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An effective resource allocation medium access control protocol for radio-over-fiber access networks based on wavelength reuse

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ABSTRACT

Users' rapidly increasing demands for bandwidth and mobility in conjunction with the surge of delay-sensitive applications, creates the necessity for further research and development of new energy- and cost-effective technologies such as radio-over-fiber (RoF) and radio-and-fiber (R&F). The research community is dealing with medium access control (MAC) protocol design for RoF networks, so that it can support bandwidth-demanding multimedia services such as voice over IP, video on demand, video conferencing, etc. In this work, a novel MAC protocol for RoF access networks is proposed, which is based on a modification of the multipoint control protocol (MPCP). The network's decision centre receives detailed feedback from the mobile client queues via MPCP's GATE/REPORT mechanism so as to efficiently allocate the bandwidth and the wavelength resources in a dynamic manner. The novelty of this protocol is that since wavelength reuse is achieved a single wavelength can be used by more than one remote antenna unit (RAU). The proposed MAC protocol also adapts its operation according to the clients' actual traffic demands and manages to exploit the huge capacity that the optical medium provides. Furthermore, a best-fit algorithm is applied in order to achieve further optimization. Simulation results reveal the superior performance and the better scalability of the proposed protocol compared with similar proposals reported in the literature.

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1. Introduction

Lately, there has been a sharp increase in the number of Internet users [1]. This, in conjunction with the growing bandwidth demand owed to the increasing use of the new multimedia-based services, e.g. video on demand, voice over IP, etc., has led to the design and use of new and more efficient access networks. The continuous growth in the use of wireless devices like PDAs, mobile phones, and laptops combined with the growth in the use of the delay-sensitive applications [1] leads to the extended use of wireless telecommunications, resulting in demand for high wireless capacities with improved latency and throughput characteristics. Therefore, the design of new Medium Access Control protocols for networks such as hybrid wireless-optical access networks, are of significant interest to the research community. The use of such networks is intended to combine the large amount of bandwidth (in the order of Gbps) that an optical network can provide and the ubiquity and mobility of a wireless access network, in order to serve a large number of mobile users who require large amounts of bandwidth [2].

Therefore, in the present research we intend to create a MAC protocol for hybrid wireless-optical networks, in order to achieve a cost and energy-effective solution for transmitting efficiently, large amount of delay-sensitive data. This is achieved through both the use of a proper architecture for hybrid wireless-optical networks and an efficient MAC protocol. Two are the prevalent approaches in the literature: radio-over-fiber (RoF) and radio-and-fiber (R&F) [3]. In RoF networks, RF signals propagate over a fiber link from a Central Office (CO) to remote antenna units (RAUs) and then transmitted to clients through the air. RoF networks are considered as centralized, because of the procedures of data analysis and decision-making taking place in the CO. Thus the CO is considered as the network's center of intelligence while RAUs are only responsible for signal conversion. In R&F, an optical and a wireless network are combined to form a single integrated network. In those kinds of networks two different MAC protocols are used, one for accessing the optical medium and one for accessing the wireless medium. The optical line terminal (OLT) is responsible for the traffic arbitration in the optical domain and Optical network units-base stations (ONU-BS or antennas) are responsible for traffic arbitration in the wireless domain. Thus, R&F requires the use of fully functioning

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intelligent (they arbitrate traffic) along with more complex ONU-BS on the contrary to the RoF RAUs, which have simpler functionality.

From the above derives that the RoF network's components are superior in terms of cost and energy consumption compare to the R&F counterparts. This is due to that the complexity in RoF is located in the CO and therefore RAUs have simpler functionality and fewer components compared with ONU-BS. This results in lower implementation and operational costs. Moreover, the most vulnerable network elements are antennas, which are exposed to different kinds of dangers such as extreme weather conditions. Therefore, lower maintenance cost also characterizes RoF in comparison with R&F technology. Apart from the comparison of low component, fabrication and implementation cost the hybrid networks can also be used to support a wide variety of radio signals. RoF networks are more attractive in this field contrary to R&F networks, since they can provide more transparency against signal modulation techniques and are able to support various digital formats and wireless standards in a more cost-effective manner [4]. Thus, RoF technologies are considered both as a highly effective solution for bridging the ultra-fast optical buses with the increasingly utilized wireless connectivity systems [5] and as a cost effective paradigm for extended range passive optical-wireless networks.

So, in this research we conclude to deal with a RoF network which consists of a Wavelength Division Multiplexing Ethernet passive optical network (WDM E-PON) [11] and a high bit rate 60 GHz wireless network [10]. The WDM E-PON network is used because it is already known as the dominant solution for 'last mile' access [6–9] and the 60 GHz frequency range is used because it has been identified as a region for high-speed wireless data transfer [10,11]. More specific, radios operating in the license-free 60 GHz band have unique characteristics that make them significantly different than radios operating in the traditional 2.4 and 5 GHz license free bands. These qualities give 60 GHz millimeter wave band radios operational advantages not found in other wireless systems. The 60 GHz millimeter wave radio technology presents the optimal opportunity to achieve orders of magnitude higher link budgets than IEEE 802.11n and Ultra Wideband (UWB) systems, which translates into reliable and affordable gigabit-plus wireless connections. Specifically, the advantages listed below [11,12]

- Spectral availability to achieve gigabit-plus data rates
- High allowable transmit power for solid signal strength and range
- Worldwide availability and acceptance
- Narrow beam width and oxygen absorption for interference immunity and highly secure operation
- Excellent Return On Investment/ROI
- Lower fabrication and component costs due to economies of scale and widespread adoption.
- High reliability and integration level
- Readily amenable to mass production
- High efficiency which implies low-loss feed

More analytically, the WDM E-PON consists of a central office (CO) and multiple 60 GHz remote antenna units (RAUs) connected to the CO via fiber buses. The wireless network consists of the RAUs and multiple wireless users.

For the aforementioned RoF network, we design a new and effective MAC protocol to address the listed main issues:

- fiber propagation delay. This issue is mainly derived from the absence of a client recognition and contention procedure for hybrid networks. So there are two main reasons that affect the network's performance a) the contention and recognition procedure, in which a lot of packets are required to be exchanged, and b) the centralized nature of the network, in which the packets used in the above procedures have to propagate both through the optical and the wireless medium in order to be collected from the CO. So the use of the existing recognition and contention procedures have as a result the increase of the mean delay because they are not designed for hybrid networks, where the delay mainly derives from the fiber propagation delay, which is much bigger than the air propagation delay. Thus, we created a new procedure to address these issues as it is described in the following paragraphs and in Section 4.
- the unutilized optical bandwidth which is derived from the huge bandwidth difference between the optical and the wireless media. This is the main issue we came confronted with because the unutilized optical bandwidth decreases the network's throughput and increases the time that a packet takes to be served (mean delay time). More details are presented in the following paragraphs and in Section 4.

To address fiber delay issue analyzed in [2] as well as to optimally arbitrate the 60 GHz spectrum, our protocol employs a polling mechanism based on MPCP, analyzed in Section 4, that has been shown better performance than the carrier sense multiple access/collision avoidance (CSMA/CA) and time division multiple access (TDMA) schemes when operating in the millimeter-wave domain [13]. In addition, our protocol defines two distinct contention periods to optimally regulate the access to both optical and wireless media addressing the network from the RAU and end-user perspective, respectively.

To address the unutilized optical bandwidth issue, our protocol can serve multiple RAUs simultaneously in the same wavelength. This is achieved via modified multipoint control protocol (MPCP) [14], the store-and-forward technique and a best-fit algorithm. With MPCP, the CO receives detailed feedback for all clients' queues from the GATE/REPORT [14] mechanism and arbitrates traffic by allocating dynamically both the bandwidth and the limited wavelength resources depending on the exact demands of the wireless clients. So MPCP specifies point-to-multi-point communication between CO and RAUs' clients.

- Provide client timing synchronization
- Bandwidth/Timeslot assignments to clients

The store-and-forward technique is applied to the RAUs and takes advantage of the network's bottleneck by enabling the simultaneous use of wavelengths. More specifically, by inserting a small buffer in the RAUs and using the aforementioned store-and-forward technique, we artificially create an idle time space named, empty time window, in the wavelength in order to serve data packages from a client under a different RAU. The best-fit algorithm is used in order to fill better the empty time window in the optical media. In that way we can manage optimally the empty time windows in the wavelength which help us to exploit the unutilized optical bandwidth by "ejecting" data packets in these empty windows. Contrary the existing protocols consuming the same transmission time both on the optical and the wireless medium, waiting for the last bit of the packet to be transmitted in the wireless domain in order to propagate it in the optical domain. This results to unutilized optical bandwidth. Thus the existing protocols are limited to the bandwidth of the wireless medium. Simulation results reveal the superior performance of the proposed protocol compared with similar schemes.

