Wavelength-agile and radio-agile FiWi access network using dynamic scheduling to improve upstream delay and resource utilization

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ABSTRACT

Fiber wireless (FiWi) access network which is also referred as hybrid wireless optical broadband access network is one of the modern architecture to solve the problem of bandwidth availability and flexibility simultaneously. It integrates wireless frontend with optical backend. In FiWi network most of component remains idle for large duration, hence efficiency is very crucial. To improve energy efficiency in FiWi many multiple access (MA) techniques had been implemented at backend. However inclusion of multiple access techniques usually incur problem of delay, as data transfer in such network takes place only in the assigned slot of access technique. In this paper a novel architecture is proposed for FiWi which implements wavelength agile hybrid multiple access at backend and radio agile access technique at frontend. Further to improve delay performance, bandwidth availability and utilization of resources; a new scheduling approach is proposed for multiple access techniques implemented at frontend as well as backend. Delay performance, wavelength availability and load handling capacity of proposed approach is compared with different hybrid multiple access architecture. To best of our knowledge, wavelength agile and radio agile MA has been used for the first time in FiWi, moreover the proposed scheduling approach implemented on MA provide promising results in terms of delay and resource utilization. The performance of proposed work is also evaluated in terms of service and reservation delay component to indicate its utility in terms of actual information content per frame. The result shows effectiveness of proposed architecture over other existing architectures.

1. Introduction

In today's world of high bandwidth applications and rapid growing ICT, demand of bandwidth is increasing exponentially. To match the demand of bandwidth, many newly developed technologies had been adapted in modern world [1]. Access network being the crux of networking architecture, which is also responsible for bandwidth usage and its utilization, becomes a prone target amongst the researcher. Fiber wireless (FiWi) access network is one of the best solutions to achieve bandwidth utilization and flexibility simultaneously in access network [2]. A FiWi access network contains optical backend and wireless frontend, technologies used at the backend are such as Ethernet PON (EPON), next generation PON (NG PON) (1 Gbps), 10G PON (10Gbps), wavelength division multiplexing (WDM) PON or wavelength agile (WA) PON [3]. While in the frontend, technologies like IEEE 802.11 (54–100 Mbps), IEEE 802.16 or LTE are preferred [4, 5]. OLT and ONU transfer their data using REPORT and GATE message while access point and stations uses

PS-POLL and BECON messages. The combination of passive optical network (PON) and wireless access network at backend and frontend respectively is also considered very effective for achieving scheduling which improves the bandwidth utilization. PON offers different multiple access (MA) techniques, to utilize the available resources and maintain energy efficiency [6]. Similarly at the frontend MA techniques such as time division multiple access (TDMA) has been implemented to reduce the energy consumption of wireless stations [7]. The main objectives of using MA at frontend and backend of FiWi are to improve energy efficiency and resource utilization. But it degrades the delay performance, hence implementing dynamic bandwidth allocation and scheduling approach play a vital role in optimizing the delay performance.

Among different MA techniques, hybrid-MA has been considered as the most promising, as it incorporates the benefits of both time division and wavelength division MA. For effective scheduling and bandwidth utilization in next generation Ethernet PON (NG-EPON), hybrid-MA is classified by IEEE as multi scheduling domain (MSD) PON, single
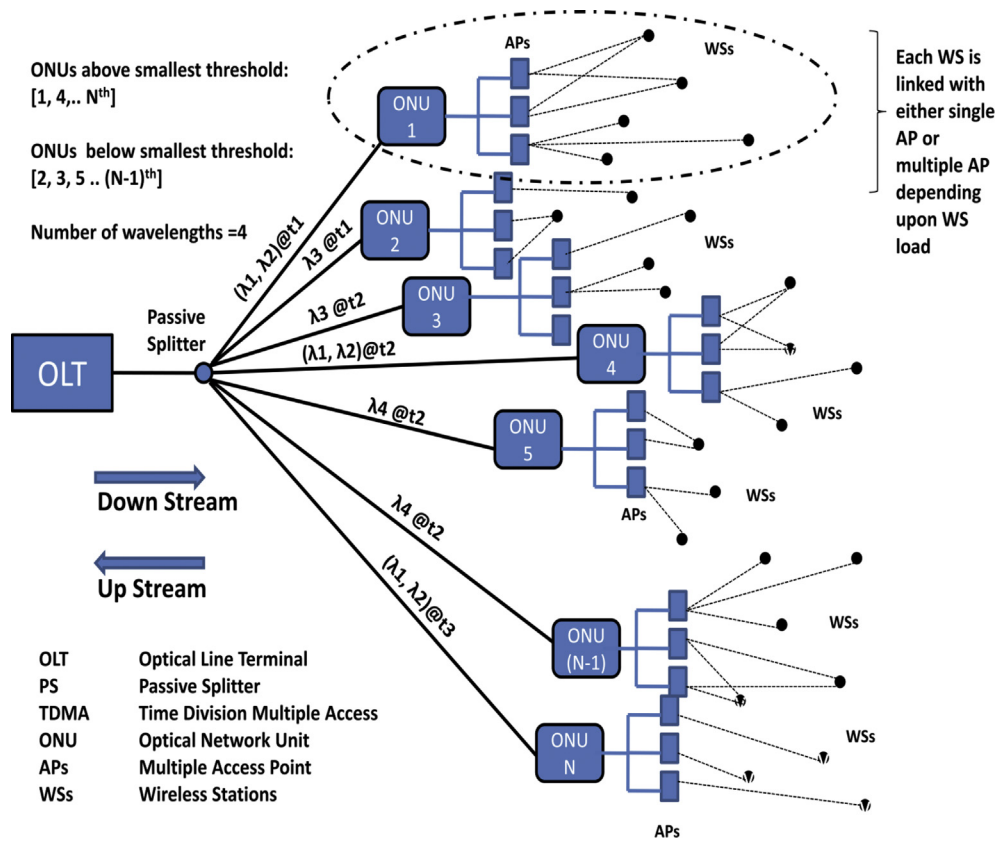

Fig. 1. Architecture of proposed WA-RA FiWi.

scheduling domain (SSD) PON, and wavelength agile (WA) PON; depending upon how optical network units (ONUs) are allotted wavelength or group of wavelengths [8]. There had been a lot of work already done on MSD and SSD-PON, but WA-PON, which is a newly added mechanism of hybrid PON, needs to be explored specially for FiWi access network. In MSD, each ONU transmits at one wavelength at one instance of time and multiple ONUs can transmit simultaneously at different wavelengths. On the other hand, in SSD each ONU can simultaneously use multiple wavelengths. WA-PON can use multiple wavelengths to transmit traffic to single ONU or a group of ONUs and simultaneously it can also take multiple ONUs traffics on single wavelength using time division multiple access (TDMA). WA-PON is considered to be the better approach for utilizing and scheduling bandwidth in PON [9]. Hence in the proposed architecture, WA-PON has been implemented at the backend of FiWi. At the frontend, rather than using traditional TDMA, radio agile (RA) WLAN with multiple APs is proposed and implemented. RA is similar to the WA of backend, which aims to improve resource utilization and delay performance at the frontend as well.

