An Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation Algorithm for Integrated Hybrid PON with Wireless Technologies for Next Generation Broadband Access Networks

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***Abstract*—Optical and wireless technology integration schemes merge the high-speed and high-capacity of the optical networks with the low-cost, wide-coverage and mobility features of wireless counterparts for Subscriber Stations (SSs). It is also financially viable for the telecommunication service providers particularly in rural areas. In order to successfully integrate the two technologies, there are some technical concerns in terms of Architectural aspects, Physical Layer features and Media Access Control (MAC) related issues. This paper is mainly focused on the analysis of the key topics in MAC-related issues over the converged scenario and proposes an Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm where the hybrid Passive Optical Network (PON) acts as a backhaul technology for the wireless counterpart. Performance of the proposed algorithm is evaluated through conducted simulation scenarios in terms of different Quality of Service (QoS) metrics where the IIDWBA algorithm shows a better performance when it is compared with the scenario in which it has not been employed.**

Keywords: optical and wireless technology integration, Media Access Control (MAC), resource allocations

I. INTRODUCTION

PON [11], [12], and [27] is the most promising candidate among optical access solutions in terms of maintainability and robustness. There have been various efforts on PON multiplexing techniques such as Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) and Code Division Multiplexing (CDM). TDM-PON reduces the cost per subscriber and has inexpensive network components as it requires only one transmitter in the Optical Line Terminal (OLT), as well as only one type of transmitter in Optical Network Units (ONUs) [23]. However, TDM-PON sacrifices the maximum available bandwidth per subscriber and limits the number of supported subscribers up to 32 [21]. On the other hand, WDM-PON provides multiple wavelength channels with a good security and protocol transparency which offers higher bandwidth and supports more subscribers [6]. In WDM-PON, a WDM transmitter, particularly in a subscriber side, is the most critical component where the associated transmitter should be precisely aligned with the allocated channel [21]. Unlike TDM-PON, in WDM-PON, the OLT needs to have an array of transmitters with one transmitter for each ONU. Every ONU also needs to have a wavelength-specific laser. Generally speaking, although PON has been viewed as an attractive solution for the “first/last mile” bandwidth bottleneck problem, extending fibre-based infrastructures of PON to the rural area is either too costly or inaccessible. Moreover, PON is unable to provide wireless access services.

World Wide Interoperability for Microwave Access (WiMAX, IEEE 802.16 [10]) standard comes into play as a wireless matching part for PON technology. WiMAX aims to reduce the equipment, operation and maintenance costs and capable of providing the low-cost, wide coverage, fixed and mobile broadband access connections with the QoS provisioning scheme [5]. It also provides wireless access services for rural areas where the development of copper-based technologies or fibre-based broadband is too expensive or inaccessible. However, WiMAX copper-based backhaul technology is still a controversial issue. This is the point where optical and wireless technology integrations come into play. PON can be used as a scalable, cost-aware and potential solution for WiMAX backhaul problem whereas WiMAX can extend PON infrastructure to rural areas with relatively lower cost. In order to successfully integrate the optical and wireless technologies, there are some challenging issues that need to be addressed efficiently and effectively in order to provide the smooth End-To-End (ETE) technology integrations.

To the best of our knowledge, the traditional single channel TDM-PON has been addressed in most of the existing work related to the optical and wireless integration scenarios. Therefore, we are motivated to combine the wavelength routing and high-capacity of WDM-PON, the power-splitting and lower-cost of TDM-PON with high coverage and mobility features of the wireless counterpart for the integrated scenario. In order to provide the full dynamic wavelength/bandwidth allocations across hybrid PON integration with wireless technology, an IIDWBA algorithm is proposed. The remainder of this paper is prepared as follow. In Section II, the existing work related to the optical and wireless technology integrations is briefly discussed. The proposed IIDWBA algorithm is discussed fully in Section III. Sections IV and V include the simulation model and the captured results, respectively followed by the conclusions in Sections VI and references.

