

# On the Orchestration of Robust Virtual LTE-U Networks from Hybrid Half/Full-duplex Wi-Fi APs

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**Abstract**—Two promising solutions have been recently proposed to address the massive growth in mobile traffic and wireless devices: LTE-U and in-band full-duplex (FD) wireless. LTE-U extends the benefits of LTE-A to the unlicensed 5 GHz band, used mainly by Wi-Fi users. However, the uncertainty in Wi-Fi user activities makes provisioning QoS guarantees to LTE-U users challenging. On the other hand, FD wireless can double spectrum efficiency by enabling simultaneous transmission and reception over the same frequency band. Our objective in this paper is to exploit excess capacity of deployed Wi-Fi networks (operating in the 5 GHz band) to orchestrate a ‘robust’ virtual LTE-U network from a hybrid set of half-duplex (HD) and FD Wi-Fi access points (APs). Although the orchestrated LTE-U network does not support *deterministic* QoS guarantees, it is designed to provide prespecified *probabilistic* QoS guarantees (hence, it is robust). Towards achieving our goal, we develop novel stochastic resource allocation formulations that optimally orchestrate a virtual LTE-U network from a hybrid set of HD/FD APs with the minimum cost. We first consider the single small-cell problem and propose a stochastic formulation, which we refer to as  $CCLTEU_{single}$ . Then, we study the multi-cell stochastic allocation problem and develop another formulation, which we refer to as  $CCLTEU_{multi}$ . Our formulations adopt a ‘chance-constrained stochastic programming’ approach. We derive the deterministic equivalent programs of  $CCLTEU_{single}$  and  $CCLTEU_{multi}$  and evaluate them numerically under various system parameters.

## I. INTRODUCTION

The massive growth in mobile traffic and wireless devices has motivated research and development on the next generation wireless networks. Among the promising solutions that have been recently proposed are LTE-U [1] and in-band full-duplex (FD) wireless [2]. LTE-U extends the benefits of LTE-A to the unlicensed 5 GHz band (used mainly by Wi-Fi users), exploiting the excess capacity in the deployed Wi-Fi access points (APs) to meet the increasing demand of LTE-U users. On the other hand, by enabling simultaneous transmission and reception over the same frequency band, in-band FD provides an attractive solution for the massive growth in mobile traffic, by doubling the spectrum efficiency of wireless devices. Several studies [3]–[6] have successfully demonstrated the feasibility of FD communications using self-interference cancellation techniques.

In the 5 GHz band, there are 23 non-overlapping channels (each of 20 MHz) available for Wi-Fi users. In some scenarios, this number of channels is enough to allow for an LTE-U/Wi-Fi coexistence solution that is based only on dynamic channel selection (DCS) [7]. In DCS, LTE-U small cells perform inter-

ference measurements, both at the initialization phase as well as on a regular basis. LTE-U users monitor the interference level over the selected Wi-Fi channels; if the interference goes above a certain threshold, a channel switch will be triggered. In parallel, some Wi-Fi APs employ a similar technique, known as the least congested channel search (LCCS), which contributes to this coexistence approach. However, in dense deployment scenarios, the number of available channels in the 5 GHz band may not be enough to enable an efficient LTE-U/Wi-Fi coexistence based only on DCS. Furthermore, recent IEEE 802.11 standards, such as the IEEE 802.11ac, use channel widths of up to 160 MHz, which severely decreases the number of orthogonal channels.

The other coexistence proposals can be grouped into two categories; one for listen-before-talk (LBT) LTE-U devices and the other for non-LBT devices. LBT means that an LTE-U device can transmit only when no ongoing transmission is detected for a specific period of time. The distributed coordination function (DCF) employed in Wi-Fi uses this approach. As an example, the European Telecommunications Standards Institute (ETSI) presented an LBT specification for time-frame-based devices. According to this specification, the user equipment (UE) and the base station (BS) sense the channel for a certain period to detect the energy level over this channel, named clear channel assessment (CCA). Figure 1 illustrates how the LBT approach from ETSI controls the medium access. If the UE or the BS senses the interference level below a predefined threshold, the channel is considered idle and can be used during the channel occupancy time. The idle period is at least 5% of this time. In [8], the authors proposed another LBT approach, which is very similar to the DCF. According to the approach in [8], the UE and BS sense the medium every time there is a packet to send and employ backoff if the channel is busy. This approach follows closely the dynamics of the shared medium, which is an advantage for coexistence with Wi-Fi devices, however the implementation cost is higher than the ETSI approach.

