

On converged Medium-Transparent MAC protocols for mm-wave Fiber-Wireless Networks

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Abstract— This paper describes and summarizes the notion of medium-transparency in the access control protocols. Two versions of the medium transparent MAC protocols have been presented to this day. The first is the pure Medium Transparent MAC (MT-MAC) that assigns optical capacity for equal time intervals to every RAU of the network. The second version is the Client-Weighted MT-MAC (CW-MT-MAC) that assigns wavelengths based on the number of active users that reside within each RAU, and for time proportionate to the latter, with the purpose of providing capacity fairness among the users. The CW-MT-MAC exhibits improvement on user throughput and delay equalization for various network conditions such as different user distribution patterns and loads under specific wavelength availability constraints. The results conclude that the medium transparent MAC protocols can operate successfully over converged Radio-over-Fiber (RoF) networks, confirming their agility and showing that extended range 60GHz LAN areas between wireless users even without line of sight conditions can be obtained. In addition, the results show that the CW-MT-MAC alleviates the inter-user standard deviation in terms of throughput and packet delay, thus proving its enhanced user-fairness properties, highlighting its ability to serve modern applications where Packet Delay Variation is a major issue.

Keywords—Medium-Transparent MAC; Client-Weighted vs. Round-robin capacity assignment; Radio-over-Fiber Network; mm-wave; optical wireless

I. INTRODUCTION

To address the explosive demand for high-capacity and omnipresent wireless access, modern wireless networks are slowly adopting two solution roadmaps. The first is the employment of small-cell formations to increase the overall spectral efficiency[1]-[2], whereas the second is the employment of higher frequency bands, such as the mm-wave 60GHz band, that offers vast amounts of bandwidth[3]-[4]. The above solutions inevitably require the installation of large amounts of Base Stations (BSs) or Access Points (APs), which diminishes the network's cost-effectiveness. To this end, Radio over Fiber (RoF) technology has been put forward as an ideal candidate solution, since it provides low-complexity Remote Antenna Units (RAUs) that are connected to a Central Office (CO), via an optical fiber, as depicted in Fig. 1. RoF offers several advantages such as transparency regarding bandwidth and modulation techniques, functionally simple and energy efficient RAUs, and centralized operation that allows for optimum end-

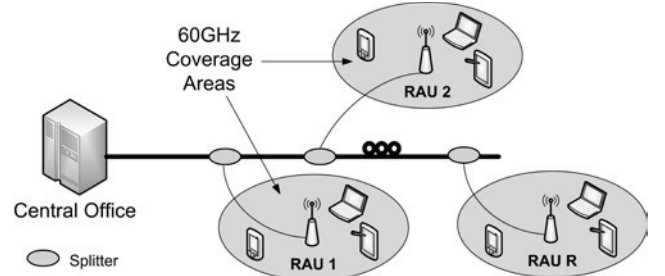


Fig. 1 Representation of an MT-MAC Radio-over-Fiber bus architecture.

to-end resource management[5]. Although physical layer (PHY) convergence has been realized and researched to a great extent, access control in hybrid RoF environments remains an open issue. In general, two traditional approaches have been considered for resource management in Fiber/Wireless (FiWi) networks[6]. The first is the use of distinct wired and wireless MAC protocols that communicate at the optical/wireless routers interface. However, such architectures, often termed Radio-and-Fiber[7], fracture access control into two parts, creating separate networks that are hidden and often irrelevant to each other. This approach goes against the physically intertwined nature of the converged communications, alleviates the advantage of centralized network overview and requires the installation of a series of active access equipment, making it practically unsuitable for deployment in mm-wave radio applications. The second approach is the direct adaptation of currently existing wireless MAC protocols directly on top of RoF infrastructures[8]. As it is expected, all wireless MAC protocols are completely oblivious to the optical infrastructure that lies beyond the wireless physical layer, and therefore can function only if there is a constant and static active optical connection to carry the radio signals between every RAU and the CO. Due to the high propagation and penetration losses exhibited by mm-wave radio, numerous antennas are required to cover an area, even as small as the size of a single apartment. In such environments, it becomes obvious that the direct adaptation of currently existing wireless protocols is impractical and leads to major resource and energy waste. To this end, there is a fundamental requirement for implementing new converged optical/wireless MAC protocols, that have the complete overview of both available re-sources and can therefore effectively administer the hybrid RoF networks.

