A Just-in-Time Medium-Transparent MAC Protocol for Multi-Service 5G X-haul Transport Networks

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***Abstract*—We introduce a Just-In-Time Medium-Transparent MAC (jMT-MAC) protocol that provides a transmission schedule for Analog-RoF Fiber-Wireless 5G and beyond X-haul networks supporting multiple services with variable packet sizes. jMT-MAC efficiently places each pending data packet in the polling-sequence, according to an elegant multi-objective optimization model, targeting the employment of the whole available delay budget of the higher priority flows while also considering the delay minimization of all packets, including Best Effort flows. Simulation results show the optimization model of jMT-MAC achieving the 5G fronthaul and URLLC KPIs while reducing delays for low-priority traffic by up to 100% compared to State-of-the-Art protocols.**

Keywords*— *Analog Radio-over-Fiber; 5G; Fronthaul; Fiber-Wireless; Medium Transparent MAC (MT-MAC); Optimization

I. Introduction

Millimeter wave (mmWave) radio has been established as a key supporting technology for reaching the massive peak and user data rates KPIs established by 5G New Radio (NR). The high propagation losses of mmWave, however, necessitate extensive Radio Access Network (RAN) densification placing additional strain on the infrastructure of Mobile Network Operators (MNOs) to carry the large data volumes from the remote Service Access Point regions back to the 5G core. To alleviate this problem, the industry has been vigorously working on combined Fiber-Wireless (FiWi) RAN transport solutions [1], as a feasible framework for Front-, Mid-, and Back-haul (X-haul) deployment, that offers the necessary RAN flexibility without expensive fiber-trenching.

FiWi networks are often categorized into two classes: Radio and Fiber (R&F) and Radio-over-Fiber (RoF). In R&F networks, each discrete network segment, i.e., the wireless and the wired, implements its own MAC layer scheduler, and protocol translation takes place at each segment's interface. R&F networks are less cost-effective for use in densely populated areas and are efficient only in a decentralized RAN (D-RAN) scenario [2]. Due to their benefits in terms of spectrum efficiency and the low complexity of the analog Remote Antenna Units (RAUs), Analog-RoF (A-RoF) has drawn a lot of attention for convergent FiWi networks [3]. For A-RoF FiWi networks to provide optimal end-to-end (E2E) performance, signals must be simultaneously considered in the optical and wireless domains, which requires new medium access control protocols that jointly allocate the wireless and optical resources optimally. A Medium Transparent-Medium Access Control (MT-MAC) protocol first appeared in [4] for FiWi networks employing A-RoF. In [4] both optical and wireless resources are dynamically regulated between the wireless nodes and the MT-MAC Central Office (CO). Sending polling packets, in accordance with a Polling Sequence (PS), to every node that requests permission to transmit data facilitates the frame exchange process in the MT-MAC protocol. The packets contained in a single PS form a Superframe (SF), while the actual PS size and packet sequence is determined by the specific MT-MAC protocol. In the first MT-MAC protocol [4], a static SF size was applied regardless of the traffic load offered by the network's nodes. A variant of [4] was proposed in [5] to reduce handover latency. A hybrid active user enumeration technique was presented in [6] to minimize user identification delay, while support for Quality-of-Service (QoS) was added to MT-MAC in [7]. A first non-static SF size version of the MT-MAC was presented in [8], where the CO assigns transmission windows to each RAU based on the number of served active users, but without accounting for the actual load on each node. The latter functionality was accomplished by Gated-MT-MAC (gMT-MAC) [9], which greatly outperformed [4] and [8], providing up to 20X higher throughput and 2X lower delay, by creating the SF duration using the Gated service paradigm, i.e., each node was granted the amount of time proportional to the number of outstanding packets in its buffer. gMT-MAC, on the other hand, lacks the QoS elements required to successfully manage traffic classes with varying bandwidth, latency, and jitter requirements, as the latter have been established in 5G-NR's disaggregated RAN, comprising Centralized/Distributed/Remote units (CU/DU/RUs) and forming the various X-haul network segments.

A QoS-aware MT-MAC (qMT-MAC) protocol was proposed in [10] to provide QoS assurances for multiple X-haul traffic flows and was shown to successfully meet the appropriate 3GPP latency and jitter criteria. In qMT-MAC, higher priority packets are always scheduled first in the PS, followed by medium priority packets, while Best Effort (BE) packets are scheduled iff there are any remaining unoccupied slots in the PS, i.e., the PS produced in qMT-MAC schedules the various traffic classes in a particular order, which ensures reduced latency of express packets at the expense of lower-priority traffic. However, due to its slot-based time nature for PS creation, qMT-MAC was unable to account for packets with payloads smaller than 1500 bytes, which effectively harmed the protocol's performance in some essential 5G/6G applications, such as remote control and Machine Type Communications, which employ packets as small as 200 bytes [11]. To this end, the enhanced MT-MAC (eMT-MAC) protocol was presented in [12], effectively transforming the PS from slot-based to byte-based granularity, and shown to be capable of accommodating varying packet sizes, boosting its efficiency for low-payload services. eMT-MAC demonstrated excellent protocol efficiency regardless of the service's packet size while fully satisfying the low-layer split X-haul criteria, albeit at the expense of BE traffic flows again. Since 5G/6G latency specifications exhibit a "threshold" aspect, where any packets achieving latency less than a set target are regarded to meet their QoS requirements and no gain is obtained if the E2E packet latency is further decreased, [13] proposed the oMT-MAC protocol. The latter used a Mixed Integer Linear

