Non-saturation delay analysis of Medium Transparent MAC protocol for 60GHz Fiber-Wireless towards 5G mmWave networks

G. Kalfas, J. Vardakas, L. Alonso, C. Verikoukis and N. Pleros

Abstract—In this paper we demonstrate an analytical model for computing the end to end packet delay of a converged Optical/Wireless 60GHz Radio-over-Fiber (RoF) network operating under the Medium-Transparent MAC (MT-MAC) protocol. For the calculation of the cycle times this model considers the protocol time consumed for contention and data exchange over both optical and wireless media, a feature of the MT-MAC that effectively enables it to provide direct and seamless interaction between the RoF Central Office (CO) and the end users. This new analytical model enables us to conduct an extensive delay performance analysis of the various performance aspects of hybrid RoF networks operating under the fixed service paradigm, such as various optical capacity availability scenarios, varying load conditions, optical network ranges, transmission window lengths and data packet sizes. The derived theoretical results present an excellent match with the respective simulation findings, providing sub millisecond latency values for a plethora of network conditions, confirming that the MT-MAC scheme can effectively be incorporated into the upcoming mm-wave 5G era.

Index Terms—5G; Radio-over-Fiber; small cells; Medium-Transparent MAC; Delay analysis; non-saturation conditions; Integrated wired/wireless access;

I. INTRODUCTION

THE profound data service proliferation and the ever-growing need for wireless broadband services have incentivized the speedy development of the 5th Generation of cellular systems (5G) [1]. 5G specifications have evolved around the “everything in the cloud” notion which envisions an unhindered desktop experience while the consumers are on the move. To this end, 5G technology is being currently

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

developed to go far beyond that of 4G and to adhere to a plethora of advanced requirements such as peak data rates up to 10 Gbps, cell edge data rate of 1 Gbps, mobility up to 500 km/h, a million simultaneous connections per km², and perhaps most importantly a latency of 1 ms[2],[3]. In order to address the arising needs, industrial and academic partners alike foresee the need for a “revolution” not only in the peripheral but also at several core elements of the network[4]. Recent studies have testified the excellent capacity of the mm-wave bands towards bridging the gap between the currently established 4G networks with 5G specifications by augmenting the currently congested sub-2.6 GHz spectrum bands employed in the telecom industry[5]-[7]. Albeit a limiting factor, the mm-waves’ high propagation losses property, remains inherently compatible with the trend to establish pico-cells and increase spatial reuse, a fact that has proven to be the most effective way to enhance the spectral efficiency[8]. Moreover, the combination of broader channel allocations, together with matured cost-effective mm-wave CMOS technology bolsters the argument for adopting mm-wave solutions in the 5G era[9],[10]. However, the possibility of using mm-wave bands to increase capacity, necessitates completely new access schemes not only for building RF transceivers and base stations but also regarding architectural convergence and protocol operation.

The Medium Transparent MAC (MT-MAC) protocols have been proposed as efficient schemes to seamlessly converge the mm-wave small-cell wireless architecture with the optical backhaul infrastructure towards minimizing communication latency, providing ultra-high speed wireless access with centralized overview and optimizing resource utilization [11],[12]. Similar to other access control protocols that have been proposed for converged Radio-over-Fiber(RoF) networks[13][14], the MT-MACs are specifically designed to

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

operate upon a hybrid optical/wireless underlying infrastructure, as depicted in Fig. 1. The MT-MAC protocols aim at providing dynamic optical and wireless resource allocation directly between a central intelligent entity (the Central Office -CO) and the mm-wave wireless terminals through the Remote Antenna Units (RAUs) that act solely as RF/optical signal converters. The MT-MAC protocols that have been presented to date operate under two service schemes: i) the fixed-service regime where each RAU is granted a static size transmission window, and, ii) the Client-Weighted MT-MAC (CW-MT-MAC) that utilizes a modified version of the gated service paradigm where each RAU is granted a transmission window with size based on the number of terminals residing within its range. The authors have presented a mathematical model that provides an analytical framework for calculating the saturation throughput for the MT-MAC[12] and CW-MT-MAC[15] protocols. However, despite the framework that enables the analysis in terms of throughput under saturation conditions, there is still no theoretical framework for the non-saturated conditions, which would allow a delay analysis and a deeper insight into the credentials of the MT-MAC protocols and the fixed service regime to support the highly demanding latency requirements in 5G environments.

