IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received May 17, 2020, accepted June 29, 2020, date of publication July 7, 2020, date of current version July 20, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3007778

Resource Allocation and QoS Guarantees for Real World IP Traffic in Integrated XG-PON and IEEE802.11e EDCA Networks

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This work was supported in part by a project titled "Designing a cost efficient and optimised Green Broadband Access Network for Rural India using Fiber Wireless (FiWi) Access Network Architecture appropriate for NoFN", funded by the Ministry of Electronics and Information Technology (MeitY), Govt of India, Reference: Administrative approval dated 4th December 2018, under Grant GG-11/1/2018-EMCD-MeitY.

ABSTRACT Globally, there is a significant rise in the number of connected devices. Every device has an access to wide variety of telecom services among which voice, video and best effort (BE) contribute significantly. There is a noticeable growing trend towards upstream BE traffic besides real time e-services that demand high quality of service (QoS). Converged next-generation fiber-wireless (FiWi) access networks composed of next-generation passive optical network (XG-PON) and 802.11n based wireless local area network (WLAN) has emerged as a suitable choice to provide high quality and affordable e-services to plenty of subscribers as they possess both high bandwidth and flexibility. In this paper, we study the performance of the integrated network architecture which combines XG-PON and enhanced distributed channel access (EDCA) under real time bursty traffic derived from the current global IP traffic distribution. The joint tuning of various crucial parameters of both XG-PON and EDCA with incorporation of an efficient deficit dynamic bandwidth algorithm (DBA) at optical line terminal (OLT) is done by exhaustive simulations in network simulator-3 (NS-3). Through intensive simulations and tuning, we are able to achieve a end-to-end delay performance of $<$ 150 ms for voice, $<$ 500 ms for video and a few seconds for BE upto full capacity. Also, a packet loss ratio (PLR) of $<$ 3% and $<$ 6% is achieved for voice and BE respectively upto full load. For voice PLR is $<$ 1% upto 60% total offered load. Further, it is observed that the fine tuning of key parameters has also resulted in increased bandwidth for dominant BE services. Therefore, this optimized network architecture is 20% more fair to BE services as compared to the conventional integrated FiWi architectures.

INDEX TERMS Fiber-wireless (FiWi), XG-PON, EDCA, DBA, PPBP, global IP traffic.

I. INTRODUCTION

The convergence of the optical and wireless technologies can be used to realize FiWi architecture systems. This architecture has gained a lot of attention for supporting large number of potential subscribers with universal access to information and advanced services in a cost efficient manner [1]. By utilising next generation WLANs, such as IEEE 802.11n and 802.11ac and 10-Gigabit-capable passive optical networks (XG-PON), we aim to achieve high quality broadband connectivity to provide critical information related to education, health services, agriculture, e-government, etc. to the citizens in rural areas at low cost. Wi-Fi based WLANs operate on unlicensed bands, possess broadband capabilities and are easy to deploy which makes them a much more cost effective choice compared to broadband cellular network. In order to provide quality of service (QoS) differentiation, IEEE 802.11e was introduced that defines two

The associate editor coordinating the review of this manuscript and approving it for publication was Tianhua Xu.

mechanisms, enhanced distributed channel access (EDCA) and hybrid coordination function (HCF) controlled channel access (HCCA), both backward compatible with the legacy distributed coordination function (DCF) access mechanism to provide QoS support at medium access control (MAC) layer for different kinds of applications in WLANs. IEEE 802.11e EDCA standard specifies four access categories (ACs): voice, video, BE and background as shown in Fig. 1. To impart service differentiation among wireless stations, each AC employs specific parameter set that includes: (a) Minimum contention window (CW_{min}), (b) Maximum contention window (CW_{max}), (c) Arbitrary inter-frame space number (AIFSN) and (d) Transmission opportunity ($TXOP$). Based on the values assigned to these parameters, the ACs performance can be altered.

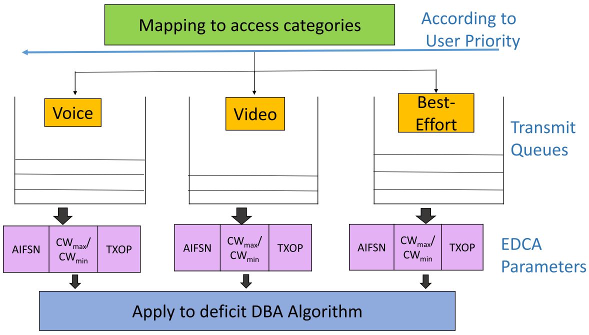

FIGURE 1. **EDCA schematic architecture.**

XG-PON system is a flexible access network system that operates over a point to multi-point optical access infrastructure with nominal data rate of 10 Gbps downstream and 2.488 Gbps line rate upstream. Considering cost-effectiveness and interoperability capability granted by standards and certifications, there is a need to analyze the performance of Wi-Fi based WLANs in conjunction with high capacity XG-PON that can serve high quality and affordable e-services to a plenty of subscribers. There are advances in XG-PON in recent times, like 10-Gbps capable symmetric PON (XGS-PON) [2] which provide nominal data rate of 10 Gbps in both downstream and upstream directions. In the paper, we focus on the performance improvement for scenario where typically XG-PONs are deployed. The work presented in the paper can be extended to future XGS-PONs.

Globally, there is a noticeable growing trend towards upstream BE traffic. Considering the typical IP traffic scenario, there is a significant number of subscribers using internet for email, text chatting, general information search clearly indicating the major amount of BE traffic flow in upstream direction. A typical example is National Optical Fiber Network (NOFN) of India which aims to provide higher broadband capacity across all Village Councils in the country due to the growing demand of data and proliferation of video for both utility and entertainment purposes. This will facilitate human development, boost economic development and improve quality of life of people in rural India. In order to provide high speed digital connectivity to rural people at an affordable price, the broadband and entertainment services can be sent over FiWi networks [3]. In Africa, there is a substantial amount of traffic due to file sharing, web browsing and mix of voice over Internet Protocol (VoIP) and over the top (OTT) messaging applications. In Asia Pacific region, major amount of upstream traffic is generated due to file sharing [4]. In regions, such as North America, according to the report [5], considering upstream scenario, it is observed that cloud based storage applications have surpassed file sharing as the leading upstream traffic category on fixed networks.

