Coexistence Between Wi-Fi and LTE on Unlicensed Spectrum: A Human-Centric Approach

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***Abstract*— In recent years, there has been great interest from the cellular service providers to use the unlicensed spectrum for their service offerings. On the other hand, existing unlicensed users in these bands (e.g., Wi-Fi in the 5-GHz band) have serious concern that such coexistence will jeopardize their service quality. Although there are some proposals on how to achieve coexistence, they are driven by the service providers and as such there remain many issues and skepticism. In this paper, we take a novel human-centric approach to understand coexistence between Wi-Fi and LTE by focusing on human satisfaction. Through mathematical modeling, problem formulation, and extensive simulations studies, we show that in terms of maximizing total human satisfaction function, there does not appear to be any advantage with the coexistence of unlicensed spectrum for Wi-Fi and LTE under static partitioning of unlicensed spectrum. This finding serves as a powerful counter argument to some LTE service providers' proposal to share the unlicensed spectrum with Wi-Fi through static partitioning. On the other hand, we find that there is a significant improvement in human satisfaction in coexistence between Wi-Fi and LTE under adaptive spectrum partitioning. Since adaptive spectrum partitioning may require a user to change its service provider whenever there is a change among the users, we propose a practical (semi-adaptive) algorithm for implementation without affecting existing users' service providers. Through performance evaluation, we show that the proposed semi-adaptive algorithm is highly competitive.**

***Index Terms*— Wi-Fi, LTE, coexistence, spectrum sharing, human satisfaction.**

I. Introduction

TODAY there are over 350 million cellular subscribers in the US and 70% of them possess smartphones. The data traffic carried by these subscribers has exceeded 4.8 exabyte per year and is growing at 50% annually. But the radio frequency spectrum that can be used for wireless communications is a finite and extremely valuable resource. With the proliferation of new wireless applications, the use of the radio spectrum has intensified to the point that new spectrum policies are needed.

On the other hand, there is a significant amount of unlicensed spectrum available. For example, in the 5 GHz band, there is a close to 500 MHz of spectrum bandwidth available (e.g., [5.15, 5.25] GHz and [5.47, 5.85] GHz in the US). Currently, the widely deployed wireless technology on the 5 GHz unlicensed band is Wi-Fi. The idea of deploying cellular over unlicensed spectrum is attractive for telecommunications carriers as it allows them to increase overall capacity without paying billions of dollars that they do for a licensed spectrum. Already, US cellular operators such as Verizon and T-Mobile are exploring this possibility and making plans to deploy LTE Unlicensed (LTE-U [1], [2], [16], [26]) technology in the unlicensed bands (especially in the 5 GHz band). For the Wi-Fi community, there is a grave concern that the entry of LTE-U (and LAA [3]) protocols will degrade the service quality of Wi-Fi devices since LTE does not employ CSMA (or listen-before-talk (LBT)), which is the key technology for Wi-Fi users to access and share the spectrum. When Wi-Fi and LTE operate in the same unlicensed band, the transmission of Wi-Fi users will be deferred by LTE signals, which leads to degradation to Wi-Fi throughput. In [4], [15], and [22], experimental results showed that Wi-Fi throughput may be reduced by 90% when interfered by LTE. To address this issue, the cellular carriers have proposed more friendly coexistence between Wi-Fi and LTE. In Section VIII, we review related work in this area and point out some fundamental issues with the proposed coexistence schemes.

Instead of taking any side in the coexistence debate, we take a neutral approach to gain a fundamental understanding of coexistence between the two technologies. We take a novel approach to focus on human satisfaction rather than following either Wi-Fi or LTE service providers' perspective. This human-centric approach is attractive as a major goal of any Wi-Fi or cellular carrier is to maximize human satisfaction (in addition to making a profit). In this paper, we ask the following two fundamental questions: (1) From human-satisfaction perspective, is there any benefit in coexistence between Wi-Fi and LTE? (2) If there is a benefit for coexistence, then how to achieve such benefit in practice?

We address the above two questions by studying several spectrum sharing strategies. We consider a wireless service area on the order of a picocell which can be served by one LTE

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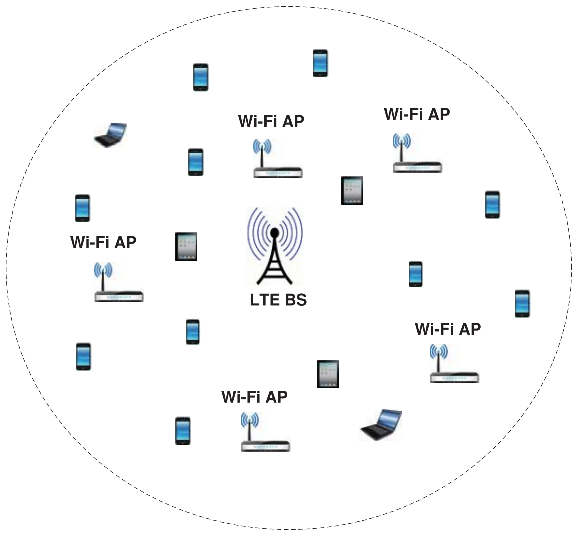


Fig. 1. The coexistence of Wi-Fi and LTE in a picocell-sized area.

base station (BS) or multiple Wi-Fi APs (see Figure 1). For a user, it has the option to use Wi-Fi for free or LTE for a fee. We introduce a human satisfaction function and study the problem of how to maximize total human satisfaction among all users under different spectrum sharing strategies. Through rigorous mathematical modeling and extensive simulation studies, we find that in terms of maximizing total human satisfaction function, there does not appear to be any benefit when the unlicensed spectrum is partitioned statically between Wi-Fi and LTE. This is interesting as it suggests that one might just deploy Wi-Fi without LTE in the unlicensed spectrum, if the goal is to maximize total human satisfaction. This finding serves as a powerful counter argument to some of the LTE service providers' proposals to enter the unlicensed spectrum space through static partitioning of the unlicensed band between Wi-Fi and LTE. On the other hand, we find that there is a significant benefit in deploying adaptive spectrum partitioning between Wi-Fi and LTE. That is, the total human satisfaction can be significantly increased when spectrum is partitioned adaptively between Wi-Fi and LTE.

Based on the above findings, we conclude that adaptive spectrum partitioning is the only viable approach for coexistence between Wi-Fi and LTE in the unlicensed spectrum. However, such fully adaptive spectrum partitioning is based on global optimization, which means that an existing user may have to change its service provider whenever there is a new user request arrival or a departure of another existing users. This is not practical as frequent changes of service provider for a user could be disruptive at the application layer. To address this problem, we propose a practical semi-adaptive algorithm without affecting existing users' service providers. Through performance evaluation, we show the performance of the proposed practical semi-adaptive algorithm is highly competitive when compared to fully adaptive spectrum partition.

The remainder of this paper is organized as follows. In Section II, we propose a network architecture for coexistence between Wi-Fi and LTE. In Sections III, IV, and V, we present three service deployment strategies: (1) Wi-Fi only (no LTE); (2) static spectrum partitioning; (3) fully adaptive spectrum partitioning. In Section VII, we propose a practical semi-adaptive algorithm to implement fully adaptive spectrum partitioning and present its performance results. Section VIII presents related work and Section IX concludes this paper.

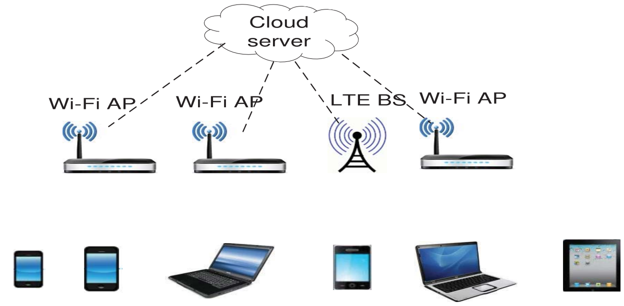


Fig. 2. A cloud-based control plane that coordinates spectrum sharing between Wi-Fi APs and LTE BS.