Problem (MILP) model formulation to construct a PS capable of intelligently and dynamically delaying higher-priority packets, without violating their QoS specifications, at the benefit of BE traffic. However, oMT-MAC's model is based on the slotted time frame of qMT-MAC and cannot handle the more flexible byte-based PS formation needed for many envisioned 5G/6G service types. We also note that optimization models in the flow scheduling literature cannot be applied as oMT-MAC alternatives since they either have different objectives and constraints (functional split selection in [14]), operate above Layer-2 (flow routing in [15]) or lack some of the performance metrics (time-triggered flow scheduling in [16]) used in oMT-MAC.

To this end, this paper proposes and evaluates a Just-In-Time MT-MAC (jMT-MAC) protocol with a novel MILP formulation and byte-based granularity combining eMT-MAC's flexible payload sizes with oMT-MAC's deferred scheduling of higher-priority packets in favor of BE packets while meeting all QoS requirements. Unlike oMT-MAC, jMT-MAC's byte-based granularity and variable packet length introduce many artifacts in the PS creation, such as possible gaps and additional scheduling choices, which require a more elaborate model and additional PS creation mechanisms (compared to oMT-MAC) to address the above issues and strike the proper balance between express and BE traffic. To the best of our knowledge, the proposed jMT-MAC model and protocol is the first enhancement of optimization-driven MT-MAC protocols supporting flexible packet size and converts the typical zero-sum game relation between express and BE traffic into a "win-win" situation for both.

The rest of the paper is organized as follows: Section II contains the system model. In Section III, the proposed jMT-MAC optimization model and protocol and its comparison to State-of-the-Art (SoA) MT-MAC protocols is described. Section IV contains the performance evaluation of jMT-MAC compared to the SoA, while Section V concludes the paper. Notation-wise, sets are denoted as $\mathcal{A}$, set difference as $\setminus$, the Boolean indicator as $\mathbb{I}[X]$ (i.e., $\mathbb{I}[X]=1$ if X is true, 0 otherwise) and we define $[x]^+ \triangleq \max(x,0)$.

II. System Model

As seen in Fig.1, we consider a 5G FiWi Point-to-MultiPoint (PtMP) transport network with a central location linked to many remote locations. Depending on the level of RAN disaggregation, the centralized MNO hardware may consist of a 5G core baseband unit (CU) or CU+DU. The CO receives the Ethernet payload intended for the remote site, encapsulates it into MT-MAC packets, and modulates it onto A-RoF signals, which are transmitted to the RAUs via fiber. MT-MAC remote nodes, also known as MT-MAC Lamppost Units (MT-LPs) receive the wireless signals from the RAUs and interface via Ethernet to the remote MNO equipment, which can be a 5G Base Station, a DU+RU, or an RU module, depending on the RAN disaggregation. Two wavelengths are utilized for Uplink (UL) and Downlink (DL) communications, respectively, at the CO-to-RAU section, exploiting Wavelength Division Multiplexing (WDM) to provide higher resource utilization at the fiber segment. For network management, a dedicated wavelength pair known as a common Control Channel (CC) is also utilized.

We consider UL traffic sent to the MNO centralized equipment from MNO nodes located in the remote areas. It is expected that each RAU would employ a Wavelength Selectivity Device (WSD) for wavelength allocation, such as

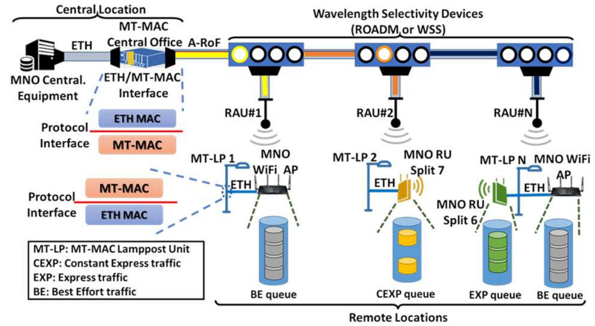

Fig. 1: MT-MAC generic network architecture.

a Reconfigurable Optical Add-Drop Multiplexer (ROADM) or a Wavelength Selective Switch (WSS), as seen in Fig. 1. This hardware capability enables the network to dynamically reconfigure its capacity in response to load variations and optimize optical wavelength usage. The Ethernet-based enhanced Common Public Radio Interface (eCPRI) X-haul protocol is utilized for communication between the MNO nodes and MT-LPs. We examine three traffic classes, which correspond to particular eCPRI functional splits:

- Constant Express traffic (CEXP) mimics low-split Constant Bit Rate (CBR) fronthaul transport and has stringent jitter and delay constraints. This traffic captures 3GPP splits 7 and 8 (legacy CPRI), whose traffic patterns are independent of the cell's active users. For example, CPRI-based CEXP traffic must have jitter < 65 ns and a one-way latency < 100 µs [17].
- Express traffic (EXP) captures 3GPP split 6 fronthaul and exhibits a load-dependent traffic pattern [17]. We anticipate that the latency of EXP traffic should not surpass 250 µs [18].
- Best Effort (BE): This load-varying traffic captures all other forms of X-haul traffic, including mid-/back-haul traffic and 3GPP splits greater than 6, and imposes no requirements.

Each MT-LP aggregates traffic for the lamppost MNO equipment, as shown for MT-LP N in the lower-right corner of Fig. 1. We consider a time-slotted system and assume random packet arrivals at the beginning of a slot $t = 1,2, \ldots$. Let $\mathcal{C}$ be the set of traffic flows, where traffic flow $c \in \mathcal{C}$ is the pair $c = (T_c, \langle d_c \rangle)$, with $T_c \in \{CEXP, EXP, BE\}$ a flow class identifier and $\langle d_c \rangle$ an (optional) tuple with T_c-dependent semantics. Specifically, for $T_c = CEXP$, it holds $\langle d_c \rangle \triangleq \langle uid_c, IFG_c, is_c \rangle$, with uid_c a unique CEXP flow id, IFG_c (Inter-Frame Gap) the number of slots between two consecutive arrivals of packets of CEXP flow c and is_c the slot of the earliest scheduled packet for flow c. Hence, IFG_c effectively determines the load of CEXP flow c, which has its packets scheduled in slots of set $\mathcal{S}_c \triangleq \{is_c + k \cdot IFG_c : k \in \mathbb{N}\}$. We assume that is_c values are properly selected so that all $\mathcal{S}_c$ are disjoint sets. For $T_c = EXP$, we define $\langle d_c \rangle \triangleq \langle \tau_c \rangle$, with τ_c the maximum allowed queueing delay (measured in slots), which can be easily derived from the E2E (which, in our context, is the lamppost-to-rooftop segment) latency KPI by excluding the transmission/propagation delay, which is a constant term for all packets flowing *along a given path*. We assume a *single BE traffic flow*, so that, for $T_c = BE$, $\langle d_c \rangle$ is empty. We uniquely identify packet u via pair (c_u, i_u) where $c_u \in \mathcal{C}$ is the packet's flow, and i_u is the packet's index, so that we hereafter refer to "packet (c, i)".

III. The jMT-MAC Protocol

The functionality of jMT-MAC is described next. Section III-A outlines the shared features of jMT-MAC with other

SoA MT-MAC protocols, such as qMT- and eMT-MAC (see [12] for a thorough description of eMT-MAC), while Section III-B describes jMT-MAC's unique optimization aspects.

A. Common features of MT-MAC protocols

The CO is responsible for managing all data plane packet scheduling and is fiber-connected to many RAUs that offer wireless communication to MT-LPs. Two separate Contention Periods (CPs) are considered: the first CP determines which RAUs are connected to MT-LPs serving active MNO nodes (and, therefore, require wavelength allocation); the second CP aims to ascertain the Buffer Status (BuS) of each active MT-LP and allocate the appropriate Transmission Windows for them. If there are more RAUs with active MT-LPs than available wavelengths, the CO in the first CP assigns the available wavelengths to an equivalent number of RAUs and consequently proceeds through the RAUs in a Round Robin (RR) manner (see Fig 3 in [10]).

To acquire BuS data, the CO exchanges Resource Request Frames (RRFs) with each MT-LP that has packets in its buffer during the second CP. When every active MT-LP has successfully sent their RRF, the 2nd CP concludes, and the DATA_TX period, which consists of a sequence of Data Frames (DFs), begins. Every DF includes sending and receiving DATA_POLL, DATA, and ACK packets. The maximum amount of packets of a given kind that the MT-MAC client may transmit after receiving the DATA_POLL is specified in the DATA_POLL packets that the CO broadcasts. Examples of these packet types include CEXP, EXP, and BE. Depending on the particular MT-MAC protocol, the DATA_POLL payload is created in accordance with the PS, as discussed in Section III-B. After the MT-LP node transmits the necessary data packets in response to the DATA POLL reception, the CO sends an ACK packet to the MT-LP to confirm successful data reception. The DFs that are included inside a single PS form a SuperFrame (SF).