This paper goes beyond the two previously mentioned approaches and presents the notion of medium transparency in

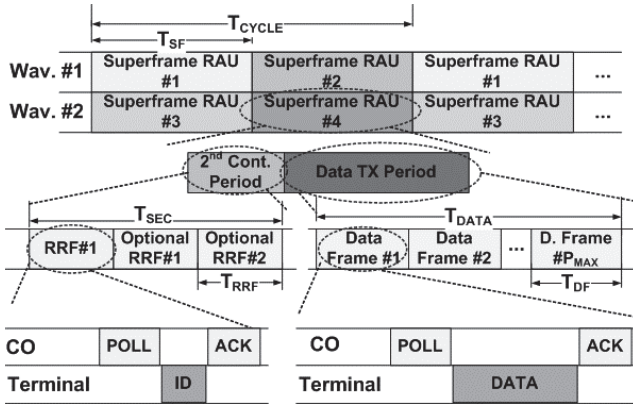


Fig. 2 Example of network with 2 wavelengths and 4 RAUs.

the MAC layer. The Medium-Transparent MAC (MT-MAC) protocols[9]-[10] have the unique ability to concurrently administer the optical and wireless resources of a hybrid RoF based network, seamlessly connecting the CO to the wireless terminals through minimal RAU intervention. In this way, the MT-MAC protocols form extended reach 60GHz WLAN networks offering connectivity amongst wireless devices that are attached to the same or different RAUs under both Line of Sight (LOS) and non-LOS conditions. The notion of medium-transparency relies on two parallel contention periods, the first in the optical domain and the second in the wireless frequency and time domains, with nested dataframe structures. The MT-MAC operation is based on a proposed RAU design that allows for wavelength selectivity functions, thus being compatible with completely passive optical distribution network implementations that are predominately used by telecom operators to-day. Two variants of the MT-MAC protocol are recapped here. The first offers dynamic wavelength allocation with fixed time windows, whereas the second offers dynamic wavelength allocation with dynamic transmission opportunity window sizes, based on the number of active clients connected at each RAU.

This paper is organized as follows: Section II presents the MT-MAC protocol overview. Section III presents the Client-Weighted MT-MAC protocol and provides the respective differences with the plain MT-MAC protocol. Section IV presents the performance evaluation of both the aforementioned protocols in terms of throughput and mean packet delay. Finally, Section V concludes the paper.

II. MEDIUM-TRANSPARENT MAC PROTOCOLS OVERVIEW

This section summarizes the main operational characteristics of the MT-MAC protocol. For a complete description of the MT-MAC protocol and all the underlying 60GHz RoF network mechanisms we refer the reader to [9].

In the Medium-Transparent MAC all traffic exchange takes place over both optical and wireless media concurrently, with the CO communicating to the wireless nodes through the fiber-based network that terminates in a series of RAUs, while the 60GHz wireless interfaces contained in each RAU provide the last-meters wireless link to the terminals as shown in Fig. 1. In the optical part of the network, all wavelengths employed for uplink and downlink transmission are generated by the CO and

divided logically into wavelength pairs: one wavelength is used for downlink transmission (CO to RAU) and the other for the corresponding uplink path (RAU to CO). One reserved wavelength pair, referred as the Control Channel, is used as the common control signaling link to tune the RAU elements to the assigned wavelength pair that will be used for the actual data transmission. Service and capacity requests are directly negotiated between the terminals and the CO without any intelligent operation taking place at the RAU units. In this way, the MT-MAC transforms the currently distinct optical and wireless networks into a hybrid converged extended reach network between wireless end-users served by the same CO, even for users residing in different cells with no Line-Of-Sight conditions. Access control is performed using two distinct contention periods that are executed in parallel: the First Contention Process (FCP) is carried out in the optical domain and informs the CO which RAUs contain terminals with pending traffic in their range, whereas the Second Contention Process (SCP) is being carried out in the wireless domain and is used to administer the wireless bandwidth allocation between the wireless terminals located in the radius of the same RAU cell.