II. RELATED WORK

To date, a wide range of research has been carried out on the successful integration of the optical and wireless technologies. The integrated scenario has been considered in three categories: *Architectural*, *Physical layer* and *MAC layer* issues. The *Architectural* aspects [1], [3], [7], [13], [16], [17], [24], and [25] include the way two technologies connect to each other. In *Physical layer* issues, most of the works were focused on providing the cost-effective and reliable Radio over Fibre (RoF) systems [19]. As the research in this paper is related to the MAC-related issues of the converged scenario, the previous works related to this aspect are selected and discussed as follow. The MAC-related issues for the integrated scenario were discussed for the first time in [7]. The authors raised several issues for the bandwidth allocations, packet scheduling and QoS support. Ou et. al [29] investigated the scheduling techniques aimed at improving the performance and guaranteeing the QoS for different class of services. Ou et. al [3] proposed a slotted Dynamic Bandwidth Allocation (S-DBA) algorithm which aimed to increase the bandwidth utilizations by reducing the signaling overhead caused by the cascading bandwidth requests and grants. Ou et. al [22] proposed an intra ONU-Base Station (BS) scheduling algorithm termed Hybrid Priority Weighted Fair Scheduling (HPWFS) to progress the QoS performance without bandwidth starvations for the lower priority class of services. Ou et. al [13] proposed a DBA algorithm for the suggested Optical-Optical-Wireless (OOW) architecture which was executed in three levels. Ou et. al [20] investigated the possible challenging issues for the integrated structures of the TDM-PON and WDM-PON with WiMAX and Wireless Fidelity (Wi-Fi) networks. Performance evaluations of the existing scheduling techniques for three popular service classes were studied which showed the strong impact of using an efficient up-link scheduler in converged scenario. Please refer to [4], [8], [15], [18], and [25] for more work related to the MAC-layer aspects of the converged scenario. To the best of our knowledge, TDM-PON has been addressed in most of the existing work related to the integration scenario. Using the traditional single channel TDM-PON, where a group of ONUs (typically 16) sharing a single channel as a backhaul for 802.16 BS, provides each BS with ~ 62.5 Mb/s capacity which is almost matched the 802.16 channel capacity (~ 70 Mb/s over a 20 MHz channel). However, 62.5 Mb/s does not seem to be enough when a given ONU is employed as a backhaul for more than a single BS. This is the point where WDM-PON comes into play where multiple wavelengths will be available over a same fibre channel. Thus higher bandwidth can be provided by the OLT for a given ONU, more BSs and, finally, more number of SSs can be supported. In terms of MAC-related issues, an IIDWBA algorithm is proposed in this paper to provide the full distributed and dynamic wavelength/bandwidth allocations across OLT - ONUs as well as ONU - BSs. While a given DBA algorithm deals with bandwidth allocations inside a given channel, the IIDWBA algorithm works on top of a given DBA algorithm inside the OLT and ONU in association with multiple channels.

III. IIDWBA ALGORITHM

In order to save space, a given Server Station is termed SST, which can be the OLT or ONU, and a given Client Station is termed CS, which can be the ONU or BS. An SST is an element that provides resources for a given CS periodically and a given CS is an element that asks for resources from a given SST regularly. A given SST can be a CS and vice versa at any time. In this paper, a given ONU is a CS when it asks for resources from the OLT and is a SST when it provides resources for a given BS. Moreover, a given BS is a CS when it asks for resources from the associated ONU and an SST when it provides resources for the associated SSs. However, the OLT and the SSs are the ultimate SST and CSs, respectively. The IIDWBA algorithm works in three phases as follow.

