MatchMaker: An Inter-operator Network Sharing Framework in Unlicensed Bands

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***Abstract*—In this paper, we consider the scenario in which mobile network operators (MNOs) share network infrastructure for operating 5G new radio (NR) services in unlicensed bands, whereby they reduce their deployment cost and extend their service coverage. Conserving privacy of MNOs' users, maintaining fairness with coexisting technologies such as Wi-Fi, and reducing communication overhead between MNOs are among top challenges limiting the feasibility and success of this sharing paradigm. To resolve above issues, we present *MatchMaker*, a novel framework for joint network infrastructure and unlicensed spectrum sharing among MNOs. MatchMaker extends the 3GPP's infrastructure sharing architecture, originally introduced for licensed bands, to have privacy-conserving protocols for managing the shared infrastructure. We also propose a novel privacy-conserving algorithm for channel assignment among MNOs. Although achieving an optimal channel assignment for MNOs over unlicensed bands dictates having global knowledge about MNOs' network conditions and their interference zones, our channel assignment algorithm does not require such global knowledge and maximizes the cross-technology fairness for the coexisting systems. We let the manager, controlling the shared infrastructure, estimate potential interference among MNOs and Wi-Fi systems by asking MNOs to propose their preferred channel assignment and monitoring their average contention delay overtime. The manager only accepts/rejects MNOs' proposals and builds contention graph between all colocated devices. Our results show that MatchMaker achieves fairness up to 90% of the optimal alpha-fairness-based channel assignment while still preserving MNOs' privacy.**

***Index Terms*—Cross-technology coexistence, network sharing in unlicensed bands, NR-U, LAA, IEEE 802.11, Wi-Fi, graph coloring evolution, cloud-RAN, v-RAN.**

I. INTRODUCTION

The popularity of smart phones and data-intensive mobile applications has led to explosive growth in mobile data traffic, straining the capacity of the licensed spectrum. To relieve the high demand on the licensed spectrum, Federal Communications Commission (FCC) opened up the Unlicensed National Information Infrastructure (U-NII) radio bands at 5 GHz for commercial cellular mobile network operators (MNOs) [1]. FCC is also considering opening up new unlicensed bands at 6 GHz for 5G-unlicensed and Wi-Fi operations [2]. MNOs across the globe invest heavily in network infrastructures supporting services in unlicensed band.

To extend the Third Generation Partnership Project (3GPP) 5G New Radio (NR) service into unlicensed bands, a.k.a., NR-Unlicensed (NR-U), basestations and user equipments (UEs) must follow listen-before-talk (LBT) procedures, based on CSMA/CA, prior to their channel access [3]. Although unlicensed spectrum is promising for industry, MNOs will undoubtedly face difficulties in providing coverage in some important sites, such as international airports, stadiums, big malls, etc., due to issues related to site security, logistics, and cost of deployment. For example, the FCC significantly limits the transmit power over unlicensed spectrum to 30 dBm, and providing coverage in sites such as airports will require each MNO to deploy tens or even hundreds of basestations, a costly operation that could also be prohibited by the site authority. In such scenarios, the site authority builds a neutral-host-based network infrastructure and share it with other MNOs for a fee.

Network sharing has been promoted by 3GPP as a promising solution for MNOs to increase their accessibility over licensed spectrum and reduce the system roll-out cost. Currently, 3GPP's network sharing architecture only supports the sharing in licensed spectrum. Multi-operator network sharing in unlicensed bands is notoriously difficult due to many concerns, including privacy, fairness, and communication overhead. For instance, due to security and privacy reasons, MNOs might opt to avoid disclosing information that are important for site operator to both managing the shared infrastructure and allocating resources among MNOs. The communication overhead between infrastructure manager and MNOs could also become a bottleneck reducing the feasibility of the solution. The non-exclusiveness and license-exempt nature of the unlicensed spectrum also raise concerns on the fair allocation of unlicensed spectrum resources between MNOs and existing Wi-Fi systems. Addressing this fairness issue requires obtaining oracle knowledge on networks' conditions, conflicting with providing MNOs a private access to the network infrastructure.

To address the above conflicting challenges and reduce the communication overhead between MNOs and the infrastructure manager, we propose *MatchMaker*, a cloud-centric-

This research was supported in part by NSF (grants # IIP-1822071, CNS-1563655, CNS-1731164) and by the Broadband Wireless Access & Applications Center (BWAC). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of NSF.

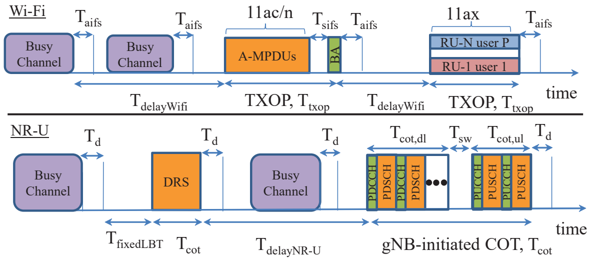


Fig. 1: Arbitrary examples of channel access procedure for Wi-Fi and NR-U; EDCA (top), CAT2-LBT/CAT4-LBT (down).

oriented infrastructure sharing and channel assignment framework that ensures MNOs have private and fair access to unlicensed channels, while maintaining fairness with coexisting Wi-Fi systems. The 3GPP network sharing architecture consists of management and control planes for facilitating the coordination between MNOs, a.k.a., Participating Operators (POPs), and the site operator, a.k.a., Master Operator (MOP) [4] [5]. The MOP is trusted for deployment, management, and daily operation of the shared infrastructure, while POPs are service providers who make use of the shared infrastructure and licensed spectrum resources. Our contributions are two folds. First, we extend the 3GPP network sharing architecture for operating 5G NR-U service over unlicensed bands, and propose privacy-conserving protocols to let MNOs have private access to the shared network infrastructure. In our model, MNOs play the role of POPs and the infrastructure manager plays the role of MOP. We let POPs handle their user scheduling and baseband processing on their own cloud-based infrastructure and send their I/Q OFDM modulated data to the shared network in which RF-related processing takes place. POPs only coordinate with the MOP their access to the shared network and transmission over the unlicensed channels.