B. Optimization-driven PS creation in jMT-MAC protocol

We define a ***slot*** as the time interval required for the transmission of N_{by} bytes corresponding to the largest packet size allowed (e.g., N_{by} =1500) and a ***cycle*** $l = 1,2,...$, as the interval of N_c consecutive slots in set $\mathcal{R}_l \triangleq \{(l-1)\cdot N_c + 1,\cdots, l\cdot N_c\}$. The notion of slot is only used as a time-keeping mechanism and does **not** place any restrictions on fitting packet transmissions within a slot. In fact, contrary to [13], it is permissible and beneficial for jMT-MAC to schedule a packet across the boundary of two consecutive slots. jMT-MAC performs scheduling on a cycle basis as follows:

• in cycle l, the CEXP packets are always scheduled for transmission in slots of set $\mathcal{S}_{CEXP}^l \triangleq \mathcal{R}_l \cap \left(\cup_{c:T_c=CEXP}\, \mathcal{S}_c\right)$. Hence, only slots in set $\mathcal{A}^l \triangleq \mathcal{R}_l \setminus \mathcal{S}_{CEXP}^l$ are available for serving EXP/BE traffic during cycle l. We define a Scheduling Window (SW) as a set of consecutive slots in $\mathcal{A}^l$. We denote with $\mathcal{W}^l$ the set of SWs within cycle l and with $w \in \mathcal{W}^l$ the actual SW (note that w is also a set of slots) and write F_w^l, L_w^l for the first and last slot, respectively, of SW w. We also denote with W_j the SW containing slot j.

• at the start of cycle l, jMT-MAC schedules EXP/BE packets in the slots of $\mathcal{A}^l$ according to the solution of the optimization problem formulated below. Note that some packets may remain unscheduled by the end of cycle l. Also, any EXP packets arriving after the first slot of $\mathcal{R}_l$ are not scheduled during cycle l but may be scheduled in cycle $(l+1)$.

Let $a_{c,i}^l$ be the number of slots that packet (c,i) has been stored in queue Q_c until the start of cycle l. Let $e_{i,j}^{c,l}, r_{i,j}^{c,l}$ be the Boolean indicators of whether an EXP/BE packet (c,i) is scheduled such that it crosses the left (resp. right) boundary of slot j in cycle l. Let $m_{i,j}^{c,l}$ be the Boolean indicator of whether an EXP/BE packet (c,i) is scheduled *entirely within* slot j in cycle l. Unless otherwise noted, all (c,i) indices range over the set of EXP/BE packets while j indices range over $\mathcal{A}^l$.

We formulate a *distinct* problem for each cycle l and define $y_{i,j}^{c,l} \triangleq m_{i,j}^{c,l} + r_{i,j}^{c,l}$ (resp. $z_{i,j}^{c,l} \triangleq m_{i,j}^{c,l} + e_{i,j}^{c,l}$) as the Boolean indicators of whether the first (resp. last) byte of packet (c,i) is scheduled in slot j, so that the following holds:

$$\sum_{c,i} e_{i,j}^{c,l} \le 1, \qquad \sum_{c,i} r_{i,j}^{c,l} \le 1, \quad \forall j, \tag{1}$$

$$e_{i,F_w^l}^{c,l} = r_{i,L_w^l}^{c,l} = 0, \quad \forall (c,i), \forall w \in \mathcal{W}^l, \tag{2}$$

$$m_{i,j}^{c,l} + e_{i,j}^{c,l} + r_{i,j}^{c,l} \le 1, \quad \forall (c,i), \forall j, \tag{3}$$

$$\sum_j y_{i,j}^{c,l} \le 1, \quad \sum_j z_{i,j}^{c,l} \le 1, \qquad \forall (c,i), \tag{4}$$

$$r_{i,j}^{c,l} = e_{i,j+1}^{c,l}, \quad \forall (c,i), \forall w \in \mathcal{W}^l, \forall j \in w \setminus \{L_w^l\}, \tag{5}$$

where (1) requires at most one scheduled packet to cross any slot's boundary, (2) enforces that no packet can cross the edge boundaries of a SW, (3),(4) require that each scheduled packet is either contained within a slot or crosses one slot boundary and (5) expresses the fact that the right boundary of a slot also constitutes the left boundary of the subsequent slot.

The number of bytes E_j^l that "spill into" slot j due to a scheduled packet crossing its left boundary from slot $j-1$ is:

$$E_j^l = \left[B_j^l - (j - F_{W_j}^l)N_{by}\right]^+, \quad \forall j, \tag{6}$$

where $B_j \triangleq \sum_{k\in W_j:k<j} \sum_{c,i} y_{i,k}^{c,l} L_{c,i}$, with $L_{c,i}$ the length of packet (c,i) in bytes. Similarly, the number of bytes "spilling from" slot j into $j+1$ is:

$$R_j^l = \left[E_j^l + \sum_{c,i} y_{i,j}^{c,l} L_{c,i} - N_{by}\right]^+, \quad \forall j, \tag{7}$$

along with the following consistency conditions:

$$R_j^l = E_{j+1}^l, \quad \forall w \in \mathcal{W}^l, \forall j \in w \setminus \{L_w^l\}, \tag{8}$$