A. Phase one: Initialisation phase

Phase one includes the auto-discovery and registration processes during which the CSs join the converged network and a wavelength will be assigned to each of them. In this phase, the IIDWBA algorithm first identifies the total number of the supported channels as well as the total number of the CSs associated per SST. The average number of the CSs per channel will be calculated next. Then it starts randomly allocating the channel identifiers (IDs) to all the CSs in such way that the number of the CSs per channel will be the same. Finally, the allocated channel IDs will be acknowledged to all the CSs associated with a given SST. In phase one, the objectives are as follow:

1) Identifying the average number of the CSs per channel per SST.
2) Assigning a default channel ID to all the CSs associated with a given SST.
3) Finishing the registration process for each CS and receiving the first associated queue status.

B. Phase two: Intra-channel bandwidth allocations phase

Phase two will be executed immediately after phase one and will be accomplished once per service cycle inside all the channels per SST. This phase is responsible for allocating bandwidth inside a given channel by considering the actual bandwidth requests and minimum guaranteed bandwidth per CS per service cycle. At the end of a given bandwidth allocation cycle, the local information such as the total number of the heavily loaded CSs and associated MAC addresses, the total excess bandwidth, the total excess requested bandwidth and the generated service cycle will be delivered to the phase three. In order to distinguish how the bandwidth is granted from a given SST to the associated CSs during a given service cycle, the *Limited Bandwidth Allocation Scheme* [14] and [50], is discussed first as follows. In Limited Bandwidth Allocation Scheme, if the requested bandwidth from a given CS is less than the minimum guaranteed bandwidth, the requested bandwidth will be granted; otherwise the minimum guaranteed bandwidth will be granted. This approach provides excess bandwidth remaining from the CSs which requested bandwidth less than the minimum guaranteed bandwidth (lightly loaded CSs).

One solution to employ the excess bandwidth is to distribute it fairly among those CSs, which requested bandwidth more than the minimum guaranteed one (heavily loaded CSs), as proposed in [8]. However, the difference between the work in this paper and the work in [8] is that, in this paper, the excess amount of bandwidth, which is remaining from a given channel, will be used globally if it is not employed by the local CSs associated with it. In phase two, the objectives are as follow:

1) Allocating bandwidth to local CSs on a given channel.
2) Scheduling the local service cycle.
3) Capturing the total number of the heavily loaded CSs and their MAC addresses, total local excess bandwidth and total local excess requested bandwidth.
4) Sending objective two and three to the Global scheduler.

C. Phase three: Inter-channel bandwidth allocations phase

Phase three will be executed immediately after the phase two and includes three real-time stages of *Collect*, *Schedule* and *Distribute*.

During the *Collect* stage, the IIDWBA algorithm collects the local information from each channel including the number or the local heavily loaded CSs with associated MAC addresses, total excess bandwidth, total excess requested bandwidth and the latest scheduled service cycle. During the *Schedule* stage, based on the number of the total heavily loaded CSs on all the channels (globally heavily loaded CSs), global excess requested bandwidth, and the global excess available bandwidth, the IIDWBA algorithm schedules the global excess bandwidth among all the globally heavily loaded CSs. During the *Distribute* stage, the globally scheduled excess bandwidth will be distributed among the globally heavily loaded CSs inside the associated service cycle and be immediately broadcast to all the channels. In phase three, the objectives are as follow:

1) Receiving the total number of the heavily loaded CSs and their MAC addresses, total local excess bandwidth, and total local excess requested bandwidth from all the channels on a given SST.
2) Receiving the latest scheduled service cycle from all the channels.
3) Identifying the lightly/heavily loaded channels.
4) Calculating the total number of the heavily loaded CSs across all the heavily loaded channels.
5) Calculating the total excess bandwidth across all the lightly loaded channels.
6) Calculating the average granted excess bandwidth from each lightly loaded channel to a given globally heavily loaded CS.
7) Allocating the global excess bandwidth to the globally heavily loaded CSs according to the actual need.
8) Scheduling and embedding the global allocated excess bandwidth inside associated service cycle.
9) Sending all the service cycles for all the channels to broadcaster.