Second, we develop a novel privacy-conserving algorithm, called *graph coloring evolution*, for the MOP to assign channels among POPs in a semi-distributed fashion. Our algorithm adopts proposal/rejection rules to learn the potential interference and contention among POPs and Wi-Fi systems. The MOP builds a contention graph that evolves overtime by letting POPs propose their preferred channel assignments to the MOP and monitoring the average contention delay experienced by POPs and coexisting Wi-Fi systems. In this algorithm, POPs need not to disclose any information about their user topology or their channel gains. We design our algorithm with the goal of maximizing the α-fairness [6] among POPs and Wi-Fi systems while maintaining their maximum tolerable channel access delay. Our results reveal that MatchMaker could achieve up to 90% of the optimal proportional fair channel assignment.

II. BACKGROUND & PRELIMINARIES

A. Unlicensed Channel Access Procedures

IEEE 802.11-based Wi-Fi and 3GPP 5G NR-U standards follow similar LBT procedures for accessing unlicensed channels, however, they adopt different parameter settings [3], [7]. Wi-Fi devices rely on the Enhanced Distributed Channel Access (EDCA) procedure to access unlicensed channels. NR-U devices rely on the most recent LBT procedures, i.e., *Category-4-* and *Category-2-* LBT, as specified by the 3GPP *'further enhanced licensed assisted access'* (feLAA) [3] technology. A MAC timeslot T_{macSlot} is the basic unit for Wi-Fi and NR-U MAC operation ($T_{\text{macSlot}} = 9\ \mu sec$). EDCA and CAT4-LBT are based on CSMA/CA with exponential backoff. A device must first sense the channel for a fixed period of time known as the *arbitration inter-frame space* (AIFS) (T_{aifs}), a.k.a., *defer duration* (T_d) in NR-U, before starting transmission. If the channel becomes busy during the AIFS, the device should back off for random k idle slots, where k is an integer in $[0, W_{\min} - 1]$ and $W_{\min}$ is the minimum size of contention window. When the channel becomes busy, the device freezes its backoff process and resumes backing off after the channel returns idle. The channel is deemed idle if it remains so for a T_{aifs} duration. When the device finishes backing off, it starts transmitting for a *transmit opportunity* (TXOP) duration (T_{txop}), a.k.a., *channel occupancy time (COT)* (T_{cot}) in NR-U. If the device still have more frames to serve, it should backoff again. After a failed/collided transmission, the device should double its contention window and contend for a new channel access with a new k value:

$$k \in [0, \min\{2^i W_{\min}, W_{\max}\} - 1] \tag{1}$$

where i is the number of retransmission attempts and $W_{\max}$ is the maximum size of contention window. The process continues until the maximum retransmission limit is reached.

NR-U and Wi-Fi differ on how they allocate time and frequency resources to their users during the TXOP duration. In IEEE 802.11n/ac-based Wi-Fi, one user can be served during TXOP where multiple MAC protocol data units (MPDUs) can be aggregated, a.k.a., (A-MPDU) (see '11ac/n' in Figure 1). In IEEE 802.11ax-based Wi-Fi, it is possible to multiplex different users to different resource units (RUs) separated in frequency domain (see '11ax' in Figure 1). In NR-U, the *gNB-initiated COT*, i.e., T_{cot}, is time-slotted to downlink (DL) and uplink (UL) occasions. If switching between DL and UL communications takes a time (T_{sw}) longer than 16 microseconds, UEs should perform CAT2-LBT procedure, where they ensure the channel is idle for a fixed duration (T_{fixedLBT}) before they start transmission (see the bottom part in Figure 1). UEs receive and send their control messages at the *physical DL control channel* (PDCCH) and *physical UL control channel* (PUCCH) channels, as well as they receive and send their data messages on the *physical DL shared channel* (PDSCH) and *physical UL shared channel* (PUSCH) channels. To send critical messages, such as the *discovery reference signal (DRS)* that is important for initial network access and discovery, the gNB performs CAT2-LBT procedure.

B. Measuring and Calculating Contention Delay

EDCA and CAT4-LBT procedures resolve collisions among devices by forcing them to delay their transmission to different random instants. This contention delay affects the performance of Wi-Fi and NR-U links. NR-U contention delay can be expressed as:

$$T_{\text{delayNR-U}} = T_{\text{d}} + \sum_{j=1}^{N_{\text{busy}}} (T_{\text{d}} + T_{\text{busy},j}) + kT_{\text{macSlot}} \tag{2}$$

where N_{busy} is the number of occasions the channel becomes busy and $T_{\text{busy},i}$ is the duration of the ith busy occasion. Similarly, the contention delay experienced by a Wi-Fi device can be expressed as:

$$T_{\text{delayWiFi}} = T_{\text{aifs}} + \sum_{j=1}^{N_{\text{busy}}} (T_{\text{aifs}} + T_{\text{busy},j}) + kT_{\text{macSlot}}\cdot \tag{3}$$

IEEE 802.11 standards support the *Radio Measurement Service (RMS)* function that allows a station and/or an AP to measure and announce their contention delay, a.k.a., *average access delay* [7]. Commercial small cell base stations are often equipped with Wi-Fi chips [8], and technically future NR-U small cells can be made capable of overhearing Wi-Fi transmissions and read their contention delay measurements. If the RMS function is not supported, Wi-Fi contention delay can still be estimated using the approximations presented in [9].

C. Alpha-Fairness Measure

We consider the following fairness metric, a.k.a., α-fairness [6], to account for fairness among POPs and Wi-Fi systems:

***Definition** 1:* Consider N agents who share an arbitrary resource. Let ν_i be the utility received by the ith agent. Let $\bar{\nu} = \langle \nu_1, \cdots, \nu_N \rangle$ be utility vector of the N agents. The α-fairness metric $\mathcal{F}(\bar{\nu}; \alpha)$ measures the fairness among the N agents as follows:

$$\mathcal{F}(\bar{\nu}; \alpha) = \begin{cases} \sum_i^N \nu_i^{1-\alpha}/(1-\alpha) & ,\alpha \neq 1 \\ \sum_i^N \log(\nu_i) & ,\alpha = 1\cdot \end{cases} \tag{4}$$

When $\alpha = 0$, the α-fairness quantifies how efficient the resource is utilized without any fairness guarantees. As $\alpha \to \infty$, α-fairness becomes equivalent to the max-min fairness, while $\alpha = 1$ leads to the proportional fairness.