$$R_j^l \ge \sum_{c,i} r_{i,j}^{c,l} \ge \frac{R_j^l}{N_{by}}, \ \forall j, \tag{9}$$

$$E_j^l \ge \sum_{c,i} e_{i,j}^{c,l} \ge \frac{E_j^l}{N_{by}}, \ \forall j, \tag{10}$$

$$E_j^j + \sum_{c,i} m_{i,j}^{c,l} L_{c,i} \le N_{by}, \qquad \forall j, \tag{11}$$

where (8) captures the shared boundary of consecutive slots, (9) imposes the consistency condition $\sum_{c,i} r_{i,j}^{c,l} = \mathbb{I}[R_j^l \ge 1]$ (and similarly, (10) for $\sum_{c,i} e_{i,j}^{c,l}$ and E_j^l), while (11) ensures that no more than N_{by} bytes can be scheduled within a slot.

If packet (c,i) is actually scheduled in cycle l, the total number of slots it has been enqueued prior to transmission is $a_{c,i}^l + \sum_{j\in\mathcal{A}^l} (j - l\cdot N_c) z_{i,j}^{c,l}$; otherwise, it will hold $a_{c,i}^{l+1} = a_{c,i}^l + N_c$. We can combine both cases above as $a_{c,i}^{l+1} \triangleq a_{c,i}^l +$

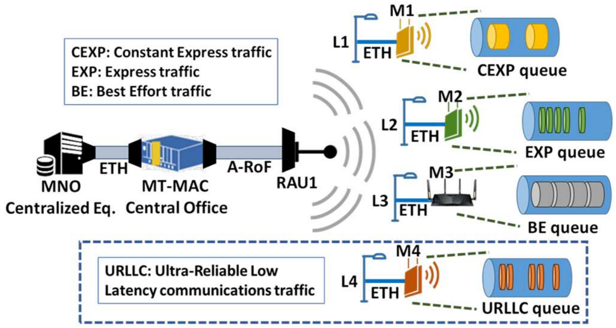

Fig. 2: Network configuration in simulation for performance evaluation.

$\sum_{j\in\mathcal{A}^l}(j-l\cdot N_c)z_{i,j}^{c,l}+N_c\big(1-\sum_{j\in\mathcal{A}^l}y_{i,j}^{c,l}\big)$. For EXP flow packets (only), we define $v_{c,i}^l \triangleq \mathbb{I}[a_{c,i}^{l+1}>\tau_c]$ as the Boolean indicator of whether the queuing delay of EXP packet (c,i) exceeds τ_c at the end of cycle l, and transform this into

$$\begin{aligned} &v_{c,i}^l \in \{0,1\},\ \ \forall(c,i){:}\,T_c=EXP,\\ &v_{c,i}^l \geq \frac{a_{c,i}^{l+1}-\tau_c}{M},\ \forall(c,i){:}\,T_c=EXP, \end{aligned} \tag{12}$$

for a sufficiently large constant $M>0$. We also impose a penalty $p_c>0$ ***for each*** EXP packet (c,i) whose queueing delay exceeds τ_c (i.e., if $v_{c,i}^l=1$) at the end of cycle l, and define $P_{EXP}^l \triangleq \sum_{(c,i):T_c=EXP}p_c v_{c,i}^l$. To achieve low BE delay, we employ a multi-objective model and add the objective of minimizing the maximum BE packet delay at the end of cycle l, i.e., $maxBE^l \triangleq \max_{(c,i):T_c=EXP} a_{c,i}^{l+1}$, which can be converted to:

$$maxBE^l \geq a_{c,i}^{l+1},\quad \forall(c,i){:}\,T_c=EXP. \tag{13}$$

We also introduce three more objectives in our multi-objective formulation. First, to protect against unscheduled EXP (only) packets getting close to their τ_c threshold (while still not exceeding it), which could lead to these packets violating τ_c at the next cycle, we introduce an integer offset parameter $\tau_{off}>0$, along with a penalty $p_d>0$ for any EXP packet enqueued longer than $\tau_c-\tau_{off}$ at the end of cycle l, and Boolean decision variables $d_{c,i}^l \triangleq \mathbb{I}[a_{c,i}^{l+1}>\tau_c-\tau_{off}]$, so that we seek to minimize $P_D^l \triangleq \sum_{(c,i):T_c=EXP}p_d d_{c,i}^l$. For efficiency reasons, we also seek to maximize the number of scheduled bytes $nSch^l \triangleq \sum_{(c,i)}\sum_j z_{i,j}^{c,l}L_{c,i}$ and, as the tie-breaker of lowest priority, maximize the number of scheduled EXP packets $nEXP=\sum_{(c,i):T_c=EXP}\sum_j z_{i,j}^{c,l}$.

