Medium Transparent MAC Access Schemes for Seamless Packetized Fronthaul in mm-Wave 5G Picocellular Networks

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ABSTRACT
Telecom operators are racing towards upgrading their facilities and broadband services in order to meet the highly challenging 5G operational framework in dense urban landscapes. The oversubscribed sub-6 GHz wireless band is lacking the necessary bandwidth to support the envisioned 5G data rates, suggesting the transition to mm-wave bands as the only viable scenario. In conjunction with the cell densification that is required to achieve the desired frequency reuse factor, it becomes obvious that the current CPRI-based fronthaul cannot cope with massive multi-Gbps traffic streams and a paradigm shift in resource allocation and network intelligence is necessary. To this end we propose the Medium Transparent MAC protocols as the solution towards forming and managing a converged mm-wave FiWi fronthaul infrastructure. Our approach allows for directly negotiating wavelength, frequency and time resources between the centralized unit and the wireless terminals, while offering fast on-demand link formation following closely the demand fluctuation at the picocell level. In this paper we investigate the functional and physical consolidation as well as the respective performance of MT-MAC-enabled fronthaul and report on its application and suitability for mm-wave 5G access networks.

Keywords: radio-over-fiber (RoF), optical-wireless, passive-optical-networks (PON), SCM, 60 GHz.

1. INTRODUCTION
Next generation wireless access networks are gradually adopting two reform roadmaps. The first is the deployment of small-cells that targets to enhance spectral efficiency [1]-[2], whereas the other is adopting mm-wave bands as the primal radio solution since they provide enormous bandwidth[3]-[4]. However, the above inevitably lead to the installation of large amounts of active equipment (Base Stations (BSs)/Access Points (APs)), a fact that reduces the network’s efficiency. RoF has been proposed as an ideal solution to the above problem, since it offers several advantages such as low-cost, functionally simple and energy efficient Remote Antenna Units (RAUs), transparency regarding modulation and central control thus providing optimal resource management that traverses the entire network [5]. Even though Layer-1 functionality has been researched extensively, Layer 2 MAC RoF protocols remain an unresolved research topic. Until recently, resource management for converged Fiber-Wireless schemes was based on two approaches [6]: i) the use of different and distinct wireless and wired protocols that interface at the router (Radio-and-Fiber – R&F [7]) or ii) the direct implementation of pre-existing pure wireless MAC protocols (such as the 802.11) directly on top of RoF architectures [8]. R&F architectures however split the control algorithms in two, create two separate and hidden network portions and ultimately go against the intertwined RoF structure, disrupt the centralized control and demand a series of active APs. Regarding the second solution, all wireless MAC protocols do not consider and are unaware of the underlying optical components and therefore depend on the existence of a persistent active connection that can simply transfer bits of information whenever and however they arrive from the wireless clients to the RAU and traverse them to the CO. Considering the extremely high propagation losses that are dominant in the mm-wave bands, it becomes obvious that a large array of interconnected antennas are necessary in order to provide service to an area even at the size of an apartment. In the above circumstances, it is clear that the above solutions are not applicable. This paper provides a summary on the notion of transparency and functional split in the converged RoF Layer 2 and explains how the MT-MAC protocols can form extended reach 60GHz Wireless Local Area Networks (WLANs) that can interconnect wireless terminals even under and non-Line of Sight (LOS) circumstances.

2. MEDIUM- TRANSPARENT MAC PROTOCOLS
This section provides a short summary regarding the main features of the MT-MAC protocol. The main characteristic of the MT-MAC protocols is that the wireless nodes and the optical CO communicate simultaneously over a continuous stream of information that operates utilizes both optical and wireless media. In the MT-MAC architecture, the CO is connected through an optical fiber to a series of RAU modules that are in turn connected through mm-wave radio to the wireless terminals that are located within the range of former, as shown in Fig. 1a. All optical wavelengths used for uplink and downlink transmission are generated by the CO and are injected into the optical fiber in pairs: one for downlink (CO to RAU) and the other for uplink (RAU to CO). A special wavelength pair is set aside to use for control signalling link (hence termed the Control Channel). Amongst other operations, the control channel’s main task is to carry the necessary information to the RAUs regarding which data wavelength should the latter tune into in order to carry out the data transmission.
Bandwidth between the wireless clients and the CO is negotiated in a direct manner between the involved entities without any Layer-2 involvement on behalf of the RAUs. To this end, the MT-MAC merged the optical and wireless networks into an amalgamated network and manages to interconnect wireless terminals located in different RAUs but are served by the CO and thus overcome the LOS and even range restrictions that are always present in the traditional wireless networks. To achieve this kind of operation, the MT-MAC employs two contention periods that run over both media in parallel: the First Contention Process (FCP) is executed in both the optical and wireless networks and its purpose is to inform the CO on whether there are wireless terminals with outstanding capacity claims in any of the RAUs and if yes in which RAUs these terminals are connected to. The Second Contention Process (SCP) is employed in order to allocate optical and wireless bandwidth slots to the wireless terminals.