The remainder of this work is organized as follows. Section 2 reviews related work, Section 3 describes the proposed network architecture, Section 4 presents the proposed protocol and Section 5 discusses the simulation results. Section 6 concludes the paper.

2. Related work and motivation

2.1. Related work

A lot of research been performed in the field of MAC protocols and hybrid wireless-optical networks. In the field of R&F networks, one work is the WOBAN [16]. In WOBAN two different MAC protocols are used for managing network resources. The optical domain is a WDM-EPON, which uses the IPACT algorithm [15] for arbitrating traffic between the ONU-BS and the OLT. The wireless domain uses the standardized IEEE 802.11 g, which applies the carrier-sense multiple-access with collision avoidance (CSMA/CA) MAC protocol. Another MAC protocol is SuperMAN [2], which is essentially a hybrid network employing IEEE 802.16 WiMAX in the wireless part and IPACT [15] in the optical part of the network, and operates according to the EPON standard. Other similar approaches show the integration of EPON/GPON with Worldwide Interoperability for Microwave Access (WiMAX)/ Long-Term Evolution (4 G LTE)/ Data Over Cable Service Interface Specification (DOCSIS) [17–21] or mesh networks [22,23]. R&F approaches have the potential to provide high data transmission rates with minimal time delay through arbitrating traffic with different protocols in wireless and optical media. However, in comparison with RoF, they still require the use of intelligence in antennas, which increases the cost of implementation.

So far the majority of research focuses on exploiting the fiber infrastructure used only as a passive distribution network for long-distance wireless services. To this end a lot of work has been done in the field of physical layer technologies and architectures for high-capacity RoF networks [24–29]. However, there are few researches that have attempted to integrate the optical and wireless part of a hybrid network functionally in order to achieve allocation of dynamic resources and the simultaneous use of wavelengths.

To the best of our knowledge there are only a few proposals in the field of MAC protocols for RoF networks. MAC protocols in RoF implementations have been considered, so far, only within the framework of adapted existing wireless technologies like 802.11 with an RTS/CTS exchange mechanism with RoF architectures [30–32]. Other works propose protocols that dedicate one whole wavelength only to one RAU [33].

Because of the huge amount of bandwidth provided by an optical network, it is considered necessary to employ wireless frequencies capable of delivering very high data rates. Thus the 60Ghz band was introduced to the industry for high bit rate wireless transfer. A number of relevant proposals have accordingly been standardized, such as 802.11ad [34], 802.15.3c [35–37], WirelessHD [38] and WiGig [39].

A recent proposal in the field of RoF networks is the medium-transparent (MT) MAC protocol [40], which arbitrates traffic through both optical and wireless media, being capable of serving multiple RAUs and multiple wireless users by dynamically assigning/reassigning one wavelength to each RAU. More specifically, MT uses an EPON and a 60 GHz wireless network and promises high throughput and low latency. It assigns dynamically and exactly one wavelength per RAUs through a control channel. The traffic arbitration between wireless clients served by the same RAU is achieved via a SuperFrame. Superframes are frames of a fixed size which consist of contention frames and DATA frames. This protocol is characterized by the following: (1) contention frames are fixed in duration and used for arbitrating medium access in the wireless media via a fixed number of time slots; (2) DATA frames are of fixed sized also; (3) DATA frames are assigned only to one user; (4) wavelengths are assigned only to one RAU.

The above four characteristics create problems when the protocol has to work in realistic wireless environments, where changes in the number of users per RAU are not known. This lack of adaptability leads to the possibility of unutilized optical bandwidth and users who cannot be served. More specifically, too many users per RAU leads the contention frames to monopolize the superframe, which results in fewer DATA frames being sent. Additionally, the restricted use of only one wavelength per RAU in conjunction with the fixed duration of superframes in both optical and wireless media does not allow us to take advantage of the huge bandwidth difference between them. So a single wavelength can't be used by more than one remote antenna unit. The MT protocol, as well as all the aforementioned protocols in this section, has certain problems: (1) it lacks the capability of employing feedback in order to adapt to the current traffic demands of the wireless users so that contention frames do not monopolize the superframe, (2) it cannot reuse the optical network's resources among RAUs in order to utilize in the best way the huge bandwidth that an optical medium can provide.

A spin-off of the MT protocol is the CW-MT-protocol [41], which focuses on client fairness and is a user-centric protocol. Although this protocol results in a fair bandwidth allocation among RAUs and their clients, it has no big impact in terms of improving networks' performance and the aforementioned disadvantages remain.

2.2. Motivation for the proposed protocol

The proposed protocol is named efficient resource allocation (ERA) protocol and is derived from our previous research on Simple Polling Adaptive (SPA) Protocol [42]. SPA also arbitrates traffic through MPCP and uses the same contention mechanism with ERA. Although SPA solves a lot of the aforementioned MT's disadvantages, it cannot use simultaneously a wavelength from 2 or more different RAUs. This is the main difference between SPA and ERA, as SPA is unnecessarily utilize optical bandwidth because for each packet, it consumes the same transmission time both on the optical and the wireless medium, despite the fact that these media exhibit a huge bandwidth difference (1 Gbps in optical domain, 155 Mbps in wireless domain). This mainly derives from the fact that in SPA every client send the whole/or a part of queue as frame in contrast with the ERA where the store-and-forward technique is applied and has as a consequence each client to send the whole/or a part of queue as a sequence of packets. All of the aforementioned problems led us to design a new protocol to combat them and thus increase performance by utilizing smart and efficient use of network resources. The proposed protocol has the following characteristics, which are solving the most of the aforementioned issues of MT and SPA.

1. It gets detailed feedback about clients' requirements and gives to clients transmission grants according to their actual requirements. Our detailed feedback defines the exact number and size of packets of client queues. This helps us to transmit the packages more efficiently by using a best-fit algorithm and the store-and-forward technique in RAUs.
2. It allows the CO to dedicate wavelengths dynamically to the RAUs and therefore provide resources to the clients that the RAU serves and allows the simultaneous use of wavelengths by more than one RAU. For each client, after collecting all REPORT messages with client demands for medium access, the CO informs all clients via a GATE message how to access both the wireless and optical media. This procedure is a function of MPCP which is described in more detail at Section 4.
3. It addresses the problem of too many users per RAU leading to contention frames monopolizing the superframe by increasing the slots used for recognition and thus can give transmission grants to all active users. This is achieved through a dynamic contention mechanism, which after a recognition failure

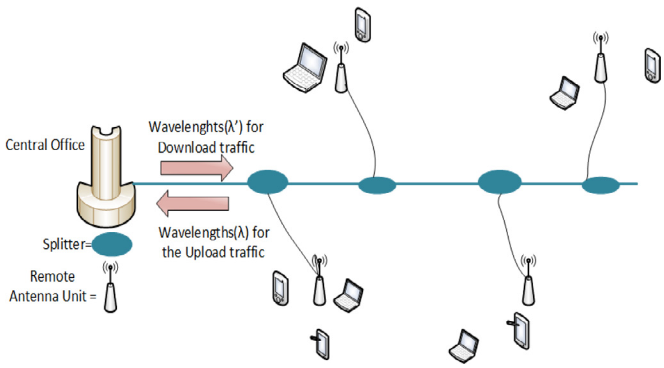

Fig. 1. A 60 GHz RoF network consisting of the optical domain and multiple antennas connected to the CO through a fiber bus.

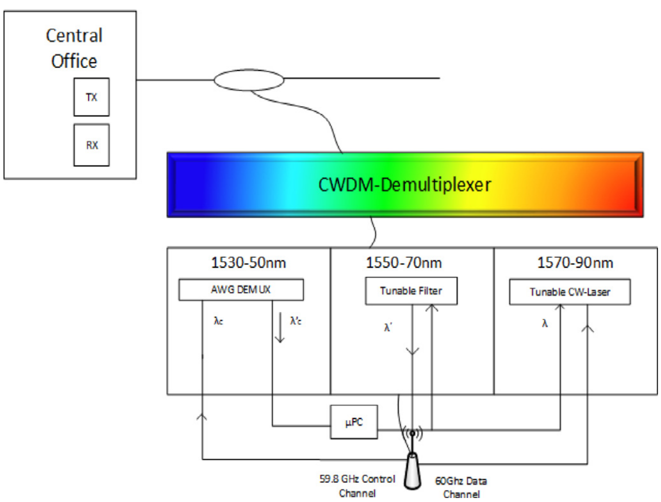

Fig. 2. RAU components.

uses an exponential back off mechanism and increases exponentially the number of the recognition slots. Recognition slots are time slots fixed in duration which are created by the CO. This slots are used from the clients in order to compete for gaining access. Additionally, the GATE, REPORT and ACK messages are used to arbitrate the recognition procedure. This procedure is described in more detail at Section 4.