In this article, we demonstrate an analytical model and a highly detailed delay analysis for the RoF-enabled MT-MAC protocol described in [11], considering various wireless network load conditions, optical wavelength availability ratios, fiber lengths, wireless transmission windows sizes and data packet payloads. This way, the proposed analysis becomes the first non-saturation model to concurrently address optical and wireless resources allocation, since other state-of-the-art RoF models consider contention solely in the wireless medium with only fiber delay aspects being accounted as part of packet delay estimation[16]-[18]. The model proposed in this paper combines a 2D Markov chain for calculating the delay of the wireless contention process with the cycle estimation analysis regarding the Interleaved Polling with Adaptive Cycle Time (IPACT) protocol carried out in [19]. In order for the latter to account for the converged optical/wireless cycle time and the dynamic wavelength allocation scheme, the cycle estimation has been extended to include the RAUs' waiting times caused by the wavelength assignment delays and the optical contention process. The proposed analytical formula and the respective outcomes

coincide with the simulation-derived results, confirming the validity of the presented dual-medium MT-MAC delay model and its applicability as a roadmap towards identifying the optimal configuration of a hybrid RoF network. This first successful non-saturation optical/wireless MT-MAC delay model confirms that the Gb/s-scale data-rate optical-wireless convergence can yield even sub-msec delay values in non-saturation network conditions, suggesting novel and efficient resource allocation concepts suitable for future 5G networks.

The paper is outlined as follows: Section II describes the MT-MAC protocol operational functions. Section III presents the analytical model for deriving the packet delay of the bimodal MT-MAC network. Section IV presents the performance evaluation through an extensive series of analytical and simulation results. Finally, Section V concludes the paper.

II. MEDIUM-TRANSPARENT MAC PROTOCOLS OVERVIEW

This section summarizes the main operational characteristics of the MT-MAC protocol that affect the produced packet delay performance. For a complete description of the MT-MAC protocol, including full Physical Layer specifications and all the underlying 60GHz RoF network mechanisms we refer the reader to [11].

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 in order 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 packet's 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 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. In parallel to the data exchange, the CO re-executes the FCP process, so as to update the list of RAUs requesting traffic.

III. MATHEMATICAL ANALYSIS

For the mathematical model we consider an MT-MAC network consisting of the CO, w wavelength pairs and R RAUs connected to the CO through an optical fiber of length L km. The network is utilizing an optical bus topology and the inter-RAU fiber interval is l km, i.e. the first RAU is L km away from the CO, the second RAU is $L + l$ km away from the

CO, etc. Data packets are generated based on a Poisson generation model with bit rate of λ Mbits/s and a fixed size of B bits. Traffic is assumed to be symmetric, meaning that all clients introduce the same load into the network. The fiber transmission links provide 1 Gbit/s of bandwidth to each RAU which is shared amongst the wireless terminals serviced by each RAU. All RAUs are considered to serve the same number of clients n and therefore the symmetric traffic property applies in the RAU domain as well. We declare T_{cycle} to be the time interval that takes place between the start of two successive data transmission windows for a specific RAU.

Since the MT-MAC operates under fixed service we can derive an accurate estimation of the cycle duration. To do that we need to specify the duration of the SF T_{SF} and the waiting period T_{WAIT} . T_{WAIT} refers to the time that a RAU has no assigned wavelengths either due to lack of pending traffic or due to wavelength time sharing amongst the network's RAUs. T_{SF} is equal to the sum of the duration of the SCP T_{SEC} and the data transmission period T_{DATA} . The first is comprised of one mandatory RRF followed by optional RRFs in case the first does not suffice in resolving the clients that request channel access. According to the MT-MAC rules the duration of the RRF frame T_{RRF} is defined as:

$$T_{RRF} = 3\delta_{FIBER} + s(3\delta_{AIR} + T_{POLL} + T_{ID} + T_{ACK}) \quad (1)$$

where δ_{AIR} is the propagation delay in the wireless medium, s is the size of the slots pool that the clients choose a random number from and T_{POLL} , T_{ID} and T_{ACK} are the transmission delays of the POLL, ID and ACK packets respectively. On the other hand, T_{DATA} is defined as the time it takes to transmit several sequential DFs plus the corresponding POLL and ACK frames. In the fixed service regime, the number of sequential DFs that is granted per RAU is immutable and always equal to P_{MAX} . DF's duration T_{DF} is defined as:

$$T_{DF} = \frac{2\delta_{FIBER} + 3\delta_{AIR} + P_{MAX}(T_{POLL} + T_{DATA} + T_{ACK})}{P_{MAX}} \quad (2)$$

where T_{DATA} is the transmission delay of the DATA packet. Based on the above we define T_{SF} as:

$$T_{SF} = T_{RRF} + P_{MAX}T_{DF} \quad (3)$$

Notice that at this point we consider only one RRF per SF. As described before, due to the MT-MAC rules this is not the only possibility since it could take more than one RRFs for the SCP to resolve. Later on, a corrective factor will be added to account for that event, but at this point only the mandatory RRF is taken into account. Having defined T_{SF} , T_{cycle} is calculated as:

$$T_{cycle} = \frac{R}{w}T_{SF} \quad (4)$$

Since T_{cycle} is considered to be constant, the system can be considered at discrete moments that are apart T_{cycle} seconds as depicted in the example provided in Fig. 2.