After finalization of the FCP, the CO assigns a data transmission wavelength pair to each RAU that has requested access. When the number of RAUs containing active clients exceeds the number of available wavelength pairs, such as in the case of high load conditions, the CO assigns the wavelengths in a Round-Robin fashion. The actual data traffic exchange is divided logically into Superframes (SFs). Each SF contains two kinds of frames: the Resource Requesting Frames (RRFs) that carry out the SCP process and the Data Frames (DFs) that compose the DATA TX period, as shown in Fig. 2. The final number of RRFs is variable and depends on the successful or failed outcomes of the SCP, whereas the number of DFs is static and always equal to P_{MAX} as stated by the MT-MAC operational rules under the fixed service regime. The RRF packets' purpose is twofold. First is to identify the nodes that reside within the radius of a RAU cell and secondly is to determine the ones that contain packets waiting for transmission. This will allow for optimum channel utilization, since only the active nodes will be chosen for participation in the upcoming DATA TX period, whereas other nodes will remain silent. Once the active users have been identified after one or several RRFs, the SCP terminates and the DATA TX sequence commences. During the latter, a series of DFs that carry the actual communication payload is transmitted according to a polling sequence.

The SCP is based on a random choice scheme. To this end, the RRFs comprise s slots, with each slot containing an exchange of POLL, ID and ACK packets between the CO and the wireless nodes. When the RRF commences, each active node randomly selects an integer value y in the interval $[1, s]$. The y value corresponds to the number of POLL packets that the end node must receive before replying with an ID packet. The POLL packets transmitted at this stage by the CO are intended towards all users and have no specified receiver. If the CO receives the ID packet correctly it responds with an ACK packet targeted at the transmitter of the ID packet, notifying it that it has been correctly identified and will be placed in the polling sequence. The now resolved node will abstain from any subsequent RRFs that might follow within the current SF. In the case two or more

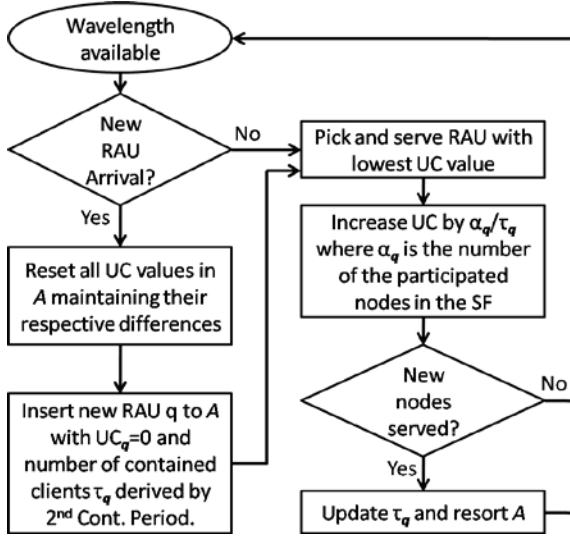


Fig. 3 CWA's flowchart.

nodes choose the same random value y , all will transmit within the same slot, rendering the ID packets unreadable. In this case the CO will not respond with an ACK packet, therefore forcing the unresolved nodes to choose a new y value and participate in the next RRF. The CO transmits RRFs until there are no detected collisions, which in turn means that all wireless nodes have been successfully resolved. With the complete knowledge of all the active nodes in every RAU, the CO initiates the DATA TX period where P_{MAX} DF sequential transmissions take place until the end of the SF is reached.

