

# Bargaining Game for Effective Coexistence between LTE-U and Wi-Fi Systems

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**Abstract**—LTE over unlicensed band (LTE-U) has emerged as an effective technique to overcome the challenge of spectrum scarcity. Using LTE-U along with advanced techniques such as carrier aggregation (CA), one can boost the performance of existing cellular networks. However, if not properly managed, the use of LTE-U can potentially degrade the performance of co-existing Wi-Fi access points which operate over the unlicensed frequency bands. Moreover, most of the existing works consider a macro base station (MBS) or a small cell base station (SBS) for their proposals. In this paper, an effective coexistence mechanism between LTE-U and Wi-Fi systems is studied. The goal is to enable the cellular network to use LTE-U with CA to meet the quality-of-service (QoS) of the users while protecting Wi-Fi access points (WAPs), considering multiple SBSs from different operators in a dense deployment scenario. Specifically, an LTE-U sum-rate maximization problem is formulated under a user QoS and WAP-LTE-U co-existence constraints. To solve this problem, a cooperative Nash bargaining game is proposed. This game allows LTE-U and WAPs to share time resource while protecting Wi-Fi system. For allocating unlicensed resource among LTE-U users, a heuristic algorithm is proposed. Simulation results show that the proposed method is better than the comparing methods regarding per user achieved rate, percentage of unsatisfied users and fairness. The result also shows that the proposed method protects Wi-Fi user far better way than basic listen-before-talk (LBT) does.

## I. INTRODUCTION

Recent studies by Cisco [1] have shown that the mobile wireless traffic will continuously increase over the foreseeable future, with mobile video traffic constituting the main chunk of this traffic. As such, cellular network operators (CNOs) and service providers (SPs) must revisit the design of their network, in order to meet the quality-of-service (QoS) needs of their users. In particular, CNOs must increase the capacity of their radio access networks (RANs) by exploiting new spectrum bands, in conjunction with their existing licensed spectrum. But the licensed spectrum is both expensive and inadequate. Moreover, this superfluous traffic does not guarantee proportional revenue gain to the CNOs because of monstrous competition among themselves. Thus, CNOs are continuously trying to find the cost-effective solution to handle this hazard and Long Term Evolution (LTE) was a logical evolution to meet growing requirements of the users. Even though there are some alternative technologies like massive multiple inputs multiple outputs (MIMO) [2], co-operative communication [3],

D2D (Device to Device) communication [4], etc., these were not enough to meet the ITU requirements of 4G. On the consequence of this ongoing process, LTE-Advanced (LTE-A) came, which brought cellular networks into true 4G era [5]. Furthermore, CNOs are also focusing the reusing technique of licensed spectrum by deploying low-cost and low power small cell base station (SBS) with carrier aggregation (CA), the technology of LTE-A to meet QoS requirements of the users.

However, despite these advances, the scarcity of the licensed spectrum will remain a key limitation for the cellular networks. Consequently, mobile data offloading from cellular to Wi-Fi has gained recent attention [1]. In fact, some CNOs have already deployed Wi-Fi Access Points (WAPs) to offload part of their cellular traffic and, in 2015, more than 50% of cellular network traffic was offloaded to the Wi-Fi [1]. However, such traffic offloading faces major technical and economic challenges due to coordination between two technologies and potential revenue losses. Moreover, the performance of Wi-Fi technology is not good with a large number of users. Thus, the weakness of such offloading can be brought down by augmenting the blessings of LTE-A in the unlicensed spectrum known as LTE-U. LTE-U will ameliorate RAN capacity at a minimal cost, and resolve the revenue issue of the cellular system. It will increase the performance of the mobile network better than Wi-Fi does [6] by utilizing the already deployed network. But the transmission range of the unlicensed spectrum is small in comparison with licensed one owing to low power regulation, and higher frequency. Hence, SBS is the appropriate option for LTE-U deployment, and CNOs can transform their already deployed SBS into co-located ones (works in both licensed and unlicensed spectrum) for this purpose. It can be technically ensured via the utilization of CA technology which was standardized in LTE Releases 10-12. LTE-U is already inaugurated (part of the LTE Release 13) to allow consumers to accommodate licensed, and unlicensed carrier under a single LTE network infrastructure [7]. Moreover, inter- and intra-band CA, licenses assisted access to the ISM band, TV white space, and other under-utilized resources are urgently necessary for making 5G realm true [8].

One of the main limitations of LTE-U is that it can cause considerable performance degradation of other existing technologies like Wi-Fi system if it operates in the same

unlicensed band. Thus, an LTE-U SBS should not generate more interference to the WAP than another WAP does in the same unlicensed band if it wants to operate in that band. On the contrary, WAPs, and other CNOs are also obstructing LTE-U users, and leads to inadequate data rate to meet the QoS who are operating both in the same region, and same unlicensed band because of their ad-hoc deployment. So, there exists mutual interference among SBSs of different CNOs, and between SBSs, and WAPs which can diminish each others' benefits in the unlicensed spectrum. Thus, co-existence with WAPs is the main challenge of LTE-U system.

There are several works ([10], [11], [12]) that deals with the co-existence of LTE-U, and Wi-Fi system. But very few of them have considered inter-operators' interaction in their model and very few of them find guaranteed concrete closed-form for Wi-Fi system protection. As LTE-U and WiFi systems affect negatively on each other, and within themselves in case of performance, this interaction can be modeled as a game theory framework namely bargaining game to promote their mutual benefits. So, we propose a coexistence mechanism that can deal multiple CNOs while protecting Wi-Fi users in the same unlicensed band. The main contributions of this paper are as follows:

- We derive the interaction among SBSs and WAPs mathematically and find LTE-U users' achieve rate.
- We formulate an optimization problem to maximize the sum-rate in log-term of LTE-U users considering QoS requirements, and co-existence issue with WAPs.
- We decompose the optimization problem into two sub-problems namely time sharing, and resource allocation problem. We solve the time sharing problem between LTE-U and Wi-Fi system with the help of Nash bargaining game (NBG), and resource allocation problem of LTE-U system with a heuristic algorithm.

