONU to have exactly one Asleep and Listen state at maximum during the Watch state. This maximize the ONU energy savings without significantly impacting the upstream and downstream delays.

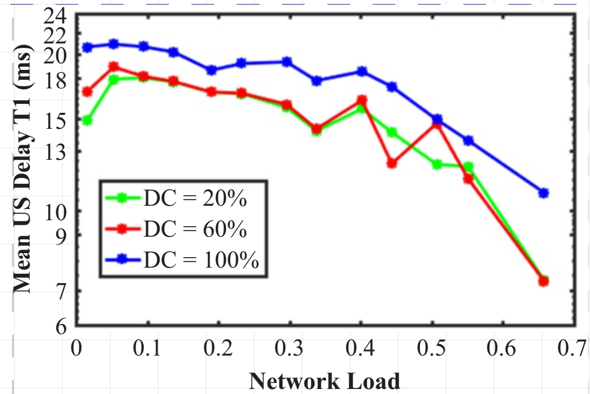

Fig. 12. Average upstream delay T1 traffic per ONU

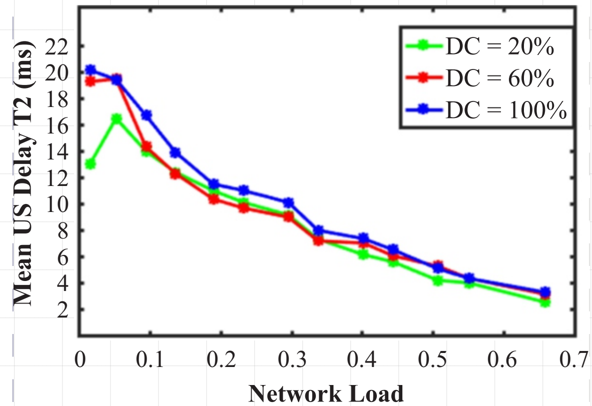

Fig. 13. Average upstream delay of T2 traffic per ONU

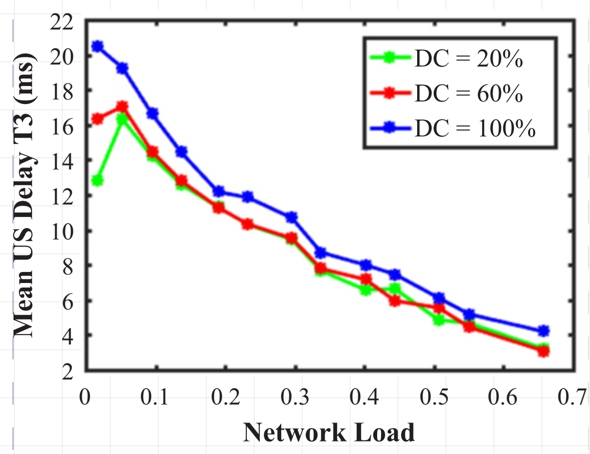

Fig. 14. Average upstream delay of T3 traffic per ONU

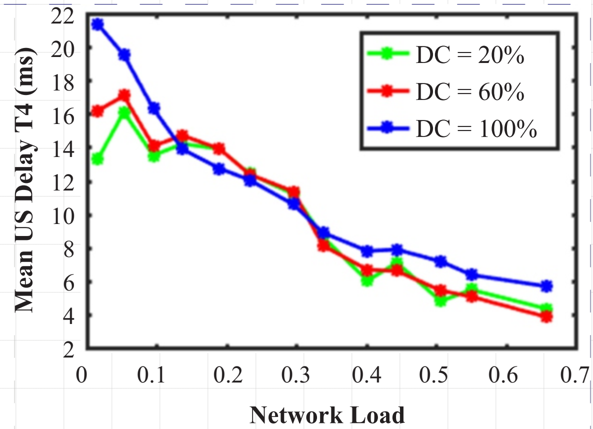

Fig. 15. Average upstream delay T4 traffic per ONU

For the delay sensitive network services, the delay variance is also an important parameter to be considered. Due to ONUs frequent state transitions during the WSM process, the delay variance increases. The downstream traffic is more impacted compared to upstream traffic because of ONU frequently switching to Listen state as evident from Fig.15 to Fig.19. In the upstream traffic classes, the T1 traffic class is highly impacted as it has only a fixed bandwidth assignment. For Downstream traffic, the maximum delay variance variation recorded is 0.8 mS^2. For T1 traffic class it is 0.28 mS^2, for T2 traffic class it is 0.28 mS^{2}For T3 traffic class it is 0.4 mS^2 and for T4 traffic class, it is 0.35 mS^2. Thus, increasing the DC leads to a delay increase within 1mS^2 for all the downstream as well as upstream traffic classes. This is in line with ITU recommendation for PON delay sensitive services as mentioned in G.987.1.