III. THE CLIENT-WEIGHTED MT-MAC PROTOCOL

Instead of the Round Robin Algorithm (RRA) employed so far in the MT-MAC approach of [9], the Client-Weighted MT-MAC[10] pursues a client-based approach to the wavelength-to-RAU distribution when the number of requesting RAUs R exceeds the number of available wavelengths λ . The Client-Weighted Allocation (CWA) mechanism is designed to distribute capacity based on the projected demand, which is considered analogous to the number of clients requesting traffic. CWA's operation is based on matrix A where each row q refers to the RAU with ID q . Matrix A is always sorted in descending order regarding the number of the contained clients per RAU. In each row, a Utilization Counter UC_q is maintained which indicates the total amount of serving time granted to RAU q . The higher the UC_q , the lowest the priority that RAU q has in the selection process. When a SF ends, UC_q is increased by α_q/τ_q , where α_q is the number of active nodes that participated in the current SF and τ_q is the total number of nodes residing in RAU q . The value τ_q is accumulatively calculated and updated as time progresses and different users become active within RAU q . Each time a wavelength becomes available, the RAU with the lowest UC value and, in case of a tie, the RAU with the greatest value τ_q , is chosen as the one to be served next. In case α_q equals zero, meaning that the chosen RAU q had no active clients, UC_q is increased by 1, denoting that all users were served and therefore rapidly dropping in priority. If RAU q remains with no requesting clients for some time, then it is removed from A . In addition, when RAU q requests capacity and is not present in the

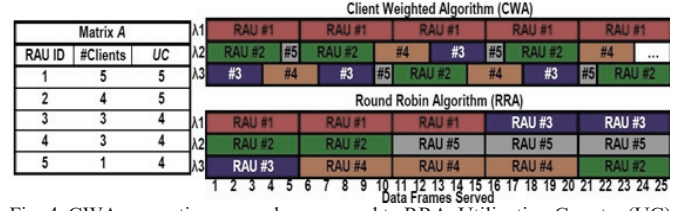


Fig. 4 CWAs operation example compared to RRA. Utilization Counter (UC) refers only to the Client Weighted scenario. Different colors correspond to packets originating from different RAUs.

Fiber Prop. Delay	1 μ s per 200m	Air Prop. Delay	0.16 μ s
Slots in RRF	10	ACK Size	8 bytes
DATA Size	1288 bytes	ID, POLL Size	64 bytes
Data Bitrate	1 Gbps	Buffer Size	80 pack.
Mean Burst Length	1.5 Kbytes	Burst Length Std. Deviation	1,42 Kbytes
CWA TX_OP Size	30 packets	RRA SF Size	150 packets

matrix, it is inserted in A and given the lowest existing UC value. The latter aims in providing the newly inserted RAU with the maximum priority, enabling the CO to become rapidly acquainted with τ_q and maintain A correctly updated. With each RAU addition, all UC counters are reset in order to keep their numbers small, whilst preserving their respective differences. For example, if the UC values for RAUs 1, 2 and 3 are 8, 8 and 7 respectively, with the addition of RAU 4 they become 1, 1, 0 and UC4 initializes at 0. CWA's flowchart is depicted in Fig. 3.

It is essential to note here that, due to constraints applied by the PHY specification, CWA is facing an upper barrier in certain extreme cases regarding the maximum achievable equalization of bandwidth allocation. Even though densely populated RAUs can in theory be granted a larger portion of the available optical capacity, no more than one wavelength can be physically assigned to a single RAU, thus forming a maximum fairness limit. This limit effectively corresponds to the maximum number of users that can be served by a single RAU before overcoming CWA's operational capacity and is denoted as $n_{MAX} = z/\lambda$, where z is the total number of active clients served by the CO. When the number of active nodes residing in a RAU surpasses n_{MAX} , CWA chooses to grant a dedicated wavelength to this RAU element for if the above condition applies. In this case, the CWA subtracts the dedicated wavelength and the number of users served by it and functions recursively for the remaining wavelengths and nodes.