II. Network Architecture

We describe a system architecture for coexistence and spectrum sharing between Wi-Fi and LTE networks. To concretize our discussion, we consider wireless access at an airport or a similar area on the scale of a picocell. We assume this area can be served by one LTE base station (BS) or multiple Wi-Fi APs. As shown in Figure 1, the LTE BS has coverage of all users in the area while a Wi-Fi AP can only cover a smaller sub-area and thus multiple Wi-Fi APs are needed. Suppose there is a set of users (e.g., laptops, cellphones) in this area wishing to access network services. A user may choose either the LTE BS or one of the Wi-F APs in her neighborhood. If a user chooses LTE, then rate that she subscribes will be guaranteed during the lifetime of the connection, but for some price per unit of data rate. On the other hand, if a user chooses Wi-Fi, then her data rate cannot be guaranteed, but the service is free. This service-based policy structure is consistent to what is happening in many airport or public infrastructures. We assume that each user has her particular financial means (affordability). This affordability is non-negative and reflects how much money a user is willing to pay to access the network. If it is zero, this user can only access the Wi-Fi network; otherwise, she can access either the LTE or the Wi-Fi network.

Figure 2 shows a conceptual control plane for our architecture. We assume there is a cloud server deployed at the backend, which connects to both the Wi-Fi APs and LTE BS. The cloud server has powerful computation capability and can compute optimal solutions to maximize users satisfaction based on input from the Wi-Fi and LTE. By default, a user's request for network access goes to a Wi-Fi AP, which will relay the request to the centralized cloud server. Upon receiving the request, the cloud server finds the optimal solution for the user (Wi-Fi AP or LTE service selection) and associated spectrum allocation for the user with the goal of maximizing total human satisfaction. The service offered to each user is ultimately decided by the centralized back-end server by solving an optimization problem. The solution obtained by the centralized architecture will be sent to all users and users

TABLE I
NOTATION

L	LTE base station.
$\mathcal{N}$	The set of users in the area.
$\mathcal{A}$	The set of Wi-Fi APs in the area.
$\mathcal{N}_i$	The set of users that are within the CSMA contention range of user $i \in \mathcal{N}$.
$\mathcal{A}_i$	The set of Wi-Fi APs the covers user i.
p	The price charged by LTE per unit of data rate.
P_i	The maximum price for data rate that user i can afford.
B	The total available bandwith for unlicense spectrum.
B_W	Partition of bandwidth B that is allocated to Wi-Fi.
B_L	Partition of bandwidth B that is allocated to LTE.
B_i^L	Bandwidth assigned to user i under LTE.
x_{ij}	A binary variable indicating whether or not user i is assigned to Wi-Fi AP j.
x_{iL}	A binary variable indicating whether or not user i is assigned to LTE BS L.
r_{ij}^W	Achievable uplink throughput for user i when served by Wi-Fi AP j.
r_i^L	Achievable uplink throughout for user i when served by LTE.
S_W	Human satisfaction coefficient per unit of data rate under Wi-Fi.
S_L	Human satisfaction coefficient per unit of data rate under LTE.
α	The spectrum efficiency for Wi-Fi.
Q_i^W	The transmission power density at user i under Wi-Fi.
Q_i^L	The transmission power density at user i under LTE.
λ_{ij}	The antenna gain between user i and its service provider j (either Wi-Fi or LTE)
d_{ij}	The distance between user i and its service provider j (either Wi-Fi or LTE)
σ	Path loss index.

are assumed to follow this solution regarding their service providers and bandwidth allocation.[1] For a user with zero affordability, the cloud server will only assign the user one of the Wi-Fi APs. Otherwise, the cloud server can assign either a Wi-Fi AP or the LTE BS to the user.

In this network architecture, denote $\mathcal{A}$ as the set of Wi-Fi APs and L as the LTE BS. Denote $\mathcal{N}$ as the set of users in this area and denote $\mathcal{N}_i$ as the subset of users that are within the CSMA contention range of user i. That is, user i is allowed to transmit only when the set of users in $\mathcal{N}_i$ is not transmitting. Define $\mathcal{A}_i$ as the subset of Wi-Fi APs that covers user i. We assume the bandwidth of unlicensed spectrum in the area is B. Denote p as the price per unit of data rate imposed by LTE service provider and denote P_i as user i's ($i \in \mathcal{N}$) affordability, i.e., the maximum payment that user i is willing to pay. When P_i is 0, then user i is not willing to pay and only wants to use free Wi-Fi service. Otherwise, user i can get up to P_i/p amount of data rate if she chooses LTE. Note that LTE provides guaranteed data rate while Wi-Fi only provides average rate (based on contention) which is likely to fluctuate over time. So, even for the same "rate", user experience under LTE and Wi-Fi will differ. To capture such difference in a human experience, we introduce two satisfaction parameters for rates under LTE and Wi-Fi. We denote S_W and S_L as the human satisfaction parameters per unit of data rate under LTE and Wi-Fi, respectively. Table I lists notation in this paper.

[1]It is not hard to see that our architecture can be easily extended to support the scenario if some users wish to make their own choice of service providers, even though this may deviate from global optimum. In this scenario, we can fix relevant decision variables for those users (who choose their own service providers) to constants and solve an optimization problem for the other users. This constrained optimization will offer a smaller total human satisfaction than the unconstrained optimization that we solve in the paper.

Based on this setting, we are interesting in total human satisfaction under the following coexistence and spectrum-sharing strategies:

- *(a) Wi-Fi only:* Only Wi-Fi is deployed in the area and the entire unlicensed spectrum is used by Wi-Fi. In this case, each user can only be served by one of the Wi-Fi APs.
- *(b) Static partitioning of unlicensed spectrum between Wi-Fi and LTE:* Both LTE and Wi-Fi are deployed in the area. The unlicensed band is partitioned into two fixed portions: one for Wi-Fi and the other for LTE. A user may be served by either a Wi-Fi AP or LTE BS. This is one of the coexistence strategies advocated by cellular carriers for sharing unlicensed spectrum between Wi-Fi and LTE.
- *(c) Adaptive spectrum partitioning of unlicensed spectrum between Wi-Fi and LTE:* Both LTE and Wi-Fi are deployed in the area. The unlicensed spectrum band is dynamically partitioned between Wi-Fi and LTE (no fixed allocation on unlicensed band) based on current user population and their affordabilities.