We define $Q(m)$ to be the queue size of a RAU at time $t = m * T_{cycle}$. $Q(m)$ is a discrete homogeneous Markov chain, which effectively means that $Q(m)$ depends on the "past" states $(Q_0, Q_1, \dots, Q_{m-1})$ only through the present state and is independent of m . Therefore, we are able to define the

Fig. 3 The 2nd Contention Resolve Markov chain.

transition probabilities and the corresponding transition matrix as it has been similarly done in [19]:

$$p_{i,j} = \Pr[Q(m+1) = j | Q(m) = i] \quad (5)$$

$$P = \begin{pmatrix} p_{0,0} & p_{0,1} & p_{0,2} & \cdots & p_{0,M} \\ p_{1,0} & p_{1,1} & p_{1,2} & \cdots & p_{1,M} \\ p_{2,0} & p_{2,1} & p_{2,2} & \cdots & p_{2,M} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & p_{M-1,M} \\ 0 & 0 & 0 & \cdots & p_{M,M} \end{pmatrix} \quad (6)$$

The transition probabilities of matrix P are given below:

$$p_{i,0} = \sum_{k=0}^{P_{MAX}-i} e^{-\frac{\lambda}{B} T_{cycle}} \frac{\left(\frac{\lambda}{B} T_{cycle}\right)^k}{k!} \quad (7a)$$

for $i \leq P_{MAX}$,

$$p_{i,j} = e^{-\frac{\lambda}{B} T_{cycle}} \frac{\left(\frac{\lambda}{B} T_{cycle}\right)^{P_{MAX}+j-i}}{P_{MAX}+j-i} \quad (7b)$$

for $i \geq 0, j > 0$ and $j-i \geq -P_{MAX}$,

$$p_{i,j} = 0 \quad (7c)$$

for $i, j \geq 0$ and $j-i < -P_{MAX}$.

Equation (7a) states that if the number of Poisson generated packets is less or equal to the maximum size of the transmission window, then all the packets will be sent within that transmission window. This probability is calculated as the sum of probabilities for having 0 up to P_{MAX} packet arrivals. The general probability of having a transition from i packets in the queue at the instant m to j packets in the queue at instant $m+1$ in a cycle period is equal to the probability of

generating exactly $P_{MAX} + j - i$ packets and is given in (7b). Equation (7c) is a special case of (7b) and it states that if j is smaller than $i - P_{MAX}$ then $p_{i,j}$ is zero since that transition would require a transmission window greater than P_{MAX} . In order to be able to derive results we must set the upper limit M of the buffer size. This limits the dimension of the matrix P , causing the sum of the elements of all the lines to be less than one, which contravenes the mandatory property of a Markovian matrix. The solution is provided by defining the last element of each row of matrix P as:

$$p_{i,M} = 1 - \sum_{j=0}^{M-1} p_{i,j} \quad (8)$$

In order to derive the stationary probabilities denoting the queue sizes, we must solve the following linear system of equations:

$$\pi P = \pi \quad (9)$$

$$\sum_{i=0}^M \pi_i = 1 \quad (10)$$

where π is the vector defining the probabilities of the queue sizes ranging from 0 to M in the steady state. The average queue size $\hat{Q}$ at the end of each transmission cycle is:

$$\hat{Q} = \sum_{i=0}^M \pi_i i \quad (11)$$

In order to derive the average queue size Q in the continuous time domain we must add the terms that account for the packets that have been produced during the SCP that precedes each SF and the packets that are born in between the discrete moments, i.e. T_{cycle} intervals. For calculating the average number of RRFs that will take place at the beginning of each SF we employ a two-dimensional (2-D) Markov chain model, depicted in Fig. 3, which represents the SCP again from the perspective of a single RAU. The model follows the $S_{i,k}$ naming convention, where i signifies the i -th RRF frame of the current SF, whereas k signifies the number of wireless nodes that have not yet been identified by the SCP process. The states of the form $S_{0,k}$ denote the initial state of the users, i.e. the beginning of the SF.