III. MATCHMAKER: FRAMEWORK AND ARCHITECTURE

MatchMaker guarantees POPs, i.e., MNOs, efficient and private access to the shared network. We next present MatchMaker architecture and explain how it extends the 3GPP model for a virtualized and clould-centric network sharing and operation over unlicensed bands. MatchMaker architecture is composed of several domains, as shown in Figure 2, including the network infrastructure domain, the MOP domain that includes the site controllers, the POP domain that includes MNOs, and the Wi-Fi domain that includes Wi-Fi systems who share the unlicensed channels with the POPs. We describe protocol design and communication overhead between the aforementioned domains in Section V.

A. Network Infrastructure Domain

We consider a shared network infrastructure that consists of a set $\mathcal{R} = \{R_i\}_{i=1}^{N_r}$ of N_r *shared remote radio head* (sRRH) units, *Wi-Fi listener* (WL) units, and *channel access controller* (CAC) units (see 'Infrastructure Domain' in Figure 2). The sRRH units are spread across the site to provide coverage for user equipments (UEs). Each sRRH unit includes a set of RF chains that can be tuned to different channels and perform NR-U RF-related processing, including ADC/DAC, up/down conversion, power amplification, RF filtering, etc. We consider a set $\mathcal{H} = \{h_i\}_{i=1}^{N_c}$ of N_c unlicensed carriers, i.e., channels, that can be shared by POPs and Wi-Fi systems. In order to monitor and/or compute the delay experienced by Wi-Fi networks, we attach a WL unit to every sRRH. WL units overhear beacons/frames sent by neighboring Wi-Fi systems to track their numbers and their reported measurements. WL units provide information that helps the MOP ensure fairness between POPs and Wi-Fi systems. To let the MOP control the access of POPs to the sRRH units, we attach a CAC unit with each sRRH. The CAC unit is used by the MOP to decide on which POP is allowed/blocked from accessing the sRRH unit. The CAC unit performs the CAT2- and CAT4-LBT procedures. Each CAC has access to a set of downlink/uplink buffers that are used to save POPs' uplink and downlink OFDM I/Q data for a short period of time.

B. MOP Domain

The MOP domain consists of two management modules: *Resource allocation manager* (RAM) and *channel access manager* (CAM) (see 'MOP Domain' in Figure 2). The RAM module handles channel assignment for POPs. It also manages the WL units and requests them to report it back with any Wi-Fi measurements they can overhear. The CAM module handles POPs' access to the shared infrastructure, and it instructs the CAC units to perform the required LBT procedures in order to clear the channel for POPs' transmissions. Although MOP manages POPs' access to the shared infrastructure, it still cannot preview private information about their UEs and/or their channel conditions, and this is because UE's data, control messages, and reference signals are usually encrypted or protected by scrambling.

C. POP Domain

POP domain consists of a set $\mathcal{P} = \{P_i\}_{i=1}^{N_p}$ of N_p MNOs who take the role as POPs (see 'POP Domain' in Figure 2). Each POP owns a pool of *gNB distributed units* (gNB-DUs), which can be virtualized and implemented on a *centralized radio access network* (C-RAN) [10]. gNB-DU is a baseband unit that performs NR-U radio stack functions, including radio link control (RLC), MAC, scheduling, and PHY-layer processing. The gNB-DU generates transmit blocks (TBs). Each TB contains multiple control and data messages that are targeted to multiple UEs. After coordinating with the MOP, gNB-DU generates DL TBs that are OFDM modulated and sends them to the CAC unit that is connected to the sRRH unit of interest. Once the CAC unit clears the channel, it

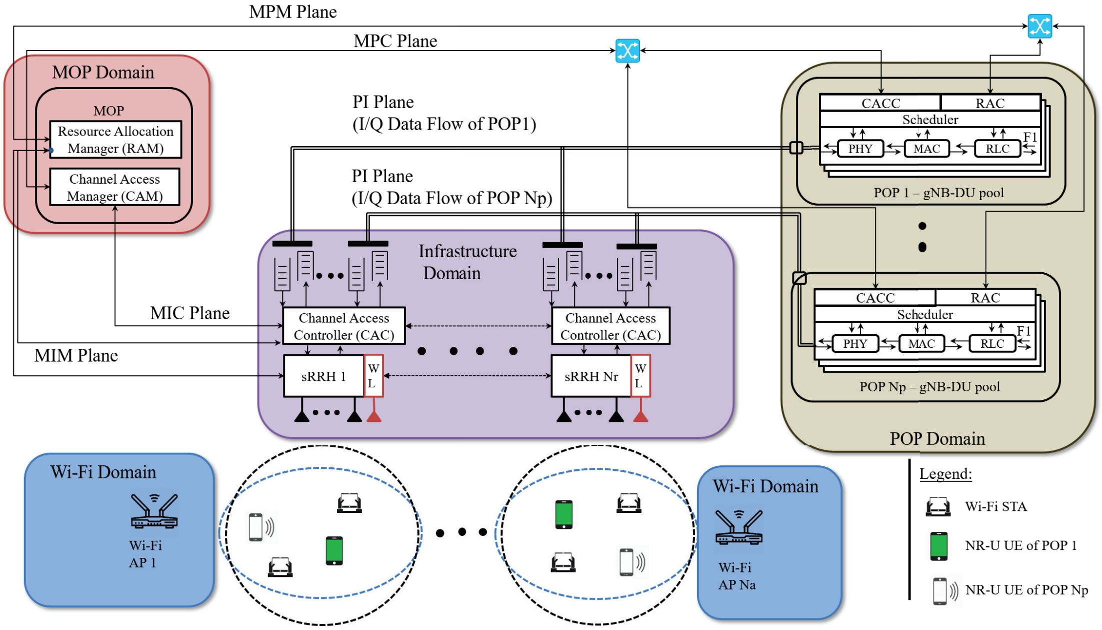


Fig. 2: Architecture of Matchmaker framework.

passes these I/Q samples to the sRRH unit to apply further RF processing and transmission. For UL communication, the sRRH unit receives the uplink waveform and applies RF filtering, down-conversion, and sampling. The CAC unit then passes these UL I/Q samples back to the gNB-DU to apply further processing.

To facilitate the coordination between gNB-DUs and MOP, We add two coordination units at every gNB-DU: *Channel access coordinator* (CACC) and *resource allocation coordinator* (RAC) units. The RAC unit coordinates with the RAM module information related to channel assignments. The CACC unit, on the other hand, coordinates with the CAM module at MOP channel access requests and related notifications.