The proposed FiWi architecture in this paper is referred as WA-RA FiWi (wavelength agile and radio agile fiber wireless) access network. WA-RA at the backend contains OLT and ONUs with multiple transceivers, so that multiple wavelengths can be used simultaneously during scheduling. On the frontend, multiple APs are associated with each OUN, which are further connected with multiple stations on fix frequency band. Data transfer between stations and ONU-AP uses single stage PS-POLL and BECON; and similarly to transfer data between ONU and OLT single stage REPORT and GATE messages are used. WA-RA FiWi being different in functionality and allocation requires a new scheduling approach, which can establish cooperation between front and backend during communication; and provides bandwidth utilization for wireless stations as well as ONUs. In backend of WA-RA FiWi, WA is implemented with multiple wavelengths, in which wavelengths will be allocated to each ONU depending upon its individual load. On the other hand, RA is

implemented at frontend with multiple access points (APs), where number of APs assigned to each station depends upon the load of wireless stations. Hence WA-RA FiWi architecture is deduced to provide better bandwidth utilization, quality of service and optimum delay.

In the initial phase of FiWi development, Z. Zheng et.al in [10] has discussed the communication related issues in FiWi. The main objective of their work was to integrate wireless and optical access network to obtain better throughput and optimum delay performance. Other than conventional parameters, bandwidth utilization and effective scheduling is of high significance for FiWi access network. H. Mouftah et.al in [11] suggested the decentralized Dynamic Bandwidth Allocation where computation head is decentralized to improve delay and allocate bandwidth for inter ONU communication. In [12] a brief discussion is shown on the importance of centralized DBA. It also mentions the significance and implementation of DBA for cluster routing in FiWi. B. Kantarci et.al. in [2] uses the existing DBA scheme which mainly focuses to reduce energy efficiency, it also handles the problem related to quality of service. A survey of different DBA schemes and their associated architectures had been shown in [13], which provides different allocation problems in integrated fiber wireless network. K. Yang et.al. in [14] implements a new DBA scheme on integrated EPON and WiMAX networks (WE DBA), in which author provides two distinct DBA algorithms for frontend and backend. In [15] hierarchical QoS-aware DBA, resources are assigned on the basis of queuing request and user demand. It also shows that proposed DBA reduces the packet drop probability. DBA algorithm providing minimum guaranteed bandwidth along with sharing the excess bandwidth with stations is proposed by C.L. Lai et.al in [16], which is implemented with wavelength division multiplexing PON and multi channel wireless network. In [17, 18] concepts of ant colony optimization and game theory have been used respectively to enhance fairness while providing bandwidth allocation. In literature there have been few dynamic bandwidth allocation schemes suggested for FiWi access network but none of them based on the concept of wavelength
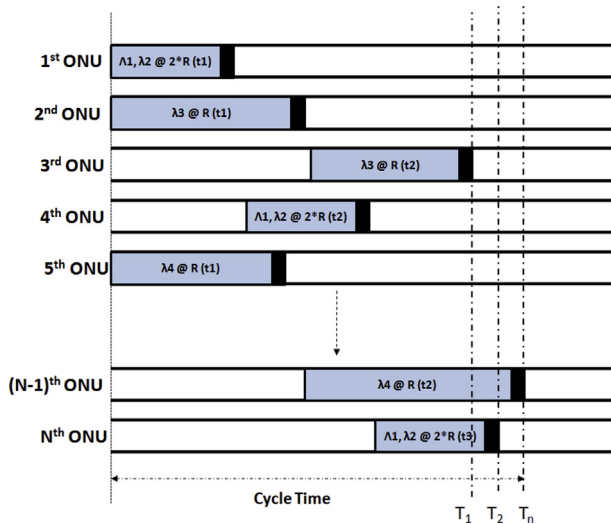
Fig. 2. Allocation of wavelengths (λ) and time slot (t) to each ONU.

agile hybrid multiple access. On the other hand concept of sharing APs (radio agile) at the frontend is a novelty in itself. Further, to improve cooperation between front and backend same DBA and scheduling is proposed in the paper at both ends, which ultimately improves bandwidth allocation for stations at wireless end and ONUs at optical end; using radio agile and wavelength agile techniques respectively.

2. Model

2.1. Architecture of WA-RA FiWi

The proposed FiWi architecture, Wavelength Agile and Radio Agile FiWi (WA-RA FiWi) access network shown in Fig. 1; consist of 10GPON at the backend and WLAN with multiple access points (APs) at frontend. Generally wireless access network is categorized as infra structure network and ad-hoc network. In proposed architecture we have selected infra structure at frontend. 802.11 is used as the frontend technology where MAC layer functionalities of all its variants is same and difference is only in physical layer standards. Among different variants, 802.11ac standards are preferred, which is having the data rates of 433 Mbps per spatial stream, or 1.3Gbps in a three stream design. It operates in 5GHz frequency range and also supports for wider channels.

In frontend of WA-RA FiWi, wireless stations associated with each ONU is connected through multiple APs. It is assumed that all ONUs are at equal distance from OLT and approx distance between them is 1–2 km. The proposed scheduling approach, based on the load of each station, categorizes stations in two groups with respect to a mean load referred as threshold. The group of stations with load greater than threshold is assigned with more number of APs as compared to the group with load less than threshold. Stations of each group transmit there traffic in TDMA manner to ONU through assigned number of APs. Each station remains active in its own TDMA slot which helps to improve energy efficiency of system. Due to this dynamic allocation of APs to the stations, cumulative delay of the WA-RA FiWi will reduce significantly and resources will be utilized more efficiently. Scenario shown in fig for frontend of WA-RA FiWi assumes that, each ONU is associated with 3 APs, and stations with higher load than threshold are assigned 2 APs while rest are assigned with single AP.