The 2nd Contention Markov chain can be logically divided into distinct rows and columns. The first row corresponds to the initial state of the SCP where all wireless clients are unresolved, whereas each individual row after that corresponds to a single frame in the SF, i.e. the 2nd row corresponds to the 1st frame, the 3rd row to the 2nd frame and so forth. The columns correspond to the number of nodes that have not yet been resolved by the SCP. To this end, the outmost left column denotes the maximum number of unidentified nodes n , whereas the outmost right column represents the minimum number of unresolved clients, i.e. zero. Therefore, all states of the type $S_{i,0}$ represent the DATA TX period, whereas states of type $S_{i,0}$ with $k > 0$ represent the SCP. Note that states of type $S_{i,1}$ are not included in the Markov diagram, since under no circumstances can only one user remain unresolved.

TABLE I SIMULATION SPECIFICATIONS

Parameter	Symbol	Value/Range
Number of Wavelengths	w	3-10
Number of RAUs	R	10
Fiber Length between CO and 1st RAU	L	200m-10km
Packet arrival rate at the RAU	λ	0.1-1 Gbps
Fixed Transmission Window	P_{MAX}	30
Fiber propagation delay	δ_{FIBER}	$1\mu s = 200m$
Slots in RRF	s	10
Number of clients per RAU	n	5
RAU range	r	10m
Air propagation delay	δ_{AIR}	$0.032\mu s$
Number of RRFs per SF	N_{RRF}	Variable
Wireless Data Bitrate	C	1 Gbps
ACK Size	B_{ACK}	8 bytes
DATA Packet Size (at the MAC layer)	B	1500 bytes
POLL Size	B_{POLL}	64 bytes
ID Size	B_{ID}	64 bytes

The initial steady state probabilities are set based on the stationary distribution of queue sizes π :

$$\begin{cases} S_{0,0} = \pi_0 \\ S_{i,0} = \pi_i \text{ for } 0 < i < n \\ S_{n,0} = \sum_{i=n}^M \pi_i \text{ for } i \geq n \end{cases} \quad (12)$$

The transition probability from state $S_{i,k}$ to state $S_{i+1,k-x}$ equals to the event of having x unresolved nodes making a unique y value choice. This probability is provided by the equation:

$$p_k(x) = \frac{(-1)^x s! k!}{x!} \sum_{a=x}^k \frac{(-1)^a (s-a)^{k-a}}{(a-x)! (s-a)! (k-a)!} \quad (13)$$

for $k \in [2, n]$, $x \in [0, k] \setminus \{k-1\}$.

Equation (14) provides all the non-null one-step transition probabilities:

$$\begin{cases} p\{i+1, k-x|i, k\} = p_k(x) \\ p\{i+1, 0|i, 0\} = 1 \end{cases} \quad (14)$$

for $i \in [1, i_{\max}]$, $k \in [0, n] \setminus \{1\}$, $x \in [0, k] \setminus \{k-1\}$. The second part of (14) signifies the end of the SCP once all nodes have been resolved. From that point on, the CO begins the DF series transmission until it reaches the end of the SF duration.

The steady state probabilities of type $S_{k,0}$ (with $k > 0$) form the Cumulative Distribution Function (CDF) of the numbers of RRFs that are necessary for completing the SCP. Since the number of RRFs is an integer, we obtain the Probability Mass Function (PMF) from the CDF by means of subtraction. In turn, the PMF is used to derive the average number of RRFs N_{RRF} necessary to complete the SCP. In turn N_{RRF} is used to calculate the average number of packets that have been produced during the SCP:

$$Q_{RRF} = \frac{\lambda}{B} (N_{RRF} - 1) T_{RRF} \text{ for } N_{RRF} \geq 1 \quad (15a)$$

$$Q_{RRF} = 0 \text{ for } N_{RRF} = 1 \quad (15b)$$

Notice that in (15a) 1 was subtracted from N_{RRF} , since in the initial calculation of T_{cycle} the first RRF, which is mandatory, was already included.