D. Wi-Fi Systems Domain

The Wi-Fi domain consists of a set $\mathcal{A} = \{A_i\}_{i=1}^{N_a}$ of N_a Wi-Fi access points (APs) (see 'Wi-Fi domain' in Figure 2), where each AP, e.g., A_i, serves a set J_i of Wi-Fi stations. In our model, Wi-Fi APs select their operating channels independently and operate without any coordination with MOP.

IV. PROBLEM FORMULATION AND SOLUTION

The objective of the MOP is to provide a fair and efficient channel assignment among POPs, while preserving their privacy and meeting their performance constraints. We explain the problem for an arbitrary site covered by an sRRH unit. The same analysis can extended for an area covered by multiple sRRH units.

A. Maximizing NR-U/Wi-Fi Fairness

The MOP maximizes the fairness among the POPs and Wi-Fi systems, given their maximum tolerable contention delay. Let $D_{j,k}$ be the average contention delay experienced by POP P_j on channel k. Let D_j^* be the maximum average contention delay that POP P_j can tolerate, which is set by an agreement between the MOP and POP P_j. Let $B_{i,k}$ be the average contention delay experienced by Wi-Fi AP A_i on channel k, and B_i^* is the maximum average contention delay that A_i can tolerate. $D_{j,k}$ and $B_{i,k}$ can be measured as in (2)-(3), or computed approximately as in [9]. Let $\mathbf{1}_{j,k}$ be a binary decision variable indicating that POP P_j is assigned to operate on channel k. Let $n_k = \sum_{j=1}^{N_p} \mathbf{1}_{j,k}$ be the number of POPs sharing channel k, and m_k the number of Wi-Fi transmitters using channel k. We write the utility vector for POPs and Wi-Fi systems sharing channel k as $\bar{\nu}_k = \langle 1/D_{1,k}, \cdots, 1/D_{n_k,k}, 1/B_{1,k}, \cdots, 1/B_{m_k,k} \rangle$ and formulate the problem of assigning POPs to different channels as follows:

$$\max_{\{\mathbf{1}_{j,k}\}} \quad \sum_{k\in\mathcal{H}} F(\bar{\nu}_k;\alpha), \tag{5}$$

$$\text{s.t} \quad 1 \leq \sum_{k=1}^{N_c} \mathbf{1}_{j,k} \leq N_c, \qquad \forall j \in \mathcal{P}, \tag{6}$$

$$D_{j,k} \leq D_j^*, \qquad \forall j \in \mathcal{P}, \tag{7}$$

$$B_{i,k} \leq B_i^*, \qquad \forall i \in \mathcal{A} \tag{8}$$

where $F(\bar{\nu}_k;\alpha)$ is the α-fairness metric defined in (4). In order to maximize the fairness among colocated POPs and Wi-Fi devices, we set the elements in the utility vector $\bar{\nu}_k$ to be the inverse of contention delay experienced by the POPs and Wi-Fi systems. This setting allows the MOP to jointly minimize contention delay and maximize the fairness among the POPs and Wi-Fi systems. The constraints in (6) ensure that every POP is assigned at least one channel, while the constraints in (7) and (8) ensure the contention delay for POPs and Wi-Fi systems do not exceed their maximum tolerable contention delay. Contention delays experienced by POPs and Wi-Fi systems depend on the number of NR-U and Wi-Fi transmitters sharing the same channel, and thus they can be expressed as $D_{j,k} = f(\{\mathbf{1}_{j,k}\})$ and $B_{i,k} = g(\{\mathbf{1}_{j,k}\})$ [9]. However, the formulation of $f(\cdot)$ and $g(\cdot)$ is nonlinear and notoriously complicated. The nonlinear integer program in (5)-(8) is NP-hard and solving it requires having oracle knowledge about network topology and channel gains for POPs' and Wi-Fi users, which conflicts with our goal of preserving the privacy of POPs and reducing their communication overhead with the MOP. Therefore, we seek a heuristic approach for solving the problem in (5)-(8) according to the following two steps. In the first step, we let POPs balance their traffic loads by dividing their UEs into groups in which each UE group is served on a different channel. This step offers the POPs the flexibility of adopting their own UE grouping criterion. In the second step, we let the POPs propose their preferred channel assignment for their UE groups to the MOP. The MOP accepts these proposals tentatively for a period of time, called *engagement period* (T_{engage}). During T_{engage}, the MOP monitors/computes the mean average contention delay for the POPs and Wi-Fi systems, and use these statistics to learns the potential interference among them. The MOP then decides on whether it should reject any of POPs' proposals. The second step is private and neither requires POPs to reveal their users' identities nor their network/channel conditions. The second step is powered by a novel graph coloring algorithm.

B. Step1: Intra-POP User Grouping

POPs can consider different criteria for establishing their UE groups. We adopt a criterion that simplifies the design of the scheduler and power control procedures. Although UEs might be distributed nonuniformly within cell area, grouping UEs that experience equivalent path loss and serving them over the same channel has the advantage of facilitating the job of the scheduler and transmit power control procedures [11]. Let U_{ij} be the set of UEs who belong to POP P_i and located in an area that is covered by the sRRH R_j. POP P_i divides U_{ij} into L_i groups $\{S_{i,l}\}_{l=1}^{L_i}$ based on their path loss estimation, where each group can be assigned one channel and served by one gNB-DU. UEs of the same group are scheduled to orthogonal uplink and downlink resource blocks, and thus they will not interfere with each other. The number of UE groups should not exceed the number of channels N_c. Increasing L_i requires POP to allocate more MAC- and PHY-layer chains for every channel.

UE groups that belong to the same POP are supposed to be served on different channels, and thus they can be modeled as a complete graph (see the right-most bottom part of Figure 3 for an arbitrary example). Channel assignment can be handled by applying a proper graph coloring to this graph. Because UE groups of different POPs are co-located, they can interfere with each other, and thus the graph coloring for POPs' graphs should be handled carefully to limit inter-POP interference. Therefore, the MOP can consider a larger graph that includes the individual complete graphs of POPs (see Figure 4 for an arbitrary example). The MOP can apply a proper coloring to this established graph, however, the MOP does not know the full graph structure, e.g., dashed edges in Figure 4. Recall that, due to the privacy concern, the MOP has limited knowledge about users' channel gains and localization information. We next tackle this challenge and show that the MOP can still infer this graph structure by monitoring the average contention delays experienced by POPs and Wi-Fi systems.