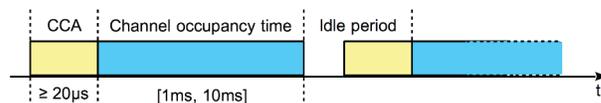


Fig. 1: Listen-before-talk approach proposed by ETSI.

The approaches that are not based on LBT reserve time slots in the LTE-U frame for the transmissions of the other technologies. The carrier-sensing adaptive transmission (CSAT) [7] is an example. CSAT defines a TDM cycle during which an LTE-U cell (UE or BS) alternates between transmission and silence. The silence slot gives opportunity for other technologies to transmit and it is also used by the LTE-U users to monitor the channels activity. Thus, the ON/OFF cycle can be adjusted by taking into account the sensed channel activity. In Figure 2, we illustrate the almost blank subframe (ABS) scheme [9], which is part of the LTE standards for interference coordination between macro and small cells. ABSs are subframes with reduced downlink transmission power that transport only some control and synchronization signals. In [10], [11], the authors proposed to adapt ABS by completely removing the LTE signals from these special subframes, making them suitable to support the coexistence with Wi-Fi. These works also evaluate the LTE-U performance and the impact on the Wi-Fi users while using different numbers of ABSs. An adaptive ABS mechanism is proposed in [12], in which the number of subframes is adjusted periodically according to the traffic load from the Wi-Fi devices.

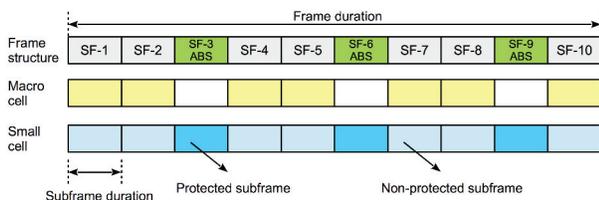


Fig. 2: Almost blank subframes.

In all existing (LBT/non-LBT based) approaches for LTE-U/Wi-Fi coexistence, the availability of the channels in the 5 GHz band is not *deterministically* known to the LTE-U system, making the provisioning of QoS guarantees to LTE-U users very challenging. This paper focuses on mitigating the negative impact of this uncertainty on the applications performance and users satisfaction. We assume a context in which channels have different levels of occupancy, thus the interference levels are different over different channels. Our proposal chooses multiple non-contiguous channels in order to meet user demands.

**Our Contributions**—Our goal in this paper is to exploit the excess capacity of the already deployed Wi-Fi networks, operating in the 5 GHz band, to compose a virtual LTE-U network from a hybrid set of half-duplex (HD) and FD Wi-Fi access points (APs). The virtual LTE-U network is designed to provide certain *probabilistic* QoS guarantees to its users, hence it is robust. Towards achieving this goal,

- First, we develop a stochastic resource allocation scheme for optimally orchestrating a single-cell virtual LTE-U network from a hybrid set of HD/FD APs with the minimum cost. We refer to this scheme as  $\text{CCLTEU}_{\text{single}}$ . Adding the uncertainty in the channel availability to the allocation problem causes the feasibility region of the

problem to be uncertain. Different stochastic optimization approaches have been proposed in the literature to deal with the uncertainty of the feasibility region of an optimization problem [13]. In  $\text{CCLTEU}_{\text{single}}$ , we adopt a ‘chance-constrained stochastic programming’ approach.

- Second, we extend  $\text{CCLTEU}_{\text{single}}$  to compose a multi-cell virtual LTE-U network with heterogeneous (cell-dependent) coverage demands.
- Third, we develop a stochastic allocation scheme for composing a multi-cell virtual LTE-U network with homogeneous coverage demand. We refer to this scheme as  $\text{CCLTEU}_{\text{multi}}$ .
- Finally, we numerically evaluate the performance of our stochastic allocation formulations under various system parameters.

**Paper Organization**—The rest of the paper is organized as follows. We present the system model in Section II. The single-cell stochastic AP allocation problem is formulated and solved in Section III. In Section IV, we formulate and solve the multi-cell stochastic AP allocation problem. All proposed resource allocation schemes are numerically evaluated in Section V. Finally, in Section VI we conclude the paper.