4. It exploits the unutilized optical bandwidth in a dynamic manner by using one wavelength from more than one RAU. Critical part of this mechanism is the creation of the empty time windows in the optical domain, which are the consequence of both sending one packet at a time and having different transmission times in optical and wireless media for the same packet size. More details of how we exploit the unutilized optical bandwidth are presented in Section 4-Wavelength reuse

3. Network architecture

The RoF network used is a combination of an optical and a wireless network as depicted in Fig. 1. The optical domain is an EPON in bus topology which is composed of the central office (CO) and the remote antenna units (RAUs) as shown in Fig. 2. The 60 GHz wireless domain is composed of the remote antenna units and the clients. The RAU modules are responsible for two procedures, the optical-to-wireless signal conversion and handling packets via the store-and-forward technique. Therefore, similarly to the MT-MAC, all RAUs employ a coarse wavelength division multiplexing demultiplexer, in order to separate the signal into three

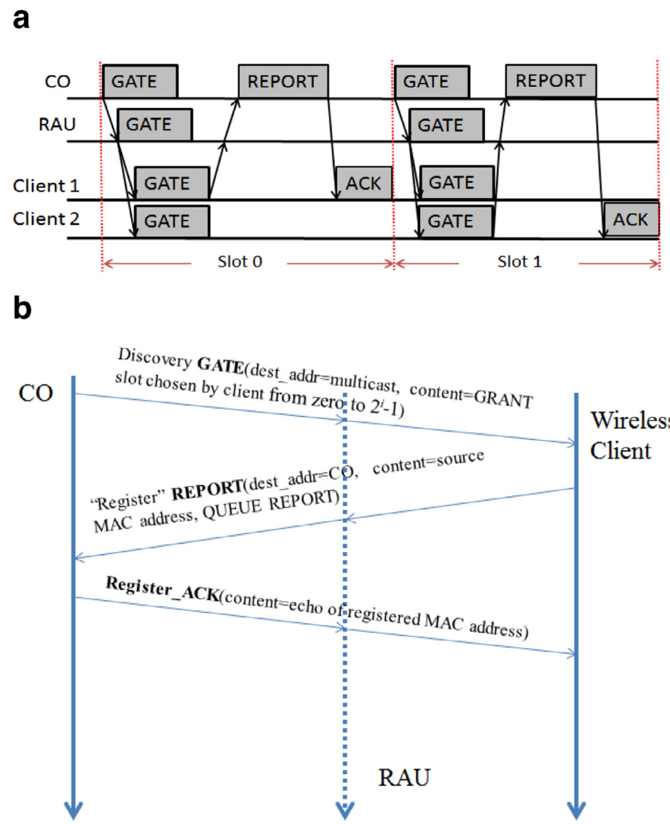

Fig. 3. (a) Recognizing wireless clients through the exponential back-off recognizing mechanism and traffic request collection procedure. (b) Wireless client's recognition and the structure of messages used for recognition.

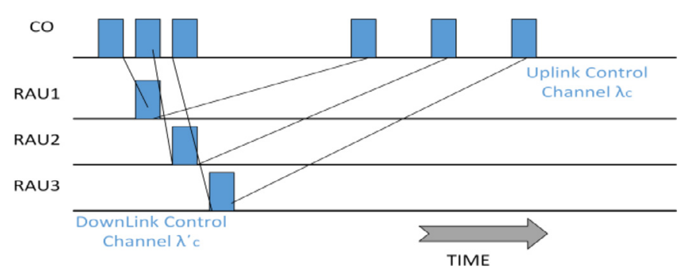

Fig. 4. Wavelength assignment to RAUs.

spectral areas: (1) 1530-1550 nm, (2) 1550-1570 nm, and (3) 1570-1590 nm (Fig. 2). The first spectral area is used for control signals, and the second and third areas are used for carrying the downlink/uplink data traffic. The downlink data channels are generated at the CO, whereas the uplink channels are generated by a coarse wave laser at the RAU. Assuming that there are N wavelengths, N wavelength pairs are formed for the DL/UL respectively as follows, $\{\lambda_1, \lambda'_1\}\ldots\{\lambda_n, \lambda'_n\}$, the λ' wavelengths are responsible for the download traffic from CO to RAUs and subsequently to clients at 60 GHz RF signals and the λ wavelengths are for the upload traffic from the clients to the RAUs and respectively to the CO (Figs. 1, 2).

There is also a control wavelength pair $\{\lambda_c, \lambda'_c\}$ which is used for controlling the wavelength allocation themes. In more detail, the downlink wavelength λ'_c is used (1) for recognizing clients, (2) for competing in order clients to gain access in the transmission period (Figs. 3a, 3b, 4), (3) for wavelength tuning of the RAUs' downlink filter in order to receive appropriate information about the upcoming transmission period, and finally (4) for tuning the RAUs' laser to the allocated wavelength. At the same time λ_c

Table 1
GATE message structure 64bytes.

Destination address	Source address	Type 88-08	Opcode 03	Timestamp	Report number of packets	report size of a packet(19 individual packets)	Zero padding	CRC
6 bytes	6 bytes	2 bytes	2 bytes	4 bytes	1 byte	19*2 bytes		4bytes

carries information to the CO about clients' specific demands for the next broadcast cycle.

When the RAU receives a control signal, it separates λ_c, *and* λ'_c via an arrayed waveguide (AWG). The λ'_c is converted into an electrical signal via a photodiode, and then it is transmitted to the wireless domain at 59,8 GHz RF signals in order to serve ERA protocol operations such as competing and recognizing clients. The controls messages are transmitted through a subcarrier signal at 59,8 GHz in order to avoid collision with the data signals which are transmitted at 60 GHz. So clients could start transmitting DATA while others clients in the same RAU are waiting for a GATE message receptions or are reporting their demands via a REPORT message. Furthermore the λ'_c goes through a low-rate microcontroller (μPC), which in turn tunes the DL filter and the uplink laser. The DL wavelengths pass through an optical tunable filter controlled by the μPC, which selects the appropriate wavelength (λ') for each RAU, while the UL data wavelengths (λ) are generated through a tunable laser controlled by the μPC. In order for RAUs to be compatible with handling packets via store-and-forward each RAU employs a small buffer with maximum size equal to the packet's maximum size and a timer to determine when the whole packet is received in order to start forwarding it.

The CO is responsible for taking decisions on wavelength assignment between RAUs and for the medium access arbitration among the clients. Therefore the resource allocation is negotiated directly between the wireless users and the CO, which means that the intelligence centre of the network is located in the CO. As stated previously, the CO is responsible for the wavelength assignment and assigns the earliest available channel to RAUs in a round robin fashion. It can also assign a wavelength pair to one or multiple RAUs for simultaneous use in order to achieve wavelength reuse and dynamic allocation. For that purpose the CO employs a tunable transmitter and a tunable receiver as depicted in Fig. 2.

4. The proposed protocol

The proposed ERA protocol consists of two time periods the first period is used for recognizing both RAUs and clients and the second period is both for transmitting data and assigning wavelengths. The ERA protocol it is based on the multipoint control protocol (MPCP) [15] which is modified to our needs. This means that it uses two types of messages to facilitate arbitration traffic, the REPORT message and the GATE message. The REPORT message is used by a client to report bandwidth requirements (typically in the form of queue occupancies) to the CO and the GATE message is used by the CO to issue transmission grants to the clients. Specifically, in this work the REPORT message gives information about the exact number and size of packets in client queues and the GATE message grants multiple transmissions to each client. The number of transmissions is proportional to the number of packets and the duration is proportional to the size of each packet. The structure and size of a REPORT and GATE message [15] are depicted in Tables 1 and 2. Depending on the maximum size of 64 bytes that the REPORT and GATE message have, we can only report up to 19 packets on client queues and grant up is limited to 6 transmission windows to each client. We choose to report and grant each individual packet and not the whole queue in order to achieve the wavelength reuse. The 'How to' is explained later in this Section.

