A Novel Medium Access Control Protocol for Radio-Over-Fiber Access Networks

G.Vasileiou[1], G. I. Papadimitriou[1], *Senior Member, IEEE*, P. Nicopolitidis[1], *Senior Member, IEEE,* P.G. Sarigiannidis[2], *Member, IEEE*, M. Louta[2], *Member, IEEE* and M. S. Obaidat[3], Fellow of IEEE

[1] *Department of Informatics, Aristotle University of Thessaloniki, Greece*

[2] *Department of Informatics and Telecommunications Engineering, University of Western Macedonia, Kozani, Greece*

[3] *Department of Computer Science, Monmouth University, USA*

gvasile@csd.auth.gr, gp@csd.auth.gr, petros@csd.auth.gr, psarigiannidis@uowm.gr, louta@uowm.gr and msobaidat@gmail.com

***Abstract*— Radio over fiber (RoF) technology is considered as an energy and cost-effective solution to cover the users' rapidly increasing demands for bandwidth and mobility. However, integration of a wireless and an optical network into a hybrid one needs the design of new protocols. In this work, a novel MAC protocol based on the MultiPoint Control Protocol (MPCP) is proposed. The network's decision center receives feedback from the mobile clients via MPCP's GATE/REPORT mechanism so as to efficiently allocate the bandwidth and the wavelength resources in a dynamic manner. The proposed MAC protocol adapts its operation according to the actual client traffic demands. Simulation results reveal the superior performance of the proposed protocol compared to other similar competing proposals reported in the literature.**

Keywords- Medium Access Control (MAC) protocol, Simple Polling Adaptive Protocol, MPCP, Passive Optical Network (PON), Radio-over-Fiber (RoF) network, 60 GHz wireless network.

I. INTRODUCTION

Currently, the number of Internet users keeps increasing at an astonishing rate [1]. This, in conjunction with the growing bandwidth demand due to the increasing use of the new multimedia-based services, e.g. video on demand, voice over IP, etc., are leading to the design of new, and more efficient access networks. The spreading usage of wireless devices like PDAs, mobile phones, and laptops rapidly increases the use of wireless telecommunications, resulting in demand for high wireless capacities. Therefore in present days, networks such as the hybrid wireless-optical access networks, are considered of high interest in the research community. The use of such networks aims at combining the huge amount of bandwidth that an optical network provides and the ubiquity and mobility of a wireless access network, in order to provide a large amount of bandwidth to mobile users.

There are two main approaches investigated for the integration of optical and wireless networks: Radio over-Fiber (RoF) and Radio-and-Fiber (R&F)[2]. In RoF systems, RF signals from a Central Office (CO) are being propagated over a fiber link to Remote Antenna Units (RAUs), and then transmitted to clients through the air. RoF technology is based on centralized processing where network's decision center is the CO. In R&F, optical and wireless networks are combined in order to form one single integrated network. In such networks different MAC protocols are used, one for accessing the optical medium and one for accessing the wireless medium. Therefore, the Optical Line Terminal (OLT) is responsible for the traffic arbitration in the optical domain and Optical Network Units-Base Station (ONU-BS or Antennas) are responsible for traffic arbitration in the wireless domain.

The RoF in this work, consists of an Ethernet Passive Optical Network (E-PON) [3] and a high bit rate 60 GHz wireless network [4]. The E-PON consists of the Central Office and multiple Remote Antennas Units (RAUs) connected to CO via fiber buses. The wireless network consists of the RAUs and multiple wireless users. Early works in the field of MAC protocols in RoF implementations ([5]-[7]) dedicated one whole wavelength to every Remote Antenna Unit (RAU) without performing Dynamic wavelength assignment to the RAUs according to their traffic needs. The most recent work proposal, the MT-Protocol proposed in [8], arbitrates traffic through both optical and wireless media, being capable of serving multiple RAUs and multiple wireless users by dynamically assigning a limited number of wavelengths. The main problem of the aforementioned work is lacking of adaptability that should exist in the dynamically changing environment of a wireless network, where the number of users per RAU often changes. This lack of adaptability, leads to the possibility of users who cannot be served.