The rest of the paper is organized as follows. In Section II, we discuss the system model and problem formulation. The solution of the problem is discussed in Section III. Performance evaluation has been performed in Section IV. Finally, the paper is concluded in Section V.

## II. SYSTEM MODEL AND PROBLEM FORMULATION

Currently, small cell networks are the probably feasible solution to meet data demand of the users, CNOs are deploying more and more SBSs to facilitate growing services. This ultra-dense nature of SBSs from different operators are bound to conflict with each other, and also with local WAPs if they want to operate in the same unlicensed band. As each operator can control the interference between macro base station (MBS) and it's associated SBSs, we are considering a scenario with SBSs, and WAPs as shown in Figure 1. This dense deployment scenario consists of a set of dual-mode (which can act both in the licensed and unlicensed spectrum) LTE-A SBSs,  $\mathcal{S} = \{1, 2, \dots, S\}$  operated by  $S$  different CNOs, and a set of non-overlapping WAPs denoted by  $\mathcal{W} = \{1, 2, \dots, W\}$ . That means WAP's performance will be affected by the SBSs only if they use the same unlicensed band. Each SBS  $i \in \mathcal{S}$  can

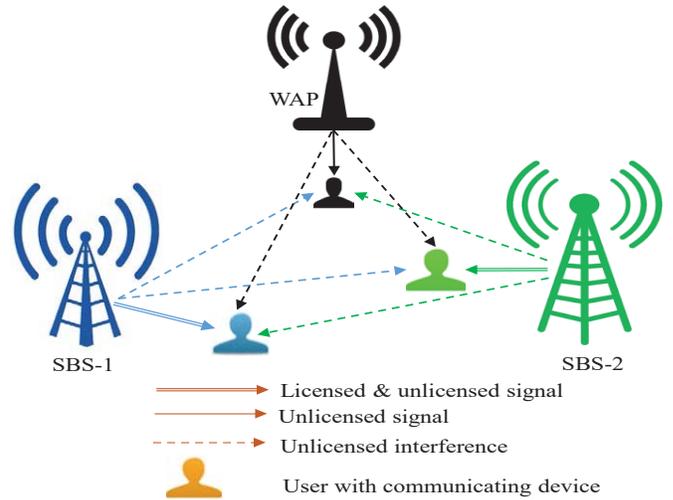


Figure 1: Illustration of the system model

serve downlink operation of a set of LTE-U users, denoted by  $\mathcal{U}_i$ . Each SBS  $i \in \mathcal{S}$  owns  $K_i^l$  orthogonal licensed subchannel of uniform bandwidth  $B_l$ , denoted by  $\mathcal{SC}_i^l = \{1, 2, \dots, K_i^l\}$  to support it's users. We assume that each WAP  $w \in \mathcal{W}$  has  $V_w$  active users currently, and is denoted by  $\mathcal{V}_w = \{1, 2, \dots, V_w\}$ . Both SBSs and WAPs operate in the same unlicensed band. As the unlicensed channel is much wider than one licensed subchannel, and the LTE system works centrally, so each SBS divides this unlicensed spectrum into  $K^u$  subchannels with bandwidth  $B_u$  each, represented by  $\mathcal{SC}^u = \{1, 2, \dots, K^u\}$  for efficient management of this resource. For reliable transmission of control signals from the SBS to the user, each SBS allocates at least one licensed subchannel to its active LTE-U user. We assume that one subchannel can be allocated to a maximum of one LTE-U user. SBSs work in the supplemental downlink (SDL) mode with CA technology.

### A. Data Rate of LTE-U User

As SBS employs the OFDMA technique to allocate resources among it's users, there is no intra-operator interference in licensed spectrum. When SBS  $i \in \mathcal{S}$  allocates licensed subchannel  $k \in \mathcal{SC}_i^l$  to user  $j \in \mathcal{U}_i$ , the achieved rate of that user is as follows:

$$R_{i,j}^{l,k} = B_l \log_2 \left( 1 + \frac{x_{i,j}^k P_i^l |h_{i,j}|^2}{\sigma^2} \right). \quad (1)$$

where  $x_{i,j}^k$  indicates the allocation of licensed subchannel  $k \in \mathcal{SC}_i^l$  by SBS  $i \in \mathcal{S}$  to user  $j \in \mathcal{U}_i$ , and  $x_{i,j}^k = 1$  when SBS  $i \in \mathcal{S}$  allocates the subchannel to user, and  $x_{i,j}^k = 0$ , otherwise.  $P_i^l$  is the transmission power from SBS  $i$  to it's user  $j$ , and it is fixed for all of it's users.  $|h_{i,j}|^2$  is the channel gain from SBS  $i$  to user  $j$  considering a free space propagation path-loss model with Rayleigh fading, and  $|h_{i,j}|^2 = G d_{i,j}^{-\alpha} |h_0|^2$  where  $G$  indicates the constant power gain factor introduced by amplifier and antenna,  $d_{i,j}$  is the distance between SBS  $i$  and user  $j$ ,  $\alpha$  is the path-loss exponent, and  $h_0 \sim \mathcal{CN}(0, 1)$