The first period is called the recognition period and it is used for recognizing both RAUs and clients. At the start of every period, as depicted in Fig. 4, the CO transmits a small burst of packets in the control channel to RAUs in order to be recognized and assigned a specific wavelength. **.** If the number of RAUs exceeds the number of available wavelengths the CO assigns the earliest available wavelength to the next RAU in a round robin fashion, in order to recognize all clients of all RAUs. Then, for each RAU, the CO broadcasts a "discovery" GATE message to all clients of the RAU, as shown in Fig. 3a and b. This forces the clients to compete in order to gain access to the wireless media. Each client after receiving the initial GATE message selects a random number from zero to 2^i-1, where i is the number of recognition attempts by a client. The starting slot number is selected randomly according to a uniform distribution from zero to 2^{i+1}-1 (with minimum $i = 3$). This random number indicates how many time slots a client has to wait in order to send its REPORT. If clients choose different slots then there are no collisions and as a result a register ACK packet is returned to inform clients that they have been identified. The clients that receive the register ACK will not participate in the next recognition cycle. However, if two or more clients choose the same number they will start transmitting a REPORT message to the same slot, resulting in collision. The collision will render the message unreadable and the CO will not transmit any ACK. In this case, the process is repeated with the contention slots increasing exponentially. The recognition period ends when all the active clients of all RAUs are recognized. Upon receiving the REPORT messages from the clients, the CO is informed of both their existence (and so to which RAU belong) and their bandwidth requirements, which are piggybacked by the clients on their REPORT messages. The CO identifies to which RAU each client belong via the RTT time. The RTT time is computed with the help of the timestamp in the REPORT messages.

After the end of the first period, the period of transmitting data follows, as depicted in Fig. 5. Having full knowledge about clients' bandwidth requirements from the previous period, the CO calculates a collisionless transmission schedule for clients based on IPACT. Thus we are confronted with the difficulty that IPACT has in scheduling the traffic between end-users and the CO. More specifically, IPACT uses the exact knowledge of distances (round-trip time, RTT) between the ONUs and the CO to interleave packets, which is not an issue for wired networks. However, when it is applied in RoF networks, where the end-users are mobile and the distances are not fixed, it seems to be an issue. The CO addresses this issue by adding a waiting time (Δt) to the RTT equal to the maximum air propagation delay in order to recognize correctly who has sent the packet and when the packet is completely received. This is depicted in Fig. 5.The wavelength assignment to RAUs is done in the following way. At the start of every broadcast cycle the CO transmits a small burst of packets to every RAU in order to tune into specific wavelength pairs. The assignment is done in the exact same way as in the recognition period (Fig. 4). The CO assigns the earliest available wavelength to the next RAU in a round robin fashion. However, contrary to the approach of MT-MAC which dedicates one wavelength per RAU, a reuse of wavelengths is performed by giving access to the same wavelength to more than one RAU at the same time. This is achieved by exploiting the fact that the data rate at the optical part of the network significantly exceeds that of the wireless part. So, our prtotocol exploits

Table 2
REPORT message structure 64bytes.

Destination address	Source address	Type 88-08	Opcode 02	Timestamp	Number of grants	Grant start time	Grant length	(Start +length)*Num of grants(Max grants = 6)	CRC
6 bytes	6 bytes	2 bytes	2 bytes	4 bytes	1 bytes	4 bytes	2 bytes	(4+2)*n bytes	4 bytes

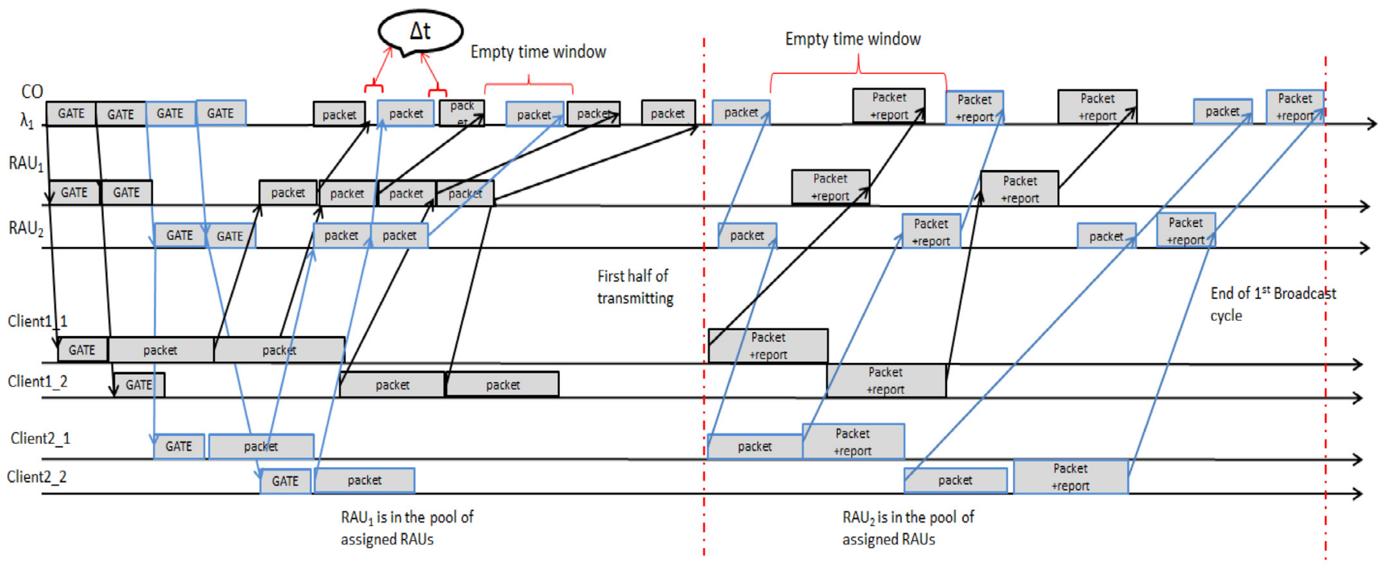

Fig. 5. The broadcast DATA period. This figure shows how the MPCP functions, specifically how a GATE message grants a transmission and the REPORT messages are collected in order to conduct a collision-free broadcast schedule. Additionally it shows the simultaneous use of wavelengths as aforementioned.

the unutilized optical bandwidth in a dynamic manner by using one wavelength from more than one RAU. Critical part of this is the creation of the empty time windows in the optical domain, which are the consequence of both sending one packet at a time and having different transmission times in optical and wireless media for the same packet size. More details of how we exploit the unutilized optical bandwidth are presented later in this Section.

Afterwards the wavelength assignment, the CO transmits GATE messages individually to clients of every RAU to inform them when each transmission starts and ends. After receiving the GATE message each client starts transmitting data depending on the broadcast schedule announced. Each GATE message can give up to four transmission windows. The following paragraphs provide a detailed analysis of:

- how the wavelength reuse is achieved
- how the collisionless broadcast schedule is conducted.

1. **Wavelength assignment:** The rule is followed is: assign the earliest available wavelength to the next RAU in a round robin fashion. The clients of RAUs that are first assigned a wavelength send their packets through the assigned wavelength based on the GATE messages. As Fig. 5 and Fig. 7 depict, $RAU_{1,}$ $Client_{1\_1}$ and $Client_{1\_2}$ are transmitting in the assigned wavelength λ_1. The redundant RAUs and their clients wait for wavelength λ_1 reuse, using empty time windows in λ_1. In the figure those components are $RAU_{2,}$ $Client_{2\_1}$ and $Client_{2\_2}$.
2. **Wavelength reuse:** in order to be able to succeed in the reuse of wavelengths we must take the following rules into consideration.
   (1) First, the numbers of RAUs must exceed the number of wavelengths.
   (2) Second, the aforementioned redundant RAUs, to which no wavelength has been assigned, and their clients have not been given the priority to transmit packets; there must be at least one client that has excess packets in its queue.
   (3) Third, RAUs and clients must be able to send one packet at a time in order to create artificially empty time windows, which help us to exploit the unused optical bandwidth.
   (4) Fourth, to exploit the excess bandwidth in the optical domain it is essential for a successive transmission of packets, whereby first a smaller packet must be sent and then a bigger or an equal one, in order for an idle time to be created in the optical domain (empty time window). The size (in bytes) of the packets in the queue of each client is already known to the CO from the REPORT message. The packets are transmitted sequential from the queue (FIFO). So the CO, having knowledge of the size of the packets and the sequence that they will be transmitted, knows that an empty time window is created and gives grant for transmission on another client lying under a different RAU from the RAU that is now transmitting packets.