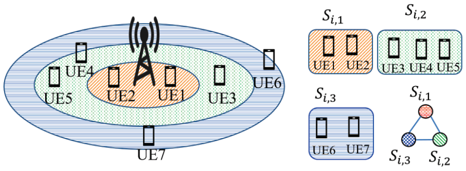


Fig. 3: Arbitrary example of one POP that divides its UEs into three groups based on their path loss estimates ($L_p = 3$).

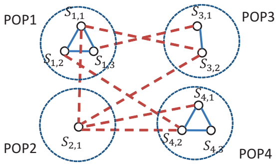


Fig. 4: Arbitrary example of contention graph $\mathcal{G}_m$ that represents intra- and inter-POP interference (solid edges: Intra-POP interference; dashed edges: inter-POP interference; $L_1 = 3$; $L_2 = 1$; $L_3 = 2$; $L_4 = 3$).

C. Step2: Channel Assignment Using Graph Coloring Evolution (GCE) Algorithm

Inspired by stable matching algorithms [12], the GCE algorithm involves a sequence of subgraph coloring proposals offered by the POPs and acceptance/rejection made by the RAM module at MOP. Acceptance/rejection dynamics can be modeled as *graph evolution* because based on these acceptance/rejection the MOP can add edges and change graph coloring overtime. We define the evolving graph as follows:

***Definition** 2:* Let $\mathcal{G}_m^{(t)} = (V^{(t)}, E^{(t)}, C^{(t)})$ be the evolving contention graph at time t. The set of vertices $V^{(t)}$ includes POPs' UE groups, and it has a cardinality of $N_s = \sum_p^{N_p} L_p$. The set of edges $E^{(t)}$ represent the intra- and inter-POP interference. The set of colors $C^{(t)}$ includes the channel IDs that are assigned to UE groups, i.e., vertices in $V^{(t)}$.

Let $\mathcal{L} = \{l_i\}_{i=1}^{N_c}$ be the set of possible colors that has a one-to-one mapping with the set of channels, i.e., $\mathcal{H}$. Let $x_i^{(t)} = \{l_k : l_k \neq l_j\}_{j,k=1}^{L_i}$ be the coloring proposal, i.e., channel assignment proposal, of POP P_i at time t. Let $y_i^{(t)} = \{b_k\}_{k=1}^{L_i}$ be the decision taken by the MOP at time t about the most recent proposal raised by POP P_i, where b_k is a binary flag indicating rejection/acceptance of coloring proposal of UE group $S_{i,k}$. POP's proposals and MOP's acceptance/rejection messages are encapsulated in the `ChProposal`, `ChProposalAck`, and

`ChProposalReject` messages, as explained in Section V. The GCE algorithm works as follows:

1) Initialization: The MOP starts with an initial graph $\mathcal{G}_m^{(0)} = (V^{(0)}, E^{(0)}, C^{(0)})$ at time $t = 0$ that includes N_p complete and disconnected subgraphs. Each complete subgraph corresponds to UE groups of one POP. All vertices at the start has no color, i.e., $C^{(0)} = \{0\}_{i=1}^{N_s}$.

2) Engagement: At time t, a random POP, say POP P_i, sends its coloring proposal $x_i^{(t)}$ to the MOP. The MOP accepts this proposal tentatively for a duration T_{engage} during which it monitors and/or computes the average contention delay for POPs and Wi-Fi systems. At the end of T_{engage}, the MOP computes the normalized differential change ($\Delta F_{i,k}$) that POP P_i caused to the objective function in (5) at all channels:

$$\Delta F_{i,k} = (F(\bar{\nu}_k^{(t)}; \alpha) - F(\bar{\nu}_k^{(t-1)}; \alpha))/F(\bar{\nu}_k^{(t-1)}; \alpha), \ \ \forall k \in \mathcal{H} \tag{9}$$

where $\bar{\nu}_k^{(t)}$ is the utility vector of POPs and Wi-Fi systems at time t over channel k. The MOP keeps tracking to $\Delta F_{i,k}$ for all POPs and channels. To decide on whether the MOP should accept or reject POP's coloring proposal $x_i^{(t)}$, the MOP verifies on whether the constraints in (7) and (8) are satisfied. If all constraints are satisfied, the MOP proceeds and repeats the above procedure again for a new POP. If at least one constraint is not satisfied, the MOP tags the corresponding channel as being at the *state of rejection.*

3) Rejection: For each channel tagged in the state of rejection, say channel k^*, the MOP ranks the POPs based on their $\Delta F_{i,k^*}$ values, and finds the POP whose proposal caused the least improvement:

$$r = \underset{n \in \mathcal{P}}{\arg\min} \qquad \Delta F_{n,k^*} \tag{10}$$

The MOP sends a rejection decision $y_r^{(t)}$ to POP P_r encapsulated in the `ChProposalReject` message. The MOP, then, updates the contention graph $\mathcal{G}^{(t)}$ and removes the color for the vertex corresponding to the rejected UE group, say vetrex $v \in V^{(t)}$, and adds edges between v and all other vertices having the same color as vertex v. The MOP monitors and computes the average contention delay for POPs and Wi-Fi systems for another T_{engage} period, and checks whether the constraints in (7) and (8) become satisfied. If they still unsatisfied, it repeats the same rejection rule discussed above for another proposal and waits for another T_{engage} period. The rejection process repeats until all constraints become satisfied. POPs with rejected proposals should propose again with a new coloring proposal until they do not receive any more rejection messages. In the worst case, every POP might be rejected for most of its coloring proposals. Because POPs should propose sequentially, the GCE algorithm has a worst cast complexity of $O(N_p L_m!)$, where L_m is the maximum number of channels that a POP might request.

V. MATCHMAKER PROTOCOL DESIGN

To facilitate network sharing and operation over unlicensed bands, MOP, POPs, and controllers at the infrastructure require a protocol to manage their communications. We define the following planes to facilitate communications among all domains, as shown in Figure 2. The *MOP-POP Management* (MPM) and *MOP-POP Control* (MPC) planes include messages required to facilitate the coordination between the MOP and POPs. The MOP manages the controllers located at the network infrastructure through the *MOP-Infrastructure Management* (MIM) plane, and controls the access of POPs to the network infrastructure through the *MOP-Infrastructure Control* (MIC) plane. POPs access the shared network infrastructure through the *POP-Infrastructure* (PI) plane. The messages sent over the aforementioned planes and their flow diagram are shown in Table I and Figure 5, respectively.