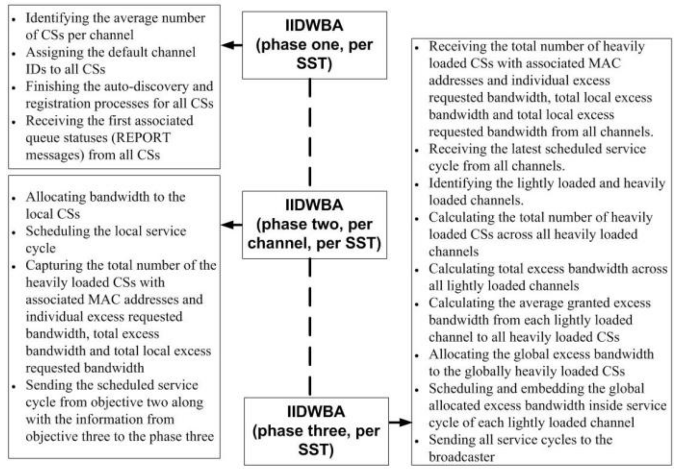

Figure. 1 Specific tasks for each phase of the IIDWBA algorithm

The specific tasks for each phase of the IIDWBA are specified in Fig. 1 per channel per SST.

The next Section evaluates the performance of the IIDWBA algorithm through simulated scenarios.

IV. SIMULATION MODEL

The performance of the proposed IIDWBA algorithm is evaluated by conducting a simulated scenario using OPNET Modeler [9]. The simulation scenario, Fig. 2, includes: a single OLT in Central Office (CO), which supports four channels ($w_1,\ldots,w_4$) and is related to 16 ONUs, a 1:4 sized Arrayed Waveguide Grating (AWG) with a co-located amplifier and four 1:16 sized TDM Splitters. AWG and TDM Splitters are seated between the OLT and ONUs, respectively. A given ONU is also assigned to 16 BSs and supports the same four channels ($w_1,\ldots,w_4$). A 1:4 sized AWG with a co-located amplifier and four 1:16 sized TDM Splitters are also located between a given ONU and BSs, respectively. Each BS is also associated with 10 wireless SSs which will be increased to 100 SSs in stage by 10 to evaluate the performance of the IIDWBA algorithm under the different load values. A given BS also supports the same four channels ($w_1,\ldots,w_4$). Simulation parameters, see Table I, are employed for the experiments. Moreover, the simulation scenarios ran for three seed values of 128, 166 and 90. However, we depicted the average plots from three runs in this paper. Based on widely used configurations for the converged scenario and traditional TDM-based PON [1] and [14], the simulated scenario is carried out as follow. The buffer sizes inside the ONUs and BSs are set to finite 10 Mbytes and the maximum cycle time is considered as 2 ms. A fixed 192µs is considered as the Round Trip Time (RTT) delay for each CS in every service cycle. Moreover, 100 Mb/s and 1Gb/s are the upstream data rates between a given BS and the associated ONU as well as a given ONU and the OLT. A fixed guard time of 5µs is considered for the light sources on ONUs and BSs. Moreover, the MPCP Extension protocol [2] is employed to support all the communications among the components. An uneven