At backend of WA-RA FiWi, cumulative data obtained from associated stations will be considered as the load of ONU [19]. Using load of ONU and maximum permissible load at ONU, normalized load at each ONU will be evaluated. Now to implement scheduling on wavelength agile PON at backend, following issues need to be resolved: (1) How many wavelengths to be assigned to each ONU, (2) For what duration each

wavelength need to be assigned, (3) How many ONUs will get single wavelength for transmission and (4) How the utilization of resources will be achieved while allocating wavelengths [8, 9]. In the proposed work at backend, multiple thresholds are generated depending upon the number of ONUs and load of ONUs. Using these thresholds, ONUs will be categorized in different categories. Based on the load of ONUs of each category, number of available wavelengths will be allocated to each group. Multiple ONUs with normalized load lesser than smallest threshold will be assigned to transmit their traffic on single wavelength, where number of such wavelengths will be determined on basis of resource utilization, cycle time and availability. All ONUs having load less than smallest threshold transmit in TDMA manner. Each ONU will remain active only in the assigned slot of transmission and for rest of the time it remains in sleep or idle depending upon the processor used in architecture. It will improve energy efficiency of the system significantly. On the other hand, ONUs with load greater the smallest threshold will assigned with multiple wavelengths. Number and duration of wavelengths are decided, depending upon proposed DBA.

Scenario shown for backend assumes to be consists of N ONUs; where ONU [1, 4… N^{th}] are assumed to be having normalized load above smallest threshold while rest are below threshold. Using proposed DBA and scheduling, available numbers of wavelengths (4) are distributed among less loaded group ONUs and high loaded group of ONUs.

2.2. Scheduling in WA-RA FiWi

Fig. 2 indicates the allocation of wavelengths and time slots to each ONU, depending upon DBA. It can be observed in the figure that, for group of ONUs which are having load larger then threshold value (1, 4,… N) are assigned with multiple wavelengths ($\lambda 1$ and $\lambda 2$) simultaneously under TDMA manner. The main objective of such allocation is to provide higher link rate (R) to those ONUs which are having relatively larger load by providing multiple wavelengths simultaneously. On the counter part of it, ONUs with lower load (2, 3, 5, …. (N-1)) are allocated with single wavelength at one instance, using principle application of wavelength agile PON [8]. Multiple ONUs assigned with single wavelength transfer their traffic in TDMA manner to OLT. Maximum TDMA duration among all the group of ONUs is referred as cycle time (t_c). To improve the bandwidth utilization and delay performance, WA-RA FiWi tries to minimize the difference between cycle times of individual TDMA groups (T_1, T_2 and T_3 as shown in figure). Pseudo code for WA-RA FiWi is given as follow:

Pseudo Code: Steps performed for scheduling WA-RA FiWi	
Input:	N, $N_i \in \{1, 2, …N\}$; M, $M_{i,j} \in \{(1,1), (1,2)…(N,M)\}$, ; λ, $\lambda_i \in \{1, 2, …\lambda\}$; R_{OO} ; R_{AS} ; L_ONU_{max} ; L_STA_{max}
1	Initialize L_STA_i = Random (M,1); //Random load on Stations associated with each ONU.
2	Th_STA = mean (L_STA_i);
3	S_STA_j = (sort (L_STA_i(:), 'descend'); //Arrange station in descending order of their load.
4	**for** (j = 1; j<=M; j++)
5	{ **if** ($S\_STA_j > Th\_STA$)
6	Low_STA (m) = S_STA_j ; m++;
7	**else**
	High_STA (n) = S_STA_j ; n++;}
8	$T\_Sl\_LSTA = \sum_{k=1}^{m} \left(\frac{2*Low\_STA}{n_{AP}*R_{AS}} \right)$; $T\_Sl\_HSTA = \sum_{k=1}^{m} \left(\frac{2*High\_STA}{(1+n_{AP})*R_{AS}} \right)$;
9	$L_{ONU i} = \sum_{j=1}^{m} S_{STAj}$;
10	Th_ONU = mean (L_ONU_i);
11	S_ONU_j = (sort (L_ONU_i(:), 'descend') ;//Arrange ONUs in descending order of their load.
12	λ = (N+2)/1 Limiting to λ_{max} ; //Evaluating number of wavelengths.
13	$Th_i = \{Th\_ONU$, $(S_{ONUj} - Th\_ONU)/2$, …….} ;//Set of thresholds
14	$T_{max} = L\_ONU_{max} / R_{oo}$;
15	High_ONU = y (y~ = 0) where y = L_ONU_i (sum (L_ONU_i=> Th_ONU)); //creating subset of L_ONU_i
	Low_ONU = x (x~ = 0) where x = L_ONU_i (sum ($L\_ONU_i < Th\_ONU$));
	(continued on next page)

(continued)

```
16      for (i = 1; i<=N; i++)
17      { if (L_ONUi<Th_ONU)
18        { if (∑ Low_ONU/ Roo < Tmax )
              {
19          T_Sl_LONU = ∑ Low_ONU/ Roo ;
            elseif (∑Low_ONU/ Roo > Tmax && λL== = 1)
            T_Sl_LONU = ∑Low_ONU/ Roo ;


20          Else
            for (k = 1; k<=λ; k++)
            T_Sl_LONU (k) = ∑ Low_ONU/ (λ*Roo) ; }
21        else                  //(L_ONUi> Th_ONU)
          for (k = 1; k<= Th; k++)
22        { if (L_ONUi > Thk && λH > λmax)
23          { if (∑ high_ONU/ (λmax *Roo) > Tmax )
                {
              T_Sl_HONU(1) = ∑ high_ONU/ (λmax *Roo) less than Tmax;
              T_Sl_HONU(2) = ∑ remaining ONUs/ (λmax *Roo) ;
              else              //(∑ high_ONU/ (λmax *Roo) < Tmax )
              T_Sl_HONU = ∑ high_ONU/ (λmax *Roo) ;
                }
24        else                  //(L_ONUi > Thk && λH < λmax)
25        { if (∑ high_ONU/ (λH *Roo) > Tmax )
              {
            T_Sl_HONU(1) = ∑ high_ONU/ (λH *Roo) less than Tmax;
            T_Sl_HONU(2) = ∑ remaining ONUs/ (λH *Roo) ;
26        else              //(∑high_ONU/ (λH *Roo) < Tmax )
          T_Sl_HONU = ∑ high_ONU/ (λH *Roo) ;           }end all loops
```

In the above mentioned pseudo code we present the details and flow of WA-RA FiWi. Proposed scenario is assumed to have wireless stations ($M_{i,j}$) associated with each ONU which are connected through multiple APs. Traffic between APs and stations is transmitted using PS-POLL and BEACON messages. While on the backend multiple ONUs are connected to OLT through passive switch. Traffic between ONUs and OLT is maintained using GATE and REPORT messages.