Thus, creation of the PS for each cycle l has been reduced to the following lexicographic multi-objective MILP:

$$\begin{aligned} &Lex\_min(P_{EXP}^l, P_D^l, maxBE^l, -nSch^l, -nEXP^l),\\ &\text{s.t}\quad (1)\text{-}(13),\ e_{i,j}^{c,l}, r_{i,j}^{c,l}, m_{i,j}^{c,l}, v_{c,i}^l, d_{c,i}^l \in\{0,1\}, \end{aligned} \tag{14}$$

where the decision variables appear in the second line of (14) and each objective is given priority over all objectives appearing after it within Lex_min (i.e., minimizing P_{EXP}^l is the primary objective and, in case of multiple solutions achieving minimum P_{EXP}^l, minimizing P_D^l becomes the secondary objective etc.). The relative order of the objectives in (14) has been selected to achieve the proper balance between prioritizing EXP packets to avoid violating their delay requirements (first two objectives) but also not penalizing BE traffic unnecessarily (third objective) and not leaving any "holes" in the PS where packets could be scheduled. Note that $nSch^l$, $nEXP^l$ appear with a minus sign since we seek to maximize them.

Hence, jMT-MAC solves (14) for each cycle l and updates the values $a_{c,i}^l$ of all non-scheduled EXP/BE packets at the end of cycle l so that the next cycle can begin. As a post-processing step on the PS obtained by solving of (14), jMT-MAC also removes any gaps in the PS by shifting the packets earlier to create a contiguous PS, if possible.

IV. Performance Evaluation

This section provides a thorough performance study based on the OMNET++ simulator and CPLEX MILP solver suites (the analysis and evaluation of efficient heuristics to solve (14) with lower time complexity is outside the paper's scope) to assess the performance advantages of jMT-MAC over eMT-MAC, which is the most recent SoA protocol and the only one that supports a byte-based PS timeframe. In the following, EXP and BE packets are 750 and 1500 bytes long, respectively, and generated according to a Poisson model. The latter assumption is only made for concreteness, as the MILP formulation in (14) supports arbitrary traffic models.

A. Single express traffic use case

We use the configuration shown in Fig. 2, where MT-LPs L1, L2, and L3 are wirelessly linked to a single RAU that is connected to a CEXP, EXP, and BE traffic generator, respectively (L4 is not partaking in this arrangement). Fig. 3 displays the average packet delay (in ms) vs. normalized load for both jMT- and eMT-MAC protocols, for both EXP and BE traffic flows, and for three IFG values (5, 10, and 15) that pertain to the CEXP traffic. It should be noted that an IFG value of 5 indicates that the first of every five slots is reserved for CEXP packets (automatically satisfying the CEXP QoS requirements), i.e. CEXP traffic produces 20% (1/5th) of the normalized network load and the SF length is also set to five slots (i.e., the periodicity of CEXP traffic). The findings for the EXP and BE traffic flows are shown in Figs. 3(a) and 3(b), respectively. A normalized load of 0.1 indicates that the generated traffic rate is 10% of the channel bitrate (hereafter assumed to be 1 Gbps). The load value applies to each EXP and BE flow separately. For example, a load of 0.1 indicates that 10% of the channel bitrate is produced by each of the EXP and BE MT-LPs individually, resulting in an aggregate load of 20% for both types of traffic. In Fig. 3, it is evident that for all loads and IFG values, jMT-MAC performs worse in terms of average EXP delay than eMT-MAC, whereas BE packets exhibit greatly superior performance under jMT-MAC. As long as EXP packets are not delayed beyond their maximum delay τ_c (set to 250µs in this evaluation), which is effectively the operating principle of jMT-MAC, i.e., to defer scheduling EXP packets in favor of BE packets, this is the expected behavior. As attested by Fig. 3(a), jMT-MAC's EXP delay consistently stays below 250µs.

To better visualize and study the delay performance difference between jMT- and eMT-MAC protocols, as well as to assess the impact of load and IFG values (i.e., the cycle length) in the exhibited performance gap, Fig. 4 presents the normalized difference between jMT- and eMT-MAC, where positive/ negative values indicate that jMT-MAC delays are lower/higher, respectively, than eMT-MAC's. For example, if the value is 0.1, the jMT-MAC delay is 10% less than the corresponding eMT-MAC values; conversely, for -0.1, the jMT-MAC delay is 10% higher. Fig. 4 confirms the previously presented results, i.e., BE flows produce superior

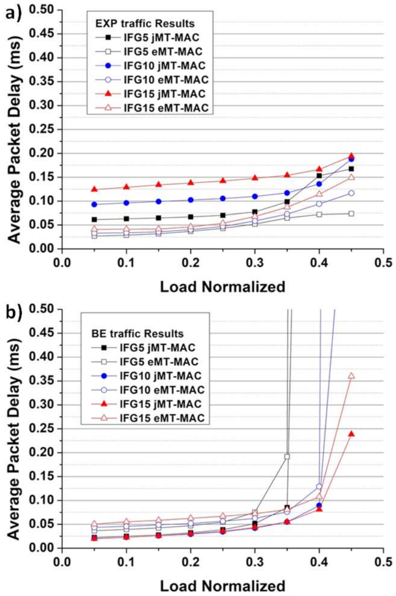

Fig. 3: jMT- vs. eMT-MAC results for IFG values 5,10,15. Lines with filled, (resp. hollow) symbols refer to jMT-MAC (resp. eMT-MAC). a) EXP traffic delay, b) BE traffic delay.