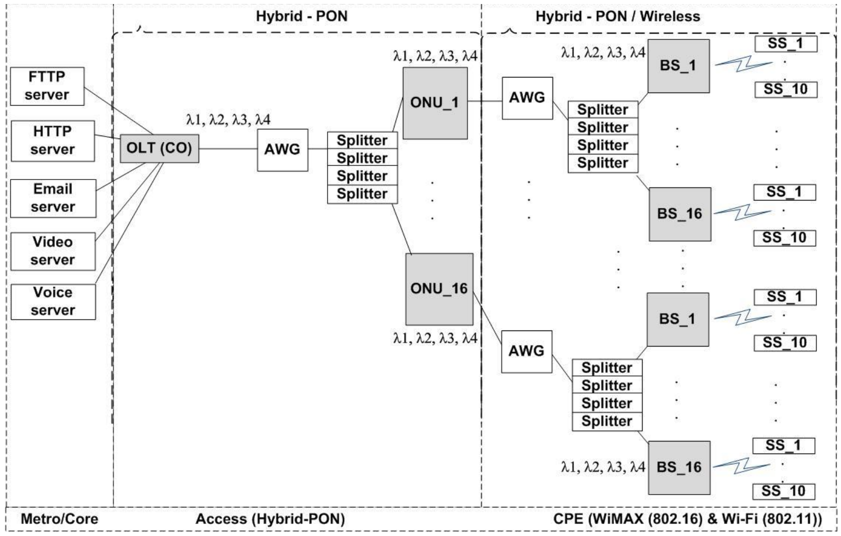

Figure. 2 Network topology for evaluating the proposed IIDWBA algorithm

traffic pattern is considered across all the channels on a given SST where lightly loaded and heavily loaded CSs are always available during the simulation run time. Two traffic patterns termed first traffic pattern and second traffic pattern are considered for the experiments. In the first traffic pattern, the load on w_1 is gradually increased from 10 SSs to 100 SSs per BS (total of 160 to 1600 SSs per ONU) while the number of the SSs on other channels are fixed, up to 10 SSs (total of 160 SSs per ONU), in order to distinguish how CSs on w_1 benefit from the available free bandwidth on the other channels when the traffic builds up. In the second traffic pattern, the load on all channels is increased by gradually raising the number of the SSs per BS from 10 to 100 (total of 160 to 1600 SSs per ONU) to distinguish the performance of the CSs associated with w_1 from the results captured in the first traffic pattern.

TABLE I. SIMULATION PARAMETERS

Traffic pattern	Burst (uneven across SSs)
ON and OFF state time (sec)	20% and 80% of simulation time
Traffic start time	even across all SSs
Traffic stop time, Packet size	Never, 500 bytes (constant)
Number of SSs per BS	10 to 100 BY 10
Traffic class	Best Effort (BE)
Simulation time, Seed	30 sec, 99, 128, 166
value per static, update interval	1600, 300000

V. CAPTURED RESULTS

After employing the first traffic pattern, as Fig. 3 reveals the proposed IIDWBA algorithm is successful in decreasing the average queuing delay to almost 14% for the ONUs associated with w_1, when it is compared with the scenario without applying the IIDWBA algorithm [8]. It is because, when the load starts increasing on channel one, w_1, the IIDWBA algorithm starts looking for the excess bandwidth on neighbouring channels (w_2, w_3, w_4) which will be collected and distributed among the ONUs associated with w_1. The average queuing delay for the ONUs associated with w_2, w_3, w_4 is also captured with and without applying the IIDWBA algorithm, Fig. 4, in which the first traffic pattern is employed. As it reveals, the IIDWBA algorithm has almost zero negative affect on the performance of the ONUs associated with w_2, w_3, w_4. It is because the allocated bandwidth from w_2, w_3, w_4 channels is the unutilised local excess bandwidth. The average extra requested bandwidth from the ONUs associated with w_1 is presented in Fig. 5, with and without employing the IIDWBA algorithm in which the first traffic pattern is utilised. As it reveals, the IIDWBA algorithm is capable of keeping the average extra requested bits from the ONUs associated with w_1 under the minimum guaranteed bandwidth by allocating the available excess bandwidth from the other channels (w_2, w_3, w_4) to them during each service cycle. In the second traffic pattern, the load on all channels is gradually increased by raising the total number of the SSs connected per BS from 10 to 100 to distinguish how the increased load on three channel (w_2, w_3, w_4) will affect the performance of the ONUs over w_1.