In line 1, we initialize the load at each station (L_STA_i) randomly under some specific bound conditions. Further using L_STA_i, mean load is evaluated which is referred as threshold for frontend (Th_STA) (line 2). All the stations are arranged in descending order of their load (S_STA_j) for the further computation. Then all the stations are categorized as: stations having load larger than Th_STA and stations having load less then Th_STA(lines 4–7). In line 8, we allocate the time slot (T_Sl_LSTA and T_Sl_HSTA) for each station depending upon the number of APs assigned to stations. Using the values of T_Sl_LSTA and T_Sl_HSTA delay and utilization of resources can be determined for the frontend of WA-RA FiWi. When traffic of all the stations reached to APs, then cumulative load of stations determine the load on each ONU (L_ONU_i) (line 9). Similar to the frontend, mean of load (Th_ONU) and sorted ONUs (S_ONU_j) are determined in lines 10 and 11. Then the required number of wavelengths (λ) is determined for given number of ONUs, limited by a predefined value (line 12). Using Th_ONU all the ONUs are divided into two subsets;

categorized as λ_H (number of wavelengths assigned for ONUs having load more than Th_ONU) and λ_L(number of wavelengths assigned for ONUs having load less than Th_ONU). In lines 16–26, multiple iterations and cases are mentioned to evaluate the values of time slots (T_Sl_LONU and T_Sl_HONU) and number of wavelengths assigned to each ONU. Using the values of T_Sl_LONU and T_Sl_HONU, delay and resource utilization can be evaluated for WA_RA FiWi.

The computation complexity of proposed approach depends upon the number of ONUs, stations, wavelengths and value of thresholds. Adding to it, complexity also depends upon maximum number of iterations and sorting technique used for arranging ONUs and stations. Since in our algorithm we have used heap sorting hence average complexity used is $O(n(logn))$. The overall complexity of the algorithm is as follows:

$O(WA\text{-}RA) = k(O(N) + O(M)) + O(NlogN) + O(MlogM) + O(N^\lambda * M^{AP}) + O(log(high\_ONU) + log (low\_ONU))$

Complexity can further be simplified as:

$O(WA\text{-}RA) = O(kNM) + O(log(N^N * M^M) + O(N^\lambda * M^{AP}) + O (log(high\_ONU * low\_ONU))$

Where N is number of ONUs, M is number of stations per ONU, λ and AP is number of available wavelengths and access points at frontend respectively and; high_ONU and low_ONU are the number of ONUs above and below the mean threshold value respectively.

3. Analysis

WA-RA FiWi access network's main objectives are: (1) To achieve better end to end delay in comparison with other existing architectures and (2) To obtain efficient utilization of resources at frontend as well as backend in terms of wavelength utilization and availability.

3.1. Cycle time

In proposed mechanism both the parameters; delay and utilization percentage depends upon the cycle time and slot duration of ONUs. Hence it is crucially important to analyze cycle time (Tp). At the front end of WA-RA, traffic of all the stations are transferred to ONU through multiple APs, therefore load of each ONU is the cumulative load of its associated stations. Depending upon the load of ONU and thresholds, each ONU is assigned with a number of wavelengths, which is used to evaluate slots of ONUs. After determining the slots of each ONU and their transmitting wavelengths, cycle time can be evaluated.

Let $(N_i,\ i \in \{1,2,\ ...N\})$, $(\lambda_j,\ j \in \{1,2,\ ...\lambda\})$ and $(Th_p,\ p \in \{1,2,\ ...Th)\})$ be the sets of ONUs, wavelengths and thresholds respectively. Normalized load obtained from the cumulative load of all the associated stations is referred as $\delta_k,\ k \in \{1,2,...k\}$. Sequence of thresholds is obtained using the principle of mean and standard deviation for the given normalized load of ONUs and number of ONUs, which is shown in Eqs. (1) and (2).

$$Th_p(n) = \delta_{max}\left[\sum\left(\frac{\delta_i}{N}\right), \frac{2*\sum\left(\frac{\delta_i}{N}\right) + \{N * \max(\delta_i) - \sum(\delta_i)\}}{2N}, \frac{2N*\sum\left(\frac{\delta_i}{N}\right) + 3N * \max(\delta_i) - \sum(\delta_i)}{4N}............Th_p\right]$$ (1)

ONUs having normalized load less than Th_{ONU} referred as Low_ONU and ONUs having load larger thanTh_ONU referred as High_ONU (line 15). Depending upon the cumulative values of Low_ONU and High_ONU, λ is

Eq. (1) can be simplified as:

$$Th_p(n) = \left[\frac{\delta_{max}}{N}\sum(\delta_i), \frac{\sum(\delta_i) + N*\max(\delta_i)}{2N}, \frac{5*\sum(\delta_i) + N*\max(\delta_i)}{4N}........Th_p\right]$$ (2)
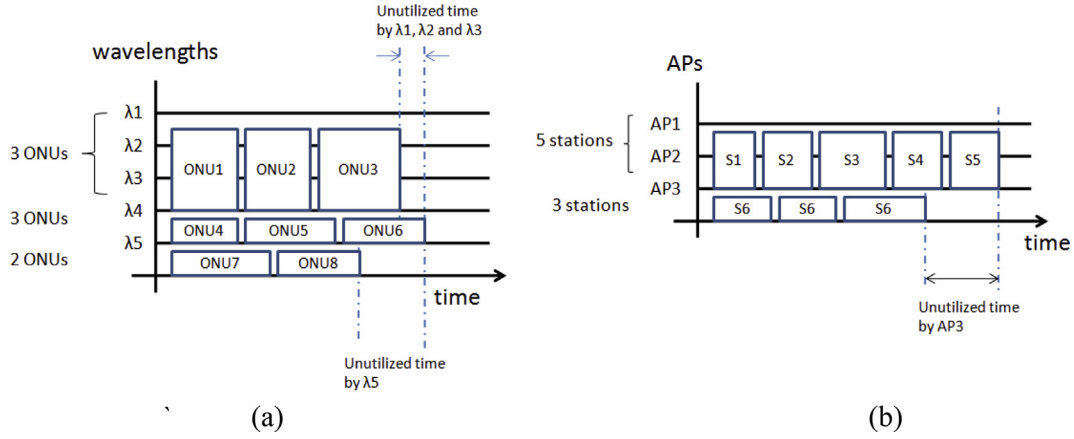
Fig. 3. (a) Illustration of unutilized duration by different wavelengths in backend of WA-RA FiWi for 8 ONUs and 5 wavelengths scenario. (b) Illustration of unutilized duration by AP in frontend for 8 stations and 3 AP scenarios.