## II. SYSTEM MODEL

We consider a geographical area that is divided into a set  $\mathcal{N} \stackrel{\text{def}}{=} \{1, 2, \dots, N\}$  of small cells. A set  $\mathcal{I}_h \stackrel{\text{def}}{=} \{1, 2, \dots, I_h\}$  of HD APs and a set  $\mathcal{I}_f \stackrel{\text{def}}{=} \{1, 2, \dots, I_f\}$  of FD APs exist in each small cell. A channel assigned to an FD AP provides twice the rate that it provides when assigned to an HD AP (i.e., the spectrum efficiency of an FD AP is twice that of an HD AP). The cost of the  $i$ th HD AP in cell  $n$  is denoted by  $h_{in}$ ,  $i \in \mathcal{I}_h$ ,  $n \in \mathcal{N}$ , and the cost of the  $i$ th FD AP in cell  $n$  is denoted by  $f_{in}$ ,  $i \in \mathcal{I}_f$ ,  $n \in \mathcal{N}$ . In our model, we assume that an AP can function as an LTE base station, exploiting its excess capacity to fulfill LTE-U user demands. Figure 3 illustrates our system model. We assume that there is a set  $\mathcal{M} \stackrel{\text{def}}{=} \{1, 2, \dots, M\}$  of mobile users. Each user, say  $m$ , requests a certain probabilistic rate, i.e., a rate (denoted by  $r_m$ ) to be satisfied with a minimum prespecified probability.

In this paper, we consider two models for probabilistic rate demands: *Heterogeneous* and *homogeneous*. In the heterogeneous model, a user, say  $m \in \mathcal{M}$ , requests (in general) different probabilities, denoted by  $\alpha_{mn} \in (0, 1]$ , for different small cells  $n \in \mathcal{N}$ . In contrast, in the homogeneous model, a user, say  $m$ , requests one probability, denoted by  $\alpha_m$ , for the entire network. In both models,  $r_m$  is the same across all small cells<sup>1</sup>. We associate with the  $i$ th HD AP in cell  $n$  a random variable  $\tilde{w}_{in}$ , which describes its availability. Similarly,  $\tilde{v}_{in}$  is

<sup>1</sup>There are several scenarios under which the objective may be providing a given user with a constant rate across all cells, but with different (cell-dependent) probabilistic guarantees. One such scenario is when a user, say  $m$ , is using an app that requires a particular rate,  $r_m$ , and wants to limit outage probability. If the user’s mobility pattern is well known, we may want to particularly guarantee performance in the cells where the user is most likely to be (e.g., achieving an outage probability of below 5% in a handful of cells and 20% in the rest may be much cheaper than achieving an outage probability of below 7% in all cells).

a random variable that describes the availability of the  $i$ th FD AP in cell  $n$ .

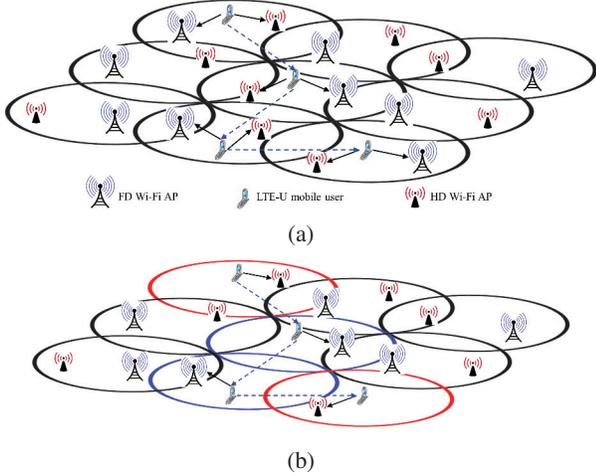


Fig. 3: (a) Illustration of the system model for  $N = 9$ ,  $I_h = I_f = 1$ , and  $M = 1$ . An FD AP is more expensive than an HD AP, but it provides twice the spectrum efficiency of the HD AP. (b) The excess capacity of the deployed HD/FD APs is used to probabilistically fulfill the demand of a mobile LTE-U user with the minimum cost.