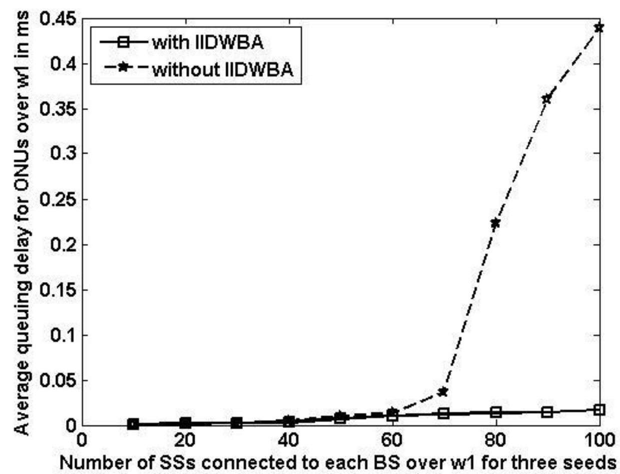

Figure. 3 Average queuing delay for the ONUs on channel one, employing first traffic pattern

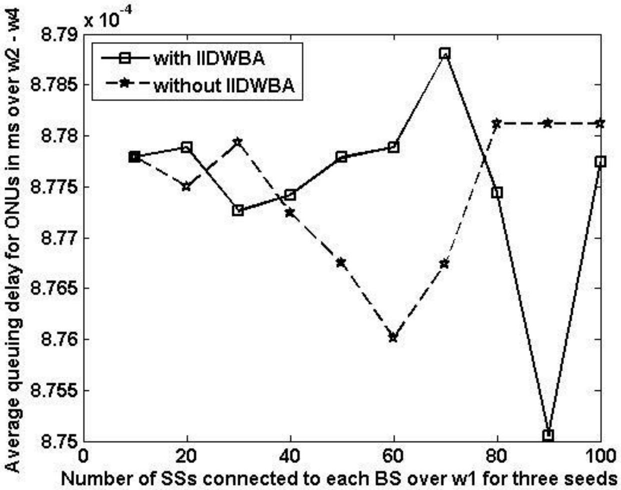

Figure. 4 Average queuing delay for the ONUs associated with channel two to four, employing first traffic pattern

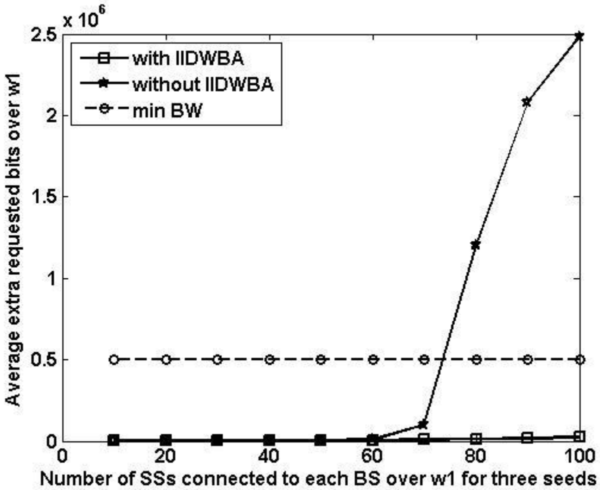

Figure. 5 Average extra requested bandwidth from the ONUs associated with channel one, employing first traffic pattern

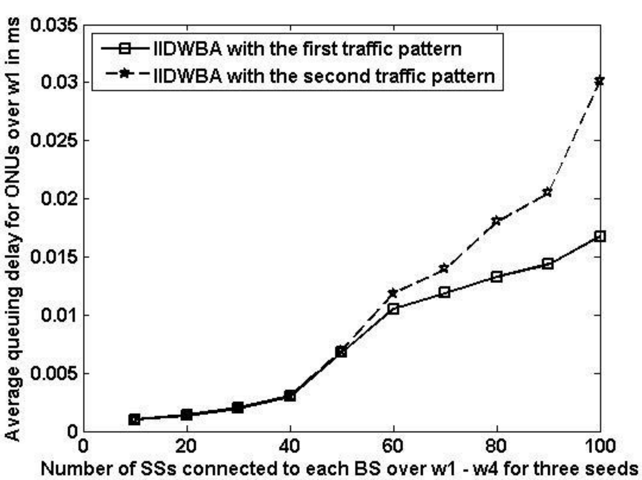

Figure. 6 Average queuing delay for the ONUs associated with channel one employing the first and second traffic patterns