Link rate between ONUs and OLT for 10GEPON is referred as $(10/\lambda)$ Gbps (R_{00}). Now using mechanism of WA-RA FiWi, total available wavelengths (λ_j) can be divided into two different subsets; i.e. wavelengths used for ONUs having load less than $Th_p(1)$ referred as λ_L and wavelengths used for ONUs having load more than $Th_p(1)$ referred as λ_H.

$$\lambda_L \subseteq \lambda_j \text{ and } \lambda_H \subseteq \lambda_j \text{ ; for all } \lambda_j = \lambda_L \cup \lambda_H \tag{3}$$

Similarly load of ONUs are classified as follow:

$$\delta_L \subseteq \delta_i \text{ and } \delta_H \subseteq \delta_i \text{ ; for all } \delta_i = \delta_L \cup \delta_H \tag{4}$$

Using Eqs. (3) and (4), relation between number of ONUs and number of wavelengths is:

$$\lambda_L : \lambda_H :: \delta_L : \delta_H \tag{5}$$

Using Eqs. (5) and (2) cycle time (T_L^P) for ONUs having load less than $Th_p(1)$ can be defined as:

$$T_L^P = \max\left[T_{L1}^P, T_{L2}^P, \ldots\ldots T_{Lj}^P\right] \tag{6}$$

And, $$T_{Lj}^P = \frac{\sum(\delta_j)}{N*\left(\frac{R_{00}}{\lambda_L+\lambda_H}\right)} \qquad \text{Where, } \delta_j \varepsilon \delta_k \text{ and } j\varepsilon\{1,2,3\ldots.\lambda_L\} \tag{7}$$

Similarly, cycle time (T_H^P) for ONUs having load more than $Th_{p=1}$ is:

$$T_H^P = \max\left[T_{H1}^P, T_{H2}^P, \ldots\ldots T_{Hi}^P\right] \tag{8}$$

And, $$T_{Hi}^P = \frac{\sum(\delta_i)}{Q*\left(\frac{R_{00}}{\lambda_L+\lambda_H}\right)} \qquad 0 \qquad \text{Where, } \delta_i \varepsilon \delta_k \text{ and } i\varepsilon\{1,2,3\ldots.\lambda_H\}$$

$$\tag{9}$$

Such that, $Q = \lambda_H$ for $\sum(\delta_H) < \dfrac{T_{max}*R_{00}}{(\lambda_L+\lambda_H)}$

$1 < Q < \lambda_H$ for $\sum(\delta_H) > \dfrac{T_{max}*R_{00}}{(\lambda_L+\lambda_H)}$

3.2. Average delay

In WA-RA average delay is evaluated for upstream as for downstream data is broadcasted hence significance of delay evaluation is less. Average delay in WA-RA can be referred as the mean of cycle time for all OUNs

and their corresponding overhead bit's equivalent time (T_{oh}). In this paper we have compared delay of WA-RA with the other scheduling mechanisms like MSD, SSD and their variants.

Delay in proposed mechanism is sum of frontend delay (ρ^f) between stations and AP; and backend delay (ρ^b) between ONU and OLT. Total delay (ρ_T) can be referred as follow:

$$\rho_T = \rho^f + \rho^b \tag{10}$$

Where. $\rho^f = mean(T_{Hi}^P, T_{Lj}^P) + T_{oh}^b$ and $\rho^b = mean(T_{Hi}^S, T_{Lj}^S) + T_{oh}^f$

In which T_{Hi}^S and T_{Lj}^S are cycle time of stations above and below threshold respectively. T_{oh}^b and T_{oh}^f are time equivalent of overhead bits required for communication at backend and front respectively. Using Eqs. (7) and (9) ρ^f can also be given as:

$$\rho^f = \left[\frac{(\lambda_L+\lambda_H)}{R_{oo}}\right]\sum_{i=1}^{\lambda_H}\sum_{j=1}^{\lambda_L}\left[\frac{\delta_i}{Q}+\frac{\delta_j}{N}\right] + \frac{N}{(\lambda_L+\lambda_H)}\left[\frac{g_b^o+GA_b+RE_b}{R_{oo}}\right] \tag{11}$$

Where, g_b^o, GA_b and RE_b are guard time equivalent bits, GATE message bits and REPORT message bits used for front data transfer respectively. Similarly ρ^b can be defined by Eq. (12), where n_L^{ap} and n_H^{ap} are the number of APs assigned for low loaded stations and high loaded stations respectively.

$$\rho^b = \left[\frac{(n_L^{ap}+n_H^{ap})}{R_{as}}\right]\sum_{i=1}^{n_L^{ap}}\sum_{j=1}^{n_H^{ap}}\left[\frac{\delta_i^s}{M'}+\frac{\delta_j^s}{M-M'}\right] + \frac{M}{(n_L^{ap}+n_H^{ap})}\left[\frac{g_b^s+PS_b+BE_b}{R_{as}}\right]$$

$$\tag{12}$$

R_{as} is the link rate between station and AP, M is the average number of stations associated with each ONUs. δ_i^s and δ_j^s are load of high loaded stations and low loaded stations. g_b^s, PS_b and BE_b are guard time equivalent bits, PS-POLL message bits and BECON message bits used for front data transfer respectively.

Using Eqs. (11) and (12), total delay can categorize as service and reservation delay.

$$\rho^{ser} = \left[\frac{(\lambda_L+\lambda_H)}{R_{oo}}\right]\sum_{i=1}^{\lambda_H}\sum_{j=1}^{\lambda_L}\left[\frac{\delta_i}{Q}+\frac{\delta_j}{N}\right] + \left[\frac{(n_L^{ap}+n_H^{ap})}{R_{as}}\right]\sum_{i=1}^{n_L^{ap}}\sum_{j=1}^{n_H^{ap}}\left[\frac{\delta_i^s}{M'}+\frac{\delta_j^s}{M-M'}\right]$$

$$\tag{13}$$

$$\rho^{res} = \frac{N}{(\lambda_L+\lambda_H)}\left[\frac{g_b+GA_b+RE_b}{R_{oo}}\right] + \frac{M}{(n_L^{ap}+n_H^{ap})}\left[\frac{g_b^s+PS_b+BE_b}{R_{as}}\right] \tag{14}$$

Eq. (12) shows that delay of WA-RA can be considered as the summation of service delay (ρ^{ser}) and reservation delay (ρ^{res}). Delay incurred

Table 1
Shows the list of parameters and their values used in simulation of results.