### III. SINGLE-CELL ALLOCATION

In this section, we consider the problem of composing a single-cell LTE-U network with stochastic QoS guarantees.

#### A. Problem Formulation

Let  $x_{im}, i \in \mathcal{I}_h, m \in \mathcal{M}$ , and  $y_{im}, i \in \mathcal{I}_f, m \in \mathcal{M}$ , be binary decision variables.  $x_{im}$  (respectively,  $y_{im}$ ) equals one if the  $i$ th HD (respectively, FD) AP is allocated to user  $m$ , and  $x_{im}$  (respectively,  $y_{im}$ ) equals zero otherwise. Then, the CCLTEU<sub>single</sub> formulation is given by:

#### Problem 1 (CCLTEU<sub>single</sub>):

$$\begin{aligned} & \underset{\substack{x_{im}, i \in \mathcal{I}_h, \\ y_{im}, i \in \mathcal{I}_f, \\ m \in \mathcal{M}}}{\text{minimize}} \left\{ \sum_{m=1}^M \left[ \sum_{i=1}^{I_h} h_i x_{im} \mathbb{E}[\tilde{w}_i] \right. \right. \\ & \quad \left. \left. + \sum_{i=1}^{I_f} f_i y_{im} \mathbb{E}[\tilde{v}_i] \right] \right\} \quad (1) \end{aligned}$$

subject to:

$$\Pr \left\{ \left[ \sum_{i=1}^{I_h} x_{im} \tilde{w}_i + 2 \sum_{i=1}^{I_f} y_{im} \tilde{v}_i \right] \geq r_m \right\} \geq \alpha_m, \quad \forall m \in \mathcal{M} \quad (2)$$

$$\sum_{m=1}^M x_{im} \leq 1, \forall i \in \mathcal{I}_h \quad (3)$$

$$\sum_{m=1}^M y_{im} \leq 1, \forall i \in \mathcal{I}_f \quad (4)$$

where  $h_i, f_i, \tilde{w}_i, \tilde{v}_i$ , and  $\alpha_m$  are as defined in Section II, after dropping the small-cell index. The objective (1) is to minimize the total cost of the composed LTE-U network, and the chance constraint (2) enforces satisfying the demand of user  $m$  with probability  $\geq \alpha_m$ .

#### B. Problem Reformulation and Solution Approach

Our approach for solving the proposed stochastic optimization formulations is to derive their deterministic equivalent programs (DEPs). The DEP is an equivalent reformulation of the original stochastic program, but contains only deterministic variables [13]. In this section, we present the DEP of CCLTEU<sub>single</sub>.

To obtain the DEP of CCLTEU<sub>single</sub>, we reformulate the chance constraint (2), so that it does not include the probability term or the random variables:  $\tilde{w}_i, i \in \mathcal{I}_h$ , and  $\tilde{v}_i, i \in \mathcal{I}_f$ . Let  $p^{(\omega)}$  be the probability of scenario  $\omega \in \Omega$ , where  $\Omega$  is the set of ‘‘scenarios,’’ various realizations of the APs availability. Let  $W$  be the cardinality of the set of values that  $\tilde{w}_i$  may take  $\forall i \in \mathcal{I}_h$ , and let  $V$  be the cardinality of the set of values that  $\tilde{v}_i$  may take  $\forall i \in \mathcal{I}_f$ . Then, the cardinality of  $\Omega$ ,  $|\Omega| = W^{I_h} V^{I_f}$ . To reformulate the chance constraint, we will introduce a binary variable  $u_m^{(\omega)}$  for each user  $m, m \in \mathcal{M}$ , and each scenario  $\omega \in \Omega$ .  $u_m^{(\omega)} = 0$  if the allocation satisfies the demand  $r_m$  under scenario  $\omega$ , and  $u_m^{(\omega)} = 1$  otherwise. Then, (2) is equivalent to the two following constraints:

$$\sum_{i=1}^{I_h} x_{im} w_i^{(\omega)} + 2 \sum_{i=1}^{I_f} y_{im} v_i^{(\omega)} \geq r_m \left( 1 - u_m^{(\omega)} \right), \quad (5)$$

$$\forall m \in \mathcal{M}, \forall \omega \in \Omega$$

$$\sum_{\omega \in \Omega} p^{(\omega)} u_m^{(\omega)} \leq 1 - \alpha_m, \forall m \in \mathcal{M}. \quad (6)$$

### IV. MULTI-CELL ALLOCATION

In this section, we consider the multi-cell allocation problem.