Table I: Notation

Symbol	Meaning
$\mathcal{S}$	Set of SBSs with $S$ elements
$\mathcal{W}$	Set of non-overlapping WAPs with $W$ elements
$\mathcal{U}_i$	Set of users associated with SBS $i$
$\mathcal{V}_w$	Set of $V_w$ active users associated with WAP $w$
$\mathcal{SC}_i^l$	Set of licensed subchannels of SBS $i$
$\mathcal{SC}_i^u$	Set of unlicensed subchannels
$\mathcal{SC}_i^u$	Set of unlicensed subchannels of SBS $i$
$B_l$	Bandwidth of each licensed subchannel
$B_u$	Bandwidth of each unlicensed subchannel
$P_i^l$	Transmission power of SBS $i$ for each user in licensed spectrum
$P_i^u$	Transmission power of SBS $i$ for each user in unlicensed spectrum
$\mathbf{x}_i$	Resource allocation vector for SBS $i$ in licensed spectrum
$\mathbf{y}_i$	Resource allocation vector for SBS $i$ in unlicensed spectrum
$ h_{i,j} ^2$	Channel gain between AP $i$ and receiver $j$
$d_{i,j}$	Distance between AP $i$ and receiver $j$
$G$	Constant power gain factor
$\alpha$	Path-loss exponent
$h_0$	Rayleigh fading
$I_{\mathcal{S}\setminus\{i\}}$	Interference from $\mathcal{S}$ to any user of $i$ in any unlicensed subchannel
$I_{\mathcal{W}}$	Interference from $\mathcal{W}$ to any unlicensed subchannel
$R_{i,j}^{l,k}$	Achieved rate of user $j$ associated with SBS $i$ in licensed subchannel $k$
$R_{i,j}^{u,k'}$	Achieved rate of user $j$ associated with SBS $i$ in unlicensed subchannel $k'$
$R_{i,j}$	Achieved rate of user $j$ associated with SBS $i$
$R_{w,v}^{max}$	Average rate of user $v$ associated with WAP $w$ when WAP is accessing the channel
$R_{w,v}^{min}$	Average rate of user $v$ associated with WAP $w$ when SBSs act like WAPs
$QoS_{i,j}$	QoS requirement of user $j$ associated with SBS $i$
$\tau$	Fraction of time that SBSs share with WAPs

is a complex Gaussian variable representing Rayleigh fading. The thermal noise has an independent Gaussian distribution with zero mean, and variance  $\sigma^2$ .

LTE-A system can employ CA technology to provide a better rate to its users for maintaining QoS if SBS has sufficient unused licensed subchannels. When SBS  $i \in \mathcal{S}$  allocates more than one subchannels to user  $j \in \mathcal{U}_i$  then the achieved rate of that user in the licensed subchannel is as follows:

$$R_{i,j}^l(\mathbf{x}_i) = \sum_{k \in \mathcal{SC}_i^l} x_{i,j}^k R_{i,j}^{l,k}. \quad (2)$$

If  $R_{i,j}^l(\mathbf{x}_i)$  is large enough to meet the QoS of user  $j$ , then it needs not using the unlicensed spectrum. On the other hand, SBS will allocate unlicensed subchannel to user  $j$  if the achieved rate is not sufficient to provide guaranteed QoS. In case of the unlicensed subchannel, the LTE-U user perceives interference from other SBSs, and WAP working in the same conflicting area over the same unlicensed band. The rate obtained by LTE-U user  $j \in \mathcal{U}_i$  over the unlicensed subchannel  $k' \in \mathcal{SC}_i^u$  is as follows:

$$R_{i,j}^{u,k'} = B_u \log_2 \left( 1 + \frac{y_{i,j}^{k'} P_i^u |h_{i,j}|^2}{I_{\mathcal{S}\setminus\{i\}} + I_{\mathcal{W}} + \sigma^2} \right). \quad (3)$$

where  $y_{i,j}^{k'}$  represents the allocation of unlicensed spectrum  $k' \in \mathcal{SC}_i^u$  to LTE-U user  $j \in \mathcal{U}_i$  by SBS  $i \in \mathcal{S}$ , and  $y_{i,j}^{k'} = 1$  when SBS  $i \in \mathcal{S}$  allocates the unlicensed subchannel to the specified user, and  $y_{i,j}^{k'} = 0$ , otherwise.  $P_i^u$  is the transmission power from SBS  $i$  to its user  $j$  in case of the unlicensed spectrum, and it is fixed for all of its users.  $|h_{i,j}|^2$  is the channel gain between SBS  $i$  and user  $j$  in the unlicensed subchannel,  $I_{\mathcal{S}\setminus\{i\}} = \sum_{s \in \mathcal{S}, s \neq i} \sum_{n \in \mathcal{U}_s} x_{s,n}^{k'} P_s^u |h_{s,j}|^2$  is the interference perceived by LTE-U user  $j \in \mathcal{U}_i$  from other SBSs in the same unlicensed subchannel  $k' \in \mathcal{SC}_i^u$ , and  $I_{\mathcal{W}}$  is the interference produced from WAP.

However, the work [9] shows that Wi-Fi presence affects negligibly to the LTE-U system performance. So we can ignore the interference generated by WAP to the LTE-U system from (3). Moreover, in a dense deployment,  $I_{\mathcal{S}\setminus\{i\}} \gg P_i^u |h_{i,j}|^2$ , so  $R_{i,j}^{u,k'}$  will be negligible, and will not provide any benefit of using the unlicensed spectrum to the LTE-U users. Thus, to take the advantage from this unlicensed band, SBSs can form a grand coalition [13], and allocate the unlicensed resources in the orthogonal fashion like the licensed spectrum. By doing this, they can avoid inter-operators' interference  $I_{\mathcal{S}\setminus\{i\}}$ , generated from other SBSs in the conflicting area. Assume the unlicensed subchannels are split as  $\mathcal{SC}^u = \mathcal{SC}_1^u \cup \mathcal{SC}_2^u \cup \dots \cup \mathcal{SC}_S^u$  where  $\mathcal{SC}_i^u = \{1, 2, \dots, K_i^u\}$ , and  $\mathcal{SC}_i^u \cap \mathcal{SC}_j^u = \emptyset, \forall i, j \in \mathcal{S}$  and divide among the SBSs based on their QoS requirement gaps (difference between total minimum QoS requirements of the associated users to the SBS and sum-rate in the licensed spectrum). Now, considering all of these in (3), the obtainable rate of LTE-U user  $j \in \mathcal{U}_i$  in the unlicensed subchannel  $k' \in \mathcal{SC}_i^u$  is shown as follows:

$$R_{i,j}^{u,k'} = B_u \log_2 \left( 1 + \frac{y_{i,j}^{k'} P_i^u |h_{i,j}|^2}{\sigma^2} \right). \quad (4)$$