TABLE 1. **Upstream global IP traffic distribution.**

Regions	Voice (%)	Video (%)	BE (%)
Asia Pacific	5	31	64
Africa	10	17	73
North America	8	22	70
Latin America	12	20	68

Applications such as video on demand and content driven application generate the major portion of upstream traffic besides storage applications. In Latin America too, file sharing and web browsing accounts for majority of upstream traffic while real time entertainment services accounts for 20% (approx.) traffic in upstream direction. This indicates that the applications such as file sharing and web browsing, control a major amount of upstream traffic across the globe [4]–[7]. In urban scenario, real time entertainment with video streaming will outspace the data consumption, however in rural scenario the traffic is still dominated by low data rate services. From these global survey reports, it is evident that BE traffic constitutes the major portion of the upstream traffic worldwide as shown in Table 1 and there is a need to provide sufficient bandwidth to BE service while keeping the delay and packet loss ratio (PLR) of real time voice and video services within the International Telecommunication Union - Telecommunication (ITU-T) Standardized tolerable limit [8].

A rich literature focused on architecture design and guaranteed QoS of stand alone architectures can be obtained. In [9], authors discussed about the impact of AIFS and CW differentiation in the performance of EDCA network and about the performance issue related to co-existence between 802.11e contention based stations with legacy 802.11 stations. But besides these parameters, impact of $TXOP$ on performance of EDCA network also needs to be considered. In [10], IEEE 802.11e EDCA network with AIFS and back off window differentiation was considered and concluded that back off window differentiation is more suitable due to its lesser tuning parameters and more exactness. But the paper [10] did not consider how $TXOP$ can effect the performance of the network. In [11], the authors introduced an advancement of EDCA scheme for dense IEEE 802.11 ax schemes. The authors extended the EDCA queues from 4 to 7 to assign the priority levels to different kinds of video traffic (HD, 4K/8K videos), but the paper did not consider the impact of tuning the network parameters. In [12], the authors presented an intelligent Prioritized Adaptive Scheme (iPAS) that provides QoS differentiation for heterogeneous multimedia delivery over wireless networks. They compared the performance of standard EDCA, DCF and iPAS and demonstrated that iPAS shows the best performance in providing multimedia delivery over wireless networks. In [13], the authors tune the *CW* value using exponential backoff method for IEEE 802.11 DCF. The authors in [13] derives optimal value of *CW* theoretically in order to improve the throughput of the system. In [14], the authors proposed an algorithm to reduce collision called differentiated reservation (DR) algorithm for IEEE 802.11e EDCA and 802.11 DCF networks. The authors in [14] also propose a group-based differentiated reservation (GDR) algorithm in which according to bit rates the nodes are divided into groups in order to reduce collision in dense network environment.

Though there are several dynamic bandwidth allocation (DBA) strategies for stand-alone XG-PON, but very few are designed for integrated architecture with XG-PON as back-haul. 10-Gigabit PON Access network (X-GIANT) DBA was designed in [15] for standard-complaint XG-PON in NS-3 and it was demonstrated that in terms of delay and throughput, XG-PON requirements are satisfied for a wide range of offered load. The authors in [16] introduced an efficient bandwidth utilization (EBU) DBA that forwards unused upstream transmission opportunity from one traffic container (T-CONT) to other T-CONT of single type. Improvement in mean delay performance for T-CONTs 2 and 3 was demonstrated whereas there was a decline in the mean delay performance for T-CONT 4 that handles BE traffic. In [17], deficit algorithm was introduced that provides required X-GIANT prioritization and fairness among three aggregated application types in LTE backhaul. These aforementioned studies either focus on performance of DBA in stand-alone XG-PON or considered XG-PON with LTE as front-haul network. In [18], the authors implemented integrated XG-PON and EDCA based Wi-Fi network by considering the QoS mapping as given in [19] with different packet sizes, data rates and utilized the efficiency of deficit DBA in improving the fairness of network by provisioning enough bandwidth for BE services.

In this work, we analyze the performance of integrated XG-PON and EDCA based Wi-Fi network with deficit DBA in XG-PON considering Poisson Pareto Burst Process (PPBP) that realistically models the real time traffic burstiness of the upstream global IP traffic. The proposed work is an extension of [18] in which the authors dealt with converged XG-PON and Wi-Fi architecture considering Pareto on-off traffic model for all incoming services (voice, video, BE) with different frame sizes and data rates and implemented deficit DBA [17] in XG-PON to reduce the average delay for BE service while maintaining the average delays for real time voice and video services within tolerable limit. The extensions include (a) Incorporating realistic traffic models to model voice, video and BE traffic each with their particular specifications as per the incoming global IP traffic and (b) Accordingly tune the values of parameters belonging to EDCA and XG-PON so that e-services can be served to a large number of potential subscribers within tolerable delay and PLR limit. This is quite a challenging task since there is a need to ensure that considerable capacity of XG-PON is effectively utilised by Wi-Fi applications and simultaneously, the resource allocation mechanism is implemented in XG-PON according to the incoming global IP traffic pattern in order to cater to the bandwidth requirement of Wi-Fi clients [17].

Rest of this paper is organized as follows. Section II briefly describes the system description demonstrating the heuristic approach followed to tune the system parameters. Then, we explain the simulation environment in section III. In section IV, we evaluate the performance of the implemented system in NS-3 and validate the results in terms of average queuing delay, average end-to-end delay, average packet loss rate, average throughput, aggregate throughput [20] and fairness index. Section V concludes the work.