**Figure 1:** (a) Architecture of the MT-MAC RoF network over bus; (b) MT-MAC Second Contention and Data transmission periods.

Following the FCP, the CO instructs every RAU with pending traffic to tune its photodiodes to specific wavelengths. For the case where there are more RAUs requesting traffic than the number of available wavelengths, the CO employs the Round Robin algorithm. All data is broadcasted in chunks entitled Superframes (SFs). Each SF is comprised of Resource Requesting Frames (RRFs), whose main purpose is to transport the SCP information, and the Data Frames (DFs) that carry the actual data payload (Fig. 1b). In the pure MT-MAC described here, the number of DFs is the same always and equal to $P_{MAX}$ (fixed service). The RRF packet’s purpose is to scan and determine the number of wireless terminals that are requesting bandwidth. This ensures that only active nodes will take place in the subsequent data exchange, whereas other nodes will not be allocated resources. After all nodes have been identified, the SCP is considered as finalized and the CO creates the polling sequence and subsequently initiates the data exchange. All data are transmitted within DFs that carry the payload according to the instructions laid out by the CO. The contention resolution process that the SCP is based on employs a random number choice scheme, and if and when all the nodes choose a unique number then all terminals will be successfully identified and therefore the SCP will conclude. As it is depicted in Fig. 1b, the RRFs are divided into $s$ slots, with each slot being long enough to support the transmission of a series of POLL, ID and ACK packets. At the beginning of the RRF, each wireless terminal chooses randomly a number $y$ between 1 and $s$. This number signifies the number of POLL packets that the wireless terminal must receive prior to transmitting its ID packet. In the case that the CO receives and decodes the ID packet successfully it will reply with an ACK, notifying the wireless terminal that is has been correctly identified. However, in case two or more terminals choose the same number $y$, they will transmit at the same time, and the transmission will be unsuccessful. In turn the CO will be incapable to correctly decode the ID packets and will realize that there has been a collision. The CO will keep on transmitting RRFs until no collisions are detected. In this case the CO will now know that every node has been correctly identified and therefore will proceed with the transmission of the data packets based on the newly formed polling sequence.

### 3. CLIENT-WEIGHTED MT-MAC

The Client-Weighted MT-MAC [10] (CW-MT-MAC) is an alternate version of the original MT-MAC protocol that was presented in the previous section. Contrary to the MT-MAC, the CW-MT-MAC assigns wavelengths not following the fixed service but a variation of the gated service. Specifically, the CW-MT-MAC assigns the wavelengths for time that is proportionate to the number of clients that have been identified by the SCP. The CW-MT-MAC’s functionality is based on maintaining a record (Matrix $A$). Matrix $A$ has $q$ rows which correspond to $q$ RAUs in the whole network, and 2 columns. The first column stores the number of clients that have been identified in RAU $q$, whereas the second column stores the Utilization Counter $U_{C_q}$. The latter is a counter that shows the number of times that RAU $q$ has been granted service opportunities. The algorithm grants the first available wavelength slot time to the RAU that has the lowest $U_{C_q}$. For the RAUs that have been granted access at the latest SF, the respective $U_{C_q}$ value is incremented by $\alpha_q/\tau_q$, where $\alpha_q$ is the number of wireless terminals that have took part in the latest SF and $\tau_q$ is the total number of wireless terminals that have been identified accumulatively throughout the whole network operation time. In case two or more RAUs have the same UC value the RAU with the highest $\tau_q$ is given priority in the selection process. If $\alpha_q$ is 0, then the
$U_C^q$ is increased by 1 (meaning that all users were served) and therefore RAU $q$’s priority sustains a significant drop. In case RAU $q$ has no terminals it is removed from $A$. In the opposite scenario where RAU $q$ requests bandwidth and is not in $A$ it is inserted and given the lowest UC. The purpose of this is to give the newly inserted RAUs the maximum priority and enable the CO to quickly discover the number of users that reside within this RAU.

4. PERFORMANCE EVALUATION

The following section presents the performance evaluation of the MT-MAC and CW-MT-MAC protocols while operating over a RoF network like the one displayed in Fig. 1. The network comprises 10 RAUs with 50 m fiber interval between every two RAUs. The RAU that is physically located first in the bus is located 500 m from the CO (total network length 950 m) and each RAU has a range of 3 m. The performance results were derived using a Java simulator that is event-based. For the simulation purposes 50 terminals have been distributed to the RAUs using an alternative to the normal distribution. This alternative provides integer “bell-shaped” numbers with mean value $\mu = 5$ users/RAU. Every RAU is considered to have at least one wireless terminal within its range, thus wavelength management spans across the whole network of 10 RAUs. The wavelengths are than the number of existing RAUs in the network and the wavelength to RAU ratio is denoted as $w/R$. The employed packet generator is based on the bursty traffic model that exhibits long-tail properties (i.e. high deviation from the distribution’s mean value). Specifically, we have considered 1.5 kB of mean bursts, with standard deviation equal to 1.42 kB. The transmission opportunity window that is granted to each user was chosen to be 30 frames long (~4 kB), to ensure that the majority of the packet birth bursts would fit in a single SF. Figure 2 presents the protocols’ performances versus the optical availability ratios ($w/R$) (Fig. 2a and 2b), ranging from 0.1 and up to 0.9 as well as versus traffic loads (Fig. 2c and 2d), ranging from 10% up to 100% of the maximum theoretical network capacity.