To finalize the transition of the average queue size from the discrete to the continuous time domain we must account for the average number of packet arrivals that occur in between

Fig. 4 Delay vs. Normalized load for 10 RAUS and 10 wav. (100% WR), 8 wav. (80% WR), 5 wav. (50% WR) and 3 wav. (30% WR).

the T_{cycle} intervals. Because Poisson arrivals are uniformly distributed in time, the continuous-time average queue size is equal to the average queue size in the middle of the cycle intervals, i.e. the middle of the cycle.

$$Q_{mid} = \frac{\lambda T_{cycle}}{B} \frac{1}{2} \quad (16)$$

The average queue size in continuous time is:

$$Q = \hat{Q} + Q_{RRF} + Q_{mid} \quad (17)$$

By means of Little's law, which states that the average number of packets in a stable system is equal to their average arrival rate multiplied by their average waiting time in the system, we yield the average waiting time or delay D :

$$D = Q * \frac{B}{\lambda} \quad (18)$$

IV. PERFORMANCE EVALUATION

This section presents the performance of the proposed analytical model and evaluates its accuracy by comparing the delay values against the respective results obtained by the non-saturation simulation platform employed in [11],[15]. The results produced here correspond to a network configuration comprising 10 RAUs in a bus topology, serviced by w optical wavelength pairs each offering 1Gbps backhaul capacity as displayed in Fig. 1. The full specification parameters utilized in the simulation run and the respective analytical model (where applicable) are summarized in Table I. Performance is tested for various load conditions, wavelength availabilities, fiber lengths, transmission window sizes and data packet sizes. In this paper load values correspond to the aggregated Poisson arrivals of all the wireless terminals per RAU and are presented in a normalized scale compared to the wireless channel capacity, ranging from 10% (100Mbps) up to 95% (0.95Gbps). Wavelength availability is referred as Wavelength to RAUs Ratio (WR) and is displayed as a percentage, i.e. for 10 RAUs and 3 wavelengths WR is 30%, whereas for 10 RAUs and 8 wavelengths WR is 80%. The different WRs allow the study of the RoF system under dynamic operative conditions where the engagement of the optical resources is assigned on the fly based on the desired service level. In all the figures that follow, simulation results are displayed with the use of a circle symbol and represent the average of 100 runs while the protruding capped vertical lines signify the 95%

Fig. 5 (a)Analytical delay results versus the length of the optical part of the network for 10 RAUs and 10 wavelengths (100% WR) for 10-95% normalized load (b)Simulation and analytical delay results versus the length of the optical part of the network for 10 RAUs/10 wavelengths (100% WR) and for 10-50%/80% norm. load.

Fig. 6 (a) Analytical delay results versus the length of the optical part of the network for 10 RAUs/5 wavelengths (50% WR) for 10-45% normalized load (b) Simulation and analytical delay results versus the length of the optical part of the network for 10 RAUs/5 wavelengths (100% WR) and for 10-20%/45% norm. load.

confidence interval, meaning that 95% of the produced simulation values fall within this interval.

A. Performance vs. Load

Fig. 4 displays the packet delay versus various load conditions for four different WRs namely 30%, 50%, 80% and 100%. By examining the curve corresponding to 100% WR we notice that delay values start off in the sub 0.4 millisecond range and remain very low as long as the per RAU load is under 80% (800Mbps). In this area we also notice that the theoretical results practically coincide with the average values of the respective simulation runs. When the offered load approaches the maximum theoretical wireless channel capacity, delay values increase rapidly as the packets remain longer in the buffer queue awaiting transmission. While the network resides in these high load conditions we also note small deviations between the average simulation and the analytical results. This discrepancy is explained by the fact that near the maximum theoretical wireless channel bitrate the average arrival rate approaches the system's capacity, resulting in the queue becoming unstable and therefore susceptible to small variations caused by the probabilistic Poisson traffic. However, even in this saturated scenario the analytical results are within the 95% confidence interval of the simulation runs.

The same behavior applies in the delay performance curvature for all other tested WR cases depicted in Fig. 4, meaning that delay values start and remain very low (sub 0.5ms) until the point that the network enters its saturation regime. Note that for each of the different presented WR, the saturation point is not constant, i.e. for 30% WR the network saturates above 20% load (200Mbps) offered load per RAU, whereas for 80% WR the saturation point is around 70% load (700Mbps) of generated traffic. This comes as a direct effect of the backhauling capability of the presented network, since the latter depends on and is limited by the number of wavelengths available to the network. In turn, the different wavelength availabilities attribute for the absolute delay value that each configuration reaches in the congested areas, since the lack of wireless capacity in the low WR ratios forces each client to wait longer periods for a wavelength assignment, thus introducing further delays.