II. SYSTEM DESCRIPTION

As shown in Fig. 2, the system is created by integrating XG-PON and EDCA based Wi-Fi modules in NS-3. XG-PON consists of active elements like optical line terminal (OLT) in central office and optical network units (ONUs) at/ near customer sites are connected via an optical distribution network (ODN) using shared optical fibre and passive optical splitter. OLT broadcasts downstream traffic to all ONUs by employing the concept of time division multiplexing (TDM) whereas time division multiple access (TDMA) principle is adopted to transmit frames in upstream direction, i.e. from ONUs to OLT.

In upstream, traffic multiplexing functionality is distributed whereas in downstream direction it is centralized [8]. Each ONU is connected to multiple Wi-Fi access points (WAPs) via point-to-point ethernet links. Number of wireless clients connected to a WAP are varied and each Wi-Fi client generates three kinds of traffic, i.e. voice, video and BE. An ethernet link is used to connect OLT to the gateway that is linked to internet servers. Voice, video and BE upstream internet traffic is generated from Wi-Fi clients. Wi-Fi packets generated from each Wi-Fi client are linked with user priority (UP) value having specific marking from 0 to 7. Based upon this UP value, they are marked with unique differentiated services code point (DSCP) value to classify packets on differentiated services (Diff-Serv) network. They are forwarded to ONU via an ethernet link and placed in appropriate T-CONT queue according to their DSCP value. UP to DSCP mapping is followed as given in [19]. Depending on the UP value and number of clients, packets are assigned *TXOP*, AIFSN and *CW* value within EDCA network. *TXOP* limit is the time period during which a particular wireless station, post the contention process, has an uninterrupted access to the channel. In order to precisely implement *TXOP*

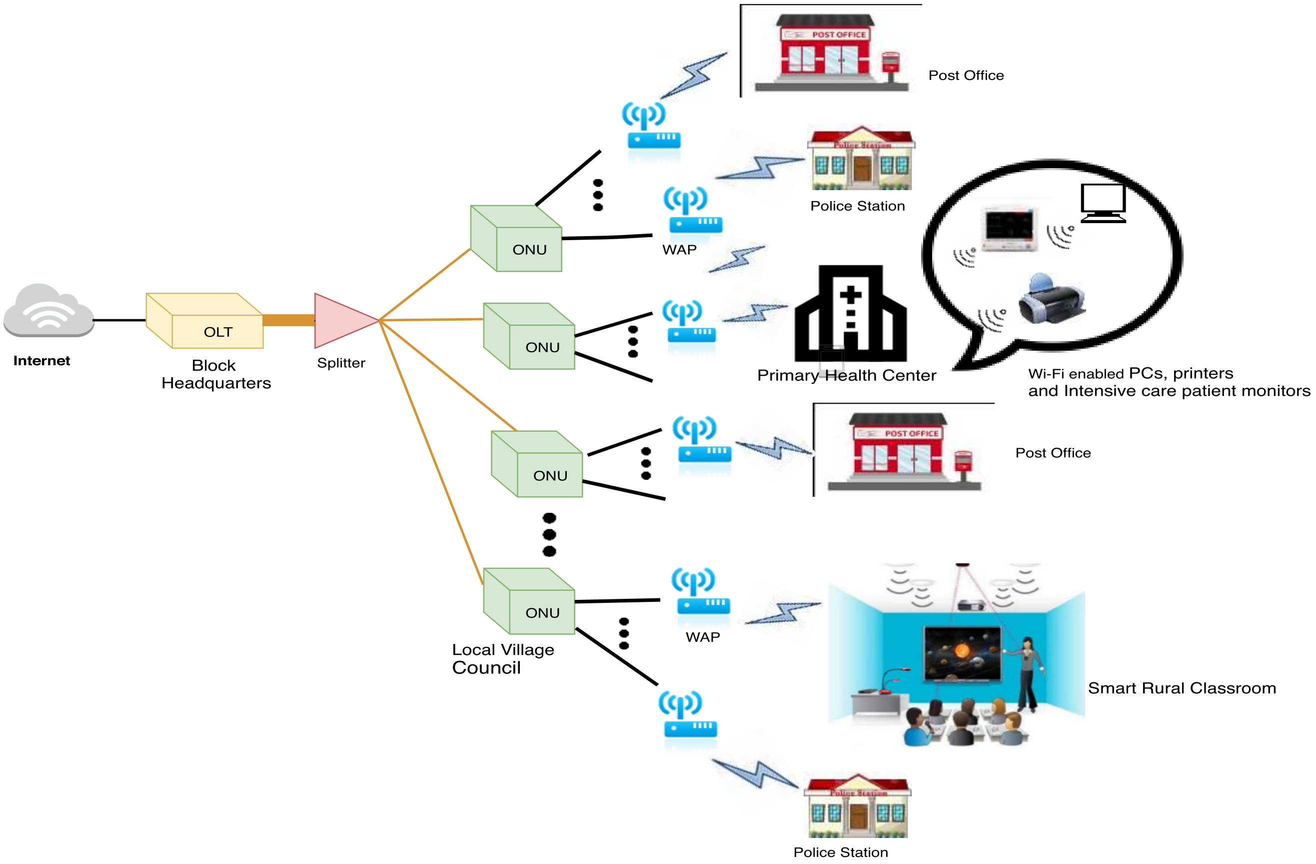

FIGURE 2. System Architecture.

limits and burst sequences, duration of each frame that is en-queued must be calculated and fixed. If frame duration exceeds *TXOP* limit, queuing is rejected. As soon as a *TXOP* is granted with *TXOP* limit > 0, the transmission duration of impending frame and the next frame also needs to be verified. If transmission of both frames with a short inter-frame spacing (SIFS) interval is possible within the *TXOP*, then this frame of burst sequence is ready to be transmitted. There is a remarkable role played by duration of *TXOP* allocation in modifying the performance of the network. Greater the *TXOP* allocations for high priority traffic classes, more will be the freezing time for lower priority traffic which may lead to avalanche effect. This is because during the freezing time of lower priority traffic, a large burst of high priority traffic might arrive and is expected to be processed before lower priority traffic class finishes back-off countdown which can have a negative effect on network fairness [21]. Therefore, a large *TXOP* value cannot be straightforwardly assigned to the higher priority traffic (such as video and voice) as compared to lower priority BE traffic as it is the majority traffic which also has to be given enough opportunity to be transmitted while maintaining the delay and PLR limits.