In this work, we present a novel MAC protocol for RoF networks, based on MPCP [9]. By using MPCP, the CO receives feedback from the GATE/REPORT [9] mechanism and dynamically allocates both the bandwidth and the limited wavelength resources depending on the demands of the wireless users. In this way the MAC protocol adapts its operation according to the clients' requests. The proposed protocol also increases the number of time slots used for recognition in order to adapt in a possible increase of the number of users. Simulation results reveal the superior performance of the proposed protocol compared to other similar competing schemes.

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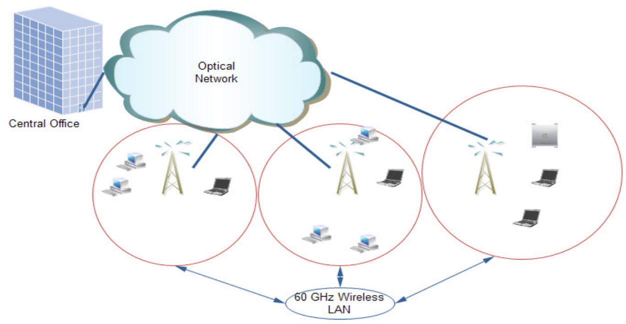

Figure 1. A 60 GHz RoF network consisting of the optical domain and multiple Antennas that are served by the Central office.

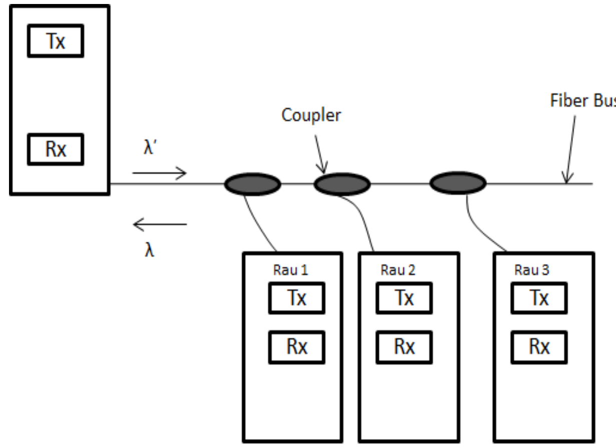

Figure 2. The optical part of a RoF network, consisting of multiple RAUs connected to CO through a fiber bus.

The remainder of this work is organized as follows. Section II reviews related work, Section III describes the proposed network architecture, while Section IV presents the proposed SPA-Protocol and Section V discusses the simulation results. Finally, conclusions are presented in Section VI.

II. RELATED WORK AND MOTIVATION

A. Related work

Extensive work has been done lately in the field of hybrid wireless-optical networks. In the field of R&F networks, a recent proposal is the WOBAN protocol [10], which uses two different protocols for arbitrating traffic. In the optical domain (which is a WDM-EPON), WOBAN uses IPACT [0] for arbitrating traffic between ONU-BS and the OLT and in the wireless domain uses the standardized IEEE 802.11g, which uses the carrier-sense multiple-access with collision avoidance (CSMA/CA) MAC protocol. Another MAC protocol is SuperMAN [11], which is essentially a hybrid network employing IEEE 802.16 WiMAX in the wireless part and IPACT [10] in the optical part of the network, which operates according to the EPON standard.

To the best of our knowledge the research that has been done in the field of MAC protocols in RoF networks, is still in early stages. MAC protocols in RoF implementations have been considered so far only within the framework of adapting existing wireless technologies like 802.11 with RTS/CTS exchange mechanism to RoF architectures ([5, 6]). Other works propose protocols that dedicate one whole wavelength only in one RAU [7].