   If the above rules are valid there is a possibility of reusing wavelengths. The reuse is achieved through multiple transmissions in the empty time windows from clients that belong to redundant RAUs.
3. **The creation of empty time window and their use for transmission of packets:** empty time windows are essential in order to succeed in wavelength reuse. The creation of the empty time windows in the optical domain is achieved through both (1) implementing the store-and-forward technique in RAUs and (2) setting a timer in each RAU. Both aforementioned (1) and (2) are useful to us, as RAUs are able to send packets one at a time to the optical domain (store-and-forward). More specifically, using the store-and-forward technique we first store the wireless transmitted packet to the RAU buffer and the timer recognizes when a packet has been completely received by the RAU in order for the transmission in the optical domain to begin. The RAU using the timer realizes that a whole packet has been received when a 12-octet idle time has elapsed. The 12-octet

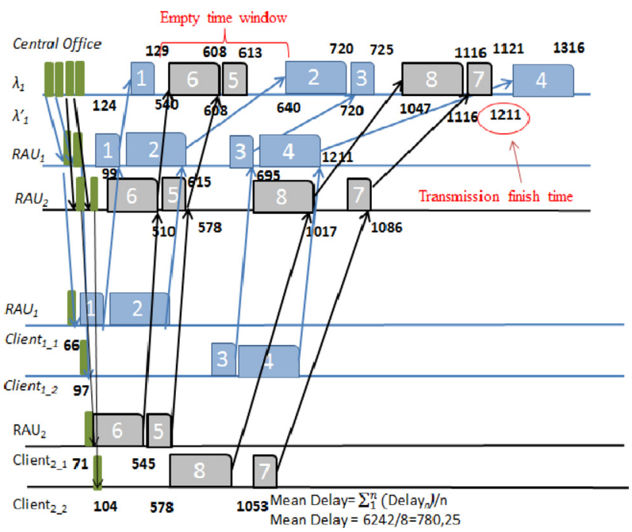

Fig. 6. ERA protocol's broadcast schedule. The numbers in the figure show us the time that a packet starts being received and when it is completely received from RAUs and afterwards from the CO.

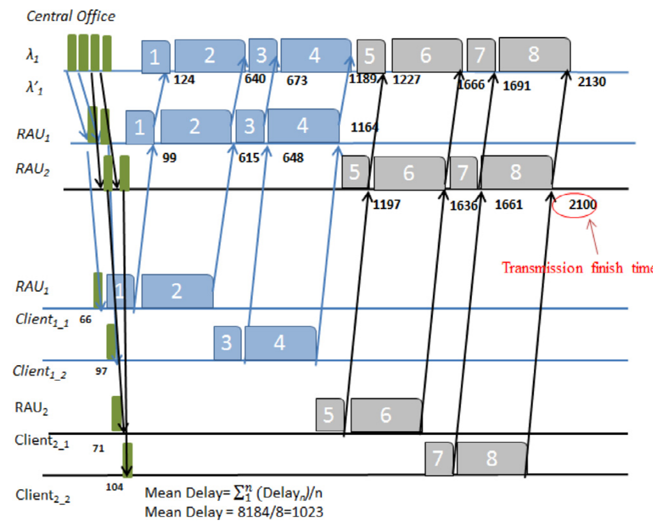

Fig. 7. MT-MAC protocol's broadcast schedule. The numbers in the figure show us the time that a packet is completely received from RAUs and subsequently from the CO.

Table 3
This table depicts the two characteristics of the packets that used in the two paradigms that follow. The arrival time and the packet size. The table also shows to which RAU each client belongs and subsequently to which client each packet belongs.

RAU	Client	Packet ID	Arrival Time in queue (10^{-7} sec)	Size in bytes
1	1	1	5	64
		2	13	1000
	2	3	9	64
		4	23	1000
2	1	5	3	64
		6	15	850
	2	7	13	64
		8	25	850

idle time indicates the end of a complete Ethernet frame, according to the Ethernet protocol [43]. In case that a smaller packet is sent first and then a bigger or even follows, it is easily to see that the time that the smaller packet spends on transmission in the optical domain is much less than the bigger spends in the wireless domain. This means the RAU has first to end the package transmission in the optical domain and then wait for the complete reception of the bigger packet from the wireless domain in order to proceed with its transmission to the optical domain. The time taken for the RAU to receive the bigger packet through the wireless domain is the specific time when nothing is sent to the optical domain, and thus empty time windows are created (see Figs. 5, 6). These empty time windows are used by the redundant RAUs, which can send packets into them. Furthermore, in order for these empty time windows to be filled, a best-fit algorithm is applied which fills them optimally. In that way the wavelength reuse is achieved. As Fig. 6 depicts, after packet1 (64 bytes) and then packet2 (1000 bytes) have been sent, an empty time window is created, which is used by RAU$_2$ for sending data simultaneously with RAU$_1$ in the same wavelength λ_1.

4. **Wavelength reassignment and the end of broadcast cycle:** afterwards, the redundant RAUs (RAU$_2$) are considered by the protocol as main RAUs and are assigned wavelengths by OLT, and the main RAUs (RAU$_1$) that previously had transmission priority now become redundant; the above procedure is repeated until each RAU had, at least once, the opportunity to use a wavelength that has been assigned to it by the CO and this assignment was not due to the wavelength reuse feature (we term such a RAU as a "main RAU"). In that way a broadcast cycle is completed. In fact, in every broadcast cycle each client of every RAU has the chance to transmit packets twice, one while its RAU is considered as main RAU and one while it is considered as redundant. When these two transmissions have been made, each client sends a report message including its new demands, so as the CO to conduct the next broadcast schedule. The aforementioned are depicted in Fig. 5, where the broadcast cycle ends after the reception of the last client REPORT message.
5. **Scanning for new clients:** After a certain number of transmission cycles, the CO broadcasts a GATE message in order to return to the recognition period to introduce new clients. In an environment that has a constant number of clients per RAU, the recognition period will not be repeated.

Every client has multiple transmission grants as derives from the structure of the GATE message and, in conjunction with the aforementioned functionality of the store-and-forward technique, empty time windows are created in the wavelengths. This helps us to send packets simultaneously in the same wavelength from two or more RAUs, resulting in the better utilization of the optical medium bandwidth. On the other hand, the CO in the MT protocol has no information about its clients' queue occupancies and this results in sending fixed-duration DATA frames to the wireless and optical medium, which leads to the underutilization of the optical medium. Thus, the proposed protocol can take advantage of both the traffic's bursty nature and the network's bottleneck.

For a better understanding of the advantages of the proposed protocol over MT, we depict two examples of broadcasting in Figs. 6 and 7. As Table 3 depicts the arrival times in clients' queues and the size of the packet. The arrival times are randomly selected, while the size of each packet is intentionally selected to be a smaller packet followed by a bigger one, in order to show the advantages of ERA, which allows to use of one wavelength by more than one RAU. The scenario analyzed here is the best case scenario. As we can see in Fig. 6, RAU1 and RAU2 are assigned with the same wavelength simultaneously and so client1_1 and client2_1 send simultaneously packets in the same wavelength with respect to GATE messages' transmission grants. Thus, although we send packets of the same size with the same arrival

Table 4
In this table is calculated the end to end delay of each packet in both MT and ERA protocol. The delay is measured in 10^{-7} sec.

Packet ID	Delay in MT(10^{-7} sec)	Delay in ERA(10^{-7} sec)
1	124-5 = 119	129-5 = 124
2	640-13 = 627	720-13 = 707
3	673-9 = 664	725-9 = 716
4	1189-23 = 1166	1316-23 = 1293
5	1227-3 = 1224	613-3 = 610
6	1666-15 = 1651	608-15 = 593
7	1691-13 = 1678	1121-13 = 1108
8	2130-25 = 2105	1116-25 = 1091

time, the mean delay of ERA is hugely improved in comparison with MT. More specifically, in Fig. 7 the packets in MT are broadcast sequentially and their broadcast duration is the same in both wireless and optical media. On the other hand, as depicted in Fig. 6, ERA has different durations for the packets in wireless and optical media. This gives us the opportunity to take advantage of the unutilized optical bandwidth by transmitting data in the empty time windows created as explained above. Fig. 6 also shows that RAU_2's clients send packets in empty time windows. The mean delay time is calculated from the difference between arrival time of packet and the time where the transmission is completed. Making the appropriate calculations from Tables 3 and 4 for MT protocol (Diff_packet1+…Diff_packet8)/8 mean delay is 1023×10^{-7} sec and the corresponding one for the ERA protocol in 780.25×10^{-7} sec. In this example the calculation of the duration of each packet transmission is done in the following way: $\frac{packet\ size\ in\ bytes \times 8}{Bandwidth(155 \times 10^6\ \frac{bytes}{sec}\ or\ 10^9\ \frac{bytes}{sec})} \times 10^7$.

Furthermore, the MT protocol, unlike the ERA protocol, has a fixed number of slots per RAU in order to recognize the clients. In conjunction with the fixed number of frames in superframes adaptability issues are created. This is significant when the protocol is applied in unstable wireless environments, where the number of users often changes. The problem is crucial for MT if the number of users exceeds the number of slots used in the contention frames and results in the use of a lot of contention frames for recognizing users other than those transmitting data with DATA frames. Even if all of the active clients are recognized in the duration of the superframe, because of the use of a lot of contention frames, there are only a few DATA frames. The number of DATA frames is often smaller than the number of users, resulting in active clients not being served in this superframe and consequently forced to wait for the next superframe in order to transmit data. This has a negative impact on the protocol's performance.