delay performance for all loads and IFG values (hollow symbol curves are always >0), while the opposite is true for EXP packets (filled symbol curves are always <0). However, jMT-MAC's normalized gain vs eMT-MAC varies depending on the network load and IFG value. For all loads up to 0.3, we notice that larger IFG values (i.e., larger SF cycles) produce greater BE gains (and greater EXP losses) by leveraging longer EXP packet stalls. This is the expected behavior of jMT-MAC, as its optimization framework operates on a per-SF basis, and the larger SF sizes allow for further delaying EXP packets by scheduling them towards the end of the SF, albeit provided that EXP flow specifications are not violated. This delayed scheduling vacates more room at the beginning of the SF for BE packets to be scheduled, therefore greatly improving the average BE delay. As load increases from 0.05 to 0.3, the general trend is for BE gains and EXP losses to decrease, since the increased number of generated packets fill in a larger portion of the cycle and therefore the optimization model carries fewer degrees of freedom towards delaying EXP in favor of BE packets. For IFG=15, however, we notice that EXP performance losses do not follow this monotonicity for loads up to 0.15. This comes as a direct consequence of jMT-MAC's PS post-processing functionality where any gaps in the PS (i.e., empty transmission opportunity windows created at low loads by scheduling EXP packets towards the end of the SF, while BE packets are scheduled at the beginning) are removed by shifting EXP packets earlier in the PS. This increases the overall efficiency of the protocol since lack of this functionality would leave randomly sized PS gaps, where a BE packet could fit or not (in the latter case, this would translate to unused transmission time, decreasing overall protocol efficiency). As load increases beyond 0.15, PS gaps that need to be filled by post-processing appear less often, as the generated packets rarely leave any empty PS space even in the large cycle size of IFG=15. For loads above 0.3, we notice that BE delay gains stop decreasing with load and instead increase, meaning that jMT-MAC gains more performance compared to SoA eMT-MAC. The specific load value where this transition occurs depends on the IFG value, i.e., at 0.35 for IFG=5 and 0.4 for IFG=10, 15. The reason

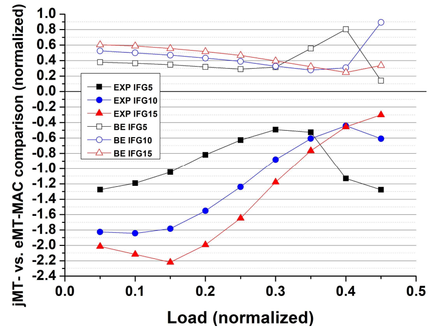

Fig. 4: jMT- vs. eMT-MAC delay performance difference (normalized).

behind this performance leap is jMT-MAC's increased efficiency due to the last two objectives in (14) leaving no unnecessary gaps in the PS, as opposed to eMT-MAC. The latter follows a simple heuristic approach where EXP packets are always placed first in the PS, and due to their different size from BE packets, the remaining PS space for BE packets could be a non-integer multiple of BE packet size, which leaves an unusable portion at the SF's end. However, since (14) aims to maximize the number of scheduled bytes, its solution always selects PS schedules without gaps, thus increasing jMT-MAC's efficiency. For IFG=5, it is observed that the BE delay gains become minimal at 0.45 load. This is due to the very high offered load (0.2 for CEXP, 0.45 for EXP/BE each, for a total of 1.1), which pushes the protocol beyond its saturation threshold and, in conjunction with the small SF size, prevents jMT-MAC from delaying the EXP packets significantly. Overall, jMT-MAC offers significantly lower BE delay over SoA eMT-MAC ranging from 20% up to 90% and **without inducing any EXP traffic violations, thus producing an "every traffic type wins" operational regime that offers** the optimal EXP/BE flow balance.

B. Dual load-dependent EXP traffic flows scenario

In contrast to eMT-MAC, which performs simple RR scheduling amongst two EXP traffic types, jMT-MAC differentiates among express flows and generates optimized schedules by appropriately delaying all EXP packets proportionally to their max delay specifications, continuing to allow appropriate delays to prioritize BE and/or less urgent express packets. We next provide a performance evaluation for the setting of Fig. 2 (including MT-LP L4), adding a second type of EXP traffic (with a latency requirement τ_c of 1 ms), referred to as "URLLC", for illustration purposes.