III. Scenario A: Wi-Fi Only

In this section, we consider the scenario where only Wi-Fi APs are deployed in the area and LTE is not deployed. For this scenario, we develop the mathematical model and problem formulation to maximize total human satisfaction. For any user, we assume she is under the coverage of at least one Wi-Fi AP. Due to overlapping of coverage areas, a user may also be in the service area of multiple APs. To model which AP is selected by a user, denote binary variable x_{ij} as whether user $i \in \mathcal{N}$ selects Wi-Fi AP j, $j \in \mathcal{A}_i$, i.e.,

$$x_{ij} = \begin{cases} 1 & \text{If user } i \text{ selects Wi-Fi AP } j \text{ as her} \\ & \text{service provider;} \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

Since user i can only select one and only one Wi-Fi AP, we have:

$$\sum_{j \in \mathcal{A}_i} x_{ij} = 1, \quad \text{for } i \in \mathcal{N}. \quad (2)$$

Since uplink and downlink traffic behavior is highly unpredictable, to simplify our study, we assume saturated traffic for each user. Also, since there does not exist a good throughput model that considers both uplink and downlink traffic for a user in Wi-Fi, we will only consider uplink traffic in this study and defer the more complex (unknown) joint uplink/downlink traffic model to future study. Such simplification allows us to employ the empirical throughput model in [7] and [22] in our formulation. On the unlicensed bandwidth B, each user needs to contend with other users to access this bandwidth. Under saturated user traffic model, air time is shared equally among all users [7], [22]. Recall that $\mathcal{N}_i$ is the set of users that are within the CSMA contention range of user i. Then user i needs to contend with all these users in $\mathcal{N}_i$ to access the same channel. The transmission opportunity for user i is therefore $\frac{1}{|\mathcal{N}_i|+1}$, i.e., air time is shared equally among the $(|\mathcal{N}_i| + 1)$ users. Denote r_{ij}^W as the achievable uplink throughput for user i

when it selects AP j. Then the achievable uplink throughput for user i can be expressed as following:

$$r_{ij}^W = \frac{\alpha}{|\mathcal{N}_i| + 1} B \log_2(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}), \tag{3}$$

where α is the channel efficiency of air time [7], [22], Q_i^W is user i' power spectral density under Wi-Fi, d_{ij} is the distance between user i and AP j, σ is the path loss index, λ_{ij} is the antenna gain between user i and AP j, and N_0 is the ambient Gaussian power spectral density.

Note the throughput in Eq. (3) is average (contention-based) throughput. The instantaneous rate will fluctuate over time. Recall S_W is the satisfaction parameter per unit of data rate under Wi-Fi. To capture a user's satisfaction, we define $f(i)$ as user i's satisfaction function as follows:

$$f(i) = S_W \cdot \sum_{j \in \mathcal{A}_i} x_{ij} r_{ij}^W. \tag{4}$$

We are interesting in maximizing the total human satisfaction in the network. That is:

$$\begin{aligned} &\text{OPT-W} \\ &\max \ \textstyle\sum_{i \in \mathcal{N}} f(i) \\ &\text{s.t. Satisfaction function: (4);} \\ &\quad \text{AP selection constraints: (2);} \\ &\quad \text{Throughput constraints: (3).} \end{aligned}$$

This problem is in the form of a mixed-integer linear program (MILP), which can be solved by commercial solver (CPLEX) efficiently.

IV. Scenario B: Coexistence Through Static Spectrum Partitioning

A. Mathematical Modeling

In this deployment scenario, both Wi-Fi APs and LTE are deployed in the area (Fig. 1). Under static spectrum partitioning, Wi-Fi and LTE will coexist on the same unlicensed band B and the total bandwidth B is statically partitioned into B_W and B_L for Wi-Fi and LTE, respectively and remain fixed. To avoid interference between Wi-Fi and LTE, there is no overlap between B_W and B_L.

B. Service Selection

A user may choose a Wi-Fi AP or LTE BS. The binary variable x_{ij} (defined in (1)) can be used as an indicator of whether user i selects AP j. Now denote x_{iL} as a binary variable indicating whether or not user i selects LTE BS as its service provider, i.e.,

$$x_{iL} = \begin{cases} 1 & \text{If user } i \text{ selects LTE BS as her service provider;} \\ 0 & \text{otherwise.} \end{cases}$$

Since a user can be served by either the LTE BS or one of the Wi-Fi APs, we have:

$$x_{iL} + \sum_{j \in \mathcal{A}_i} x_{ij} = 1, \quad (i \in \mathcal{N}). \tag{5}$$

C. Bandwidth Allocation for LTE User

LTE BS typically has advanced channel management function and can slice its bandwidth B_L into a set of different (and smaller) channels to serve its users. Denote B_i^L as the bandwidth allocated to user i by the LTE BS. To avoid potential interference among users in the LTE network, the channels assigned to different users should not overlap. That is:

$$\sum_{i:\ x_{iL}=1} B_i^L \leq B_L.$$

which is equivalent to:

$$\sum_{i \in \mathcal{N}} x_{iL} B_i^L \leq B_L. \tag{6}$$

We define $B_{\min}^L$ as the minimum bandwidth that should be assigned to a user if it is served by the LTE BS. If $x_{iL} = 1$, then $B_i^L \geq B_{\min}^L$; otherwise, $B_i^L = 0$. That is:

$$x_{iL} B_{\min}^L \leq B_i^L \leq x_{iL} B_L. \tag{7}$$

D. Throughput Analysis

We now analyze a user's throughput. As for the Wi-Fi only network in Section III, we only consider uplink traffic.

- **User i served by Wi-Fi network.** For user i that is served by the Wi-Fi network, it contends the channel access with other Wi-Fi users in $\mathcal{N}_i$. Since the set $\mathcal{N}_i$ includes all users (using either Wi-Fi or LTE service) that are within the CSMA contention range of user i, we need to identify only those users in $\mathcal{N}_i$ that are using Wi-Fi. Denote M_i as the number of users in $\mathcal{N}_i$ that are served by Wi-Fi. Then user i only contends with M_i Wi-Fi users for channel B_W that is allocated to Wi-Fi. M_i can be modeled as following:

$$M_i = \sum_{k \in \mathcal{N}_i} \sum_{a \in \mathcal{A}_k} x_{ka}, \quad (i \in \mathcal{N}). \tag{8}$$

If user i selects Wi-Fi AP j, then based on our earlier discussion in Section III, the achievable uplink throughput r_{ij}^W is:

$$r_{ij}^W = \frac{\alpha}{M_i + 1} B_W \log_2(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}). \tag{9}$$

- **User i served by LTE network.** If user i selects the LTE BS as its service provider, then LTE BS will assign a dedicated channel B_i^L to it. Denote r_i^L as the achievable uplink throughput for user i under LTE. We have:

$$r_i^L = B_i^L \log_2(1 + \frac{Q_i^L d_{iL}^{-\sigma} \lambda_{iL}}{N_0}), \tag{10}$$

where Q_i^L is user i' power spectral density under LTE, d_{iL} is the distance between user i and LTE BS, σ is the path loss index, λ_{iL} is the antenna gain between user i and LTE BS, and N_0 is the ambient Gaussian power spectral density.

E. User Affordability Constraint

Recall that a user will need to pay for accessing LTE service. We have defined p as the price per unit of data rate imposed by LTE and P_i as the upper limit that user i is willing to pay. If a user chooses LTE, we have the following constraint:

$$p \cdot r_i^L \le P_i. \tag{11}$$

1) Problem Formulation: Recall that the throughput in (10) for LTE is a guaranteed rate while the throughput in (9) is the average (contention-based) throughput. As a result, even for the same "rate", user i's experience under LTE and Wi-Fi will differ. To capture such difference in user i's satisfaction, we introduce another human satisfaction parameter for user's rate under LTE. Denote S_L as the satisfaction parameter per unit of data rate under LTE. Recall that S_W is the satisfaction parameter per unit of data rate under Wi-Fi service. Due to the difference between guaranteed rate and average rate, we should have $S_L \ge S_W$. Based on (4), we define $f(i)$ as user i's satisfaction function as follows:

$$f(i) = \begin{cases} S_W \cdot \sum_{j \in \mathcal{A}_i} x_{ij} r_{ij}^W & \text{If } \sum_{j \in \mathcal{A}_i} x_{ij} = 1; \\ S_L \cdot x_{iL} \cdot r_i^L & \text{if } x_{iL} = 1. \end{cases}$$

Since $x_{iL} + \sum_{j \in \mathcal{A}_i} x_{ij} = 1$, it is easy to show that the above definition of $f(i)$ is equivalent to:

$$f(i) = S_W \sum_{j \in \mathcal{A}_i} x_{ij} r_{ij}^W + S_L x_{iL} \cdot r_i^L, \quad (i \in \mathcal{N}). \tag{12}$$

For the objective of maximizing total satisfaction among all users, we can formulate the problem as follows:

$$\begin{aligned} &\max \ \textstyle\sum_{i \in \mathcal{N}} f(i) \\ &\text{s.t. Satisfaction function: (12);} \\ &\quad \text{Service selection constraints: (5);} \\ &\quad \text{Bandwidth allocation constraints: (6), (7);} \\ &\quad \text{Throughput constraints: (8), (9), (10);} \\ &\quad \text{User affordability constraint: (11).} \end{aligned} \tag{13}$$

In this formulation, $x_{ij}, x_{iL}, M_i, B_i^L, r_{ij}^W$, and r_i^L are optimization variables, and B_W, B_L, B, $B_{\min}^L$, $B_{\min}^W$, p, P_i, S_W, S_L, and α are constants. This optimization is in the form of a mixed-integer nonlinear program (MINLP). In the following, we show how to reformulate it into an MILP problem, which could be solved by a commercial software (such as CPLEX).