TABLE I: MatchMaker messages (see Figure 5 for timing labels)

Message	Content, (timing label)	Plane
`Request-`L_p	$\langle$`POP-ID`, `sRRH-ID`, `SendLp-F`$\rangle$, (t1)	MPM
`Report-`L_p	$\langle$`POP-ID`, `sRRH-ID`, $L_p\rangle$, (t2)	MPM
`ChProposal`	$\langle$`POP-ID`, `sRRH-ID`, x, $D^*\rangle$, (t3)	MPM
`ChProposalAck`	$\langle$`POP-ID`, `sRRH-ID`, `ACK-F`$\rangle$, (t4)	MPM
`ChProposalReject`	$\langle$`POP-ID`, `sRRH-ID`, $y\rangle$, (t14)	MPM
`ChAccRequest`	$\langle$`POP-ID`, `sRRH-ID`, `ch-ID`, `Req-ID`, `lbt-F`, $T_{\text{cot-dl}}$, $T_{\text{cot-ul}}\rangle$, (t5)	MPC
`ChAccProceed`	$\langle$`POP-ID`, `sRRH-ID`, `ch-ID`, `Req-ID`, `SendIQ-F`$\rangle$, (t6)	MPC
`ChAccEnd`	$\langle$`POP-ID`, `sRRH-ID`, `ch-ID`, `Req-ID` , `Status-F`$\rangle$, (t10)	MPC
`ChAccFeedback`	$\langle$`POP-ID`, `sRRH-ID`, `ch-ID`, `Req-ID`, `dblWind-F`, `flushBuff-DL-F`, `flushBuff-UL-F`$\rangle$, (t11)	MPC
`SetCarrierFreqs`	$\langle$`sRRH-ID`, `POP-ID`, `SetCh-F`, $x\rangle$, (t4)	MIM
`ResetMonitors`	$\langle$`sRRH-ID`, `ch-ID`, `WL-ID`, `Reset-F`$\rangle$, (t4)	MIM
`WifiStatsRequest`	$\langle$`sRRH-ID`, `ch-ID`, `Stats-F`$\rangle$, (t12)	MIM
`WifiStatsReport`	$\langle$`sRRH-ID`, `ch-ID`, `mWifi`, $T_{\text{wifiDelay}}\rangle$, (t13)	MIM
`StartLbt`	$\langle$`POP-ID`, `sRRH-ID`, `ch-ID`, `Req-ID`, $T_{\text{cot-dl}}$, $T_{\text{cot-ul}}$, `lbt-F`, `w-F`$\rangle$, (t6)	MIC
`LbtReport`	$\langle$`POP-ID`, `sRRH-ID`, `ch-ID`, `Req-ID`, `done-F`$\rangle$, (t9)	MIC

A. MOP-POP Management (MPM) Plane

To let the MOP coordinate with the POPs their channel assignments, the following messages are exchanged between the RAM module at the MOP and the RAC units at POPs: `Request-`L_p, `Report-`L_p, `ChProposal`, `ChProposalAck`, and `ChProposalReject`. In `Request-`L_p message, the MOP triggers POPs to report it back the number of channels (L_p) that they wish to operate on. POPs report back their L_p values that are encapsulated in the `Report-`L_p message. Afterward, POPs propose to the MOP the list of channels they wish to operate on by sending the `ChProposal` message, which includes the set of channels $x = \{h_i\}_{i=1}^{L_p}$ and the maximum contention delay that they can tolerate (D^*). The MOP acknowledges POP's proposal by replying back with the `ChProposalAck` message. The POP checks whether the `ACK-F` flag is set and starts operating over the proposed channels for an engagement period T_{engage}, otherwise, the POP resends a new channel proposal message. After T_{engage} period, the MOP decides on whether it should reject POP's proposal. If rejected, the MOP sends the `ChProposalReject` message to notify the POP about the channels that the POP is rejected. The rejection decision is indicated by the set $y = \{b_i\}_{i=1}^{L_p}$, which is encapsulated in the `ChProposalReject` message.

B. MOP-POP Control (MPC) Plane

To let the MOP control the access of POPs to the shared network infrastructure and manage their transmission over the unlicensed channels, the following messages are exchanged between the CAM module at the MOP and the CACC units at the POPs: `ChAccRequest`, `ChAccProceed`, `ChAccEnd`, and `ChAccFeedback`. A POP sends the `ChAccRequest` message to notify the MOP that it intends to start transmission over the channel `ch-ID` through the sRRH unit `sRRH-ID`. This message also includes the *request-ID* (`Req-ID`), the duration of the downlink ($T_{\text{cot-dl}}$) and uplink ($T_{\text{cot-ul}}$) COTs, and the `lbt-F` flag that indicates the LBT procedure required to access the channel, i.e., CAT2-LBT or CAT4-LBT. The MOP queues this request until POP's turn comes in. The MOP sends the `ChAccProceed` message to the POP in which it requests the POP to send its OFDM modulated I/Q samples over the PI plane. The MOP requests the controllers at the infrastructure to start the LBT procedure and transmit/receive over the requested channel as indicated in the `ChAccRequest` message. Once the transmission/reception is finished, the MOP sends the POP the `ChAccEnd` message in which it notifies the POP about the completion of its transmission. Upon reception of this message, the POP checks the `Status-F` flag field to see if it should send the MOP back the `ChAccFeedback` message, in which the POP updates the MOP on whether is should it should double the contention window for the next transmission by setting the `dblWind-F` flag field. The `flushBuff-DL-F` and `flushBuff-UL-F` flag fields are set to indicate whether the MOP should instruct the corresponding CAC unit to flush the downlink and uplink buffers.

C. POP-Infrastructure (PI) Plane

POPs send and receive their downlink and uplink baseband OFDM modulated I/Q samples to sRRH units through the PI plane. There are several frameworks that support the exchange of the baseband I/Q data between remote equipment, including the enhanced common public radio interface (eCPRI), open base station architecture initiative (OBSAI), and open radio equipment interface (ORI) (see References [21]-[23] in [10]).

D. MOP-Infrastructure Management (MIM) Plane

To let the MOP manage and configure equipment at the shared network, the `SetCarrierFreq`, `ResetMonitors`, `WifiStatsRequest`, and `WifiStatsReport` messages are exchanged between the RAM module at the MOP and the CAC, sRRH, and WL units located at the network. The MOP sends the `SetCarrierFreq` message to configure the different radio parameters of sRRH units. To avoid receiving outdated measurements and statistics, the MOP sends `ResetMonitors` message to the CAC and WL units, triggering them to reset/initiate their monitors. At the end of the T_{engage} period, the MOP sends the `WifiStatsRequest` message to WL units in which it requests them to report back the statistics they obtained for neighboring Wi-Fi systems. The WL units send back the `WifiStatsReport` message in which they report the number of Wi-Fi transmitters `mWifi` and the average access delay $T_{\text{wifiDelay}}$ measurements that they can overhear.