The most recent proposal in the field of RoF networks is the Medium-Transparent (MT) MAC protocol [9], which uses a 60 GHz wireless technology and promises high throughput and low latency. MT-Protocol assigns dynamically wavelengths in RAUs through a control channel. Afterwards through specific-dedicated RAU's Superframes, it arbitrates traffic between wireless clients served by the same RAU. Superframes are fixed sized frames, which consist of Contention Frames and DATA frames. This protocol is characterized by the traits that (a) Contention frames are fixed in duration and used for arbitrating medium access in the wireless media via a fixed number of time slots, (b) DATA frames are of fixed sized also and (c) DATA frames are assigned only to one user. The above three aspects create problems when the protocol has to work in realistic wireless environments, where there the changes in the number of users per RAU are not known. More specifically, when the number of users exceeds the number of slots used for recognition, more Contention Frames are used. Moreover, this in conjunction with the fixed number of frames in SuperFrames results in less DATA Frames sent. The MT-Protocol, as well as all the aforementioned protocols in this section faces the problem of lacking the capability of employing feedback in order to adapt to the current traffic demands of the wireless clients.

B. Motivation for the proposed protocol

The aforementioned problems in the MT-protocol as well as the need for a MAC protocol able to work efficiently in realistic wireless environments with varying numbers of clients per RAU have led us to design the Simple Polling Adaptive (SPA) Protocol. Using MPCP, the SPA protocol:

1. gets feedback about clients' requirements and gives to clients transmission grants according to their requirements.
2. dynamically dedicates wavelengths to the RAUs by the CO and therefore resources to the clients that the RAU serves. For each RAU, after collecting all REPORT messages with client demands for medium access, the CO informs via a GATE message all clients who belong to this RAU the schedule for accessing the wireless media.
3. The proposed protocol solves the problem of users increase per RAU, and fixed sized SuperFrames, by increasing the slots used for recognition and thus gives transmission grants to all active users.

The Radio over fiber network is a combination of an optical and a wireless network as depicted in Figure 1 The optical domain is EPON in bus topology which is composed of the Central Office (CO) and the Remote Antenna Units (RAU's) as shown in Figure 2. The 60 GHz wireless domain is composed of the Remote Antenna Units and the clients.

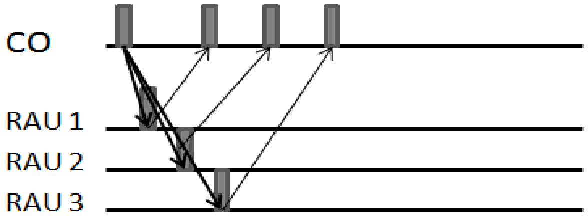

Figure 3. Wavelength assignment to RAUs.

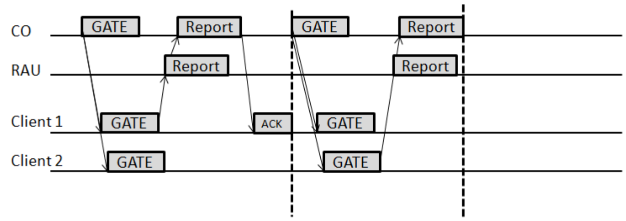

Figure 4. Recognizing wireless clients through the exponential back off recognizing mechanism.

III. Network Architecture

The RAUs modules are responsible for the optical-to-wireless signal conversion. The CO is responsible for taking decisions on wavelength assignment between RAUs and for the medium access arbitration among the clients. So the resource allocation is negotiated directly between the wireless users and the CO, which means that the intelligence center of the network is located in the CO. As stated above, the CO is responsible for the wavelength assignment. Hence, it generates the upload and download channels and assigns the earliest available channel to each RAU in a round robin fashion; choosing the earliest available wavelength pair first. There are N wavelength pairs that are generated $\{\lambda_1, \lambda'_1\}\ldots\{\lambda_n, \lambda'_n\}$. The λ' wavelengths are responsible for the download traffic from clients to the Central office and the λ wavelengths are for the upload traffic from the CO to the RAUs and respectively to the wireless clients. The CO assigns a wavelength pair to each RAU. In order to achieve a dynamic wavelength assignment, each RAU has to tune into different wavelength pairs, therefore each RAU has a tunable receiver and a tunable transmitter as depicts Figure 2. Finally, the CO also employs a tunable transmitter and a tunable receiver and uses an additional control wavelength pair $\{\lambda_c, \lambda'_c\}$ to inform RAUs to tune into a specific wavelength pair.