2) Reformulation: In above formulation, constraints (6), (9), and (12) are nonlinear. We show how to linearize them into a set of linear constraints.

In constraints (6) and (12), we have nonlinear terms $x_{iL} B_i^L$, $x_{ij} r_{ij}^W$, and $x_{iL} r_i^L$. We can use *Reformulation-Linearization technique (RLT)* [14, Ch. 6], [20] to linearize such product of variables (monomials). Define $z_{iL} = x_{iL} B_i^L$, we have the following associate constraints:

$$x_{iL} \ge 0, \quad 1 - x_{iL} \ge 0.$$
$$B_i^L \ge 0, \quad B_L - B_i^L \ge 0.$$

We can cross-multiply the two constraints involving x_{iL} with the two constraints involving B_i^L, and replacing the product term $(x_{iL} B_i^L)$ with z_{iL}. Then (6) can be replaced by the following linear constraints:

$$\sum_{i \in \mathcal{N}} z_{iL} \le B_L, \tag{14}$$
$$z_{iL} \le x_{iL} B, \tag{15}$$
$$z_{iL} \le B_i^L, \tag{16}$$
$$z_{iL} \ge x_{iL} B + B_i^L - B_L, \tag{17}$$

where $i \in \mathcal{N}$.

Following the same token, define $\mu_{ij} = x_{ij} r_{ij}^W$ and $\theta_i = x_{iL} r_i^L$, we have the following associate constraints:

$$x_{ij} \ge 0, \quad 1 - x_{ij} \ge 0, \ r_{ij}^W \ge 0, \ x_{iL} \ge 0,$$
$$1 - x_{iL}, \quad \alpha B_W \log_2\left(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}\right) - r_{ij}^W \ge 0,$$
$$r_i^L \ge 0, \quad B_L \log_2\left(1 + \frac{Q_i^L d_{iL}^{-\sigma} \lambda_{iL}}{N_0}\right) - r_i^L \ge 0.$$

We can cross-multiply the constraints involving x_{ij} with the two constraints involving r_{ij}^W and cross-multiply the constraints involving x_{iL} with the two constraints involving r_i^L, and replacing the product terms $(x_{ij} r_{ij}^W)$ and $(x_{iL} r_i^L)$ with μ_{ij} and θ_i. Then, (12) can be replaced by the following constraints:

$$f(i) = S_W \sum_{j \in \mathcal{A}_i} \mu_{ij} + S_L \theta_i, \tag{18}$$
$$\mu_{ij} \le r_{ij}^W, \tag{19}$$
$$\mu_{ij} \le x_{ij} \alpha B_W \log_2\left(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}\right), \tag{20}$$
$$\mu_{ij} \ge r_{ij}^W + x_{ij} \alpha B_W \log_2\left(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}\right) - \alpha B_W \log_2\left(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}\right), \tag{21}$$
$$\theta_i \le r_i^L, \tag{22}$$
$$\theta_i \le x_{iL} B_L \log_2\left(1 + \frac{Q_i^L d_{iL}^{-\sigma} \lambda_{iL}}{N_0}\right), \tag{23}$$
$$\theta_i \ge r_i^L + x_{iL} B_L \log_2\left(1 + \frac{Q_i^L d_{iL}^{-\sigma} \lambda_{iL}}{N_0}\right) - B_L \log_2\left(1 + \frac{Q_i^L d_{iL}^{-\sigma} \lambda_{iL}}{N_0}\right). \tag{24}$$

where $i \in \mathcal{N}$.

Constraint (9) can be written in the following form:

$$M_i r_{ij}^W + r_i^W = \alpha B_W \log_2\left(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}\right)$$

Since $M_i r_{ij}^W = \sum_{k \in \mathcal{N}_i} \sum_{a \in \mathcal{A}_k} x_{ka} r_{ij}^W$, define $\lambda_{i,k,a,j} = x_{ka} r_{ij}^W$, we have the following associate constraints:

$$x_{ka} \ge 0, \quad 1 - x_{ka} \ge 0, \ r_{ij}^W \ge 0, \tag{25}$$
$$\alpha B_W \log_2\left(1 + \frac{Q_i^W d_{ij}^{-\sigma} \lambda_{ij}}{N_0}\right) - r_{ij}^W \ge 0. \tag{26}$$

TABLE II
CONSTANTS AND OPTIMIZATION VARIABLES IN THE FORMULATION OF Wi-Fi ONLY, STATIC SPECTRUM PARTITION, AND ADAPTIVE SPECTRUM PARTITION

	Wi-Fi only	Static Spectrum Partitioning	Adaptive Spectrum Partitioning
Constants	$\alpha, S_W, B, B^W_{\min}$	$\alpha, B_W, B_L, B, B^L_{\min}, B^W_{\min}, p, P_i, S_W, S_L$	$\alpha, B, B^L_{\min}, B^W_{\min}, p, P_i, S_W, S_L$
Optimization Variables	x_{ij}, r^W_{ij}	$x_{ij}, x_{iL}, M_i, B^L_i, r^W_{ij}, r^L_i$	$x_{ij}, x_{iL}, M_i, B^L_i, B_W, B_L, r^W_{ij}, r^L_i$

We can cross-multiply the constraints involving x_{ka} with the two constraints involving r^W_{ij}, and replacing the product term $(x_{ka}r^W_{ij})$ with $\lambda_{i,k,a,j}$. Then (9) can be replaced by the following linear constraints:

$$\sum_{k\in\mathcal{N}_i}\sum_{a\in\mathcal{A}_k}\lambda_{i,k,a,j}+r^W_i=\alpha B_W\log_2(1+\frac{Q^W_i d^{-\sigma}_{ij}\lambda_{iW}}{N_0}), \quad (27)$$

$$\lambda_{i,k,a,j}\le r^W_{ij}, \quad (28)$$

$$\lambda_{i,k,a,j}\le x_{ka}\alpha B_W\log_2(1+\frac{Q^W_i d^{-\sigma}_{ij}\lambda_{iW}}{N_0}), \quad (29)$$

$$\lambda_{i,k,a,j}\ge r^W_{ij}+x_{ka}\alpha B_W\log_2(1+\frac{Q^W_i d^{-\sigma}_{ij}\lambda_{ij}}{N_0}) - \alpha B_W\log_2(1+\frac{Q^W_i d^{-\sigma}_{ij}\lambda_{ij}}{N_0}). \quad (30)$$

where $i\in\mathcal{N}$, $j\in\mathcal{A}$, $k\in\mathcal{N}_i$, and $a\in\mathcal{A}_k$.

Now, all nonlinear constraints in the original formulation are linear. We have the following new formulation:

OPT-S
max $\sum_{i\in\mathcal{N}} f(i)$
s.t. Satisfaction function: (18)–(24);
Service selection constraints: (5);
Bandwidth allocation constraints: (7), (14)–(17);
Throughput constraints: (8), (10), (27)–(30);
User affordability constraint: (11).