5. Simulation results

In this section, the performance of the ERA protocol is compared with that of MT and SPA via simulation in Java using NetBeans IDE. Table 5 provides a summary of the simulation parameters used in our simulations. Additionally, considering that the aforementioned protocols are used for connecting users in Small/Large Buildings or in medium ranged areas like a university campus, the length of the fiber bus has been set to 950 m, 3.65 km, 6.85 km.

In the first experiment the network considered consists of 10 RAUs, uses $w = 5$ wavelengths and allows each RAU five clients unless mentioned otherwise. The RAUs are connected via a fiber bus which is 950 m long. The minimum distance between the first RAU and the CO is 450 m. The distance between RAUs is 50 m. The traffic model uses Poisson distribution to compute the inter-gap time between the arrival of two packets and generates packets with a maximum size of 1512 bytes. The two protocols

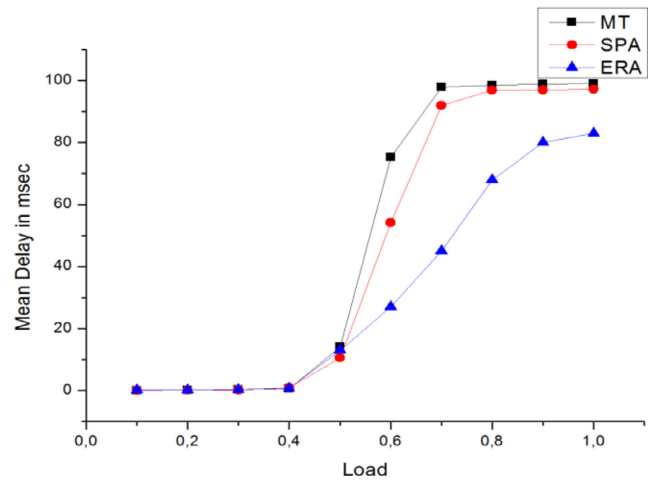

Fig. 8. Mean packet delay as a function of network load for 10 RAUs and 5 clients under each RAU, and $w = 5$ number of wavelengths.

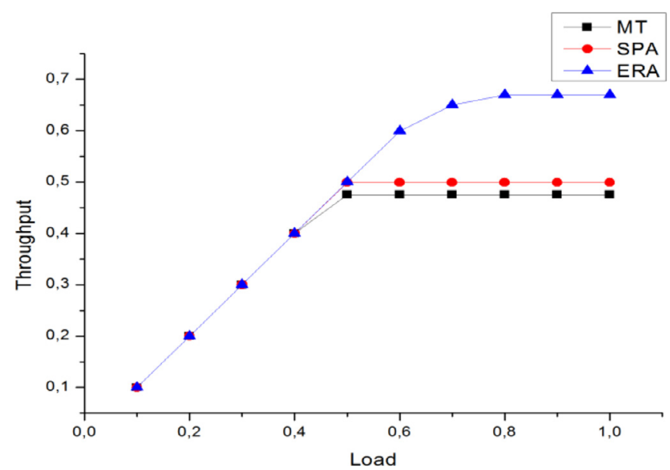

Fig. 9. Network throughput as a function of network load for 10 RAUs and 5 clients under each RAU and $w = 5$ number of wavelengths.

are compared for different values of normalized aggregated traffic load. The load values range from 10% to 100% with respect to the maximum theoretical capacity of the wireless network. The performance of the compared protocols is measured in terms of network throughput and mean packet delay. Fig. 8 shows the mean packet delay as a function of network load and Fig. 9 depicts the network throughput corresponding to different network loads. In those two figures, we can see the high performance of the three protocols for network loads ranging from 0.1 to 0.4. However, when the network load exceeds the value of 50% the performance of the MT and SPA protocols starts decreasing rapidly. ERA's performance starts decreasing when the load value exceeds 67%. This means that network saturation starts at load values over 67% and the saturation point in MT starts at 47.5% and in SPA at 49.9%. This is evident in Fig. 9.

The main conclusion that can be drawn from Figs. 8 and 9 is the huge performance improvement of the ERA protocol in comparison with the MT and SPA protocols. This is mainly because the MT and SPA protocols underutilize the optical medium. On the other hand, ERA achieves better utilization of the optical medium through a smart client synchronization transmission via REPORT and GATE messages and utilizing the empty time windows, which gives RAUs the opportunity to send data simultaneously in the same wavelength.

Table 5
Simulation parameters.

ERA Protocol	SPA Protocol	MT Protocol
Air propagation delay = 0.16 μs Fiber propagation delay = 1μs/200m ACK size: 8 bytes Data bit rate: 155 Mbps Station queue size: 100Kbytes		
GATE 64 bytes REPORT 64 bytes	GATE 64 bytes REPORT 64 bytes	ID 64 bytes POLL 64 bytes
Up to 4 transmission grants respective mean size ~1512 bytes	Window size 1512 bytes	DATA frame size 1512 bytes
Num. of broadcast cycles needed to return in the recognition period y = 10	Num. of broadcast cycles needed to return in the recognition period y = 10	Number of slots 10
– –	– –	Number of frames in superframe = 10 Contention frames + DATA frames = 10

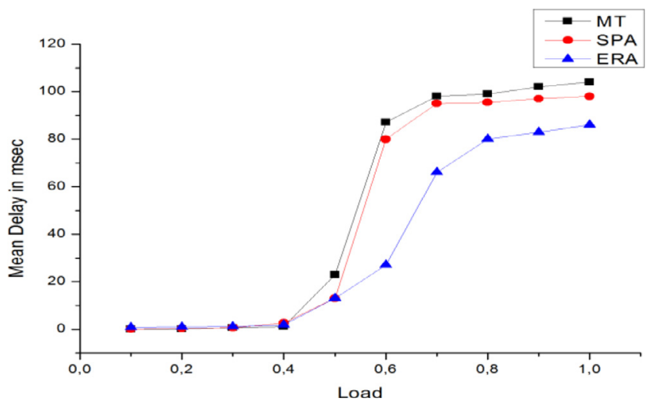

Fig. 10. Mean packet delay as a function of network load for 64 RAUs and 5 clients under each RAU, and $w = 32$ number of wavelengths.

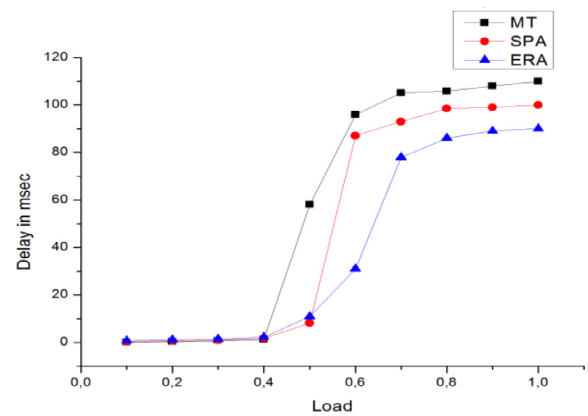

Fig. 12. Mean packet delay as a function of network load for 128 RAUs and 5 clients under each RAU, and $w = 64$ number of wavelengths.

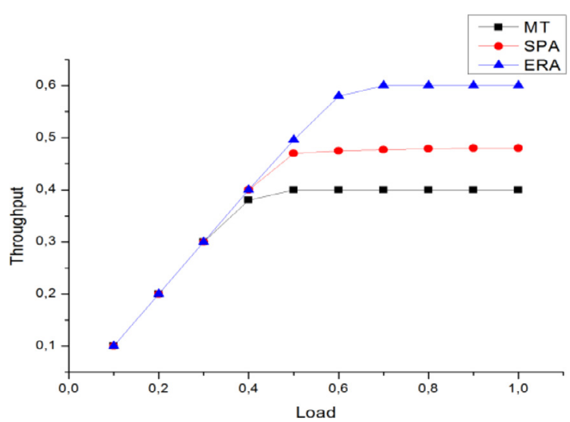

Fig. 11. Network throughput as a function of network load for 64 RAUs and 5 clients under each RAU and $w = 32$ number of wavelengths.