![Figure 2](image.png)

Both protocols were tested for an extreme user distribution standard deviation $\sigma = 4.5$ (mean is $\mu = 5$). As it is evident in Fig. 2a and 2b, the results are logically classified into subgroups. The subgroup formation is based on the normalized load that the terminals are producing. In the same manner, the results depicted in Fig. 2c and 2d are grouped in the basis of the $w/R$ ratio. As can be noted in Fig. 2a, throughput increases linearly and reaches its saturation point when at the moment $w/R$ ratio surpasses the produced load, denoting that all produced packets are served effectively due to the abundance of the optical resources and as such throughput does not increase any further. The curves denoting the 80% load scenario follow the same curvature, with the respective difference being that the linear behaviour is continued for a greater range of values. When comparing the MT-MAC and CW-MT-MAC protocols we notice a very narrow superiority of the latter. Specifically, the client weighted version of the protocol exhibits a small throughput increment in the case of 30% load. This gain increases even further and reaches the value of 4% in the respective 80% load case. The performance gain is derived from the enhanced fairness of the CW-MT-MAC algorithm which assigns the wavelengths not in affixed manner but rather proportionally to the capacity requests. Compared to the fixed service regime, the wavelength capacity is moved away from sparsely populated RAUs and instead given to heavily crowded RAUs. This behaviour is also shown in Fig. 2b which displays the average packet delay. Delay values begin at very high values in the area where the load surpasses the $w/R$ ratio. This is occurring naturally since in this part of the graph the produced load is greater than the max theoretical capacity offered by the available $w/R$ ratio. As the latter increases though, delay values drop significantly since the increased capacity can now serve the offered load. By assessing the results, it becomes evident that in the cases where the population of the wireless terminals is unevenly distributed amongst the RAUs, the CW-MT-MAC performs better. Figures 2c and 2d depict the MT-MACs’
performances for varying load conditions, namely from 10% up to 100%. Of the maximum theoretical capacity. The displayed results correspond to two different w/R ratios, namely 0.3 and 0.8. In Fig. 2c we can view the total system throughput versus load. The results indicate that there is a linear relationship between throughput and load regarding both MT-MACs at the graph area where the generated traffic is less than the w/R ratio. However, as load continues to increase, throughput stops increasing and instead stabilizes around a saturation value. This is attributed to the fact that when load exceeds the w/R value traffic is in excess of the wavelength capacity and therefore gets dropped. Correspondingly the delay results depicted in Fig. 2d start off at very low values while load is below the w/R and increase when the former approaches or surpasses the later. When generated traffic moves beyond the w/R, point the delay values continue to increase until they also reach their saturation point, since the packets that get dropped are not counted in the delay metrics. Again, we notice again a small performance gain in favour of CW-MT-MAC stemming from the more balanced and fair distribution of wavelengths.

To investigate more deeply the CW-MT-MAC’s performance on the more granular user level we present Figs. 2e and 2f. The derived results show the protocols’ performances regarding the per user throughput and packet delay versus the user distribution’s standard deviation σ. The displayed results correspond to w/R = 0.5 and 50% load. Figure 2e illustrates the per user throughput for both protocols. The symbols on the curves correspond to the mean values whereas the protruding lines correspond to the standard deviation of these mean values. The results show that CW-MT-MAC achieves higher throughput values as compared to the MT-MAC but also achieves a very low standard deviation. Where the MT-MAC standard deviation is close to 0 only in the uniform user distribution, the CW-MT-MAC’s manages to deliver 0 deviations for the first four user distributions. In this way, the CW-MT-MAC clearly outperforms the MT-MAC and offers only minimal standard deviation and thus gives a fairer and more consistent performance to the participating users. The above conclusions are also true in Fig. 2f, where we can witness that again the CW-MT-MAC offers not only lower delays but also diminishes the deviation of the mean packet delays experienced by the users.

5. CONCLUSIONS
This paper summarizes the notion of medium transparency and shows its performance under a Radio-over-Fiber architecture employing mm-wave radio. To this day, two versions of the MT-MAC protocols have been presented: The first MT-MAC assigns wavelengths based on a round robin functionality and thus for equal time intervals. The second version (Client-Weighted MT-MAC) assigns wavelengths for time proportionally to the number of users of each RAU. This variation targets use cases where capacity fairness amongst the users of every RAU is a necessity. Results show that both protocols can successfully form end-to-end converged hybrid RoF networks that provide extended range mm-wave LAN connectivity to wireless terminals even when the latter are out of LOS. Furthermore, the results indicate that the Client Weighted version of the MT-MAC diminishes the standard deviation in terms of throughput and packet delay between the users. To this end, the MT-MACs exhibit their capacity to form a complete access framework supporting for the upcoming 5G networks.

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