This formulation is in the form of mix-integer linear program (MILP), which can be solved by commercial software (CPLEX).

V. SCENARIO C: COEXISTENCE THROUGH ADAPTIVE SPECTRUM PARTITIONING

Since the cloud server can perform centralized optimization, it is possible to share the unlicensed spectrum dynamically between Wi-Fi and LTE based on the users in the network. That is, B_W and B_L can be optimization variables rather than fixed constants.

Since B is partitioned into B_W for Wi-Fi and B_L for LTE, and there is no overlap between the two, we have:

$$B_W+B_L=B. \quad (31)$$

Here B_W and B_L are variables, and could be dynamically adjusted based on the current user population in the network.

Different from Eq. (6), there is no need to allocate extra bandwidth to LTE users beyond their requirement. So the constraint in Eq. (6) should be binding rather than an upper bound. We have:

$$\sum_{i\in\mathcal{N}} x_{iL}B^L_i=B_L. \quad (32)$$

Therefore, any bandwidth unused by LTE will be allocated to Wi-Fi users.

To ensure there is some minimum bandwidth for Wi-Fi users, denote $B_{\min}$ as the minimum bandwidth that is guaranteed for Wi-Fi. Then, we have:

$$B_W\ge B^W_{\min}. \quad (33)$$

If a user is served by LTE, it has a minimum bandwidth for B^L_i, we have:

$$x_{iL}B^L_{\min}\le B^L_i\le x_{iL}B_L. \quad (34)$$

Then the objective of total users' satisfaction can be maximized with the following problem formulation:

OPT-D
max $\sum_{i\in\mathcal{N}} f(i)$
s.t. Satisfaction function: (12);
Service selection constraints: (5);
Spectrum partitioning constraint: (31);
Bandwidth allocation constraints: (32), (33), (34);
Throughput constraints: (8), (9), (10);
User affordability constraint: (11).

In this formulation, $x_{ij}, x_{iL}, M_i, B_W, B_L, B^L_i, r^W_{ij}$, and r^L_i are optimization variables, and α, B, $B^L_{\min}$, $B^W_{\min}$, p, P_i, S_W, and S_L are constants. This optimization problem is in the form of a mixed-integer nonlinear program (MINLP). Again, we can use similar linearization approaches as in Section IV-E to the nonlinear constraints. Then, the reformulated problem becomes an MILP.

Table II summarizes the constants and optimization variables in the formulation of three deployment scenarios.

VI. PERFORMANCE EVALUATION

In this section, we perform extensive simulation studies to compare human satisfaction objectives under the three spectrum usage strategies. Our findings are rather interesting. First, in terms of maximizing total satisfaction function, we find that there does not appear to be any advantage of coexistence between Wi-Fi and LTE with static spectrum partitioning (when compared to Wi-Fi only scheme). This is interesting as it suggests that one might just deploy Wi-Fi without LTE in the unlicensed spectrum. This finding serves

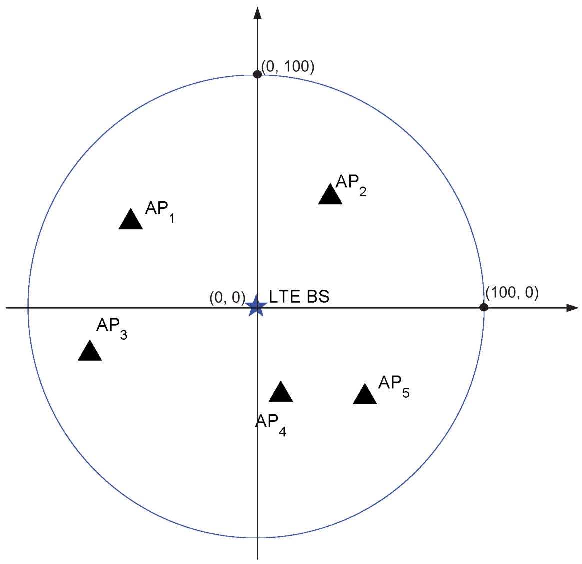


Fig. 3. One LTE BS and multiple Wi-Fi APs that are randomly deployed in a circle with radius 100.

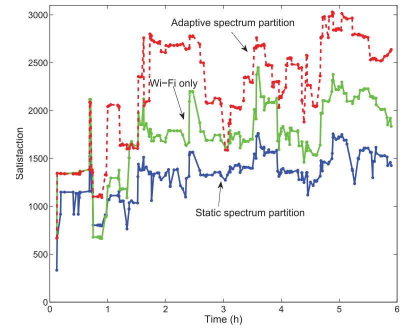
as a powerful counter argument to some telecom service providers' proposals to partition the unlicensed spectrum statically between Wi-Fi and LTE. Another finding shows that coexistence between Wi-Fi and LTE is only meaningful (or beneficial) if spectrum is partitioned in an adaptive manner.

A. Parameter Setting

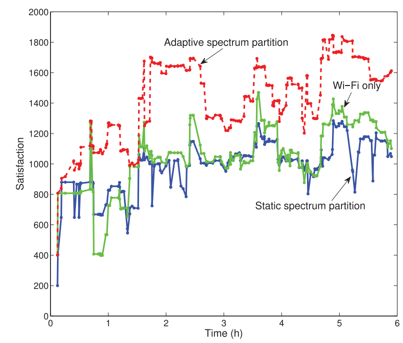
We consider one LTE BS and multiple Wi-Fi APs that are randomly deployed in a circular area with radius 100. The LTE BS is at the center of the circle (see Figure 3). For generality, we normalize units for distance, bandwidth, power, data rate, and pricing with appropriate dimensions. We assume LTE BS and Wi-Fi APs' have coverage radii (transmission range) of 100 and 40, respectively. The CSMA contention (interference) range for Wi-Fi is 70. The total bandwidth that is available in the unlicensed spectrum is $B = 100$. The minimum bandwidth reserved for Wi-Fi network is $B_{\min} = 10$ (under coexistence with LTE). The transmission power spectrum density for each user under Wi-Fi and LTE are 1.0 and 3.0, respectively. The ambient Gaussian power spectral density is $N_0 = 10^{-6}$. The path loss σ is 3. The antenna gains are 1 between user and Wi-Fi AP and 2 between the user and LTE BS. We assume channel efficiency for Wi-Fi is $\alpha = 70\%$ [7]. Assume the price per unit of data rate charged by LTE is $p = 0.1$. For each user, her affordability is generated randomly. The user satisfaction coefficients for Wi-Fi and LTE will be specified in the respective performance studies.

B. Comparison Under Different Satisfaction Coefficients

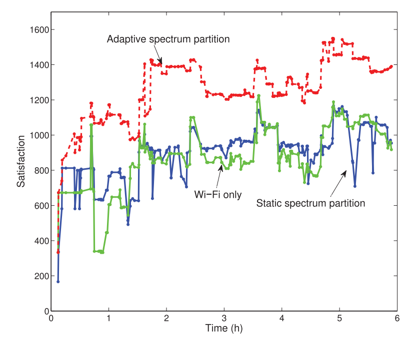
We assume users' requests arrival following a Poisson process with a rate of 20 per hour and the holding time for each user session is exponentially distributed with a mean of 1 hour. Upon arrival, the user's location may be anywhere (randomly distributed) inside the circular area. The simulation time is 6 hours. We perform simulation studies under various



(a) $S_W = 1$ and $S_L = 1$, $\frac{S_L}{S_W} = 1$.



(b) $S_W = 0.667$ and $S_L = 1$, $\frac{S_L}{S_W} = 1.5$.



(c) $S_W = 0.5$, $S_L = 1$, $\frac{S_L}{S_W} = 2$.