Parameter	Description	Value
N	number of ONUs	10
M	number of stations per ONU	16
R_{as}	link rate between station and AP	433 Mbps
R_{oo}	link rate between ONU and OLT	10 Gbps
Λ	maximum number of wavelengths	6
N_i, λ_j, Th_p	sets of ONUs, wavelengths and thresholds respectively	Refer in Section 3.1
δ_k	cumulative load of all the associated stations	Refer in Section 3.1
δ_{max}	maximum load allowed on ONU	1 Gb
g_b^o	guard time equivalent bits for frontend	1 μs
GA_b	GATE message bits	0.516 μs
RE_b	REPORT message bits	0.516 μs
g_b^s	guard time equivalent bits for backend	1 μs
PS_b	PS-POLL message bits	0.2 μs
BE_b	BECON message bits	0.2 μs

due to actual data is referred as service delay while delay due overhead bits is referred as reservation delay. It is always preferred to have reservation delay as less as possible.

3.3. Wavelength utilization and availability

Utilization of resources is referred as amount of duration in cycle time for each resource is utilized. In backend of WA-RA, wavelengths are considered as the critical resource which is quantized using utilization percentage. While at frontend, efficient use of access points determines utilization. For an efficient and realizable system, utilization of resources should be as high as possible.

Utilization of resources at frontend and backend of WA-RA FiWi can be seen in Fig. 3. At frontend of proposed architecture stations are allocated to single or multiple AP depending upon the load of stations. Difference among the allocation duration of APs is referred as unutilized duration. Similarly at backend, difference among allocation duration of wavelengths is referred as unutilized wavelength duration. Utilization is evaluated in proposed mechanism with respect to the maximum cycle time. Average utilization percentage at backend can be defined as follows:

$$UT_b = \frac{mean\left[T_{L1}^P, T_{L2}^P, \ldots\ldots T_{Li}^P, T_{H1}^P, T_{H2}^P, \ldots\ldots T_{Hj}^P\right]}{max\left(T_H^P + T_L^P\right)} \quad (15)$$

Similarly for the frontend utilization is shown in Eq. (16).

$$UT_f = \frac{mean\left[T_{L1}^s, T_{L2}^s, \ldots\ldots T_{Li}^s, T_{H1}^s, T_{H2}^s, \ldots\ldots T_{Hj}^s\right]}{max\left(T_L^s, T_H^s\right)} \quad (16)$$

Other than wavelength utilization, wavelength availability is also considered as one of the important parameters. In hybrid multiple access architecture, wavelength availability is referred as, relative duration for which each wavelength is available for further usage. In this paper wavelength availability is evaluated with respect to maximum cycle of MSD. Wavelength availability for MSD, SSD and proposed WA-RA based FiWi are as follow:

$$A_{MSD} = \sum_{j=1}^{\lambda} \frac{\left(T_{max}^{MSD} - T_j^{MSD}\right)}{\lambda * T_{max}^{MSD}} * 100 \quad (17)$$

$$A_{SSD} = \frac{\left(T_{max}^{MSD} - T^{SSD}\right)}{T_{max}^{MSD}} * 100 \quad (18)$$

Table 2
Comparison of cycle time of different mechanism with WA-RA against average normalized load (Avg δ).

Avg δ	Tc MSD-TDMA	Tc MSD-RA	Tc SSD-TDMA	Tc MSD-RA	Tc WA-RA
0.2	0.044	0.042	0.037	0.035	0.012
0.3	0.055	0.053	0.050	0.039	0.022
0.4	0.065	0.061	0.048	0.045	0.034
0.5	0.067	0.064	0.055	0.052	0.039
0.6	0.084	0.080	0.059	0.056	0.052
0.7	0.088	0.086	0.066	0.062	0.055
0.8	0.093	0.092	0.071	0.067	0.058

Table 3
Average cycle time (sec) at different values of first threshold.

$Th_{p=1}$	N_L	N_H	λ_L	λ_H	Avg T_L	Avg T_H
0.30	7	3	2	4	0.019	0.016
0.35	6	4	2	4	0.019	0.017
0.40	5	5	2	4	0.018	0.023
0.45	6	4	2	4	0.021	0.024
0.50	4	6	1	5	0.027	0.021
0.55	5	5	2	4	0.028	0.028
0.60	6	4	3	3	0.027	0.032
0.65	4	6	4	2	0.038	0.029
0.70	4	6	4	2	0.027	0.043

$$A_{WA} = \left[\sum_{j=1}^{\lambda_L} \frac{\left(T_{max}^{MSD} - T_j^{WA}\right)}{\lambda_L * T_{max}^{MSD}} + \frac{\left(T_{max}^{MSD} - T_H^{WA}\right)}{T_{max}^{MSD}}\right] * 100 \quad (19)$$

4. Results

For evaluation of performance parameters of proposed WA-RA architecture and scheduling approach, simulation setup is created in MATLAB. It is assumed that all ONU-APs and stations are same in terms of service time and frame arrival time for upstream communication. First in first out technique is used for selecting frames during their time slot and buffers are assumed to have enough capacity to avoid loss of frame. The order of polling may change for ONUs and stations, depending upon scheduling approach. Arrival frames at stations are assumed to be buffered according to Poisson process with aggregate arrival rate. Input parameters are; number of ONUs, number of stations per ONU, link rate between station and access point, link rate between ONU and OLT and maximum number of wavelengths. Results shown below are having the confidence coefficient of 0.97 with confidence interval of +/- 0.01 s for 200 trails. Following assumptions are made for the proposed approach and description of parameters is mention in Table 1:

(1) Load at stations are generated randomly and number of stations per ONU remain fixed for the complete cycle duration.
(2) Computation time for analytical and logical permutation at ONUs and OLT is not considered while evaluating delay as its value is very small.
(3) Data rate among all the wavelengths are distributed uniformly.