#### A. Heterogeneous Allocation

We first consider the heterogeneous resource allocation case, in which a user, say  $m \in \mathcal{M}$ , requests (in general) different probabilities, denoted by  $\alpha_{mn} \in (0, 1]$ , for different small cells  $n \in \mathcal{N}$ . Define  $x_{imn}, i \in \mathcal{I}_h, m \in \mathcal{M}, n \in \mathcal{N}$ , and  $y_{imn}, i \in \mathcal{I}_f, m \in \mathcal{M}, n \in \mathcal{N}$ , as follows:

$$x_{imn} = \begin{cases} 1, & \text{if the } i\text{th HD AP is allocated to user } m \\ & \text{in cell } n \\ 0, & \text{otherwise} \end{cases}$$

$$y_{imn} = \begin{cases} 1, & \text{if the } i\text{th FD AP is allocated to user } m \\ & \text{in cell } n \\ 0, & \text{otherwise.} \end{cases}$$

Then, the heterogeneous multi-cell allocation problem is a straightforward extension of CCLTEU<sub>single</sub>. The objective

function (1) is replaced by:

$$\begin{aligned} & \left\{ \begin{array}{l} \text{minimize} \\ x_{imn}, i \in \mathcal{I}_h, \\ y_{imn}, i \in \mathcal{I}_f, \\ m \in \mathcal{M}, n \in \mathcal{N} \end{array} \right\} \left\{ \begin{array}{l} \sum_{n=1}^N \sum_{m=1}^M \left[ \sum_{i=1}^{I_h} h_{in} x_{imn} \mathbb{E}[\tilde{w}_{in}] \right. \\ \left. + \sum_{i=1}^{I_f} f_{in} y_{imn} \mathbb{E}[\tilde{v}_{in}] \right] \end{array} \right\}. \end{aligned} \quad (7)$$

Furthermore, constraints (2), (3), and (4) are repeated for each small cell.

### B. Homogeneous Allocation

Now, we study the homogeneous resource allocation problem.

1) *Problem Formulation:* To formulate the homogeneous multi-cell allocation problem, we introduce the following binary variables,  $\tilde{d}_{nm}, n \in \mathcal{N}, m \in \mathcal{M}$ :

$$\tilde{d}_{nm} = \begin{cases} 1, & \text{if } \sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} \geq r_m \\ 0, & \text{otherwise.} \end{cases} \quad (8)$$

Then, the homogeneous multi-cell allocation problem is formulated by replacing (2) with the following constraint:

$$\Pr \left\{ \left[ \tilde{D}_m \stackrel{\text{def}}{=} \tilde{d}_{1m} \text{ AND } \dots \text{ AND } \tilde{d}_{Nm} \right] \geq 1 \right\} \geq \alpha_m, \quad (9)$$

$\forall m \in \mathcal{M}.$

Next, we derive equivalent linear formulations for the indicator function (8) and the AND operation (9). Equation (8) can be reformulated as follows:

- $\tilde{d}_{nm} = 1 \Rightarrow \sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} \geq r_m$  can be reformulated as:

$$\sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} + m \tilde{d}_{nm} \geq m + r_m \quad (10)$$

where  $m$  is a lower bound of  $\sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} - r_m$ . Selecting  $m$  to be  $-r_m$ , (10) reduces to  $\sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} \geq r_m \tilde{d}_{nm}$ .

- $\sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} \geq r_m \Rightarrow \tilde{d}_{nm} = 1$  can be reformulated as:

$$\sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} - (M + \epsilon) \tilde{d}_{nm} \leq r_m - \epsilon \quad (11)$$

where  $M$  is an upper bound of  $\sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} - r_m$  and  $\epsilon > 0$  is a small tolerance beyond which the constraint is regarded as have been violated. Selecting  $M$  to be  $I_h + 2I_f - r_m$ , (11) reduces to  $\sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} \leq (I_h + 2I_f - r_m + \epsilon) \tilde{d}_{nm} + r_m - \epsilon$ .