Fig. 4. Maximum users satisfaction under Wi-Fi only, static spectrum partitioning, and adaptive spectrum partitioning with different satisfaction coefficients.

satisfaction parameters. We set the satisfaction parameter $S_L = 1$ and vary S_W to 1, 0.67, and 0.5, respectively. That is, the ratios of satisfaction coefficients between LTE and Wi-Fi, $\frac{S_L}{S_W}$, are 1, 1.5, and 2, respectively. We compare the maximum user satisfaction objective values under Wi-Fi only (no LTE), coexistence between Wi-Fi and LTE with static spectrum partitioning, and coexistence between Wi-Fi and LTE with adaptive spectrum partitioning, respectively. Under static spectrum partitioning, we set $B_W = 50$ and $B_L = 50$.

Figs. 4(a), (b), and (c) show the human satisfactions under different satisfaction parameters. We find that there is no advantage of coexistence with static spectrum partitioning (between Wi-Fi and LTE) over Wi-Fi only network. When $\frac{S_L}{S_W} = 1$ (Fig. 4(a)), coexistence with static spectrum partitioning strategy performs even worse than Wi-Fi only. This is because that when $\frac{S_L}{S_W} = 1$, for the same rate, there is no difference in terms of user satisfaction between Wi-Fi and LTE. On the other hand, static spectrum partitioning sets a hard partition between Wi-Fi and LTE. When bandwidth B_L is not fully used, the remaining bandwidth cannot be used by Wi-Fi and is wasted. Likewise when there is a need of more bandwidth for LTE users, Wi-Fi cannot release any bandwidth either. When $\frac{S_L}{S_W} = 1.5$ and 2 (Figs. 4(b) and (c)), the satisfaction parameters favor LTE network. But this still cannot overcome the adverse effect due to hard spectrum partitioning. In order words, the hard partitioning between Wi-Fi and LTE has a much more significant impact than satisfaction parameter setting. Consequently, coexistence with static partitioning is not desirable if the goal is to maximize total human satisfaction.

On the other hand, we can see that the adaptive partitioning strategy always achieves the highest human satisfaction. To see the difference more clearly, in Figs. 5 (a), (b), and (c), we plot normalized human satisfaction for Wi-Fi only and static partitioning with respect to that for adaptive human partitioning. In all cases, the ratio is less than 1, indicating adaptive partitioning has a dominant advantage over the other two.

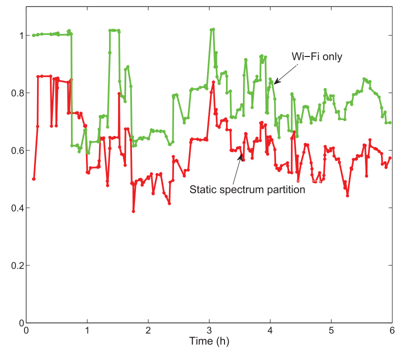
C. Different Bandwidth Allocation in Static Partitioning Scheme

In this study, we want to understand the impact of different bandwidth partitioning for B_W and B_L (under static partitioning) on human satisfaction. We change B_W from 10 to 90 (and correspondingly B_L from 90 to 10). We set $S_L = 1$ and $\frac{S_L}{S_W} = 2$, which favors LTE. Figure 6 (a) to (i) show the normalized human satisfaction for Wi-Fi only and static partitioning with respect to those for adaptive partitioning. From these figures, we can see there is no clear benefit for coexistence between Wi-Fi and LTE with static partitioning over Wi-Fi only even when the user satisfaction parameters favor LTE. This further indicates that the adverse effect from static partitioning is significant. On the other hand, coexistence under adaptive partitioning has a dominant advantage over the other two.

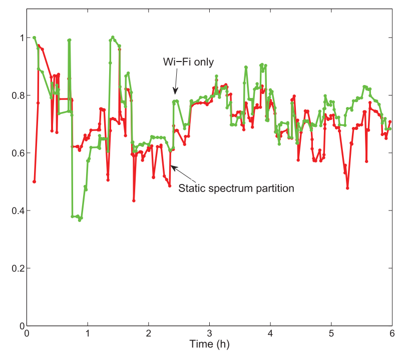
D. Varying Traffic Load

In this section, we compare maximum human satisfaction for the three strategies by varying traffic load. We set $S_W = 0.5$ and $S_L = 1$ (i.e., $\frac{S_L}{S_W} = 2$). Under static partitioning, we set $B_W = 50$ and $B_L = 50$.

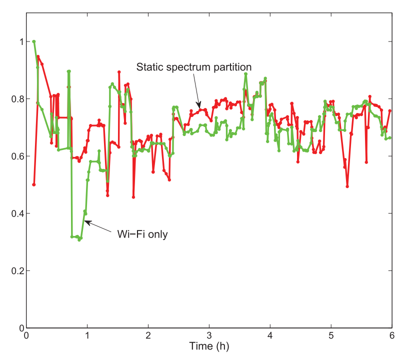
Figures 7(a), (b), and (c) show the normalized human satisfaction for Wi-Fi only and static partitioning with respect to those of adaptive partitioning when the user arrival rates are 10, 30, and 50 per hour. From these figures, we can see there is no clear benefits for coexistence between Wi-Fi and LTE with static partitioning over Wi-Fi even when human satisfaction parameters favor LTE and coexistence under adaptive partitioning has a dominant advantage over the other two.



(a) $S_W = 1$ and $S_L = 1$, $\frac{S_L}{S_W} = 1$.



(b) $S_W = 0.667$ and $S_L = 1$, $\frac{S_L}{S_W} = 1.5$.



(c) $S_W = 0.5$, $S_L = 1$, $\frac{S_L}{S_W} = 2$.

Fig. 5. Normalized human satisfaction of Wi-Fi only and static spectrum partitioning with respect to adaptive spectrum partitioning.

VII. SEMI-ADAPTIVE ALGORITHM FOR PRACTICAL IMPLEMENTING

A. Motivation

Based on our findings in Section VI, we conclude that adaptive spectrum partitioning is the only viable approach for coexistence between Wi-Fi and LTE from the perspective of human satisfaction. But the adaptive partitioning scheme in Section V is based on global optimization across all users, meaning that x_{iL}, x_{ij}, M_i, B_W, B_L, B_i^L, r_{ij}^W, and r_i^L are all optimization variables. This approach cannot be implemented in practice. This is because each time when there is a new request arrival (or a departure of an existing user), the centralized optimization will be executed and yield a new solution for all users. As a result, an existing user may need to change her current service provider (e.g., from Wi-Fi to LTE or vice versa, or switch to a different Wi-Fi AP). Such frequent

(a) $B_W = 10$ and $B_L = 90$. (b) $B_W = 20$ and $B_L = 80$. (c) $B_W = 30$ and $B_L = 70$.

(d) $B_W = 40$ and $B_L = 60$. (e) $B_W = 50$ and $B_L = 50$. (f) $B_W = 60$ and $B_L = 40$.

(g) $B_W = 70$ and $B_L = 30$. (h) $B_W = 80$ and $B_L = 20$. (i) $B_W = 90$ and $B_L = 10$.

Fig. 6. Normalized human satisfaction of Wi-Fi only and static partitioning under different bandwidth allocation with respect to those for adaptive partitioning.

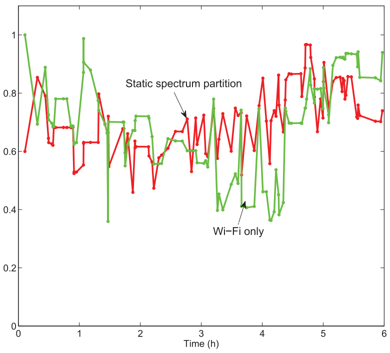
change of service provider is quite disruptive at the application layer and must be avoided. What is needed here is a semi-adaptive algorithm that does not change the service providers for existing users. In this section, we will design such a semi-adaptive algorithm in which service providers for existing users will never change but only bandwidth partitioning and allocation may change.