IV. The Proposed Protocol

The proposed protocol consists of two periods and it is based on the MultiPoint Control Protocol (MPCP) [10]. 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.

The first period is called the recognition period. In the start of every period as depicted in Figure 3, the CO transmits a small burst of packets in the control channel to RAUs in order to be recognized and assigned with a specific wavelength. Then for each RAU, the CO broadcasts a GATE message to all clients of the RAU, as shown in Figure 4. 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 0 to 2^i-1, where i is the number of recognition attempts by a client.

The starting slot numbers is selected randomly according to a uniform distribution from 0 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 exist no collisions and as a result an ACK packet is returned to inform clients that they have been identified. The clients that receive the ACK will not participate in the next recognition cycle.

However if two or more clients chose the same number they will start transmitting 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 window increasing exponentially. The recognition period ends when all the active clients are recognized. Upon receiving the REPORT messages from the clients, the CO is informed of both their existence and their bandwidth requirements, which are piggybacked by the clients on their REPORT messages.

After ending the 1st period, the period of transmitting data follows as depicted in Figure 5. Having knowledge about clients' bandwidth requirements from the previous period, the CO applies IPACT and conducts a collisionless transmission schedule for clients served by the same RAU. In 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, as it happens in the recognition period. If the number of RAUs exceeds the number of available wavelengths the CO assigns the earliest available channel to the next RAU in a round robin fashion. Then the CO transmits GATE messages individually to clients of every RAU to inform them when transmission starts and how many bytes are allowed to be sent (transmission window). After receiving the GATE message each client starts transmitting data depending on the broadcast schedule. Along with the data that were sent by the clients, new REPORT messages are sent too, in order to update the information in the CO. Each broadcast cycle ends when all RAUs and its known clients end their transmission and the new REPORT messages are collected. Based on the updated information the CO conducts for all clients a new broadcast schedule for the next broadcast cycle and re-assigns to RAUs and their clients the first available wavelength. After a certain number of transmission cycles, the CO broadcasts a GATE message in order to return in the recognition period to introduce new clients. In an environment that has constant number of clients per RAU, the recognition period will not repeat.

Based on the above discussion every client has a transmission window, which is changing dynamically according to its bandwidth requirements. This happens because each client sends in a cycle as many bytes as inserted in its queue in the previous cycle, a fact reported via the REPORT messages. On the other hand, the CO in MT protocol has no information about its clients' queues occupancies and this result in sending fixed size DATA frames. Thus, SPA protocol without fixed transmission window in comparison with MT-protocol can take advantage of the traffic's bursty nature by giving more bandwidth (larger transmission window) to the client that has more bandwidth requirements. This also indicates the superiority of SPA-protocol without fixed transmission window to the SPA-protocol with fixed transmission window.

Furthermore, MT- Protocol in comparison with both SPA-with and without transmission window, has a fixed number of

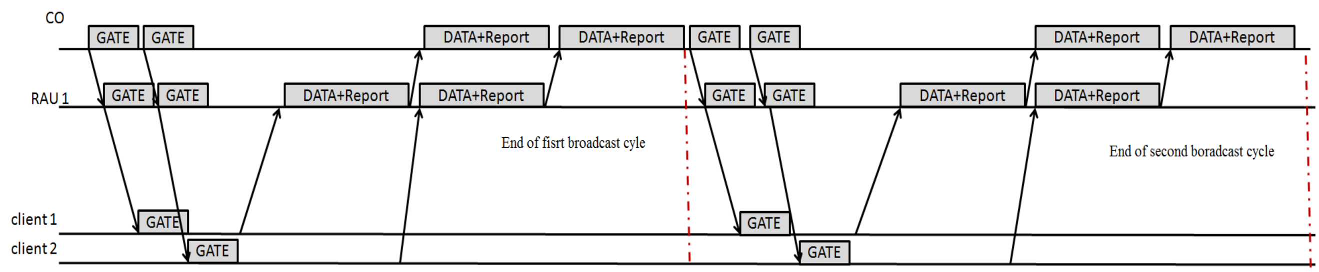

Figure 5. The broadcast DATA period. This Figure shows how functions the MPCP. Specifically how GATE message grants a transmission and the REPORT messages are collected in order to conduct a collision free broadcast schedule.