B. Performance vs. Fiber Length

Fig. 5 and Fig. 6 present the packet delay performance versus various fiber lengths ranging from 200m up to 10km for two WRs, namely 50 and 100%. The normalized load generation ranges from 10% up to the point where the network enter its saturation regime, which is 95% for 100% WR

Fig. 7 (a) Delay versus the length of the transmission window P_{max} for 10 RAUs/10 wavelengths (100% WR) and for 10-95% normalized load (b) Simulation and analytical delay results versus the length of the transmission window P_{max} for 10 RAUs/10 wavelengths (100% WR) and for 10-50%/90% norm. load

Fig. 8 (a) Delay versus the length of the transmission window P_{max} for 10 RAUs/5 wavelengths (50% WR) (a) for 10-45% normalized load (b) Simulation and analytical delay results versus the length of the transmission window P_{max} for 10 RAUs/5 wavelengths (50% WR) and for 10-30%/45% norm. load

scenario and 45% for the 50% WR case. As can be noted in the 100% WR case displayed in Fig. 5(a), for low or medium load generation ranging up to 50% of normalized load, delay values are very low and always in the sub 0.5ms range for all tested fiber lengths up to 10km. The derived delay results display only a very small performance degradation taking place between the shorter and longer tested network ranges, due to the increased propagation delay affecting every packet of the SF. This shows that when there is high optical capacity availability, the MT-MAC protocol is capable of tolerating long fiber hauls and is able to achieve optimum delay values as long as the offered network load does not exceed 50% of the maximum theoretical normalized value. At higher generated load conditions, like in the case of 60% load, the MT-MAC protocol fails to maintain its low latency properties in long fiber lengths. Specifically, when the fiber length exceeds 8km, delay values increase rapidly, as the enhanced propagation delays of all the packets accumulate and lead to larger cycle times. Since load is a constant percentage of the wireless bitrate, which is independent of the fiber length, the larger cycle times result in having more packet births than the amount of data frames that can be served by the static transmission window. The excess packets must therefore wait for the next SF assignment, which will take place after all

other RAUs have been served by the CO, as per the MT-MAC rules, thus explaining the rapid increment of the packet delay displayed in the results.

The same behavior is also evident in all displayed curves representing loads ranging from 70-95%. Here the alternating factor between the tested load conditions is the maximum fiber length that can be tolerated for each load value, i.e. at 70% load, the maximum fiber length within which the MT-MAC protocol exhibits low delay properties is around 5km, at 80% the saturation point drops to 2km and at 90% load the maximum fiber length drops to 400m. In the extreme scenario of 95% load, the network appears saturated even for the smallest fiber lengths, effectively denoting the upper limit where the MT-MAC's remote arbitration scheme is capable of delivering fast service to the end users. In order to confirm the high level of accuracy between theoretical and simulation results, Fig. 5(b) presents the derived analytical and simulation delay values for the cases of 10-50% and 80% load. Again here it can be seen that for low to medium load conditions the analytical and simulation results coincide perfectly for all derived values of fiber length, since the network does not enter its saturation regime which would cause buffer space depletions and instability in the queue. However, in high load conditions, such as 80% norm. load, the network enters its

Fig. 9 (a) Delay versus the Data Packet size for 10 RAUs/10 wavelengths (100% WR) and for 10-95% normalized load (b) Simulation and analytical delay results versus the Data Packet size for 10 RAUs/10 wavelengths (100% WR) and for 10-60%/90% norm. load.

saturation regime when the fiber length surpasses 2000m and the queue becomes unstable. This leads to small discrepancies between simulation and theoretical results that are nonetheless always within the 95% confidence interval.

Regarding the 50% WR ratio depicted in Fig. 6(a), a similar performance pattern is observed for low load values (up to 20%), with delay being constantly in the sub 0.5ms region for all tested network ranges up to 10km. However, as the ingress load increases, the network enters its saturation regime when fiber length increases beyond a certain point. As in the scenario displayed in Fig. 5, the specific length where the increased cycle time causes the network to saturate is based on the offered network load, ranging from 8km in the case of 30% load down to 200m in the extreme scenario of 45% load. It is also noteworthy that in the 50% WR scenario the actual delay is greater compared to the case of 100% WR, due to the fact that wavelength sharing causes added delays as the RAUs are forced to wait approximately 50% of the system time for a wavelength assignment. Fig. 6(b) confirms the high level of agreement between the theoretical and simulation results that are always within the 95% confidence interval even in high load conditions, such as the depicted case of 45% normalized load.

C. Performance vs. Transmission Window Size $P_{\max}$

One of the most crucial parameters that define the performance of the fixed service regime is the size of the transmission window $P_{\max}$. The analysis proposed here can be employed to derive the optimum window size based on the available WR and the load conditions. Fig. 7 and Fig. 8 present the packet delay performance of the hybrid MT-MAC protocol versus $P_{\max}$ for two different WR ratios, namely 50 and 100%. The normalized load generation ranges from 10% up to the point where the network enter its saturation regime, which is 95% for 100% WR scenario and 45% for the 50% WR case.