B. Algorithm Design

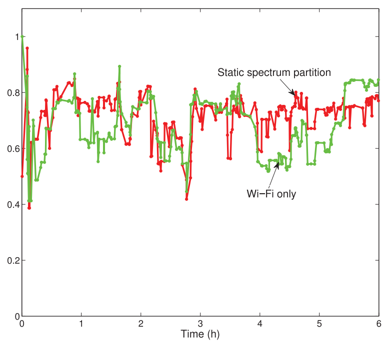
1) Roadmap: The design goal of our proposed algorithm is to optimally handle a new user's request or an existing user's departure with minimum impact on existing users. Specially, under either event (arrival or departure), the service provider for any of the existing users should not be affected. What can be changed for the existing users are the allocated bandwidth, i.e., B_W for Wi-Fi users and B_i^L for LTE users, which can be adjusted rather easily based on today's programmable radio technologies.

When a new user request arrives, the request is sent to the cloud server (via its neighboring Wi-Fi AP). Upon receiving this request, the cloud server will formulate a new satisfaction optimization problem by considering the service provider for existing users being fixed (pre-assigned) and only service provider for the new user and bandwidth allocation for all users being variables. After finding a new optimal solution, the cloud server sends bandwidth allocation to all users (via Wi-Fi APs and LTE BS) and service selection to the new user.

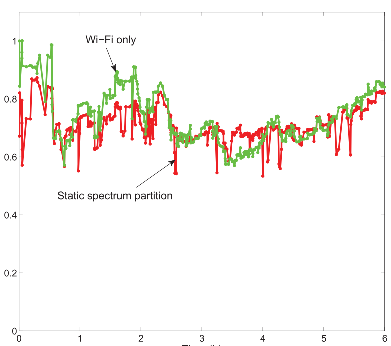
Upon an existing user terminates, the user will send a termination message to the cloud server. Upon receiving this message, the cloud server will re-optimize bandwidth allocation for all users in both Wi-Fi and LTE.



(a) Users arrival rate is 10 per hour.



(b) Users arrival rate is 30 per hour.



(c) Users arrival rate is 50 per hour.

Fig. 7. Normalized human satisfaction of Wi-Fi only and static partitioning with respect to those of adaptive partitioning when the user arrival rates are 10, 30, and 50 per hour.

Since the cloud server performs all computation for resource allocation, a set of information must be maintained at the cloud server. Specially, the following information should be maintained:

- Service Selection: The cloud server should maintain which service provider is selected for each user, i.e, x_{ij} and x_{iL}.
- Bandwidth Partitioning: The cloud server should maintain the bandwidth partition for the Wi-Fi network (i.e., B_W) and LTE network (i.e., B_L).
- Bandwidth Allocation: The cloud server should maintain bandwidth allocation for each user under LTE (B_i^L).

2) Algorithm Details: Now, we present the details of our semi-adaptive algorithm.

- **Initiation of A New User.** When a new user initiates a request to access the network, it will send a control message to its neighboring Wi-Fi AP. The request message includes the users' affordability. The Wi-Fi AP sends the request message to the cloud server. Upon receiving the request message, the cloud server solves the following optimization problem (OPT-Arrival), where k denotes the new user.

  OPT-Arrival

  max $\sum_{i\in\mathcal{N}\cup\{k\}} f(i)$

  s.t. Satisfaction function (12) with x_{ij} being constants and x_{kj} as variable;
  Service selection constraint only for new user $k: x_{kL} + \sum_{j\in\mathcal{A}_k} x_{kj} = 1$;
  Spectrum partitioning constraint: (31);
  Bandwidth allocation constraints: (32), (33), (34);
  Throughput constraints: (8), (9), (10);
  User affordability constraint: (11).

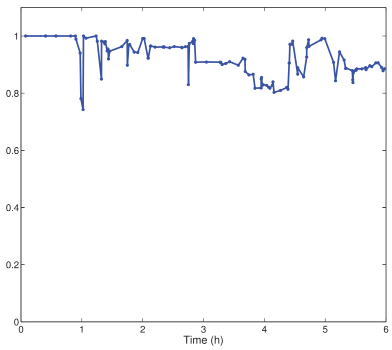
  In this formulation, x_{kL}, x_{kj}, B_i^L, B_W, B_L, M_i, r_{ij}^W, and r_k^L are variables. $\mathcal{N}$ denotes the set of existing users in the network. x_{ij} and x_{iL} for existing users $i \in \mathcal{N}$ are constants. This optimization problem is in the form of a mixed-integer nonlinear program (MINLP). We can use the same RLT technique as in Section IV-E.2 to reformulate all nonlinear constraints into linear constraints and obtain an MILP, which can be solved by a commercial solver (CPLEX).
  After finding a new solution, the cloud server stores the service selection variable x_{kL} and update spectrum partitioning variables B_W, B_L, and bandwidth allocation variable B_i^L. Then it sends updates to all user via their Wi-Fi or LTE service providers. Based on new spectrum partitioning and bandwidth allocation information, each user's radio adjusts its operating bandwidth. The service providers for existing users are not changed.
- **Termination of An Existing User.** When an existing user terminates its session, the user sends a termination message to the cloud server through its service provider. Upon receiving this termination message at the cloud server, it removes user k from $\mathcal{N}$, i.e., $\mathcal{N} = \mathcal{N} \setminus \{k\}$. Then it formulates a satisfaction optimization problem to re-optimize spectrum partition and the bandwidth allocation among the remaining users as follows:

  OPT-Departure

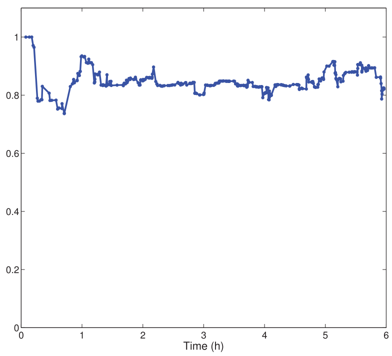
  max $\sum_{i\in\mathcal{N}} f(i)$

  s.t. Satisfaction function: (12);
  Spectrum partitioning constraint: (31);
  Bandwidth allocation constraints: (32), (33), (34);
  Throughput constraints: (8), (9), (10);
  User affordability constraint: (11).

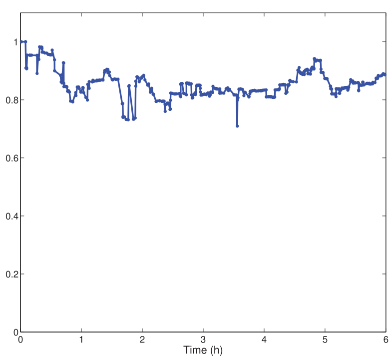
  In this formulation, B_i^L, B_W, B_L, r_{ij}^W, and r_i^L are variables, while x_{ij}, x_{iL} and M_i are constants.



(a) Users arrival rate is 10 per hour.

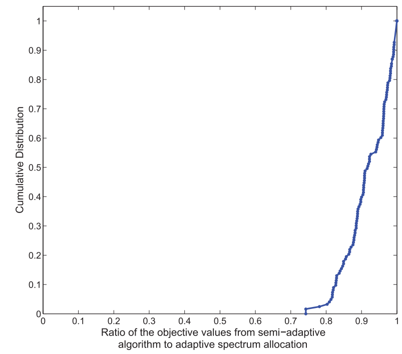


(b) Users arrival rate is 30 per hour.