Similar to the licensed spectrum, if SBS  $i \in \mathcal{S}$  needs to allocate multiple unlicensed subchannels to user  $j \in \mathcal{U}_i$ , then the achieved rate of that user is as follows:

$$R_{i,j}^u(\mathbf{y}_i) = \sum_{k' \in \mathcal{SC}_i^u} y_{i,j}^{k'} R_{i,j}^{u,k'}. \quad (5)$$

The total achieved rate of user  $j \in \mathcal{U}_i$  in both licensed and unlicensed spectrum is as follows:

$$R_{i,j}(\mathbf{x}_i, \mathbf{y}_i) = R_{i,j}^l(\mathbf{x}_i) + R_{i,j}^u(\mathbf{y}_i). \quad (6)$$

Thus, the sum-rate of SBS  $i \in \mathcal{S}$  is the total achieved rate over all the users  $\mathcal{U}_i$ , which is shown as follows:

$$R_i(\mathbf{x}_i, \mathbf{y}_i) = \sum_{j \in \mathcal{U}_i} R_{i,j}(\mathbf{x}_i, \mathbf{y}_i). \quad (7)$$

Finally, we have a set of users  $\mathcal{U}_i' \subseteq \mathcal{U}_i$  of SBS  $i \in \mathcal{S}$  who needs assistance from the unlicensed resources to meet their QoS requirements. Every user  $j \in \mathcal{U}_i'$  posses at least on licensed subchannel as it is necessary for CA. We are also assuming that every user equipment is capable enough for CA to meet its QoS.

### B. Data Rate of Wi-Fi User

When unlicensed channel is fully utilized by a WAP, then it can provide maximum rate to its users. In this case, average throughput of each user  $v \in \mathcal{V}_w$  associated with WAP  $w \in \mathcal{W}$  can be represented as follows:

$$R_{w,v}^{max} = \frac{R_w}{V_w}. \quad (8)$$

where  $R_w$  is the overall downlink throughput of the WAP  $w \in \mathcal{W}$ . Now, when all the SBSs use the same unlicensed band of WAP, the performance of WAP will be affected only from SBSs. If we consider that each SBS in the conflicting region acts just like a WAP, then normalized throughput for each WAP  $w \in \mathcal{W}$  according to the study [14] is as follows:

$$R_w^{min} = \frac{P_{tr} P_s E[P] (S+1)^{-1}}{(1-P_{tr})T_\sigma + P_{tr} P_s T_s + P_{tr} (1-P_s) T_c}. \quad (9)$$

where  $P_{tr} = 1 - (1-\tau)^{S+1}$  is the transmission probability of at least one SBS or WAP in a time slot with  $\tau$  denoting stationary transmission probability of AP.  $P_s$  is the successful transmission on the channel with  $P_s = \frac{(S+1)\tau(1-\tau)^S}{P_{tr}}$  and  $E[P]$  represents the average packet size.  $T_\sigma$  is the duration of an empty slot time,  $T_s$  presents the time duration of a successful transmission, and  $T_c$  illustrates average time of a collision. So, average downlink rate achieved by each user  $v \in \mathcal{V}_w$  of WAP  $w \in \mathcal{W}$  is represented as follows:

$$R_{w,v}^{min} = \frac{R_w^{min}}{V_w}. \quad (10)$$

So when SBSs want to use the same unlicensed band, they must have to provide an opportunity for accessing the channel by WAP so that it can provide an average throughput to its user that lies between  $R_{w,v}^{min}$  and  $R_{w,v}^{max}$  for the sake of fair co-existence.

### C. Problem Formulation

We observe that  $R_{w,v}^{max}$  is achievable when only Wi-Fi networks access the unlicensed band. But if WAP and SBSs are deployed in the same conflicting area, and work in the same unlicensed band, then Wi-Fi users will get almost no access in the channel, and achieve an insignificant data rate. So, for fair coexistence of Wi-Fi and LTE-U systems, they need to share the time slot in such a manner that WAP can maintain a minimum data rate for its users and SBSs can at least improve some of the users' QoS. As the LTE-U system manages the physical resource in a centralized manner rather than DCF of WAPs, SBSs need to decide appropriate portion of time to achieve fair amount of throughput of each Wi-Fi user. When SBSs share  $\tau \in [0, 1]$  time slot to WAP then the achievable rate of Wi-Fi user, and LTE-U user are shown as follows:

$$R_{w,v}(\tau) = R_{w,v}^{max} \cdot \tau. \quad (11)$$

$$R_{i,j}(\tau, \mathbf{x}_i, \mathbf{y}_i) = R_{i,j}^l(\mathbf{x}_i) + (1-\tau) \cdot R_{i,j}^u(\mathbf{y}_i). \quad (12)$$

So, the sum-rate of SBS  $i \in \mathcal{S}$  when it shares  $\tau$  time slot with WAP is as follows:

$$R_i(\tau, \mathbf{x}_i, \mathbf{y}_i) = \sum_{j \in \mathcal{U}_i} R_{i,j}(\tau, \mathbf{x}_i, \mathbf{y}_i). \quad (13)$$