slots per RAU for recognizing the clients and together with the fixed number of frames in SuperFrames this creates problems with the adaptability of the protocol. This is very important when the protocol has to do with unstable wireless environments, where there are a lot of changes in the number of users. The problem seems to be very crucial for MT when the number of users exceeds the number of slots used in the Contention frames resulting in using a lot of Contention frames for recognizing users and assigning traffic to them and less DATA frames for users to transmit data. Even if all of the active clients are recognized in the duration of the SuperFrame, due to the use of using a lot of Contention Frames, there are a few DATA frames. These DATA frames are often smaller in number than the number of users, resulting in having active clients that are not served in this SuperFrame and subsequently force them to wait for the next SuperFrame in order to transmit DATA. This has a negative impact on protocol's performance.

V. SIMULATION RESULTS

In this section, the performance of the proposed SPA-protocol with fixed size transmission window and without transmission window is compared to that of MT via simulation. The network considered consists of 10 RAUs, uses w=5 wavelengths and each RAU has 5 clients unless mentioned otherwise. The RAUs are connected via a fiber-bus which is 950m long. The minimum distance between RAUs is 50m. The traffic model uses Poisson distribution to compute the inter-gap time between the arrivals of two packets and generates packets with maximum packet size of 1288 bytes. Table I provides a summary of the simulation parameters used in our simulations.

In the first simulation experiment, the proposed protocol is evaluated 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. Figure 6 shows the mean packet delay as a function of network load and Figure 7 depicts the network throughput as a function of network load corresponding to different network loads. In those two Figures, one can see the high performance of both protocols for network load ranging from 0.1 to 0.4. However when the network load exceeds the value of 50% the MT-protocol's performance starts decreasing.

The main conclusion that can be drawn from Figures 6 and 7 is the slightly better performance of SPA-protocol with transmission window in comparison with MT-Protocol. This happens mainly due to the fact that each MT SuperFrame consists of at least one Contention frame. The Contention

Table I: Simulation parameters

SPA-PROTOCOL	SPA-PROTOCOL WITH FIXED TRANSMISSION WINDOW SIZE	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	GATE 64 bytes	ID 64 bytes
REPORT 64 bytes	REPORT 64 bytes	POLL 64 bytes
	Window size 1288 bytes	DATA frame size 1288 bytes
Num. of transmission cycles needed to return in the recognition period y=10	Num. of transmission 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

Frame is used for recognizing clients and for synchronizing their order of transmission. Hence, during the transmission of a Contention frame clients are not allowed to send data, which results in an additional overhead in both mean delay and throughput. On the other hand, SPA achieves clients' synchronization transmission through REPORT and GATE messages, which give clients the opportunity to send data simultaneously with the REPORT packet.

The superiority of SPA protocol is increased, when there is no fixed transmission window as both Figures 6 and 7 show. The lack of fixed transmission window gives clients the possibility to adapt their transmission according to their queue occupancies that are gathered through the REPORT messages in the previous broadcast cycle. This justifies the much better mean delay times than SPA employing fixed sized transmission window.

In the second simulation experiment we compared the protocols in a more realistic environment where the number of clients is varied from 5 to 16 for a network load of 0.5 and 1.0. The results for this experiment are depicted in Figures 8 and 9 and the main conclusions that can be drawn from these results are summarized below:

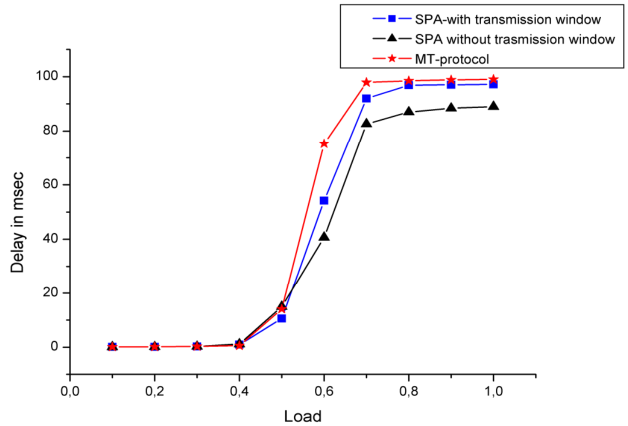

Figure 6. Mean packet delay as a function of network load for 10 RAUs and 10 clients under each RAU, and *w*=5 number of channels.