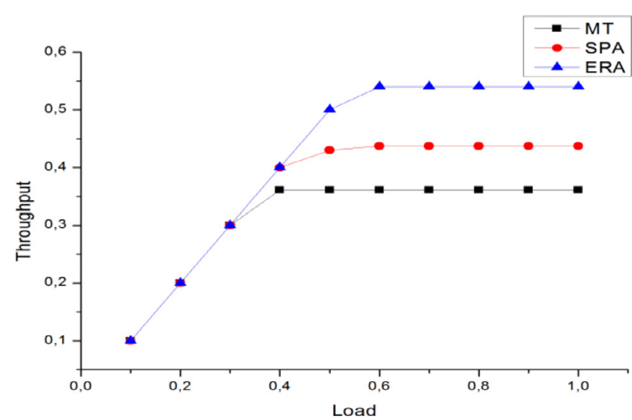

Fig. 13. Network throughput as a function of network load for 128 RAUs and 5 clients under each RAU and w = 64 number of wavelengths.

In the second simulation experiment the network consists of 64 RAUs, uses $w = 32$ wavelengths and gives each RAU five clients. The fiber bus is 3.65 km long and the load ranges from 10% to 100%. As Figs. 10 and 11 depict, the ERA protocol shows better performance in both throughput and mean delay time. It is also evident in Fig. 11 that the saturation point begins with the 40% network load in the MT protocol and the 44% network load in SPA, unlike ERA's saturation, which begins with the 60% network load.

In the third experiment a network consisting of 128 RAUs is used. The RAUs are connected to the CO through a fiber bus 6.85 km long. Under each RAU there are five wireless clients and the network load ranges from 10% to 100%. Similarly to the second experiment, the superiority of ERA is depicted in Figs. 12 and 13. The saturation point starts at 53% network load in the ERA protocol, at 36% in the MT protocol and at 43% in the SPA protocol.

In all three experiments, the ERA protocol shows huge improvement in all network metrics. The superiority in throughput is depicted in Figs. 9, 11 and 13. These figures also depict the network's saturation point, which starts from the point at which the throughput remains stable. The saturation point is also depicted in Figs. 8, 10 and 12 and it is at the point where the mean delay time is sharply increased. When the network is heavily loaded, mean

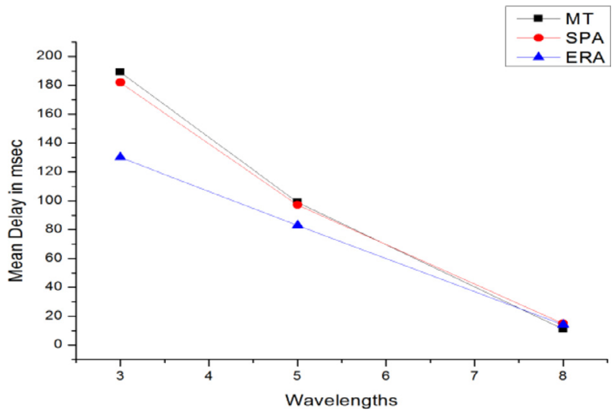

Fig. 14. Delay results for different number of wavelengths, with network load 100%, 10 RAUs and 5 clients.

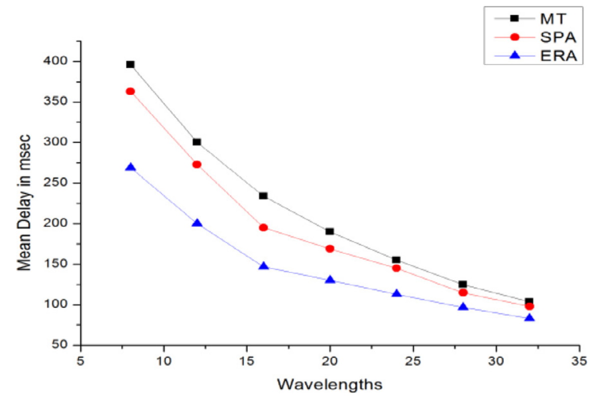

Fig. 16. Mean delay results for different number of wavelengths w = 8, 12, 16, 20, 24, 28, 32, with network load 100%, 64 RAUs and 5 clients.

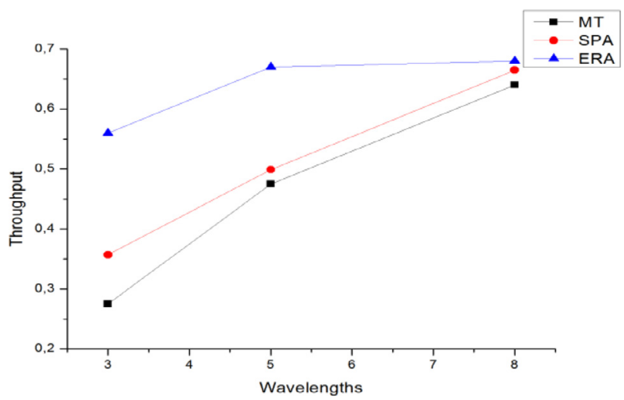

Fig. 15. Throughput results for different number of wavelengths, with network load 100%, 10 RAUs and 5 clients.

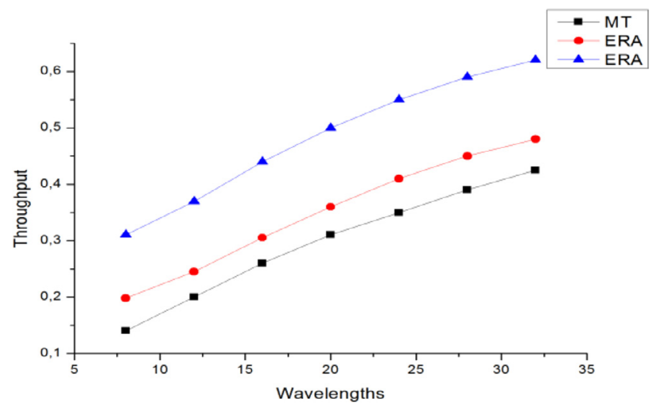

Fig. 17. Throughput results for different number of wavelengths w = 8, 12, 16, 20, 24, 28, 32, with network load 100%, 64 RAUs and 5 clients.

delay time in SPA and MT is almost steady. This is because the network reaches its saturation, and as throughput of SPA and MT indicates, only a steady number of the packets are served, when load exceed above 50%. For example when the network is consisted of 10 RAUs SPA serves only the 49% of the packets arrived and MT the 47%. The respective ERA's saturation point about at 60% of network load and the 67% of packets are served. This is because ERA's is utilizing in a more efficient way the optical bandwidth. The better utilization is achieved through wavelength reuse. The mean delay time is better for ERA in all three experiments. Namely, in the network consisting of 10 RAUs, ERA has mean delay time of 83 ms at 100% load in contrast with MT with 99 ms and SPA with 94 ms. This means an improvement of 17% and 11% respectively. For 64 RAUs at 100% load we have a 21% improvement compared with MT and 14% compared with SPA. For 128 RAUs the improvement approaches 24% for MT and 17% for SPA. The increased performance of ERA is achieved because of reuse wavelengths and transmission of data earlier in the empty time windows.

In the next experiment ERA's performance is compared with MT's and SPA's by using a different number of wavelengths in 100% network load. Figs. 14–17 show the increasingly better performance of ERA compared with the MT and SPA protocols while the number of available wavelengths is decreased. This is because of the reuse which results in better wavelength utilization. In particular, the utilization is much better when the number of wavelengths is much smaller than the number of RAUs. Namely, as depicted in Fig. 16, the improvement of ERA over MT protocol in mean delay time is 37% with 8 wavelengths and 21% with 32 wavelengths. Compared with SPA the improvement is 35% with 8 wavelengths and 14% with 32 wavelengths. As concerns the throughput, the improvement of ERA over MT as shown in Fig. 17 is 54% with 8 wavelengths and with 32 wavelengths it is 33%. Compared with SPA the improvement is 36% with 8 wavelengths and 22% with 32. However, when the number of wavelengths approaches the number of RAUs the performance of ERA converges to MT's and SPA's, which makes sense since ERA no longer provides such efficient reuse of wavelength as it does in environments with a small number of wavelengths. Specifically, when the number of wavelengths approaches the number of RAUs, there exist less RAUs that do not have a dedicated wavelength and thus are not able to exploit the artificially-created empty time windows for data transmission. This leads to either a reduced usage of empty time windows or to not using them at all. The aforementioned reduced use of empty time windows results in unexploited bandwidth, which has a negative impact on ERA's performance. However, the use of more than 50 wavelengths is an unrealistic scenario for such networks, and therefore this is not significant for the results.