Fig. 7 presents the case of the 100% WR versus the $P_{\max}$ value ranging from 10 up to 100 packets per static window assignment. A $P_{\max}$ size below 10 was not considered here, since for very small transmission windows the overhead of the SCP would occupy a significant percentage of the network

time, making it impractical for every possible application. As can be seen in Fig. 7 (a), while the offered load ranges from 10% up to 50%, delay values remain very low and increase linearly with $P_{\max}$ at a very low rate. The reason for the slow performance deterioration is that in low traffic conditions a large transmission window size leads to underutilization of the wireless channel, since the initial polling sequence constructed at the beginning of the SF is larger than the number of packets waiting in the nodes' buffers. This directly translates to unused transmission opportunities when the nodes' buffers are depleted. Moreover, larger transmission windows lead to larger cycle times and therefore to less frequent executions of the SCP which, according to the MT-MAC rules, is responsible for constructing the polling sequence in the CO. This forces the inactive users that did not partake in the last SCP to wait longer periods until the beginning of the next SF, thus introducing further delays into the network. As load increases further, we observe that the delay performance is no longer linear to $P_{\max}$, but instead very small $P_{\max}$ values (i.e. 10) exhibit higher delays than larger $P_{\max}$ values (i.e. 20). Once the delay reaches its global minimum, linearity is reestablished and any further increase in the transmission window results in a small rate linear increment of the delay, similarly to the low-medium traffic conditions. This behavior is caused by the fact that for very small $P_{\max}$ values, the transmission window no longer suffices for all packets to be transmitted, thus a part of the outstanding traffic is forced to wait for the next transmission opportunity that will take place in the following SF. When load increases even further (90% norm. load), incoming traffic greatly exceeds the capacity of the transmission window causing high delays and instability in the queue which results in the exhibited difference between the theoretical and simulation results, as it can be seen in Fig. 7 (b). As $P_{\max}$ increases however, delay values decrease and the system's utilization factor drops below 1, resulting in the theoretical results to be well within the 95% confidence interval, once again proving the excellent matching between the theoretical analysis and the simulation. Finally, in the extreme case of 95% normalized load depicted in Fig. 7(a), the system resides in unstable saturation conditions for all the tested values of $P_{\max}$, therefore exhibiting delay values above

Fig. 10 (a) Delay versus the Data Packet size for 10 RAUs/5 wavelengths (50% WR) and for 10-45% normalized load (b) Simulation and analytical delay results versus the Data Packet size for 10 RAUs/5 wavelengths (50% WR) and for 10-30%/45% norm. load

3ms for all tested window sizes.

In the 50% WR scenario depicted in Fig. 8, we note that the system exhibits the same overall behavior with the difference being that the system enters saturation regime in lower normalized load values and produces higher absolute delay values as opposed to the 100% WR scenario. The latter is again attributed to the fact that the RAUs are inactive for a significant portion of the system time while waiting for wavelength assignment, thus contributing towards higher delay values. Fig. 8(b), once again verifies the very close proximity between the theoretical and simulation results, validating once again our proposed delay analysis.

D. Performance vs. the Data Packet size

Fig. 9 and Fig. 10 present the MT-MAC's delay performance versus the size of the Data Packet at the MAC layer for two WR ratios, namely 50 and 100%. The normalized load generation ranges from 10% up to the point where the network enter its saturation regime, which is 95% for 100% WR scenario and 45% for the 50% WR case. The tested Data Packet sizes range from 500 up to 15000 bytes per packet. Fig. 9 presents the scenario of 100% WR, where we observe that in low load conditions the increment of the Data Packet size leads to a small rate linear increment in the derived delay. This is due to the fact that the larger the data packet size the more time it takes for a packet to reach the head of the polling sequence and initiate transmission. A further increment of the offered traffic above 60% of the maximum theoretical capacity creates a phenomenon similar to the previous section, meaning that very small packet sizes cause the network to perform worse than greater packet sizes. This is due to the fact that for very small payload sizes the generated traffic exceeds the capacity of the packet and therefore data has to be split into several packets. The increased number of packets reduces the protocols efficiency since it also increases the overhead of the actual transmission due to the additional headers and signaling requirements. However, we also notice that once the packet size grows large enough to accommodate the produced traffic, delay values drop until they reach their

minimum value, signifying the optimum packet size for the specific load/WR conditions. Beyond this optimum value any further increment causes the delay to increase at a low rate for the same reasons as the ones stated in the low load conditions scenario. The very high load scenarios (i.e. 80-90%) follow a different curvature than the rest of the load conditions. Specifically, in both figures delay values start low, then rapidly increase until they reach a maximum value, and in turn drop before resuming the normal linear behavior that was evident in the previous figures. In order to justify this behavior, we include Table II that presents the average normalized throughput values and packet drops percentages as they were derived by the simulator. Normalized throughput values have been calculated as the number of data packets that were correctly delivered per time slot, with a time slot being equal to the time required for a data packet to be transmitted. As it can be seen in the left-most portion of the respective curves, while the delay slope is increasing, throughput values