Next parameter which has a notable impact on the performance of EDCA based Wi-Fi network is contention window (CW). CW differentiation implies that we are changing the average time needed to successfully attain access to the channel. In order to improve the overall delay performance of the network, we need to curtail the average time needed to successfully deliver a packet. This can be achieved by reducing the value of CW [9]. Tuning of CW_{min} and CW_{max} depends on the number of competing stations in the network, the priority that needs to be given to the services and other back off parameters that is *TXOP* and AIFSN. As we consider more number of stations reducing CW value will also increase collision probability as well, overall reducing the effectiveness of random access mechanism. There needs to be a trade-off among these back-off parameters values according to the given traffic scenario in order to get a well performing wireless network that can provide the three services i.e. voice, video and BE effectively to potential subscribers in terms of delay and PLR according to ITU-T QoS standard.

Regarding XG-PON QoS parameters, XG-PON provides differentiated QoS to four service classes which are specified as T-CONT types. T-CONT 1 corresponds to fixed bandwidth, T-CONT 2 is attributed with assured bandwidth, T-CONT 3 is allotted assured as well as non-assured bandwidth and T-CONT 4 is assigned to BE traffic. Based on the proportion of traffic entering into T-CONT queue that is identified by an $Alloc-ID$, tuning of parameters i.e. service interval (*SI*) that conforms to the number of grant size allotment to each $Alloc-ID$, λ that conforms to the ratio of assured to non-assured bandwidth portion of T-CONT 3 and *ratio* parameter which is the proportion of maximum data rate assigned to each T-CONT is done. Bandwidth is dynamically assigned to the T-CONTs according to the deficit algorithm as discussed in [17], [18].

The procedure for tuning the essential performance parameters of integrated architecture according to incoming upstream traffic pattern to get the desired performance in terms of latency and PLR as per ITU-T QoS standard is discussed in Algorithms 1, 2 and 3. The notations used in algorithm are summarised in Table 2.

TABLE 2. **Summary of notations.**

Notations	Definition
n	Maximum number of Wi-Fi clients
m	Maximum number of ACs
k	T-CONT type where $k = 1, 2, \cdots, 4$
i	AC number where $i = 1, 2, \cdots, m$
CW^i_{min}	Minimum CW of i^{th} AC
CW^i_{max}	Maximum CW of i^{th} AC
Tx^i	Transmission opportunity of i^{th} EDCA service
A^i	AIFS corresponding to each AC
BW_{assign}	Assigned bandwidth
AB_{min}	Minimum allocation bytes
BW_{req}	Requested bandwidth
FB	Frame bytes
SI	Service interval that defines frequency of grant size allocation to each $Alloc-ID$
AB_{max}	Maximum allocation bytes
N_k	Number of T-CONT type k $Alloc-ID$s
$T4\_N_{unserved}$	Number of unserved T-CONT 4 $Alloc-IDs$
C_{XG-PON}	Effective upstream capacity of XG-PON (= 2.25 Gbps)
λ	Ratio of assured to non-assured bandwidth portion of T-CONT 3
p	WiFi client index where $p = 1, 2, ..., n$
r	Ratio parameter decided as per incoming traffic proportion
$T2\_BW_{unused}$	Unused T-CONT 2 bandwidth
BW_{remain}	Remaining bandwidth
BW_{thres}	Threshold bandwidth
BW_{def}	Deficit bandwidth
$Grant\_sz$	Grant size of bandwidth

Each wireless station has three different ACs corresponding to three different services, namely voice, video and BE. For service differentiation, each AC has its own set of back-off parameters (CW_{min}, CW_{max}, AIFSN and *TXOP*). AC1 and AC3 corresponds to highest and lowest priority traffic respectively. We use the PPBP model for video and BE services while an exponential ON-OFF model was used for voice services. The percentage of BE is kept highest by tuning parameter r. Algorithm 1 deals with tuning for BE traffic being dominant traffic and keeping the rest of parameters for other services as per standard 802.11n as given in Table 4. *TXOP* parameter for BE service is varied in discrete multiples of 32 μs [22] with increasing number of wireless stations in order to get the idea how it is impacting the delay and PLR of the network. It ensures the optimum value of *TXOP* for BE service while keeping the rest of the parameters of other services (voice and video) as standard such that delay and PLR for delay sensitive services within tolerable limits is assured. The time complexity of Algorithm 1 is $\mathcal{O}(n)$.