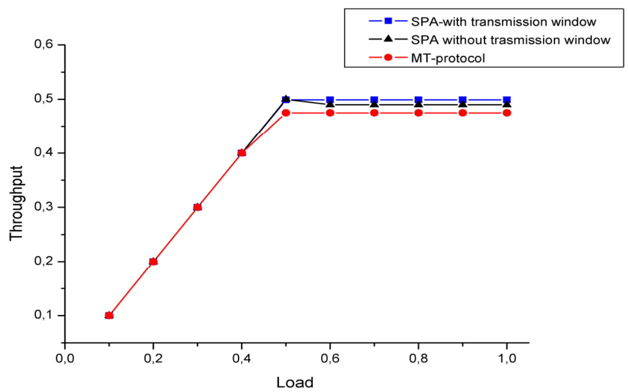

Figure 7. Network throughput (in percentage %) as a function of network load for 10 RAUs and 5 clients under each RAU and *w*=5 number of channels.

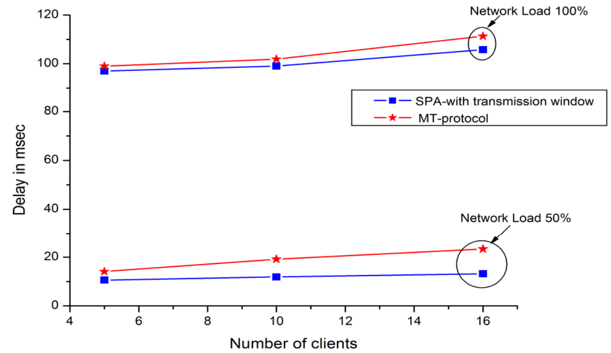

Figure 8. Delay results for different number of users per RAU, with network load 0.5, and 1, *w*=5 channels and 10 RAUs.

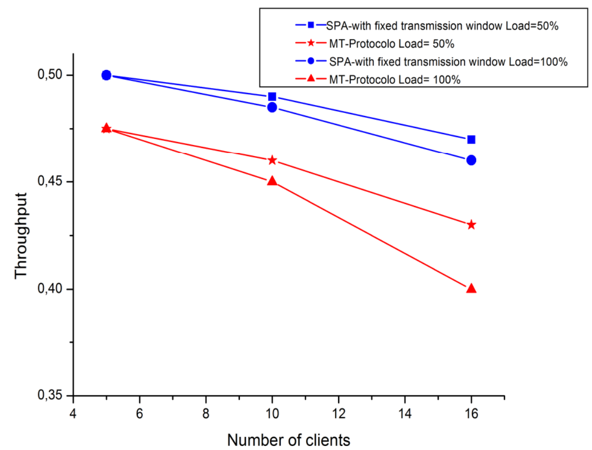

Figure 9. Network throughput results in percentage for different number of users per RAU, with network load 0.5(50%) and 1(100%), *w*=5 channels and 10 RAUs.

1. As seen in Figure 8, the performance of SPA is increased compared to MT. Figure 8 also depicts for SPA a very slight increase in mean delay when number of users grows from 5 to 16 whereas the respective increase in mean delay in MT protocol is larger.
2. As seen in Figure 9, SPA shows a slight decrease in throughput when the number of users rises from 5 to 16 whereas the respective reduction of throughput in MT protocol is more. As the number of users rises from 5 up to 16, SPA-Protocol's throughput is steadily superior to that of MT.