Therefore, (8) can be equivalently written as:

$$\begin{aligned} r_m \tilde{d}_{nm} & \leq \sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} \\ & \leq (I_h + 2I_f - r_m + \epsilon) \tilde{d}_{nm} + r_m - \epsilon. \end{aligned} \quad (12)$$

The equivalent linear representation of  $\tilde{D}_m$  in (9) is the following set of inequalities:

$$\begin{aligned} \tilde{D}_m & \leq \tilde{d}_{nm}, \forall n \in \mathcal{N} \\ \tilde{D}_m & \geq \sum_{i=n}^N \tilde{d}_{nm} - (N - 1) \\ \tilde{D}_m & \geq 0. \end{aligned} \quad (13)$$

Then, the CCLTEU<sub>multi</sub> formulation is given by:

#### Problem 2 (CCLTEU<sub>multi</sub>):

$$\begin{aligned} & \left\{ \begin{array}{l} \text{minimize} \\ x_{imn}, i \in \mathcal{I}_h, \\ y_{imn}, i \in \mathcal{I}_f, \\ \tilde{d}_{nm}, \tilde{D}_m, \\ n \in \mathcal{N}, m \in \mathcal{M} \end{array} \right\} \left\{ \begin{array}{l} \sum_{n=1}^N \sum_{m=1}^M \left[ \sum_{i=1}^{I_h} h_{in} x_{imn} \mathbb{E}[\tilde{w}_{in}] \right. \\ \left. + \sum_{i=1}^{I_f} f_{in} y_{imn} \mathbb{E}[\tilde{v}_{in}] \right] \end{array} \right\} \quad (14) \end{aligned}$$

subject to:

$$\Pr \left\{ \tilde{D}_m \geq r_m \right\} \geq \alpha_m, \forall m \in \mathcal{M} \quad (15)$$

$$\tilde{D}_m \leq \tilde{d}_{nm}, \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \quad (16)$$

$$\tilde{D}_m \geq \sum_{n=1}^N \tilde{d}_{nm} - (N - 1), \forall m \in \mathcal{M} \quad (17)$$

$$\tilde{D}_m \geq 0, \forall m \in \mathcal{M} \quad (18)$$

$$\begin{aligned} r_m \tilde{d}_{nm} & \leq \sum_{i=1}^{I_h} x_{imn} \tilde{w}_{in} + 2 \sum_{i=1}^{I_f} y_{imn} \tilde{v}_{in} \\ & \leq (I_h + 2I_f - r_m + \epsilon) \tilde{d}_{nm} + r_m - \epsilon, \\ & \quad \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \end{aligned} \quad (19)$$

$$\sum_{m=1}^M x_{imn} \leq 1, \forall n \in \mathcal{N}, \forall i \in \mathcal{I}_h \quad (20)$$

$$\sum_{m=1}^M y_{imn} \leq 1, \forall n \in \mathcal{N}, \forall i \in \mathcal{I}_f. \quad (21)$$

2) *Problem Reformulation and Solution Approach:* Similar to CCLTEU<sub>single</sub>, we solve CCLTEU<sub>multi</sub> by deriving its DEP. Similar to (5) and (6), constraint (15) can be reformulated as:

$$D_m^{(\omega)} \geq r_m \left( 1 - u_m^{(\omega)} \right), \forall \omega \in \Omega, \forall m \in \mathcal{M} \quad (22)$$

$$\sum_{\omega \in \Omega} p^{(\omega)} u_m^{(\omega)} \leq 1 - \alpha_m, \forall m \in \mathcal{M}. \quad (23)$$

In the DEP, constraints (16)-(19) are defined for each scenario  $\omega \in \Omega$ . For example, constraint (19) will be rewritten

TABLE I: Numerical values of various parameters.

Parameter	CCLTEU <sub>single</sub>	CCLTEU <sub>multi</sub>
$I_h$	4	2
$I_f$	3	2
$h_{in}$	[3, 3, 1, 1]	[3, 1]
$f_{in}$	[5, 1.5, 1.5]	[4, 1.5]
# of aggregated channels in each HD AP	[3, 3, 1, 1]	[3, 1]
# of aggregated channels in each FD AP	[3, 1, 1]	[3, 1]
$\mathbb{E}[\hat{w}_{in}]$	[0.35, 0.2, 0.35, 0.4]	[0.7, 0.65]
$\mathbb{E}[\hat{v}_{in}]$	[0.35, 0.2, 0.3]	[0.8, 0.75]