Algorithm 1 Tuning of *TXOP* Parameter

```
1: for each Wi-Fi client $p$ upto $n$ at WAP do
2:     if Wi-Fi client generates BE traffic then
3:         Perform step 6.
4:     else
           Go to step 7.
5:     end if
6:     Modify $TXOP$ parameter at discrete values 0, 1504,
       3008 and 6016$\mu$s and perform step 8 after each
       modified $TXOP$ parameter.
7:     Keep the $TXOP$ parameter as standard and perform
       step 8.
8:     Obtain average delay and average PLR for each
       Wi-Fi client to observe the impact of modification of
       $TXOP$ parameter for BE traffic on each EDCA
       service.
9: end for
```

Algorithm 2 Tuning of *CW* Parameter

```
Require: Upstream traffic with tuned $TXOP$ for each
    EDCA service
Ensure: Tuned value of $CW$ for each EDCA traffic type.
1: for each Wi-Fi client $p$ upto $n$ at WAP do
2:     if Wi-Fi client generates BE traffic then
3:         Perform step 6.
4:     else
           Go to step 7.
5:     end if
6:     Keep $CW_{min} = 15$ and decrease $CW_{max}$ in binary
       exponential pattern $(2^t - 1)$ where $t$ decreases from
       10 till 5 and perform step 8 after each decrement.
7:     Swap $CW$ ranges for voice and video traffic and
       perform step 8.
8:     Obtain average delay and average PLR for each
       Wi-Fi client to observe the impact of modification of
       $CW$ on each EDCA service.
9: end for
```

Once the tuning of *TXOP* parameter is done, the incoming traffic with tuned *TXOP* value for all EDCA services is given as an input to Algorithm 2 that deals with fixing of *CW* parameter for all services. *CW* parameter plays quite an important role in providing priority based differentiation to incoming traffic. Initially, the default values of CW_{min} and CW_{max} are considered keeping all other parameters of each EDCA service unchanged. Then, the value of CW_{max} is decremented in an exponential pattern as given in step 2 of Algorithm 2 in order to reduce the delay and PLR of BE

Algorithm 3 Dynamic Bandwidth Allocation

```
Classify EDCA traffic and associate with appropriate
    T-CONT based on UP to DSCP mapping policy [19]
Implement Deficit algorithm [18] [17] given below to
    assign bandwidth to each T-CONT according to
    proportion of incoming EDCA traffic.
    1) T-CONT 1: Fixed periodic bandwidth assignment
       = 128 Kbps.
    2) T-CONT 2: $BW_{assign} = \min\,[AB_{min}, BW_{req}, FB]$.
       $AB_{min}$ depends on $SI$ and $r$ parameters decided as
       per incoming traffic proportion and is given as
       $AB_{min} = (SI \times 125\mu s \times r \times C_{XG-PON})/N_k$.
    3) T-CONT 3: $BW_{assign} = \min\,[AB_{max}, BW_{req}]$
       • First round; i.e. assured round
         – $AB_{max} = (T2\_BW_{unused} + \lambda \times r \times C_{XG-PON})/N_k$ corresponding to each
           $Alloc - ID$ of T-CONT 3.
         – Go to step 4).
       • Second round; i.e. non-assured round
         – $AB_{max} = (T2\_BW_{unused} + (1\text{-}\lambda) \times r \times C_{XG-PON})/N_k$ corresponding to each
           $Alloc - ID$ of T-CONT 3.
         – Go to step 4).
    4) T-CONT 4:
       • $BW_{remain}$ after provisioning T-CONTs 2 and 3
         $Alloc - IDs$ is calculated once per upstream
         frame.
       • $BW_{thres}$ is calculated based on $BW_{remain}$ /
         $T4\_N_{unserved}$.
       • $BW_{def}$ is computed based on difference between
         $BW_{thres}$ and $BW_{req}$.
       • $tot\_BW_{def} += BW_{def}$
if $BW_{def} > 0$ then
    $BW_{thres} = [BW_{remain} + tot\_BW_{def}]/T4\_N_{unserved}$
    $Grant\_sz = \min\,[BW_{thres}, BW_{req}]$
end if
```

service while maintaining the delay and PLR values for real time voice and video services within tolerable limit. The time complexity of Algorithm 2 is $\mathcal{O}(n)$.

Tuned EDCA traffic is given as an input to the Algorithm 3 defined as Dynamic Bandwidth Allocation and appropriate bandwidth is assigned to each T-CONT by the concept of deficit DBA [17], [18]. T-CONT 1 provides a fixed amount of bandwidth statically in a periodic manner irrespective of whether there is demand or not. T-CONT 2 corresponds to assured bandwidth, so accordingly voice traffic which has the highest priority in EDCA standard is mapped to it. Guaranteed bandwidth is provided to it. Video traffic is managed by T-CONT 3 that provides guaranteed as well as surplus bandwidth decided as per the demand. Real time video streaming is served by guaranteed part of bandwidth. Non assured part of bandwidth handles the non real time video services such as downloadable video on demand (VoD) services. T-CONT 4 handles best effort services such as VoIP and OTT messaging applications. After serving the T-CONTs 2 and 3 services, the remaining bandwidth is utilized effectively by calculating the threshold bandwidth taking into consideration the number of unserved T-CONT 4 $Alloc-ID$'s. The BW_{def} dynamically adjusts the threshold in order to cater to burstiness of traffic fairly among $Alloc-IDs$. Amount of bandwidth that is granted to a particular $Alloc-ID$ is based on minimum of threshold and requested bandwidth. The time complexity of Algorithm 3 is $\mathcal{O}(n^2)$.

III. SIMULATION ENVIRONMENT

The standards-compliant converged system using pre-existing XG-PON and EDCA based Wi-Fi network is implemented in NS-3. XG-PON network is composed of an OLT connected with 16 ONUs via splitter and shared optical cable and ONUs are connected via ethernet links to some APs having varied number of Wi-Fi clients on the WLAN side. Each WLAN has bandwidth of 180 Mbps. Each T-CONT's queue size is taken as 1 MB [15]. There is a propagation delay between OLT and ONU of 0.4 ms that represents 60 km distance. As per the upstream global traffic scenario, specified in Table 1, majority BE traffic is generated followed by video and then voice considering the parameters mentioned in Table 3. In order to properly design and analyse the performance of converged XG-PON and Wi-Fi networks, we need to clearly understand the nature of network traffic, that is being generated from Wi-Fi clients.

TABLE 3. Incoming traffic parameters.