Fig. 4 illustrates an execution example for 3 available wavelengths, 5 RAUs and a total of 16 users served by a single CO, with the last being distributed unevenly amongst RAUs as shown in the matrix A . The figure depicts the wavelength-over-time allocation of CWA versus the corresponding RRF-based operation presented in the previous section. As it can be noted, the RRA-based approach equips each RAU with static 5-Data-Frame-long capacity "chunks" for the entire 25-Data-Frame-long running time, irrespective of the number of users served by each RAU. On the contrary the CWA mechanism clearly differentiates and promotes the densely populated RAUs by reserving the wavelengths on a balanced user-centric basis for the same period so as to provide fairness amongst the end-users.

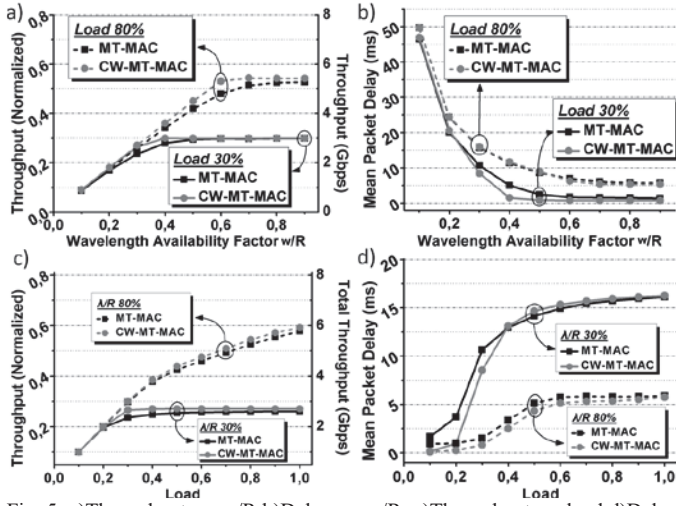


Fig. 5 a)Throughput vs. w/R b)Delay vs. w/R c)Throughput vs. load d)Delay vs. Load

IV. NETWORK PERFORMANCE EVALUATION

The following present the performance evaluation of the RRA and CWA algorithms when applied on a RoF-over-bus network. The test set up is comprised of 10 RAUs with 50m fiber interval amongst the RAUs, while the first RAU is located 500m away from the CO, thus forming a network with total length equal to 950m. To derive the respective results, we have employed a Java event-driven simulator with the full simulation parameters presented in Table I. The total number of mobile terminals located within the range of all RAUs has been set to 50, whereas all terminals have been distributed to the respective RAUs using an approximation of the normal distribution. This approximation has been properly modified in order to produce discrete values and provides “bell-shaped” populations with mean value $\mu = 5$ users per RAU. To stress test the algorithms’ capabilities, we have set a rule where each RAU has at least one user within its range. In this way, the wavelength assignment algorithms have to administer the available wavelengths to exactly 10 RAUs. The wireless medium is regarded as ideal (i.e. error free) and all users have adequate buffer space to store the generated traffic. Each RAU has a range of 3m. Since the presented framework offers a dynamic capacity allocation scheme, the number of available wavelengths is smaller than the number of existing RAUs in the network. The wavelength to RAU ratio is denoted henceforth as the wavelength availability factor w/R . Beyond being useful towards deriving useful results regarding the MT-MAC’s wavelength allocation function performance, the shortage of wavelengths carries a physical meaning as well: the high propagation losses nature of the mm-wave radio signifies the need for a large amount of very short ranged RAUs in order to provide service to a broad area. This in turn means that in real-life deployed networks the RAUs will be served by a lesser number of wavelengths either due to scale or due to energy efficiency reasons. The packet generator used in our simulations is based on the bursty traffic model that exhibits long-tail properties, meaning that generated traffic is characterized by high deviation from the distribution’s mean value of burst length, a fact which simulates IP traffic with higher accuracy. For the experimental simulation runs, we have considered 1.5kB mean burst length, with a standard deviation

of 1,42kB. Due to this high degree of deviation, the per user transmission opportunity window was set at 30 frames long (~4kB), so as to ascertain that most generated packet bursts would fit within one SF. In accordance to the above, the RRA SF size was set to 150 frames long, a value that was calculated by multiplying the corresponding CW-MT-MAC transmission opportunity window with the users’ distribution mean $\mu = 5$.