in the DEP as follows:

$$\begin{aligned}
 r_m d_{nm}^{(\omega)} &\leq \sum_{i=1}^{I_h} x_{imn} w_{in}^{(\omega)} + 2 \sum_{i=1}^{I_f} y_{imn} v_{in}^{(\omega)} \\
 &\leq (I_h + 2I_f - r_m + \epsilon) d_{nm}^{(\omega)} + r_m - \epsilon, \\
 &\quad \forall n \in \mathcal{N}, \forall m \in \mathcal{M}, \forall \omega \in \Omega.
 \end{aligned} \tag{24}$$

## V. PERFORMANCE EVALUATION

In this section, we evaluate the proposed stochastic allocation schemes. All schemes are implemented in CPLEX. The numerical values of various parameters are listed in Table I.

### A. Percentage of Satisfied Users

First, we study the percentage of satisfied users under our proposed stochastic allocation schemes. In Figure 4, we plot the percentage of satisfied users of CCLTEU<sub>single</sub> as a function of  $\alpha$  for different values of  $r$ . As expected, the number of satisfied users decreases with both  $\alpha$  and  $r$ . As shown in the figure, the orchestrated LTE-U network meets all user demands only when  $r = 1$  and  $\alpha = 0.1$ . In Figure 5, we compare the percentage of satisfied users in the single-cell case (CCLTEU<sub>single</sub>) with that in the multi-cell case (CCLTEU<sub>multi</sub>) when the demands are homogeneous. As shown in the figure, the percentage of satisfied users is significantly smaller in the case of CCLTEU<sub>multi</sub>. The reason is that the goal in CCLTEU<sub>multi</sub> is to ensure that the probability of meeting each user demand *jointly across all small cells* is above a certain threshold, as explained in Section IV-B. In contrast, cells are treated independently in CCLTEU<sub>single</sub>.

### B. Cost of the Virtual LTE-U Network

Here, we consider the cost of the composed LTE-U network as functions of  $M$ ,  $\alpha$ , and  $r$ . Considering CCLTEU<sub>single</sub>, Figure 6 depicts the cost of the virtual LTE-U network vs.  $M$  for different values of  $\alpha$ . As shown in the figure, the cost increases with the number of LTE-U users as well as  $\alpha$ . As  $\alpha$  increases, the number of LTE-U users that can be supported decreases. Furthermore, Figure 7 shows the cost for different values of  $r$ . As  $r$  increases, the cost of the virtual LTE-U network increases and a smaller number of LTE-U users can be supported. Finally, Figure 8 shows the cost vs.  $M$  for the multi-cell CCLTEU<sub>multi</sub> scheme.

## VI. CONCLUSIONS

In this paper, we proposed a stochastic resource allocation framework for exploiting the excess capacity of deployed

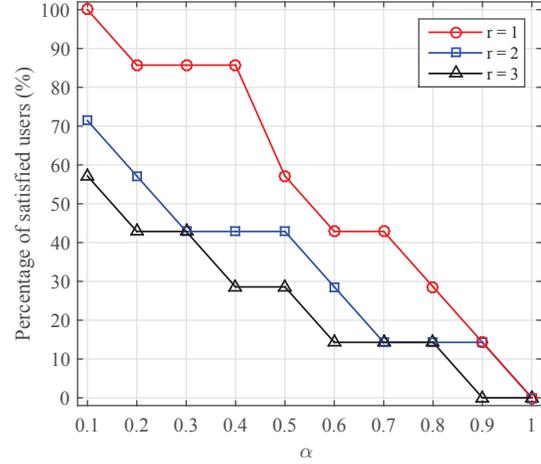


Fig. 4: Percentage of satisfied users vs.  $\alpha$  for different values of  $r$  ( $M = 7$ , CCLTEU<sub>single</sub>).