Average packet delays under jMT- and eMT-MAC, for the EXP, URLLC, and BE traffic flows, and for three IFG values (i.e., 5, 10, and 15) are shown in Fig. 5. Again, the load value pertains to each of the EXP, URLLC, and BE flows, i.e., 0.1 load implies that the EXP, URLLC, and BE flows each provide 10% of the channel bitrate (for a total aggregate traffic of 30% of the channel bitrate). Fig. 5(a)-(c) show that for all IFG values, jMT-MAC produces inferior delay results for both EXP and URLLC traffic, with the losses however being translated to great gains for the BE flow. As in Section IV-A, the performance disparity between jMT- and eMT-MAC grows as IFG increases, since jMT-MAC's optimization model has a higher availability of delayed scheduling positions for the EXP/URLLC packets and can thusly greatly favor BE packets. It is noteworthy that jMT-MAC delays URLLC more than the EXP traffic flow, as the former offers a 4X relaxed delay budget vs. the latter (1ms vs. 250μs), thus fully leveraging the distinct specifications to produce BE

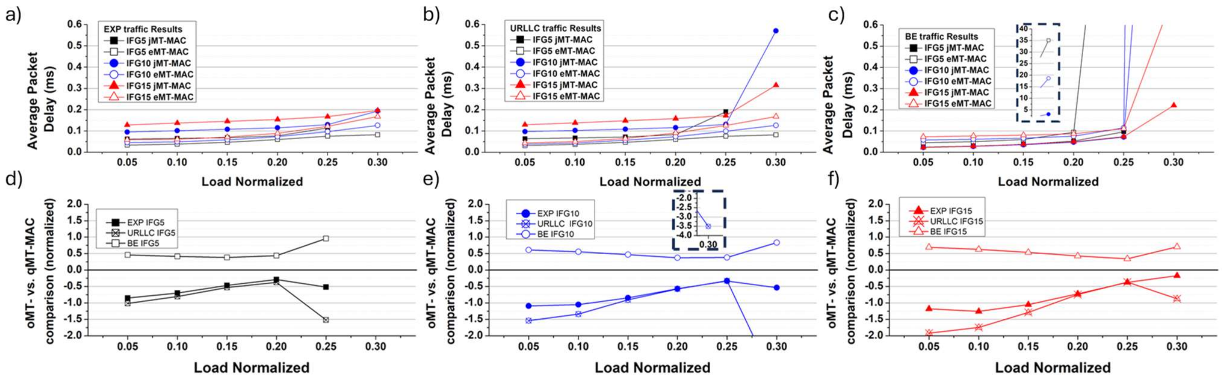

Fig. 5: jMT- vs. eMT-MAC for EXP, URLLC and BE traffic and three IFG values: a) EXP traffic results, b) URLCC traffic results, c) BE traffic results, d) performance difference for IFG=5, e) performance difference for IFG=10, f) performance difference for IFG=15.

gains. Fig. 5(d)-(f) present the normalized delay difference between jMT- and eMT-MAC, where positive/negative values again indicate that jMT-MAC delays are lower/higher than eMT-MAC's. As can be observed, jMT-MAC deliberately stalls URLLC longer than EXP flows, exploiting its more relaxed delay constraint to its fullest to produce gains for BE traffic. As the load rises, we notice diminishing gains/losses for the BE and EXP/URLLC flows respectively, since the higher number of packets decrease the number of available positions in the PS for the newly arrived packets, therefore restraining the opportunities for jMT-MAC to stall high priority packets. Towards load=0.3, we notice again that jMT-MAC's benefits increase rapidly over eMT-MAC, as the latter's heuristic method of always placing EXP/URLLC packets before BE is vulnerable to producing gaps at the SF's end. On the contrary, jMT-MAC's criterion of maximizing the number of scheduled bytes ensures that no gaps are present in the PS, by dynamically placing or delaying the packets to optimally fill the SF regardless of uneven payloads. To this end, we notice huge performance gain for BE flows reaching up to 100% for IFG=5 compared to eMT-MAC, while adhering to both EXP and URLLC delay specifications. Overall, jMT-MAC offers significant gains over SoA eMT-MAC, with a minimum of 38% delay improvement for BE traffic, observed at 0.25 load (aggregating at ~0.82 for all flows) and for IFG=15, producing a clear positive-sum game that offers the optimal balance for numerous concurrent multi-payload 5G services.

V. Conclusions

This paper presented the innovative jMT-MAC protocol, which optimizes the PS creation process to enhance BE traffic performance by exploiting the full delay budget of EXP traffic flows, while supporting the variable payload of express 5G/6G services. For a single EXP traffic flow, jMT-MAC produced BE delay reductions of up to 90%, without violating the EXP traffic delay requirements. For two types of express traffic, i.e., EXP and URLLC, BE flows achieved 100% gain compared to SoA eMT-MAC, without delay violations. The above results highlight jMT-MAC's capability to provide enhanced delay to BE packets, by taking advantage of the threshold nature of the EXP/URLLC traffic, thus increasing network efficiency while reinforcing the heterogeneous traffic co-existence capabilities of the MT-MAC framework.

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