AC	Traffic Model	Encoding bit rate	Data Packet Size
BE	PPBP, H=0.5	2 Mbps	1472 Bytes
Voice	ON-OFF model where ON and OFF durations are exponential with a mean of 0.35s and 0.65s respectively	64 Kbps	160 Bytes
Video	PPBP, H=0.9	500 Kbps	795 Bytes

The PPBP traffic model used for generating BE and video traffic characteristics satisfies pivotal statistical properties of real life IP networks. It enables ease of use and is computationally efficient to allow scalable scenarios [12]. The incoming traffic has characteristic burst length that is present on a wide range of time scales and is effectively captured in PPBP traffic model. It can be statistically interpreted by principle of self-similarity and it exhibits long range dependence [23]. The auto-correlation function of such self-similar process follows power law delay which is much slower than exponential delay. Degree of time series of self similar model is expressed by hurst parameter (H). It expresses speed of decay of series auto-correlation function and for long range dependence (LRD), its value varies from 1/2 $< H <$ 1. As it approaches 1, degree of both self similarity and LRD increases. Regarding PPBP modelling, bursts arrive according to poisson process with rate λ_P and the burst length follows Pareto distribution given by H parameter. Each burst flow has a constant bit rate (CBR) r_b [24]. Number of wireless stations generating voice, video and BE traffic are taken in such a way that approximate 5-8%, 25-30% and 65-70% is voice, video and BE traffic respectively. Each wireless station would operate only one application at a given instant of time. Each wireless station is connected to a single WAP which in turn links to a specific ONU.

IV. PERFORMANCE EVALUATION

The performance of the integrated architecture for each class using the simulation environment as provided in section IV is evaluated in terms of PLR, mean queuing-delay, end-to-end delay, per class throughput, aggregate throughput and fairness index. Mean queuing-delay of a given $Alloc - ID$ is the average queuing-delay of all the packets entered into and forwarded from the T-CONT queue in the ONU. Throughput is the average throughput per station for each AC. Jain's fairness index is used to evaluate the extent upto which the DBA allocates bandwidth to all Wi-Fi clients. It indicates the fairness of Bandwidth Allocation to all the users. As its value of fairness index becomes more closer to one, it implies that demand and allocation almost match one another and thus providing greater QoS guarantee. Each experiment is executed for 60 seconds until upstream channel gets overloaded. The experiment is repeated 100 times and for each experiment we consider 10 distinct seed value so that every pattern of packet generation in applications is mutually exclusive with one another. Confidence interval of 95% is considered for obtaining the simulation results. Margin of error for the obtained results is $< 7\%$.

TABLE 4. **Standard EDCA parameters for 802.11n.**

AC	$CW_{\min}$	$CW_{\max}$	AIFSN	Max. $TXOP$ (μs)
BE	15	1023	3	0
Voice	3	7	2	1504
Video	7	15	2	3008

The default EDCA parameters are given in Table 4 above. The three parameters of EDCA, *TXOP*, AIFS and *CW* have a complicated relationship with each other. Similarly, there are some important parameters like *SI*, λ and *r* parameters that play a crucial role in deciding the bandwidth assignment to different incoming services according to their priority. Since, one parameter effects the performance of another parameter hence joint optimization of the integrated architecture is needed. This involves a feedback mechanism to *TXOP* and *CW* values in order to get the system performance like the average end-to-end delay, mean-queuing delay and average PLR maintained according to ITU-T standard.

Taking into consideration the modeling parameters of BE traffic which also is the dominant of all, we performed Algorithm 1 and observed that by increasing the *TXOP* within tolerable range of BE traffic from 0 to 3008 μs with a step size of 1504 μs, due to bursty arrivals, *TXOP* allocations at low as well as high loads are larger due to which we are able to lower the queuing delay of the service. But as we increase beyond $TXOP = 3008\mu$s, it was observed that there is no noticeable improvement in the delay with increase in *TXOP*, as *TXOP* allocation is incremental and maximum allocation is only done at higher loads depending upon the burstiness of traffic. As the Wi-Fi clients increase, it may not be a good idea to have high *TXOP* as the chances of occurrence of avalanche effect increases which may strongly impact the PLR of low priority traffic due to high back-off time for respective AC. So, there is a limit to which we can increase the *TXOP* and gets its positive impact on the performance of network and since BE traffic is of lowest priority, we cannot afford to improve its performance at the cost of other services. Therefore, the TXOP value is selected in such a way that the values of *TXOP* remain in permissible range according to the ITU-T standard [22] and still can achieve a performance improvement.

Besides *TXOP* setting, the initial back-off window size tuning is also very crucial according to network size [10] to minimise delay in the network. CW_{min} and CW_{max} values have to be jointly tuned to minimise the mean-queuing delay, end-to-end delay and average PLR as per the number of wireless stations in the integrated network. As discussed in Algorithm 2, we need to first tune the BE traffic's *CW* range, being the dominant traffic. Since voice has the highest priority according to standard EDCA, it has minimum *CW* range as can be observed from Table 4 above followed by video traffic. Depending on the proportion of incoming voice and video traffic and their respective traffic models, we swapped the *CW* range keeping in view the ITU-T QoS standard delay and PLR values that we need to maintain for both services. It was observed that average delay for voice as well as video traffic reduced whereas delay for BE service increased. Although there is a difference in initial *CW* sizes, the two AC's, voice and video have high probability of successful transmission of their packets since it is decided based upon the activities done by each node in the network [10] and also on the proportion of kind of traffic being generated in the network. Due to decrease in initial *CW* size for video traffic, the stations generating video traffic aggressively contend for the channel along with voice, due to which the waiting time and hence the back off time of BE traffic further increases. Also, voice traffic incurs increased delay but still within the tolerable limit. With fixed *CW* size as the number of wireless stations increase, collisions too increase due to which the rate at which packets are lost in the network, PLR increases. In order to reduce PLR and delay of BE service, being the dominant traffic, we need to adaptively tune the initial *CW* size and linearly increase it with increase in number of contending stations [10].