Cycle time is a primitive parameter for the evaluation of other parameters like delay, utilization and availability. In Table 2 comparative analysis of proposed WA-RA is performed with SSD-TDMA, SSD-RA, MSD-TDMA and MSD-RA for cycle time. It is observed that, with increase in average load, cycle time of all the approaches are increasing, because to accommodate larger load, cycle duration required will also be large. Although cycle time of WA-RA is found out be the smallest among all other mechanism, which is due to effective scheduling approach and efficient hybrid-MA architecture.

Table3 indicates variation in cycle time of high loaded and low loaded group of ONUs for WA-RA, which are categorized based on the $Th_{p=1}$. It
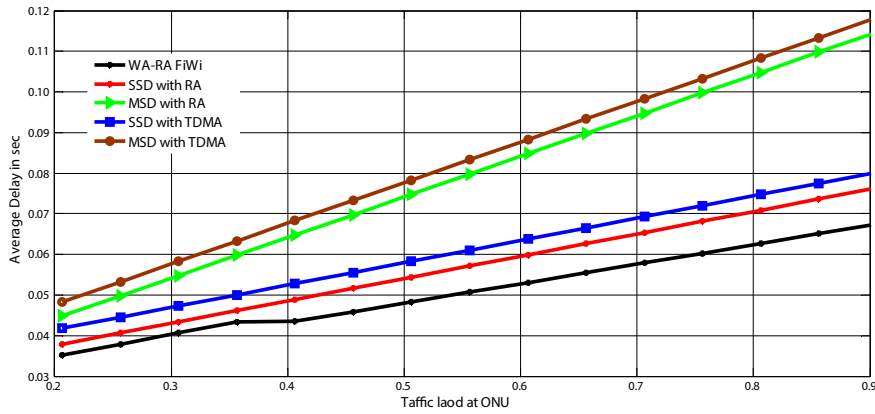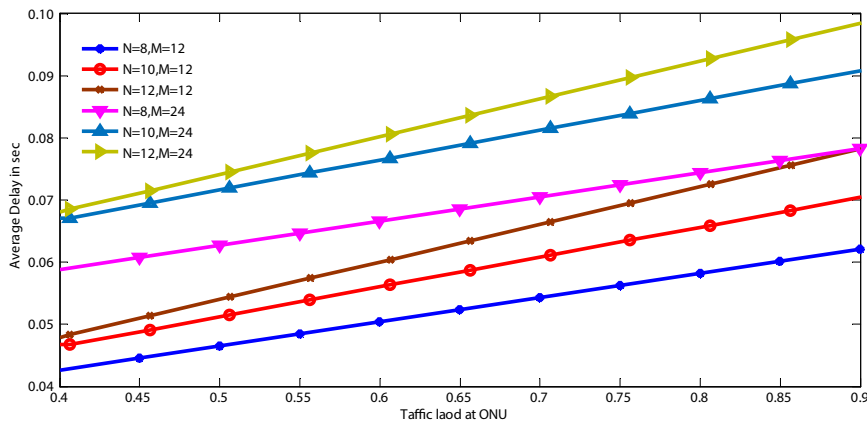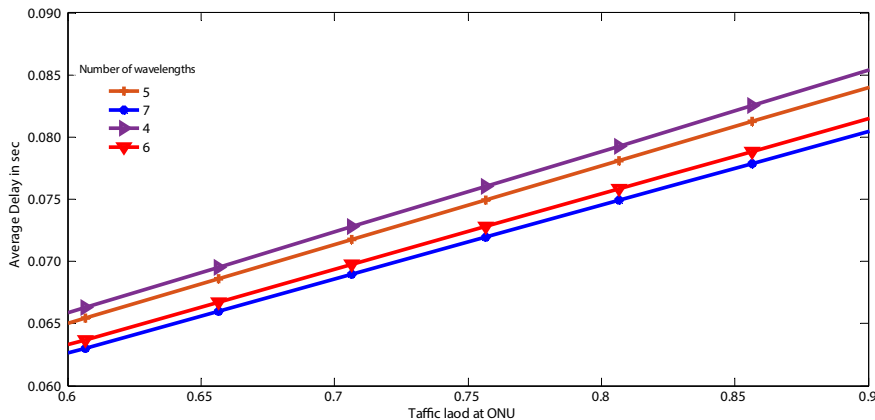
Fig. 4. Comparison of delay of different scheduling mechanisms with WA-RA FiWi.

(a)

(b)

Fig. 5. (a) Delay of WA-RA for different number of ONUs and number of station per ONU. (b) Delay of WA-RA for different number of wavelengths.

also shows distribution of available wavelengths and ONUs among the two groups. Proposed scheduling divides the ONUs in two base categories i.e. ONUs above $Th_{p=1}$ and ONUs below $Th_{p=1}$. Variation in average cycle time for both categories of ONUs is analyzed in Table 3. It is observed that for same number of ONUs (10), total average cycle time $(AvgT_L + AvgT_H)$ increase with increase in value of $Th_{p=1}$. As with increase in $Th_{p=1}$, larger number of ONUs are prone to be assigned in conventional TDMA slot under assigned wavelengths which will increase the cycle time. But for very high value of $Th_{p=1}$, cycle time is not increasing that rapidly because; larger numbers of wavelengths are

available for allocating conventional TDMA.

Fig. 4 illustrates the comparison of end-to-end delay performance of WA-RA with other mechanism (SSD and MSD for TDMA and RA at frontend) for variation in normalized traffic load. It is found that, delay performance of WA-RA is better than other mechanisms. In WA-RA data transfer at multiple wavelengths reduces the delay and proposed scheduling allocates larger number of wavelengths and radio frequencies to relatively heavily loaded ONUs and stations respectively hence WA-RA exhibits better delay performance.