Now our problem is confined with unlicensed band to maximize the the sum-rate of SBS after sharing  $\tau$ -fraction of time with WAP while maintaining QoS of most of the users. For this, we need to develop an efficient spectrum allocation scheme for each SBS  $i$  to maximize the utility function  $\mathcal{R}_i(\tau, \mathbf{y}_i) = \sum_{j \in \mathcal{U}_i''} \log_2(1 + (1-\tau) \cdot R_{i,j}^u(\mathbf{y}_i))$  in the unlicensed spectrum where  $\mathcal{U}_i'' \subseteq \mathcal{U}_i'$ , considering  $\mathbf{x}_i$  is fixed.

$$\begin{aligned} & \max_{\mathbf{y}_i, \tau} \mathcal{R}_i(\tau, \mathbf{y}_i), \forall i \in \mathcal{S} \\ & \text{s.t. } C_1 : \sum_{j \in \mathcal{U}_i''} y_{i,j}^{k'} \leq 1, \forall k' \in \mathcal{SC}_i^u \\ & C_2 : \sum_{j \in \mathcal{U}_i''} \sum_{k' \in \mathcal{SC}_i^u} y_{i,j}^{k'} \leq K_i^u \\ & C_3 : R_{i,j}(\tau, \mathbf{x}_i, \mathbf{y}_i) \geq QoS_{i,j}, \forall j \in \mathcal{U}_i'' \\ & C_4 : y_{i,j}^{k'} \in \{0, 1\}, \forall k' \in \mathcal{SC}_i^u, \forall j \in \mathcal{U}_i'' \\ & C_5 : R_{w,v}^{min} \leq R_{w,v}(\tau) \leq R_{w,v}^{max}, \forall v \in \mathcal{V}_w \\ & C_6 : 0 \leq \tau \leq 1. \end{aligned} \quad (14)$$

Here, constraints  $C_1$  tells that one unlicensed subchannel can be utilized by at most one LTE-U user. The limitation of total resources in this spectrum are represented by constraints  $C_2$  for each SBS. QoS requirement of LTE-U users is mitigated by constraint  $C_3$ . Every element of allocation vector  $\mathbf{y}_i$  will be either 0/1 that is shown in constraint  $C_4$ . Wi-Fi users are being protected by the constraint  $C_5$ . The optimization problem (14) is a Mixed Integer Non-Linear Programming (MINLP) problem, which is NP-hard due to its combinatorial property.

### III. DECOMPOSITION OF THE PROBLEM FOR SOLVING WITH NASH BARGAINING GAME AND HEURISTIC APPROACH

Now we want to decompose the problem in (14) into two sub-problems so that individual one can be solved with appropriate techniques. Firstly, with fixed  $\tau$ , unlicensed resources should be allocated to the users so that the system throughput can be maximized with satisfying some constraints, and as shown in the follows:

$$\begin{aligned} & \max_{\mathbf{y}_i} \mathcal{R}_i(\tau, \mathbf{y}_i), \forall i \in \mathcal{S} \\ & \text{s.t. } C_1, C_2, C_3, \text{ and } C_4. \end{aligned} \quad (15)$$

Secondly, with fixed resource allocation (that we get from (15)), the time sharing problem between SBSs and WAP can be represented as follows:

$$\begin{aligned} & \max_{\tau} \mathcal{R}_i(\tau, \mathbf{y}_i), \forall i \in \mathcal{S} \\ & \text{s.t. } C_5, \text{ and } C_6. \end{aligned} \quad (16)$$

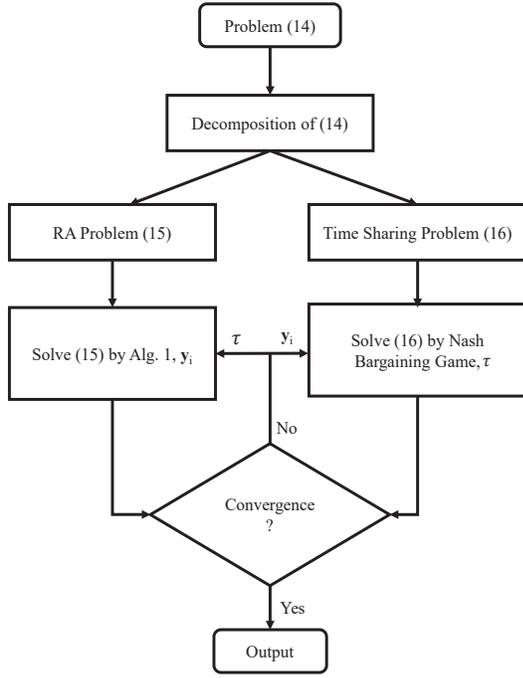


Figure 2: Solution Process of the problem (14)

Sub-problems (15) and (16) have same goal with different constraints, and they are inter-connected through the parameters  $\tau$  and  $\mathbf{y}_i$ . The solution  $(\mathbf{y}_i)$  of the first sub-problem (15) is used for solving sub-problem (16). On the contrary, the solution  $(\tau)$  of the second sub-problem (15) is used to solve sub-problem (16) and it is continued until convergence. This solution approach is shown in the Fig. 2. Now we solve the problems (15) and (16) with the help of heuristic approach, and NBG respectively. The details of these processes are represented in the following section.

#### A. Solution of Problem (15)

The problem shown in (15) is still NP-hard and cannot be efficiently solved. Therefore, we propose a heuristic algorithm as presented in Alg. 1 to solve the problem. The intuition of this heuristic algorithm is to allocate unlicensed resources in such a way that the sum-rate is maximized, and can meet the QoS requirements of as many users as possible. For that, the algorithm allocates a minimum number of unlicensed physical resources to mitigate QoS of users according to their channel gain. Thus, lines 3-7 are responsible for finding the minimum number of unlicensed subchannel required to meet the QoS of users of each SBS. Line 8 sorts users as the descending order according to their channel gain, and line 9 reorder the elements of subchannel requirement vector according to the sorted user list. Lines 11-23 are responsible for allocating the subchannels to users based on the list obtained from line 8. The complexity of the above heuristic algorithm is  $\mathcal{O}(\max(|\mathcal{U}'_i|^2, |\mathcal{S}C_i^u|))$ .