After tuning the EDCA network parameters, we need to tune the XG-PON parameters as per the incoming traffic. Voice traffic flows via T-CONT 2 queue and according to the deficit DBA, the T-CONT 2 traffic is served in every allocation cycle. Video traffic corresponds to T-CONT 3 and BE to T-CONT 4. r parameter also has to be tuned based on the proportion and priority of incoming traffic type. After exhaustive simulations it was found that to maintain the priority trend for T-CONT 2, T-CONT 3, T-CONT 4 while maintaining the proportion of incoming traffic, $r =$ T-CONT 2:T-CONT 3:T-CONT 4 $=$ 60:50:70 needs to be set. By setting ratio T-CONT 2 $>$ T-CONT 3, we are able to maintain priority of T-CONT 2 over T-CONT 3 for all loads. T-CONT 4 is also given a good proportion of bandwidth because it is the dominant one and this ratio also provide moderate over provisioning factor. Over provisioning factor should also not be too high otherwise it will itself induce DBA burstiness in XG-PON backhaul for Wi-Fi [17]. In alternate allocation cycles, the maximum allocation bytes are assigned depending upon value of λ which is equal to 0.4. The unused bandwidth of T-CONT 2 and T-CONT 3 are calculated once in every upstream allocation cycle and accordingly threshold is also calculated that also considers number of unused T-CONT 4 $Alloc - ID$s.

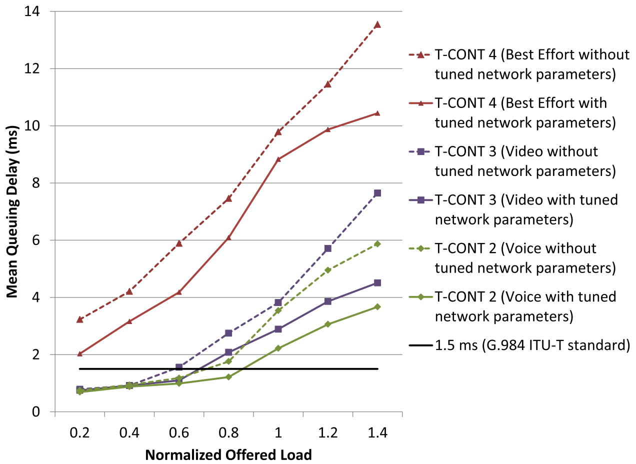

FIGURE 3. Mean queuing delay vs normalized offered load.

Fig. 3 shows the mean queuing delay performance of deficit DBA in the designed integrated architecture for all loads. It can be observed that fine tuning of XG-PON and EDCA parameters results in an improvement in the system performance for all the three types of e-services maintaining the priority among $Alloc - ID$s of all T-CONT types. It can also be observed that for real time services like voice and video, the mean queuing delay performance is maintained within the tolerable limits of ITU-T standard. The maximum margin of error for mean queuing delay is 3%.

Fig. 4 shows the end-to-end delay performance of deficit DBA. According to, the tolerable limit for delay for voice, video and BE services is 150 msec, 400 msec and 5 sec, respectively. It can be observed from Fig. 4 that using deficit DBA the end-to-end delay performance is maintained within these limits for each offered load. The tuning of network parameters further enhance the performance of the system. The margin of error for end-to-end delay analysis is less than 3%.

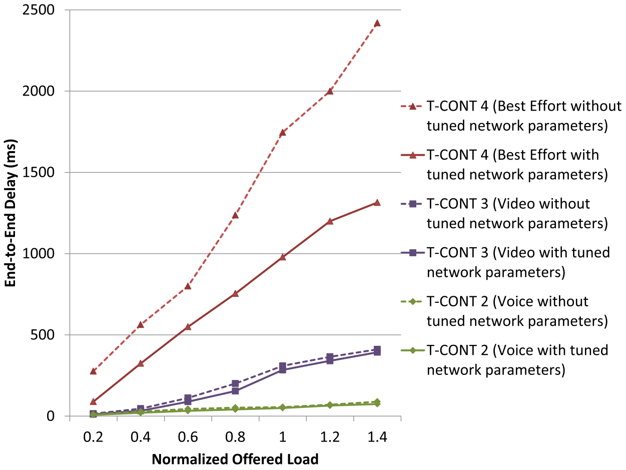

FIGURE 4. End-to-end delay vs normalized offered load.

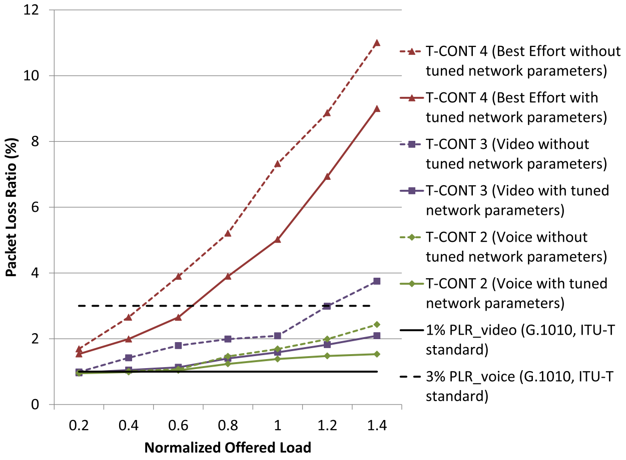

FIGURE 5. Packet loss rate (%) vs normalized offered load.

We also validated the performance of our integrated architecture in terms of PLR and throughput as shown in Fig. 5 and 6, respectively. It is observed that after thorough tuning of XG-PON and EDCA parameters, we are able to achieve PLR of $<$ 1% [8] for video upto 60% total offered load for video traffic without compromising on the standard PLR (without tuning) performance. For voice, the PLR of $<$ 3% [8] and for best effort, PLR of $<$ 6% is achieved upto full load. The maximum margin of error for each service is 5%. It can be observed that due to fine tuning of integrated architecture parameters we are able to improve throughput performance for all the three types of service. The throughput evaluation for average throughput for each AC, voice, video and best effort in Fig. 6 implies that during light load conditions, all three ACs are able to achieve approximately same throughput with margin of error upto 7%. But as we increase the offered load, the average throughput of voice and video traffic increases almost linearly which happens at the cost of best effort traffic. This is due to fact that when the network is overloaded the priority of voice and video traffic will effect performance the best effort traffic.