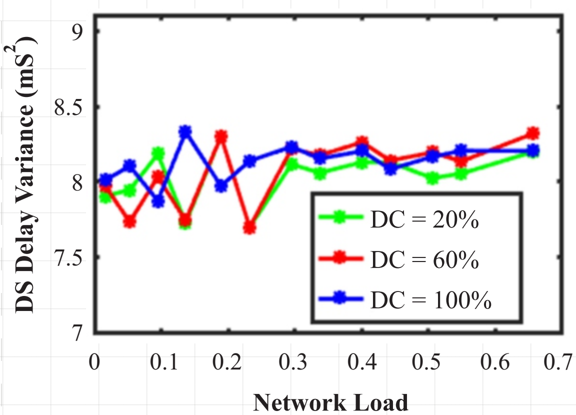

Fig. 16. Delay variance of downstream traffic

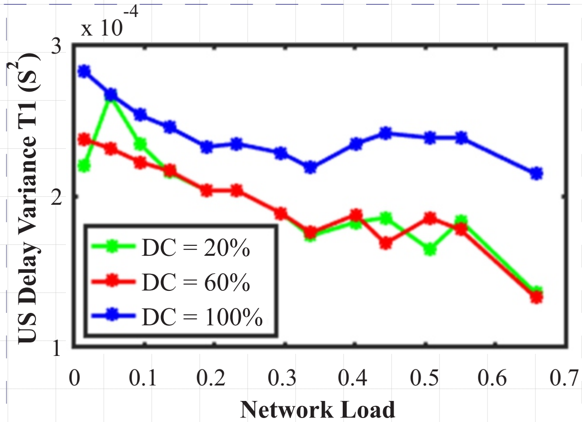

Fig. 17. Delay variance of the T1 traffic class

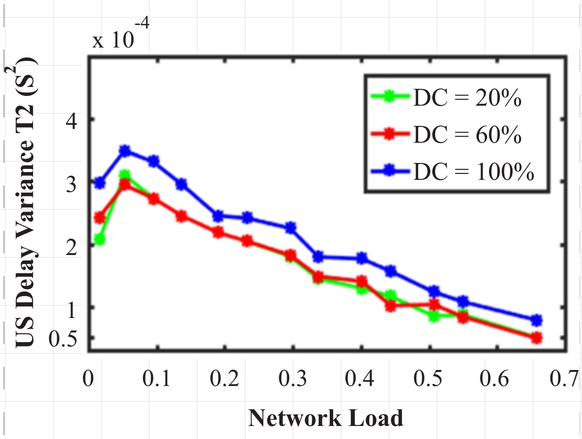

Fig. 18. Delay variance of the T2 traffic class

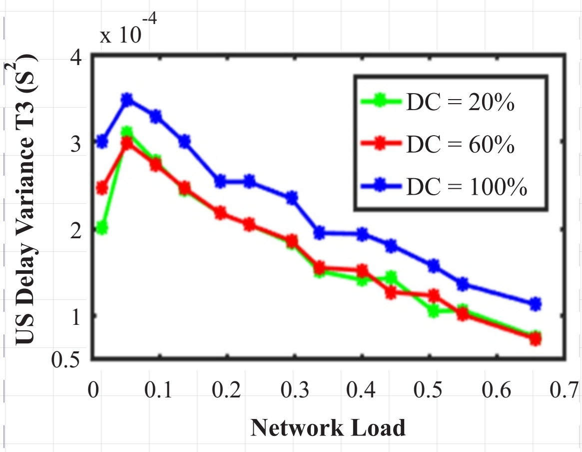

Fig. 19. Delay variance of T3 traffic class

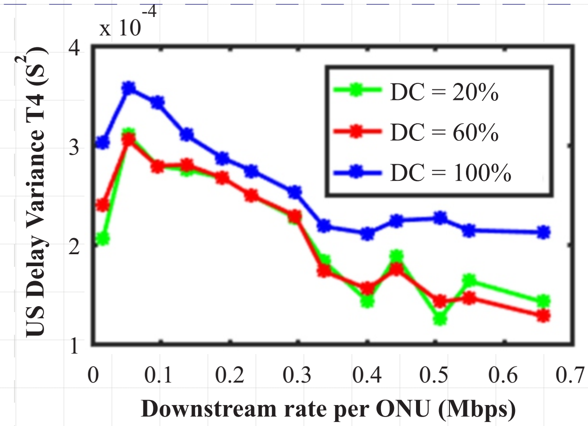

Fig. 20. Delay variance of the T4 traffic class

VI. CONCLUSION

This study investigated the impact of varying the T_{Rx_Timer} timer values on the Watchful sleep mode for XGPON. The study was performed in a simulation testbed developed in OMNET++. Contrary to the existing studies, an existing reported dynamic bandwidth assignment scheme was used and all the traffic classes T1 to T4, defined by ITU were considered. A Poisson distributed traffic generator with exponentially varying inter-arrival times was used to inject the traffic frames in the network. To emulate the behaviour of real CATV data from Broadcom, the traffic frame sizes were generated using the probability distribution (PDF) values from the real recorded traffic data. The simulation study shows that increasing the duty cycle by increasing the T_{Rx_Timer} value leads to higher ONU energy savings with negligible increase in upstream and downstream delays and variance. From this study results it can be fairly concluded that setting the duty cycle to 100% in the WSM scheme provided maximum energy savings of 78.3% compared to 69.3% and 65% for 60% and 20% duty cycle respectively, without degrading the quality of service of PON.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Higher Education Commission Pakistan for supporting this research work through research Grant No. 21-1981/ SRGP/R&D/HEC/2018.

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