#### B. Nash Bargaining game-Based Solution of Problem (16)

From the problem in (16), if we want to maximize  $\mathcal{R}_i(\tau, \mathbf{y}_i)$  for each SBS  $i \in \mathcal{S}$  then it will suppress the performance

#### Algorithm 1 $\tau$ -Based Resource Allocation for SBS $i$

- 1: Input:  $\mathcal{U}'_i, \mathcal{S}C_i^u, \mathbf{QoS}_i, \mathbf{R}_i^l$
- 2: Output:  $\mathbf{y}_i$
- 3: **for** each  $j \in \mathcal{U}'_i$  **do**
- 4:   Calculate QoS gap by  $QG_{i,j} = QoS_{i,j} - R_{i,j}^l$
- 5:   Find achievable rate of user  $j$  for a single unlicensed subchannel with the help of (4) i.e.  $R_{i,j}^{u,1} = (1 - \tau)R_{i,j}^{u,1}$
- 6:   Calculate minimum number of subchannels requirement for user  $j$  by  $mSCR_{i,j}^u = \lceil QG_{i,j} / R_{i,j}^{u,1} \rceil$
- 7: **end for**
- 8: Sort users from  $\mathcal{U}'_i$  according to channel gain on descending order
- 9: Reorder the elements of  $\mathbf{mSCR}_i^u$  according to  $\mathcal{U}'_i$
- 10: Set  $nSC = |\mathcal{S}C_i^u|, j = 1$  and  $k = 1$
- 11: **while**  $nSC > 0$  **do**
- 12:   **if**  $nSC \geq mSCR_{i,j}^u$  **then**
- 13:     **while**  $mSCR_{i,j}^u > 0$  **do**
- 14:       Set  $y_{i,k} = \mathcal{U}_{i,j}$
- 15:       Set  $mSCR_{i,j}^u = mSCR_{i,j}^u - 1$
- 16:       Set  $k = k + 1$
- 17:     **end while**
- 18:     Set  $nSC = nSC - mSCR_{i,j}^u$
- 19:     Set  $j = j + 1$
- 20:   **else**
- 21:     Set  $j = j + 1$
- 22:   **end if**
- 23: **end while**

of Wi-Fi users. In this subsection, we will find a win-win strategy for both SBSs and WAP. As the overall time slots on the unlicensed spectrum are constrained, it is impossible to maximize the benefits of both the systems simultaneously. Therefore, we need to find an effective unlicensed time slot allocation scheme to balance the benefit between SBSs and WAP.

Now redefine the problem of (16) to balance the benefits of both SBSs and WAP as follows:

$$\begin{aligned}
 & \max_{\tau} \quad \mathcal{R}_S(\tau, \mathbf{y}) R_w(\tau) \\
 & \text{s.t.} \quad R_{w,v}^{\min} \leq R_{w,v}(\tau) \leq R_{w,v}^{\max}, \forall v \in \mathcal{V}_w \quad (17) \\
 & \quad \tau_0 \leq \tau \leq 1
 \end{aligned}$$

where  $\mathcal{R}_S(\tau, \mathbf{y}) = \sum_{i \in \mathcal{S}} \mathcal{R}_i(\tau, \mathbf{y}_i)$ ,  $R_w(\tau) = V_w \cdot R_{w,v}(\tau)$ , and  $\tau_0$  is the time that is necessary for maintaining  $R_{w,v}^{\min}$  rate for each Wi-Fi user  $v \in \mathcal{V}_w$  when WAP is only using the channel. It is a multi-objective problem. So we can use the bargaining game to distribute time resource ( $\tau$ ) fairly among the players  $\mathcal{P} = \{\mathcal{S}, w\}$  and Nash Bargaining Solution (NBS) [15] method can be a good candidate for that. Let  $\mathbf{R}$  be a closed and convex subset that represents the set of payoff allocations that the players can achieve if SBSs share the time slot with WAP and  $\mathbf{d}$  is the set of disagreement payoffs. Therefore, the utilities of this game are  $U_w = R_w(\tau) - R_w^{\min} = V_w(R_{w,v}^{\max} \cdot \tau - R_{w,v}^{\min})$  and  $U_S = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} u_{i,j} = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log\{R_{i,j}(\tau, \mathbf{x}_i, \mathbf{y}_i) -$

$R_{i,j}^l(\mathbf{x}_i)\} = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log\{(1 - \tau)R_{i,j}^u(\mathbf{y}_i)\}$  respectively, in each time slice.

Now NBS can give us a unique solution concept [15] from the set of payoff  $\mathbf{R}$  that satisfies the following :

$$\mathbf{r}^*(\tau) = \phi(\mathbf{R}, \mathbf{d}) \in \operatorname{argmax}_{\mathbf{r} \in \mathbf{R}} \prod_{p=1}^{|\mathcal{P}|} U_p. \quad (18)$$

Hence, we need such a  $\tau$  that will maximize the value of  $\mathbf{r}(\tau)$  with fixed  $\mathbf{y}$  in (18). If we denote that optimal sharing time as  $\tau^*$  then that value is shown in Theorem 1.

**Theorem 1.** *With a given allocation  $\mathbf{y}$ , the optimal time slot allocation for WAP by a given set of SBSs is*

$$\tau^* = \max \left\{ \frac{(\alpha + \beta + 1) - \sqrt{(\alpha + \beta + 1)^2 - 2\alpha(\beta + \delta)}}{\alpha}, \tau_0 \right\} \text{ where } \alpha = \sum_{i \in \mathcal{S}} |\mathcal{U}'_i|, \beta = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log R_{i,j}^u(\mathbf{y}_i), \text{ and } \delta = \frac{R_{w,v}^{min}}{R_{w,v}^{max}}.$$

The proof of this theorem is out of space in this paper.