TABLE II THROUGHPUT VALUES 100% WR

P. Size (bytes)	Load 90%		Load 95%	
	TH	PD	TH	PD
500	0.692	23.0%	0.692	27.2%
1000	0.818	8.50%	0.818	14.0%
1500	0.871	3.35%	0.871	7.86%
2000	0.890	0%	0.899	3.70%
2500	0.892	0%	0.918	2.82%
3000	0.900	0%	0.930	1.01%
3500	0.890	0%	0.937	0.33%
4000	0.891	0%	0.944	0%
4500	0.897	0%	0.945	0%

TH: Average Normalized System Throughput (0-1)

PD: Average Packet Drop Percentage (0%-100%)

are less than the corresponding normalized load since the network exhibits packet losses. The latter effectively means that the system services less packets than the ones that are generated and therefore delay values are counted as lower, since the packets that succeed in entering the buffer are serviced faster while the discarded packets are not taken into consideration when measuring the system's delay performance. To this end, as long as the packet drops are more than zero, the delay measurements appear lower due to the assumption that the buffer's capacity is finite. While the

packet size increases and packet drops approach zero, delay increases since the measurement process accounts for a greater percentage of the generated packets, therefore becoming more accurate. Finally, when packet drops become zero, the curvatures of the results resume a path similar to the ones presented in the cases of 60-70% load. Note here that, due to the increased load, the packet size must increase to 4000 bytes for the system to experience zero losses in 95% traffic, whereas 2000 bytes suffice for 90% load. Again by means of Fig. 9(b) we notice that the theoretical results are always within the 95% confidence interval of the corresponding simulation results.

Fig. 10 presents the same study for 50% WR ratio. Upon examination, we notice that the results follow the same curvature, with the difference being that the absolute delay values are higher than the corresponding results of 100% WR and increase at a higher rate. The latter is attributed to the fact that insufficient packet sizes and the consequent data segmentation into multiple MAC layer packets has a more detrimental effect when the end nodes must wait for wavelength assignment before being polled to transmit.

E. Application perspectives in the coming 5G era

The non-saturation delay analysis presented here can function as a roadmap towards highlighting the applicability of the MT-MAC protocol in the upcoming era of 5G mobile networks. Given the analysis' capability to provide an end-to-end packet delay estimation for a plethora of network specifications, the latter can be employed towards identifying the conditions where the MT-MAC protocol satisfies the strict 1ms 5G packet delay mark[20][21]. The above knowledge can be directly applied towards developing an MT-MAC based packetized fronthauling solution, that overcomes the shortcomings and limitations of the Common Public Radio Interface (CPRI) that has been proven to be majorly ineffective towards interconnecting Remote Radio Heads (RRHs) to the BaseBand Unit (BBU) pool of Cloud-Radio Access Networks (C-RANs)[22]-[25]. In this way, the presented model can fully describe the optimum network specifications of a mm-wave Gigabit 5G packetized fronthauling network, since it addresses all aspects of the latter, such as load, optical capacity, fiber length, transmission window size and packet payload.

V. CONCLUSIONS

In this paper we have proposed an analytical model for calculating the end to end delay of the MT-MAC protocol that provides dynamic allocation of both fiber and wireless resources in 60GHz RoF networks [11]. The presented analytical model enabled the calculation of packet delay under non-saturation conditions, successfully validating the respective simulation results for various numbers of optical wavelength availability factors, network loads, fiber lengths, transmission window sizes and data packet payloads. In non-saturation conditions the theoretical results were found to be in the sub-ms region and in excellent agreement with respective simulation-based findings. In saturation conditions the theoretical results exhibited small variations compared to the

respective simulation outcomes which are nonetheless always within the 95% confidence interval. The above confirm that the employment of Medium Transparent MAC protocols is compatible and allows the derived results to function as a roadmap towards the efficient incorporation of the MT-MAC scheme into the envisioned era of 5G mm-wave small cell networks.

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