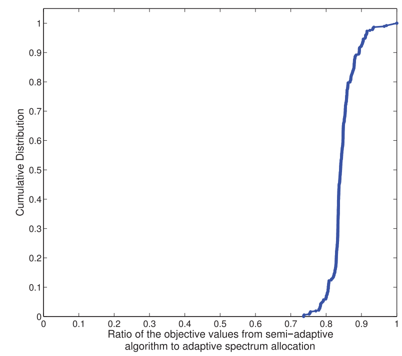


(c) Users arrival rate is 50 per hour.

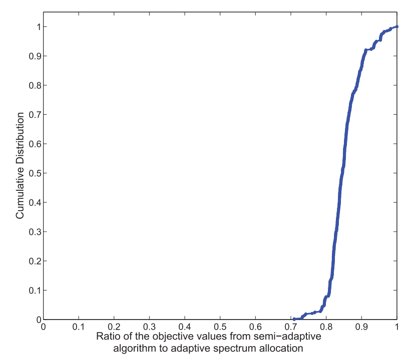
Fig. 8. Normalized objective value for the proposed semi-adaptive algorithm to fully adaptive spectrum partitioning with different user arrival rates.



(a) Users arrival rate is 10 per hour.



(b) Users arrival rate is 30 per hour.



(c) Users arrival rate is 50 per hour.

Fig. 9. The CDFs of normalized objective values for the proposed semi-adaptive algorithm to fully adaptive spectrum partitioning under different user arrival rates.

This problem is an MILP, which could be solved by CPLEX at the cloud server.

After solving the optimization problem for spectrum partitioning and bandwidth allocation, the cloud server will send this update back to the users who will then adjust the bandwidths of their radios.

C. Performance Evaluation

Now we evaluate the performance of our proposed semi-adaptive algorithm. We use the same setting as in Section VI-A. We set the satisfaction coefficients to $S_W = 0.5$ and $S_L = 1$. We compare the objective values (maximum human satisfaction) from our proposed semi-adaptive algorithm to fully adaptive partitioning.

Figure 8(a), (b) and (c) show the normalized objective values from the semi-adaptive algorithm to the fully adaptive partitioning when the users arrival rates are 10, 30, and 50 per hour. In Figure 8(a), there is a total of 122 events during this simulation, among which there are 50 events with ratio over 95%, 75 events with ratio over 90%, 101 events with ratio over 85%, and 120 events with ratio over 80%. Figure 9(a) presents the CDF of the ratio. The average ratio between the two is 91.86%.

In Figure 8(b), there is a total of 369 events, among which there are 30 events with ratio over 90%, 125 events with ratio over 85%, and 346 events with ratio over 80%. The CDF of the ratio is shown in Figure 9(b). The average ratio between the two is 84.6%.

In Figure 8 (c), there is a total of 482 events, among which there are 90 events with ratio over 90%, 197 events with ratio over 85%, and 385 events with ratio over 80%. The CDF of the ratio is shown in Figure 9(c). The average ratio between the two is 83.34%.

From the results in Figures 8 and 9, we conclude that our proposed semi-adaptive algorithm is highly competitive when compared to fully adaptive spectrum partitioning.

Following the same validation methodology, we also run results with different network settings (i.e., network topology and satisfaction parameters). The results are consistent and show that our proposed algorithm is competitive.

VIII. Related Work

A number of approaches have been proposed to allow coexistence between LTE and Wi-Fi in the unlicensed bands. These approaches achieve coexistence between the two either in frequency domain or time domain.

In the frequency domain, coexistence between LTE-U and Wi-Fi can be achieved by having the two operate on separate, non-overlapping channels in the unlicensed band [23], [24]. This is called dynamic channel selection (DCS) in LTE-U. Under this approach, each channel consists of a 20 MHz band and Wi-Fi will use one of these bands that is not used by LTE-U. Given that there is no interference between Wi-Fi and LTE users after channel assignment, LTE users do not need to employ listen-before-talk (LBT). The biggest problem with this approach is that it follows the same traditional static spectrum partitioning on the unlicensed band. As a result, this approach will inherit all of the inefficiencies associated with traditional static spectrum partitioning, as we have demonstrated in this paper (i.e., the static partitioning case). On the other hand, the adaptive spectrum allocation between Wi-Fi and LTE has been studied in [12] to balance the spectrum regulator's income and users' aggregate utility. By using game theory, the authors first derived equilibrium prices of Wi-Fi and LTE services, which were used to determine users' service providers. Then, the authors derived equilibrium spectrum allocation to maximize the spectrum regulator's income and users aggregate utilities. Their approach decoupled the two problems and solved each separately. So the final solution would be sub-optimal. Our work is different from [12] in term of both objective and approach. We jointly consider spectrum sharing and service selection from users' satisfaction perspective with the objective of maximizing total human satisfaction.

In the time domain, when both Wi-Fi and LTE are using the same spectrum, one approach is to incorporate some form of LBT in LTE to make it compatible with Wi-Fi [17], [21], [25], [28]. This is known as carrier sensing adaptive transmission (CSAT) in LTE-U [2]. There are two issues with this approach. First, due to LBT, CSAT compromises the rate guarantee that users have been accustomed to under current LTE service. As a result, it is hard to justify why a user would choose LTE-U instead of using Wi-Fi directly, especially when Wi-Fi is increasingly being offered for free and a smartphone can easily switch to Wi-Fi. Second, CSAT may not be fair to Wi-Fi users, since the transmission period and resource allocation are solely controlled by LTE-U. Since CSAT may favor LTE-U over Wi-Fi, people in industry are skeptical about fairness for coexistence between the two technologies. Another approach is to mute or limit the transmission of LTE users so that LTE users access the channel in a fraction of air time. This is accomplished by the so-called Almost-Blank Subframes [5], [6], [13], [19], [29] or time partition for Wi-Fi and LTE [8], [10], [11], [18], [22]. The biggest problem with this approach is that it requires Wi-Fi to synchronize with LTE in order to access air time, which would involve a major change to the Wi-Fi protocol.

In addition to frequency and time domain coexistence, some approaches have employed physical layer techniques to achieve Wi-Fi/LTE coexistence (e.g., power control [9] and MIMO [27]).

IX. Conclusions

This paper took a novel approach to study different Wi-Fi and LTE coexistence scenarios from the perspective of human satisfaction. We investigated three scenarios: Wi-Fi only, static spectrum partitioning, and adaptive spectrum partitioning. We developed mathematical models and studied the problems of how to maximize total human satisfaction among all users under the three strategies. We found that in terms of maximizing total human satisfaction function, there does not appear to be any advantage with coexistence between Wi-Fi and LTE when the unlicensed spectrum is partitioned statically. This is interesting as it suggests that one might just deploy Wi-Fi without LTE in the unlicensed spectrum. This finding serves as a powerful counter argument to some telecom service providers' proposals to statically partition unlicensed band between Wi-Fi and LTE. On the other hand, we find that there is significant advantage in deploying adaptive spectrum sharing (between Wi-Fi and LTE). This finding shows that a centralized coordinator is needed to dynamically partition bandwidth between Wi-Fi and LTE. Due to some practical issues in implementing fully adaptive sharing, we proposed a semi-adaptive algorithm for practical implementation. Our performance evaluation showed that the proposed semi-adaptive algorithm is highly competitive. The results in the paper shed new light on coexistence between Wi-Fi and LTE and pointed out a new direction of incorporating human factor in the design objective.

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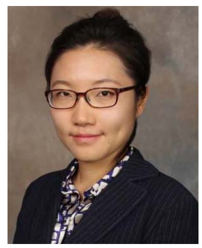

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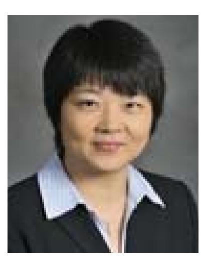

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