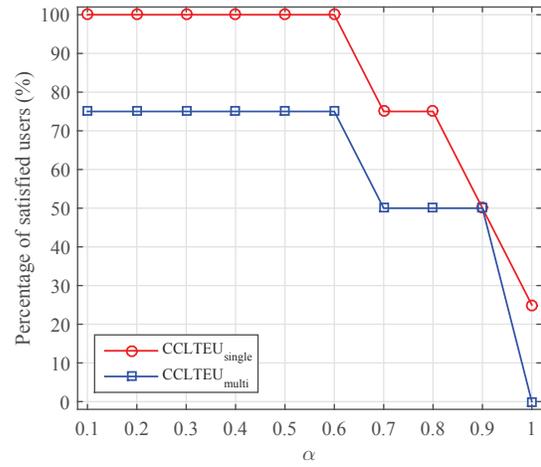


Fig. 5: Percentage of satisfied users vs.  $\alpha$  ( $M = 4$ ,  $r = 1$ ).

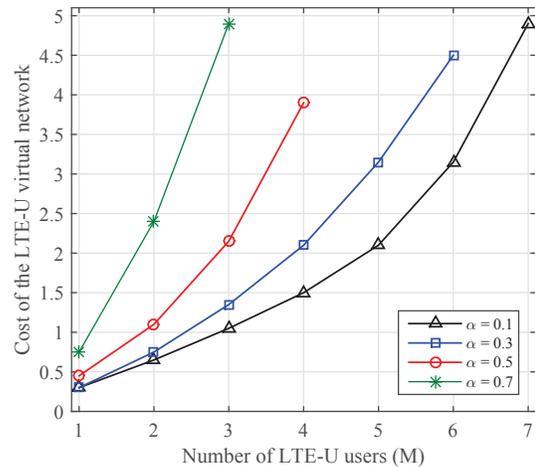


Fig. 6: Cost of the virtual LTE-U network vs. the number of users for different values of  $\alpha$  (CCLTEU<sub>single</sub>,  $r = 1$ ).

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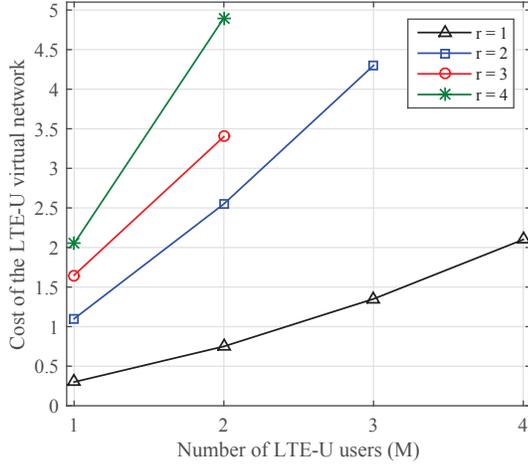


Fig. 7: Cost of the virtual LTE-U network vs. the number of users for different values of  $r$  (CCLTEU<sub>single</sub>,  $\alpha = 0.3$ ).

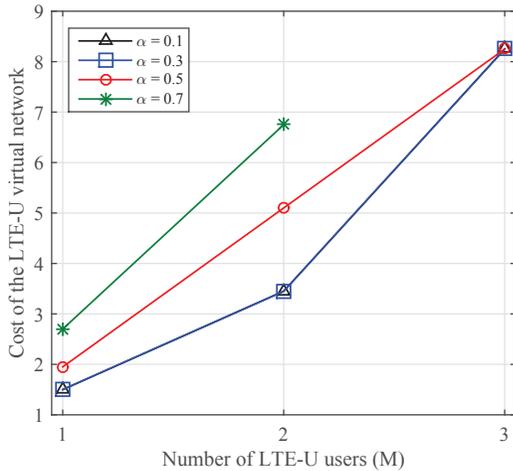


Fig. 8: Cost of the virtual LTE-U network vs. the number of users for different values of  $\alpha$  (CCLTEU<sub>multi</sub>,  $r = 1$ ).

(half/full-duplex) Wi-Fi networks (operating in the 5 GHz band) to orchestrate a robust virtual LTE-U network. The composed LTE-U network was designed to provide prespecified *probabilistic* QoS guarantees. We considered a single-cell LTE-U network first, then extended our formulation to the multi-cell case. We adopted a ‘chance-constrained stochastic programming’ approach in our formulations. Our numerical results demonstrated the ability of the proposed schemes in ensuring certain probabilistic QoS guarantees to the LTE-U users (depending on the availability of the Wi-Fi APs). We studied the impacts of the number of LTE-U users, their rate demands, and their requested QoS guarantees on the cost of the composed LTE-U network as well as the percentage of satisfied LTE-U users.