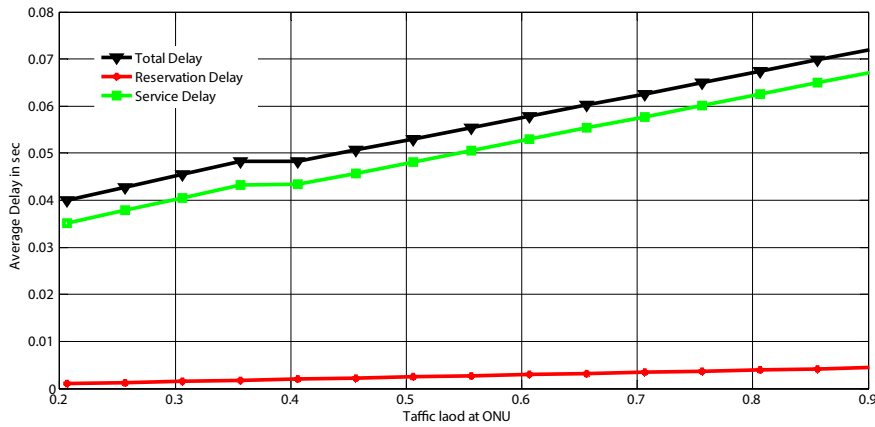In Fig. 5(a) variation in delay is observed against load variation for

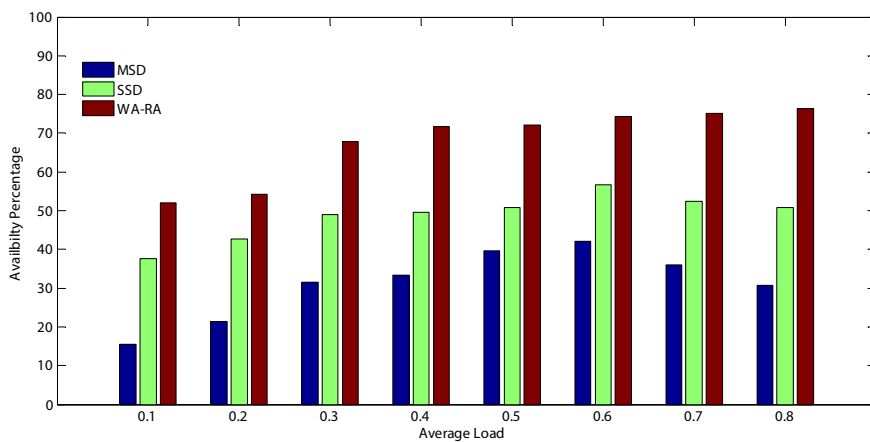**Fig. 6.** Service delay and Reservation delay for WA-RA FiWi.

Fig. 7. Comparison of WA-RA wavelength availability with MSD and SSD.
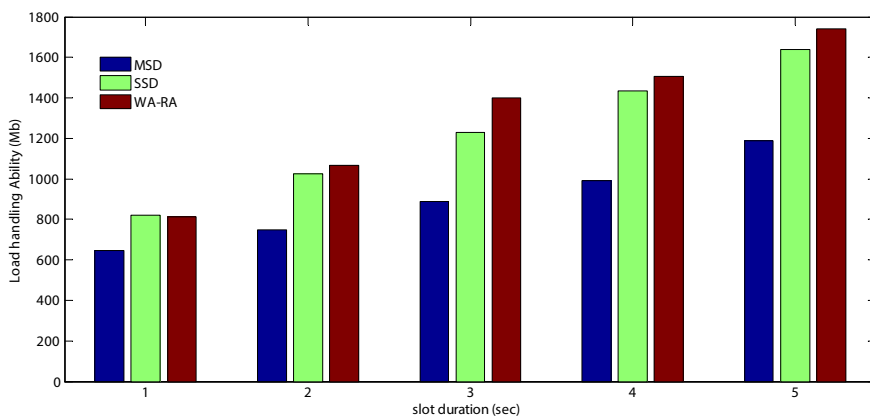

Fig. 8. Comparison of WA-RA load handling capacity with MSD and SSD.

different number of ONUs and stations. It illustrates that, end-to-end delay in WA-RA increases with increases in number of ONUs and number of stations per ONU. As with increase in number of stations, cumulative load assigned to DBA increases which increases the end to end delay.

Fig. 5(b) shows the effect of explicitly increasing the number of wavelengths for fixed number of ONUs, stations and load. It is observed that when numbers of wavelengths are increased in WA-RA, end to end delay reduces. As with larger number of wavelengths for fixed load; more wavelengths are available for simultaneously data transfer which

effectively reduces the delay. But using very large number of wavelengths also affects the OLT response time and requires larger resources; however in WA-RA distribution of wavelengths allocation depends upon the cumulative load of ONUs and thresholds, which improves the delay performance.

In conventional FiWi, a lot of bits are consumed for overhead associated with actual traffic. But when WA-RA is considered in FiWi then effect of overhead bits get reduce due to parallel cycle time slots. Fig. 6 shows the total delay of the WA-RA, which is consisting of service delay and reserxvation delay. Service delay is mainly due to the actual traffic

load, which is considered as maximum cycle time in WA-RA while reservation delay is due to overhead bits required for establishing and executing communication. In WA-RA, it is found that major component of total delay is service delay where as reservation delay has least contribution as shown.

Wavelength availability and load handling capacity are also considered as important performance parameters for selection DBA and scheduling approach. In Fig. 7, availability percentage of different architectures implemented at backend is compared with WA-RA. It is observed that, in WA-RA at any load conditions, availability of resources at backend (number of wavelengths) is high in comparison with other hybrid-MA architecture. In WA-RA, proposed scheduling reduces the cycle time by reducing the difference between allocation times of individual ONUs groups. Consequently, larger number of wavelengths gets available in WA-RA. In Fig. 8, load handling capacity of different architecture is compared with WA-RA. The primitive parameters to evaluate load handling capacity are utilization and availability. It is observed that, load handling capacity in WA-RA is better in comparison with MSD and SSD. In WA-RA, proposed DBA schedules ONUs on different wavelength such that loads are almost equally distributed among all the wavelengths hence load handling are found out to be maximum for different value of cycle time.

5. Conclusion

This paper deals with problem of delay and resource utilization, which are incurred due to the implementation of multiple access techniques at the front and backend of FiWi access network. To handle the same, WA-RA along with its scheduling approach is proposed. Pervasive analytical and simulated analysis is carried out to investigate and compare the performance of WA-RA with different hybrid-MA based FiWi architectures. Results illustrate the improvement in the performance of WA-RA in terms of delay, bandwidth utilization and load handling capacity. Scheduling performed on WA-RA minimize the difference in cycle times of different group of ONUs (grouped with respect to value of thresholds) which ultimately improves the delay performance and resource utilization. Although WA-RA and its scheduling shows poor utilization of resources and increase complexity at low traffic conditions, which can be considered as the limitation and pitfall of proposed work. In future, the significance of WA-RA and its scheduling can also be evaluated on throughout, energy efficiency, survivability and restoring interval. Multi-thread algorithms can also be implemented on proposed architecture to improve delay performance.

Declarations

Author contribution statement

Vijendra Mishra: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Raksha Upadhyay, Uma Rathore Bhatt: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Abhay Kumar: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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