Fig. 5 presents the MT-MAC’s and CW-MT-MAC’s performance versus various optical availability factors (w/R ratio) (Fig. 5(a) and (b)), ranging from 0.1 and up to 0.9 as well as versus various traffic loads (Fig. 5(c) and (d)), ranging from 10% up to 100% of the maximum theoretical network capacity. Both CW-MT-MAC and MT-MAC were tested for the extreme user distribution case with standard deviation $\sigma=4.5$, when the mean users distribution is $\mu = 5$. As it is described in the respective legends, the results displayed in Fig. 5(a) and (b) can be logically classified into groups, depending on the normalized load produced by the mobile clients. Respectively, the results displayed in Fig. 5(c) and (d) are clustered based on the respective w/R ratio. As can be noted in Fig. 5(a), throughput follows a linear increment path until it reaches its maximum value when the w/R ratio exceeds the offered load, effectively meaning that all traffic is accommodated due to the optical wavelength abundance. The same applies in the curves group depicting the 80% load scenario, with the difference being that linear properties continue for higher loads until again the point where the w/R ratio exceeds the offered load. Regarding the MT-MAC/CW-MT-MAC comparison we notice a borderline superiority of the second over first one. Specifically, CW-MT-MAC exhibits a marginal throughput gain in the 30% load scenario, whereas the gain increases and reaches its highest value of 5% in the 80% load scenario. This performance boost is the result of the proportional wavelength assignment mechanism which administers optical capacity not statically but in accordance to the received bandwidth claims. In this way, possible idle times in less crowded RAUs are avoided while the much-needed service time is extended in the densely populated areas. This performance agreement is also evident in Fig. 5(b) which depicts the mean packet delay. As can be noted, delay outcomes start at very high values while the offered load exceeds the available optical capacity ratio due to the traffic being many times greater than the maximum theoretical capacity achievable by the available wavelengths. However, as the wavelength availability rises, delay follows a decreasing slope, with the curves corresponding to 30% load dropping at higher rates than the high-load 80% scenario. By comparison it becomes clear that, when population distribution is uneven, CW-MT-MAC manages to attain higher metrics, especially while the w/R ratio remains lower than the offered load, confirming that service balancing can indeed lead to better overall system level performance.

Fig. 5(c) and (d) illustrate the protocol’s behavior versus various traffic loads, ranging from 10% up to 100% for the most extreme user distribution deviation. Performance was tested for two different wavelength availability factors w/R , namely 0.3 and 0.8. Fig. 5(c) presents the total system throughput versus various load conditions, revealing the linear exploit of the dual-medium while the offered load remains well under the corresponding w/R ratio. As load increases though, throughput