Fig. 7 demonstrates the performance of integrated system with deficit DBA in terms of fairness index. Fairness is

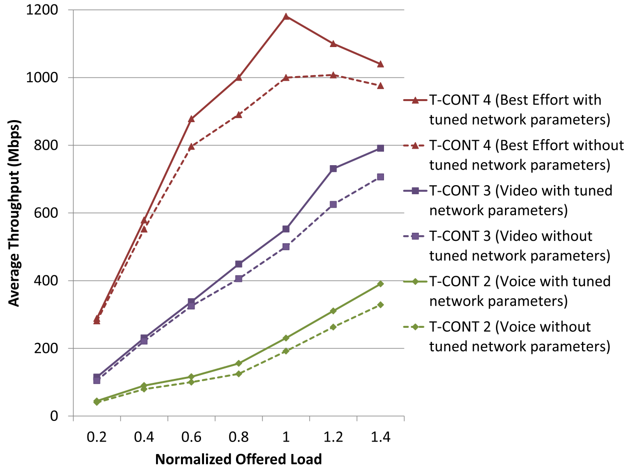

FIGURE 6. **Average throughput vs normalized offered load.**

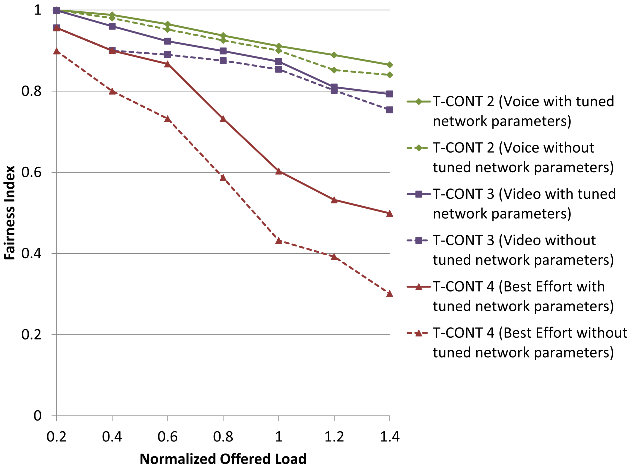

FIGURE 7. **Fairness index vs normalized offered load.**

calculated by using Jain's fairness index as:

$$f(\gamma) = \frac{\sum_{i=1}^{n} \gamma_i}{n * \sum_{i=1}^{n} \gamma_i^2}, \gamma_i > 0$$

where, $\gamma_i = a_i/d_i$ for $a_i < d_i$ and $\gamma_i = 1$ otherwise, n is the number of contending users, a_i is the resource allocated to the user and d_i is the corresponding demand. By using deficit DBA and proper tuning of integrated network parameters, we are able to improve the fairness of BE traffic but not at the cost of real time voice and video services instead the fairness of voice and video traffic also improves. This indicates that bandwidth is allocated based on the incoming traffic distribution and its priority. The maximum margin of error for the fairness index is 4%.

Fig. 8 demonstrates the aggregate throughput over the entire range of offered load considering all three service classes. The figure shows the effective utilization of upstream bandwidth capacity upto maximum of 2.20 Gbps for fully as well as overloaded conditions.

V. CONCLUSION

In this paper, we have implemented the integrated XG-PON and EDCA based Wi-Fi architecture in NS-3 considering real time traffic scenario as per current upstream global traffic distribution. The deficit DBA is implemented in XG-PON to provide prioritized and fair QoS which is demonstrated in terms of latency, PLR, throughput and fairness index in integrated network. Through intensive simulations, we tune the parameters of EDCA and XG-PON as per the upstream traffic pattern and obtained mean queuing delay and end-to-end delay within tolerable limit for voice, video and BE traffic over entire range upto 100% offered load. Regarding PLR, we are able to accomplish $< 3\%$ and $< 6\%$ for voice and BE respectively, upto full load and till 1% for video upto normalized offered load of 60%. High throughput is obtained for voice and video services while improving the BE traffic throughput also, which is due to precise tuning of key parameters of the entire network that estimates the bandwidth requirement of the incoming traffic load efficiently. In addition, we are able to achieve more stable and higher fairness index for low priority traffic as well. These results demonstrate that optimized architecture can efficiently serve QoS demands for real time communications while simultaneously providing enough bandwidth to upstream dominant BE services. Therefore, this optimized network architecture is more fair compared to the conventional integrated FiWi architectures.

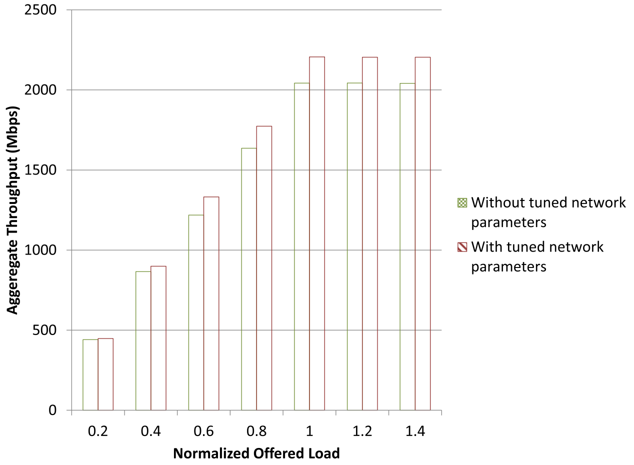

FIGURE 8. **Aggregate throughput vs normalized offered load.**

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