The aforementioned results originate from the problem that MT-protocol has with the fixed sized SuperFrames and the fixed number of slots. More specifically, in this simulation analysis the number of frames in a SuperFrame and the number of slots per frame were set to 10 for MT. The existence of at least one Contention Frame for MT means that 9 more frames remain in the SuperFrame for Contention Frames and DATA Frames. Hence, the problem with MT-Protocol intensifies when the number of users per RAU exceeds the number of slots as is the case for our simulations when the numbers of users exceed 10. Therefore, in the second simulation MT protocol's performance rapidly degrades. This happens because we may lose DATA frames in favor of Contention frames. On the other hand, in order to avoid unrecognized and not-fully served clients, SPA increases exponentially the recognition slots and gives to all active clients transmission grants. Therefore, SPA provides improved performance while the number of users per RAU increases as shown in Figures 8 and 9.

VI. Conclusion

This paper proposed a novel MAC protocol for RoF networks consisting of 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 and dynamic wavelength assignment among RAUs. The proposed protocol has been evaluated under Poisson traffic assumption for different load conditions. Performance evaluation results have shown that improvements in network's metrics including throughput and mean packet delay when compared to other existing competing protocols.

References

[1] White paper, "Cisco Visual Networking Index: Forecast and Methodology, 2009-2014".

[2] M.Maier and N.Ghazisaidi, "QoS-Aware Radio-and-Fiber (R&F) Access-Metro Networks" *(Invited Paper)*, *Wireless Communications and Networking Conference Workshops (WCNCW), 2010.*

[3] J. G. Kramer, B. Mukherjee, and G. Pesavento, "Ethernet PON (ePON): Design and Analysis of an Optical Access Network", *Photonic Network Communications.*, vol. 3, no. 3, pp. 307-319, July 2001.

[4] M.Weiß, M. Huchard, A. Stöhr, B. Charbonnier, S. Fedderwitz, and D. S. Jäger, "60-GHz photonic millimeter-wave link for short- to mediumrange wireless transmission up to 12.5 Gb/s", *IEEE Journal of. Lightwave Technology*, vol. 26, no. 15, pp. 2424–2429, August 2008.

[5] M. J. Crisp, S. Li, A. Watts, R. V. Penty, and I. H. White, “Uplink and downlink coverage improvements of 802.11g signals using a distributed antenna network”, *IEEE Journal of Lightwave Technology.*, vol. 25, no. 11, pp. 3388–3395, November 2007.

[6] A. Das, M. Mjeku, A. Nkansah, and N. J. Gomes, “Effects on IEEE 802.11 MAC throughput in wireless LAN over fiber systems”, *IEEE Journal of. Lightwave Technology*, vol. 25, no. 11, pp. 3321–3328, Nov. 2007.

[7] M.Mjeku and N.J.Gomes,”Analysis of the Request to Send/Clear to Send Exchange in WLAN Over Fiber Networks”, *IEEE Journal of Lightwave Technology*, vol. 26, no. 15, pp. 2531 – 2539, August 2008.

[8] M. Huchard, M. Weiss, A. Pizzinat, S. Meyer, P. Guignard, and B. Charbonnier, “Ultra-broadband wireless home network based on 60-GHz WPAN cells interconnected via RoF”, *IEEE Journal of Lightwave Technology* vol. 26, no. 15, pp. 2364–2372, August 2008.

[9] G.Kalfas and N.Pleros, An Agile and Medium-Transparent MAC Protocol for 60 GHz Radio-Over-Fiber Local Access Networks, *IEEE Journal of Lightwave Technology* , vol. 28, no. 16, August 2010.

[10] M.P.McGarry, M.Maier, and M.Reisslein, “Ethernet PONs: A Survey of Dynamic Bandwidth Allocation (DBA) Algorithms”, *IEEE Communications Magazine*, vol. 42 , no. 8, pp. 8 - 15 , August 2004.

[11] P.Chowdhury, B.Mukherjee, S.Sarkar, G.Kramer and S.Dixit, “Hybrid Wireless-Optical Broadband Access Network(WOBAN): Prototype Development and Research Challenges”, *IEEE Network*, vol.23, no.3, pp.41-48, May-June 2009.