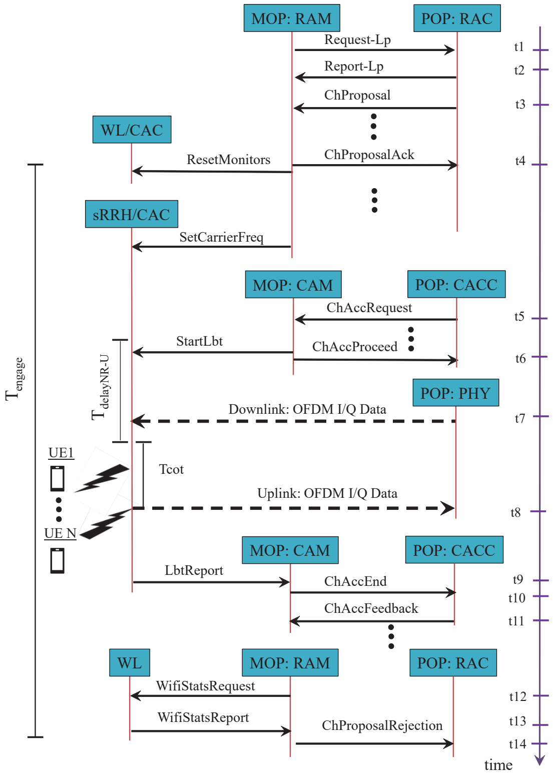


Fig. 5: MatchMaker's messages flow diagram (Solid arrows indicate management/control messages; Dashed arrows indicate NR-U OFDM I/Q data flow).

E. MOP-Infrastructure Control (MIC) Plane

To let the MOP control the access of POPs to the shared network and their transmission over the unlicensed channels, the `StartLbt` and `LbtReport` messages are exchanged between the CAM module at the MOP and the CAC units located at the network. The MOP sends the `StartLbt` message to the CAC unit in which the MOP triggers the CAC unit to start the LBT procedure. Once the CAC unit completes the LBT procedure, it passes POP's I/Q samples to the sRRH unit. The sRRH unit applies digital to analog conversion and relevant RF operation required for transmission. The `StartLbt` message includes the durations for the downlink COT ($T_{\text{cot-dl}}$) and uplink COT ($T_{\text{cot-ul}}$). It also includes the `lbt-F` flag field, which is used to notify the CAC unit on the type of LBT procedure that it should perform, i.e., CAT2-LBT or CAT4-LBT. The flag field `w-F` is used to notify the CAC unit to double its contention window. When transmission is finished, the CAC unit sends the `LbtReport` message back to the

MOP in which it updates the MOP about the completion of this channel access.

VI. Evaluation

A. Toy Example of Graph Coloring Evolution (GCE) Algorithm

We provide an arbitrary example to explain how the GCE algorithm works. We consider a site shared by three POPs, P_1, P_2, and P_3, with $L_1 = 3$, $L_2 = 1$, and $L_3 = 2$. At time $t = 0$, the MOP requests the POPs to report it back with their L_i values. The MOP constructs an initial non-colored graph with three disjoint complete subgraphs, as shown in Figure 6. At time $t = 1$, POP P_3 proposes a coloring proposal $x_3^{(1)} = \{\text{red}, \text{green}\}$ encapsulated in the `ChPoroposal` message. After acknowledging this proposal and monitoring the average contention delay for POP P_3 and Wi-Fi systems, the MOP computes the differential enhancements $\Delta F_{3,\text{red}}$ and $\Delta F_{3,\text{green}}$ and ensures that all constraints in (7)-(8) are satisfied. At time $t = 2$, POP P_1 proposes a coloring proposal $x_1^{(2)} = \{\text{red}, \text{blue}, \text{green}\}$. The MOP follows the same steps as in $t = 1$ and computes $\Delta F_{1,\text{red}}$, $\Delta F_{1,\text{green}}$, and $\Delta F_{1,\text{blue}}$. The MOP finds that one of the constraint in (7) is violated for the green channel. Then, it compares $\Delta F_{3,\text{green}}$ and $\Delta F_{1,\text{green}}$ and finds that the proposal of POP P_3, made at time $t = 1$, has a lower differential value, i.e., $\Delta F_{3,\text{green}} < \Delta F_{1,\text{green}}$. Therefore, the MOP removes the coloring of vertex $S_{3,2}$, adds an edge between $S_{3,2}$ and $S_{1,3}$, and sends POP P_3 a rejection decision $y_3^{(2)} = \{1, 0\}$ encapsulated in `ChProposalReject` message, notifying P_3 about the violation of its coloring proposal used for $S_{3,2}$. At time $t = 3$, POP P_2 proposes a coloring proposal $x_2^{(3)} = \{\text{blue}\}$. Similar to the previous steps and after T_{engage} duration, the MOP computes $\Delta F_{2,\text{blue}}$ and finds constraints in (7) and (8) are satisfied. At time $t = 4$, POP P_3 proposes an updated coloring proposal $x_3^{(4)} = \{\text{red}, \text{blue}\}$. After T_{engage} duration, the MOP finds that POP P_2 proposal made at time $t = 3$ is violating for the blue channel, and thus the MOP rejects POP P_2 coloring proposal for vertex $S_{2,1}$, leaving it uncolored, and adds two new edges between vertices $S_{2,1}$ and vertices $S_{1,2}$ and $S_{3,2}$. Finally at time $t = 5$, POP P_2 proposes an updated coloring proposal $x_2^{(3)} = \{\text{green}\}$ that the MOP accepts and finds satisfying. The algorithm terminates.

B. Experimental Results

We implemented the extended 3GPP network sharing framework, including the functional blocks of Figure 2 and the message flow of Figure 5, using our customized C++-based discrete-event system level simulator [13]. We also implemented the GCE algorithm as discussed in Section IV-C. To compare the CGE algorithm, we consider two other algorithms. In the 'Optimal' algorithm, we do an exhaustive search to find the solution for the optimization problem in (5) - (8), and then pass this solution to the MOP. In the 'Random' algorithm, we let the MOP assign channels to the POPs randomly without any QoS guarantees. The 'Optimal' and 'Random' algorithms represent two extreme cases in our problem. We set the maximum contention delay thresholds, in (7) and (8), for POPs and Wi-Fi systems to 80 milliseconds. We set the fairness parameter $\alpha = 1$ and the engagement time to 1 second, i.e., $T_{\text{engage}} = 1$ second.