### C. Alternative Sum-Rate Maximization for LTE-U Coexistence

For a fixed set of SBSs and WAPs (with their associated users), we can find  $\mathbf{y}_i^*$  and  $\tau^*$  by using the alternative sum-rate maximization approach that is shown in Alg. 2. With the given  $\tau$ , each SBS can allocate its resource ( $\mathbf{y}_i$ ) to get maximum  $\mathcal{R}_i$  by using Alg. 1 (line 5). Now with the given  $\mathbf{y}_i$  and other information, arbitrator can find  $\tau^t$  (line 9). The process (lines 5-10) continues until it reaches to convergence. Alg. 2 will converge after a finite number of steps, it tries to maximize the objective with limited resources as in each step. It will converge to some local optimums, and might not the global optimum.

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**Algorithm 2** Alternative Sum-Rate Maximization for LTE-U system

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- 1: **Input:**  $\mathcal{S}, \delta, \tau_0$
  - 2: **Output:**  $\mathbf{y}_i, \forall i \in \mathcal{S}$  and  $\tau$
  - 3: Initialize:  $t = 0, \tau^t = 0.5$
  - 4: **repeat**
  - 5: Each  $i \in \mathcal{S}$  determines  $\mathbf{y}_i^t$  by using Alg. 1 with  $\tau^t$
  - 6: Each  $i \in \mathcal{S}$  determines  $\mathcal{R}_i(\tau^t, \mathbf{y}_i^t) = \sum_{j \in \mathcal{U}'_i} \log R_{i,j}^u(\mathbf{y}_i)$  and sends  $\mathcal{R}_i(\tau^t, \mathbf{y}_i^t)$  and  $|\mathcal{U}'_i|$  to the arbitrator
  - 7: Arbitrator determines  $\alpha = \sum_{i \in \mathcal{S}} |\mathcal{U}'_i|, \beta = \sum_{i \in \mathcal{S}} \mathcal{R}_i(\tau^t, \mathbf{y}_i^t)$
  - 8:  $t \leftarrow t + 1$
  - 9: Arbitrator determines  $\tau^t$  with the help of Theorem 1 considering  $\alpha, \beta, \delta$  and  $\tau_0$
  - 10: Arbitrator informs  $\tau^t$  to  $\forall i \in \mathcal{S}$
  - 11: **until** convergence
- 

## IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed mechanism in terms of average achieved rate, the percentage of unsatisfied users, and fairness [16]. The main parameters used in this simulation are shown in Table II. All SBSs, WAPs, and

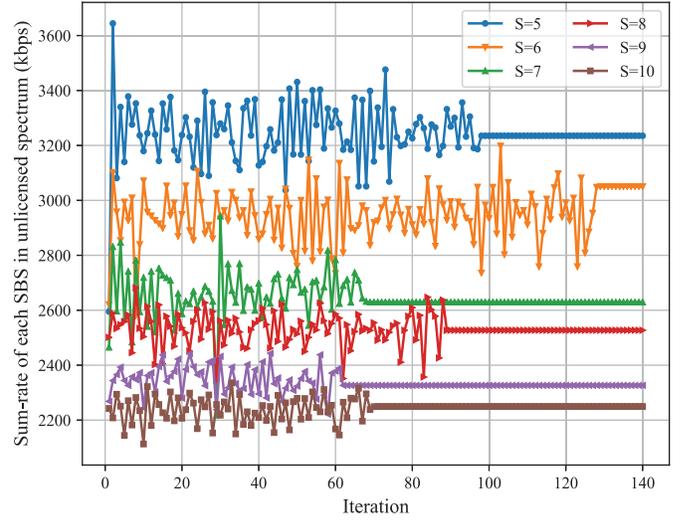


Figure 3: Convergence of Alg. 2 for different number of SBSs in the same unlicensed band

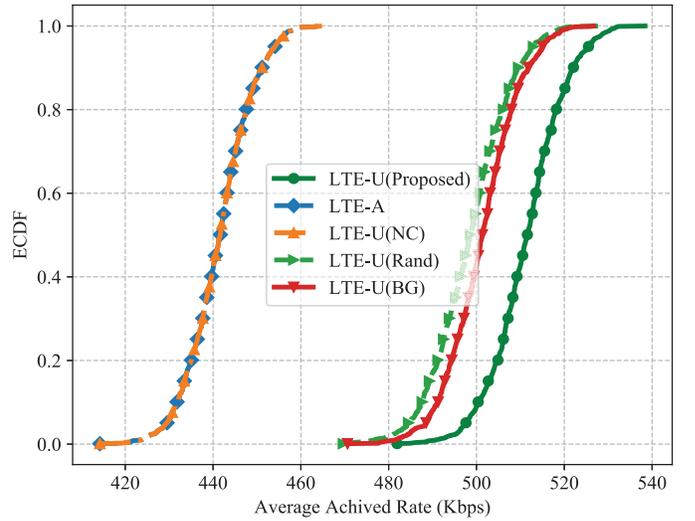


Figure 4: Comparison of per user average achieved rate

users are distributed uniformly in the conflicting area of radius 150m. Wi-Fi network operates according to the IEEE 802.11n protocol in the 5GHz band with the RTS/CTS mechanism, and the Wi-Fi parameters are similar to those of [14]. SBSs also work in the same unlicensed band as with WAPs besides the licensed spectrum. We assume that SBSs use SDL with the help of CA when the QoS of applications are not satisfied with the licensed spectrum. For our simulation, we use typical QoS requirements of multimedia applications of [17] as shown in Table III. Unlicensed resource blocks are divided among the SBSs based on SBSs' QoS gap with licensed resources as indicated in Algorithm 1. In this evaluation section, we have compared the performance of the proposed method with LTE-A, LTE-U with no coalition indicated as LTE-U(NC), LTE-U with the random selection of users from user list renamed as LTE-U(Rand), and LTE-U with bankruptcy game