In Figs. 18 and 19 ERA's scalability is examined in contrast with that of MT and SPA. Five wavelengths are used for transmitting data in 10, 16, 32, 64 and 128 RAUs. The experiments are conducted at 100% load. These experiments indicate the better scalability of ERA against both MT and SPA. Increasingly better performance is observed while the number of RAUs is increasing. As the number of wavelengths is fixed, ERA achieves better throughput and mean delay time through the reuse of wavelengths. Specifically, in 10 RAUs the difference in mean delay time between ERA and MT is about 17%, i.e. 83 ms for ERA and 99 ms for MT. Respectively, in 128 RAUs the difference is about 47.7%: namely, 812 ms mean delay for ERA and 1200 ms for MT. Compared with the SPA protocol for 10 RAUs the difference in mean delay time between

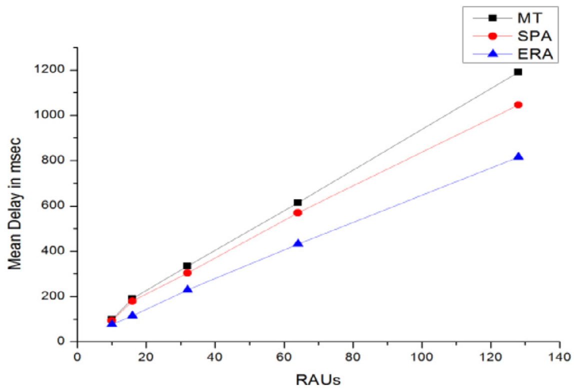

Fig. 18. Mean delay results for different number of RAUs = 10, 16, 32, 64, 128 with network load 100%, 5 clients and 5 wavelengths.

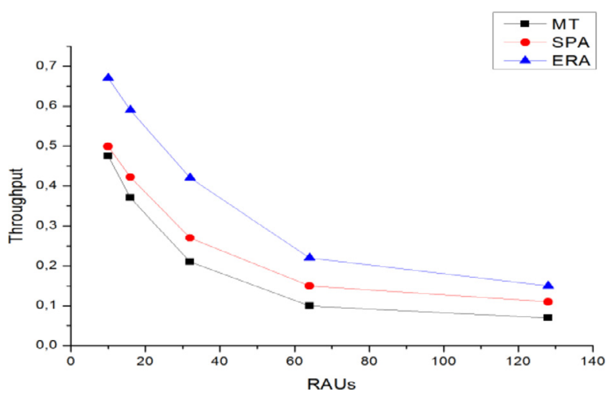

Fig. 19. Throughput results for different number of RAUs = 10, 16, 32, 64, 128, with network load 100%, 5 clients and 5 wavelengths.

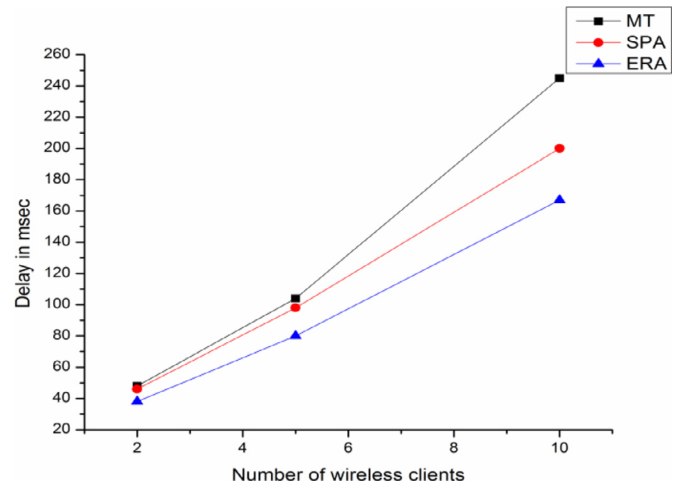

Fig. 20. Mean delay results for different number of clients = 2, 5, 10 with network load 100%, 10 RAUs and 5 wavelengths.

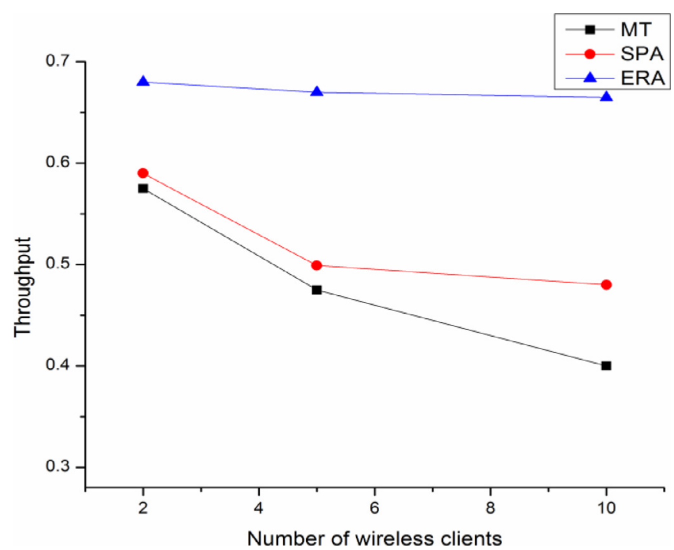

Fig. 21. Throughput results for different number of clients = 2, 5, 10 with network load 100%, 10 RAUs and 5 wavelengths.

ERA and SPA is 11% and about 32% for 128 RAUs. The above indicates that performance is better when RAUs are increased, which in turn means better scalability. The same behaviour is observed in the throughput curve shown in Fig. 19. For 10 RAUs the throughput for ERA is 67% and for MT it is 47.5%, an improvement of about 30%. Respectively, in 128 RAUs the throughput is 14% for ERA and 7% for MT, which indicates an improvement of 50%. Compared with the SPA protocol's throughput, ERA shows improvement too, as depicted in Fig. 19. Namely, for 10 RAUs the difference in throughput between ERA and SPA is 25% and for 128 RAUs it is about 33%.

In Figs. 20 and 21 ERA's scalability is also examined compare to MT and SPA, but in this experiment the scalability is tested concerning the wireless part of the network. Five wavelengths are used for transmitting data in 10 RAUs, while the number of clients under each RAU is increased. The numbers of clients are varying from 2 to 10. The experiments are conducted at 100% load. As Figures depict while the number of clients per RAU is increased the performance of MT shows a sharp decrease. This is due to the problem with the contention period which is described in Section 2. More specifically, too many users per RAU leads the contention frames to monopolize the superframe, which results in fewer DATA frames being sent. This impact is depicted in Fig. 21 where the throughput metric for 10 client in near to 40%. The SPA protocol has about the same behavior as MT, although it can address the issue with the contention period, because it has the same mechanism for contention as ERA. The sharp decrease of performance which indicated in Figs. 20 and 21 is due to the problem with the unutilized bandwidth. So the throughput of SPA when there are 10 clients under each RAU is about 45% and the mean delay is 208msec. On the other hand ERA handles both of the aforementioned problems, having as result a steady performance while the number of clients per RAU is increased. This is depicted in Fig. 21 where the throughput is steady at 65%, while the number of clients is increased. Although in Fig. 20 we can see an increase in delay, this is expected because the number of the control messages exchanged between the CO and clients is increased while the number of clients is increased too.

The aforementioned results originate from the problem that the MT and SPA protocols have with the fixed-duration superframes and DATA frames. More specifically, the duration of superframes and DATA frames is fixed both in wireless and optical media resulting in underutilization of the optical media. Hence, the problem with the MT and SPA protocols intensifies when either the number of wavelengths is decreased or the number of RAUs is increased while the number of wavelengths remains stable. Therefore, in the simulation results depicted in Figs. 14–19 MT and SPA performance rapidly deteriorates. This happens because both MT and SPA use 155 Mbps/1000Mbps = 15.5% of the available bandwidth that the optical medium can provide, which originates from the fixed-duration superframes and DATA frames. On the other hand, in order to avoid underutilized optical time, different duration transmissions are introduced in the optical and wireless media by the ERA-protocol. Thus, empty time windows are created in the optical medium, which is filled with packets from other RAUs (not the RAU that its clients transmit now). This consequently gives better utilization of the optical medium than both MT and SPA. Therefore, ERA provides improved performance both when the number of wavelengths is decreased as shown in Figs. 14–17 and when the number of RAUs is increased as depicted in Figs. 18 and 19.

6. Conclusion

We have introduced a novel concept of MAC protocols for 60 GHz RoF networks that employs wavelength reuse in the optical part of the network. The RoF consists of an EPON in a bus topology and a 60 GHz wireless network. The proposed protocol employs MPCP in order to arbitrate traffic with REPORT and GATE messages. The protocol results in dynamic bandwidth allocation among the clients, dynamic wavelength reassignment and simultaneous wavelength use among RAUs. The proposed protocol's performance is evaluated via simulations with different load conditions, different number of RAUs and different number of wavelengths. Performance evaluation results show better scalability, especially with fewer resources, and huge improvements in the network's metrics including throughput and mean packet delay compared with competing protocols. The huge improvement in performance is achieved mainly through wavelength reuse among RAUs, which means simultaneous use of a wavelength from more than one RAU and therefore better wavelength utilization.

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