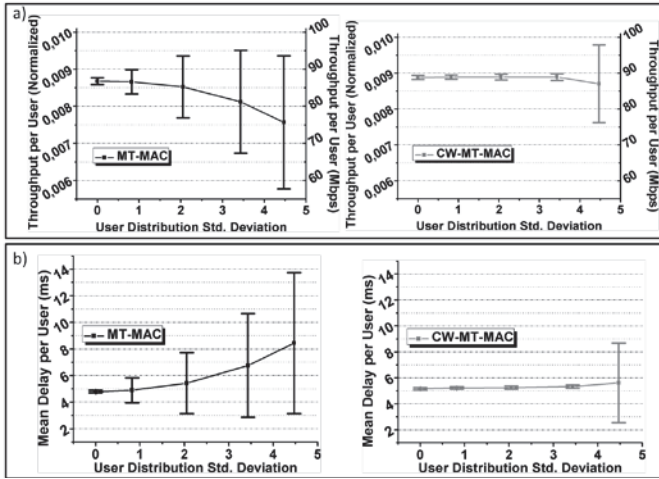


Fig. 6 a-b) MT-MAC protocol User Throughput and Mean User Delay Performance w/ Standard Deviations vs. the User's Distribution Standard Dev. c-d) CW-MT-MAC protocol User Throughput and Mean User Delay Performance w/ Standard Deviations vs. the User's Distribution Standard Dev. forms around its saturation plateau, since all traffic beyond that point is limited by the respective w/R ratio. Delay outcomes presented in Fig. 5(d) remain minimal while load is below w/R and increase rapidly when load approaches the latter. After the offered load has exceeded w/R , delay follows an increasing course before saturating at its maximum value, since all exceeding traffic beyond this point are directly dropped. Regarding the two competing schemes we notice again a marginal performance gain in favor of CW-MT-MAC. This performance thrust highlights that when faced with uneven populations, traffic provision and service distinction are necessary to achieve optimum operation.

Fig. 6 offers a more detailed observation of the protocol's performance as the latter is perceived from the user's perspective. In addition, it provides insight on how this performance fluctuates when gradually transitioning from uniform to uneven distribution of the network's nodes. The displayed results show the protocol's performance for both CW-MT-MAC and classic MT-MAC at the user level versus the user distribution's standard deviation σ . The results are shown for $w/R = 0.5$ and 50% traffic load conditions. Fig. 6(a) and (b) illustrate the mean user throughput and its respective standard deviation for both protocols. As can be noted, not only does CW-MT-MAC achieve higher and more consistent throughput output, but its main advantage lies in the latter's standard deviation, where it exhibits significantly lower deviations compared to the MT-MAC. In agreement to the respective saturation outcomes, MT-MAC's σ -value (Fig. 6 (a)) approaches zero only for the uniform user distribution pattern, whereas CW-MT-MAC's σ -value (Fig. 6(b)) succeeds in remaining zero for the first four user distribution patterns where the number of clients n is always lower than n_{MAX} . When overcoming this point, CW-MT-MAC dedicates a wavelength to all RAUs having $n > n_{MAX}$ clients, which produces inequalities and therefore deviation of throughput. However, CW-MT-MAC clearly retains the edge over MT-MAC by offering the minimum possible deviation and therefore fairer throughput delivery. The above are also reflected in the respective mean user packet delay results displayed in Fig. 6(c) and (d), where CW-MT-MAC clearly maintains the advantage of significantly lower delay and

their respective σ -values, ergo confirming the proposed scheme's increased fairness capabilities. Over all user distributions CW-MT-MAC achieves 69% reduction in the average exhibited throughput standard deviations as opposed to the corresponding MT-MAC values (2.8 vs. 8.9 Mbps) and 72% reduction in the per user packet delay (0.7 vs. 2.5 ms).

V. CONCLUSIONS

Two variants of the medium transparent MAC protocols are summarized. The first is the pure MT-MAC that assigns wavelengths to the RAUs based on a round robin algorithm for static allocation durations. The second is the Client-Weighted MT-MAC that assigns wavelengths based on the number of active users that reside within each RAU, and for time proportionate to the latter, with the purpose of providing fairness in terms of resource allocation between the wireless nodes. The results conclude that the medium transparent MAC protocols can operate successfully over converged Radio-over-Fiber (RoF) networks, confirming their agility and showing that extended range 60GHz LAN areas between wireless users even without line of sight conditions can be obtained. In addition, the results show that the CW-MT-MAC alleviates the inter-user deviation of throughput and delay, thus proving its enhanced user-fairness properties, highlighting its ability to serve modern applications where Packet Delay Variation is a major issue.

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