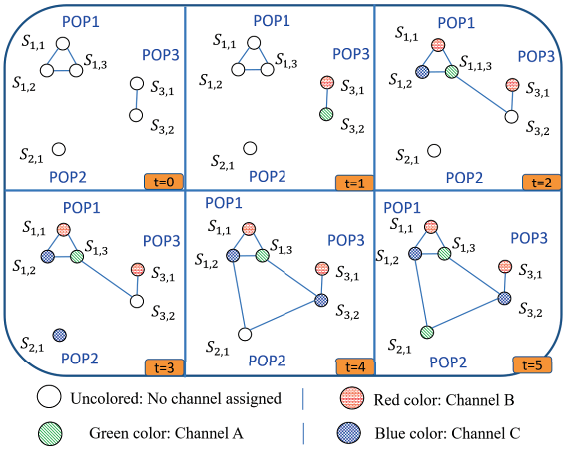
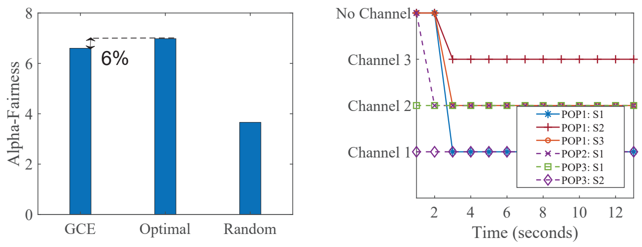


Fig. 6: Arbitrary example of contention graph coloring evolution.

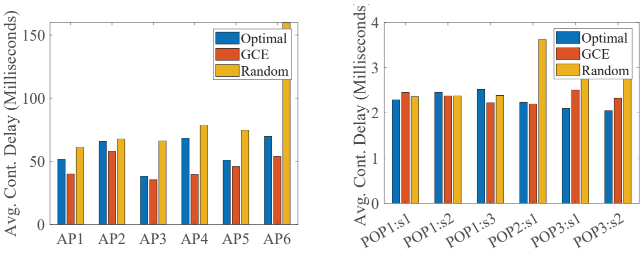
We implemented the EDCA and CAT4-/CAT2-LBT procedures, as specified by the IEEE 802.11ac [7] and 3GPP standard [3]. We consider a network with three POPs and six Wi-Fi APs, sharing three unlicensed channels, channel 1, 2, and 3, centered at 5.18, 5.2, and 5.22 GHz, respectively. Each operator serves six users. POP1 requests MOP for three channels, i.e., $L_1 = 3$, while POP2 and POP3 request one and two channels, i.e., $L_2 = 1$ and $L_3 = 2$, respectively. AP1 and AP4 operate on channel 1, while AP2 and AP5 operate on channel 2, and AP3 and AP6 operate on 3. NR-U and Wi-Fi devices are uniformly distributed in a square area of length 140 meters. We consider the following channel access parameters, $T_{\text{d}} = 25$ microseconds, $T_{\text{cot}} = 2$ milliseconds, and $W_{\min} = 4$, for NR-U operation [3], and $T_{\text{aifs}} = 34$ microseconds, $T_{\text{txop}} = 1.5$ milliseconds, and $W_{\min} = 4$, for Wi-Fi operation [7]. We run each experiment for 60 seconds and collect statistics for all devices. We repeat each experiment for 100 times. The rest of simulation parameters are specified as in [14].

In Figure 7(a), we plot the objective function of Equation (5) under the three algorithms. The GCE algorithm approaches the 'Optimal' one, while the 'Random' algorithm, on the other hand, provides a lower fairness between POPs and Wi-Fi systems without any guarantees on the contention delay. In Figure 7(b), we plot the convergence dynamics of the GCE algorithm. We also compare the average contention delay experienced by POPs and Wi-Fi systems for under the three algorithms in Figure 8. We notice the GCE algorithm provides a performance that is up to 90% of the 'Optimal' one, while the 'Random' algorithm causes higher contention delay. In some occasions, the GCE algorithm provides lower contention delay for some APs and POPs, however, this comes at the cost of reducing their fairness between POPs and Wi-Fi systems.



(a) (b)

Fig. 7: (a) Fairness measure with $\alpha = 1$, (b) Convergence of the GCE algorithm.



(a) (b)

Fig. 8: Average contention delay: (a) Wi-Fi, (b) NR-U.

VII. RELATED WORK

Several standard bodies and societies encourage infrastructure sharing among MNOs, including the 3GPP [5] [4] and the Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) [15]. Most works on infrastructure sharing focus on licensed spectrum operation [16]–[18]. Sciancalepore et al. [16] introduced a signaling-based broker solution to accurately predict traffic and schedule the shared resources. Caballero et al. [17] introduced the Fisher market mechanism to study resource allocation across the shared network resources. Leconte et al. [18] studied the problem of partitioning bandwidth and cloud processing among MNOs. Guan and Melodia [19] presented a cognitive coexistence platform for LTE-U and solved for the optimal resource allocation using mixed integer nonlinear programming. Hirzallah et al. [20] proposed a full-duplex-enabled design to reduce collisions between LTE-U and Wi-Fi systems. Xiao et al. [21] proposed a joint licensed and unlicensed network slicing framework for MNOs. Previous works provided exciting results and thorough analysis, however, they are focused on one aspect of inter-operator operations over unlicensed bands, and did not address the privacy concern and the communication overhead required between the MOP and POPs. In our paper, we extend the 3GPP network sharing framework for operation over unlicensed bands, and provide a privacy-conserving and low-overhead algorithm for assigning channels between MNOs.

VIII. CONCLUSION

We presented MatchMaker, a framework for extending the 3GPP network infrastructure sharing model for operation over unlicensed bands. MatchMaker provides a novel graph coloring evolution algorithm that assigns MNOs traffic to the unlicensed channels while preserving their privacy and meeting the fairness with Wi-Fi systems. Our results reveal that our algorithm can achieve up to 90% of the optimal α-fair channel assignment between POPs and Wi-Fi systems without requiring MNOs to reveal private information about their users and their channel conditions.

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