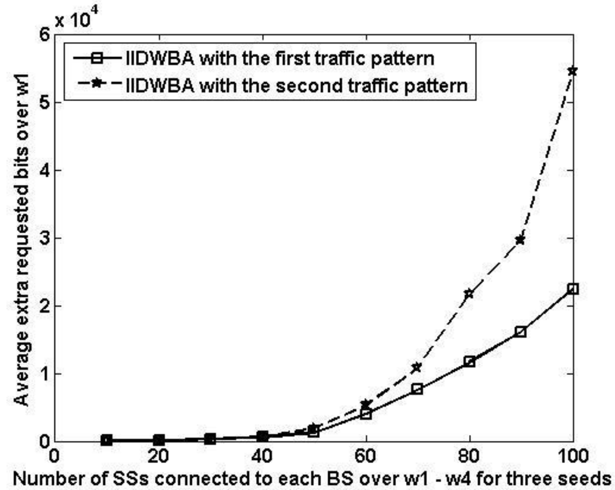

Figure. 7 Average extra requested bandwidth from the ONUs associated with channel one employing the first and second traffic pattern

When the number of the SSs connected per BS on all the channels reaches to 60, Fig. 6, the average queuing delay inside the ONUs associated with w_1 starts increasing constantly and reaches to almost 0.03 sec when it gets to 100 SSs per BS. The reason behind this degradation is that when the load on three channels (w_2, w_3,w_4) is increased gradually, the IIDWBA algorithm cannot find as much excess bandwidth for the ONUs associated with w_1 when it is compared to the first traffic pattern, where the loads on three channels is almost fixed. However, as it reveals in Fig. 6, the queuing delay for the ONUs over w_1, under the second traffic pattern, is still much lower than the scenario when the IIDWBA is not employed.

The average extra requested bandwidth (bits) over w_1 is also displayed in Fig. 7, in which the second traffic pattern is employed, and then compared with the captured results from the first traffic pattern. As it reveals, when the number of the SSs connected per BS is gradually increased from 50 to 100 SSs on all channels, the average extra requested bits over w_1 starts increasing to almost twice more than the first traffic pattern scenario. It is because, when the second traffic pattern is employed, the load on all the channels starts building up gradually. Therefore the IIDWBA algorithm cannot find as much as excess bandwidth for the ONUs associated with w_1 over w_2, w_3,w_4, when compared to the first traffic pattern. This behaviour results in accumulating more packets in the queues associated with the ONUs over w_1. Thus longer queuing delay and larger average extra requested bits will be produced.

VI. CONCLUSION

In this paper, the IIDWBA is proposed for the multi-channel PON integration with wireless technologies where the extra bandwidth from all the available channels associated with a given SST will be identified, collected, scheduled and allocated to the heavily loaded CSs, which may be scattered over the different channels in the same service cycle. Through conducted simulation experiments, it is demonstrated that the proposed algorithm is capable of collecting the excess bandwidth from the lightly loaded channels and spreading them across the heavily loaded CSs, which may be scattered over different channels. The proposed algorithm shows a better performance in terms of average queuing delays, utilisations and throughput when compared with the same simulation scenario not employing the IIDWBA algorithm.

VII. ACKNOWLEDGMENT

The authors would wish to acknowledge the support of the University of Ulster and University of Abertay Dundee for funding this work.

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