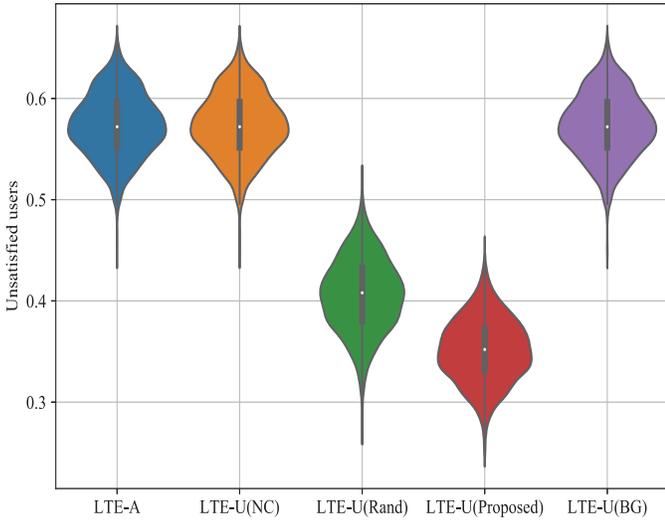


Figure 5: Comparison of unsatisfied users

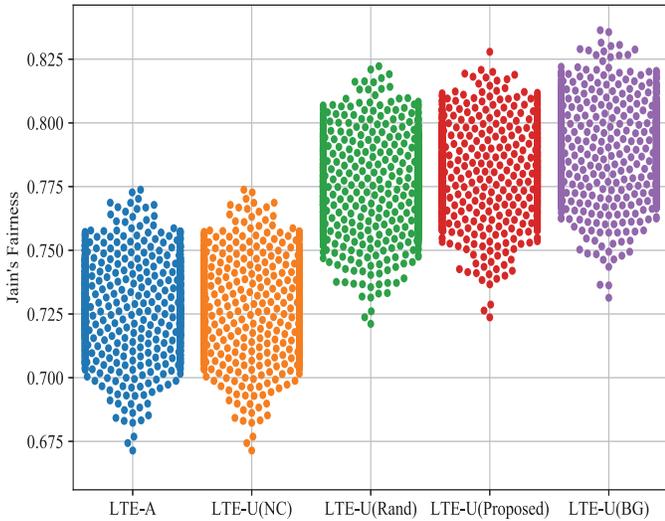


Figure 6: Comparison of fairness

[18] known as LTE-U(BG). Fig. 3 shows the convergence of the repetitive algorithm (Algo. 2). It represents that the algorithm will converge after a finite number iterations, and on average it converges after 85 iterations. For comparing the performance, we take 1000 runs of all the methods.

In Fig. 4, we manifest the comparison of the per-user average achieved rate among different methods. It shows that the per-user achieved rate of the proposed method is higher than all other comparing methods. The Fig. 4 also shows that LTE-A and LTE-U(NC) produce an average achieved rate of 420 ~ 460Kbps, and it is less than 440Kbps in 40% of the cases. On the contrary, this range is 465 ~ 520Kbps for LTE-U(Rand), 480 ~ 520Kbps for LTE-U(BG), 480 ~ 540Kbps for LTE-U(Proposed), and the average achieved rate is at least 500Kbps in 40%, 60%, and 95% of cases for LTE-U(Rand), LTE-U(BG), and LTE-U(Proposed) respectively. Moreover, the proposed method achieves 13.69%, 13.69%, 2.47%, and

Table II: Value of Simulation Parameters

Symbol	Value	Symbol	Value
$S$	5	$ \mathcal{U}_i , \forall i$	50
$B_l$	180 kHz	$ \mathcal{S}C_i^l , \forall i$	50
$B_u$	180 kHz	$ \mathcal{S}C^u $	100
$P_i^l, \forall i$	21 dBm	$P_i^u, \forall i$	17dBm
$\sigma^2$	-114 dBm	$G$	-33.5dB
$V_w, \forall w$	5	$W$	5
$\alpha$	3		

Table III: QoS Requirements of Multimedia Applications

Application	Min Requirement (Kbps)
HD video streaming	800
Video conferencing	700
VoIP	512
Audio streaming	320

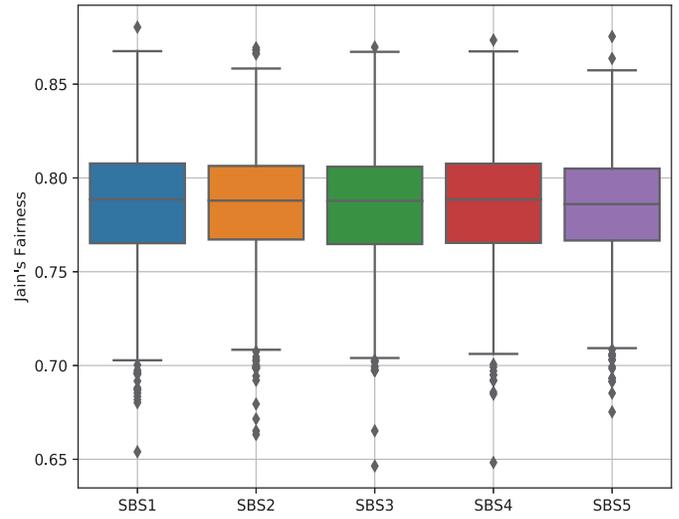


Figure 7: Comparison of fairness among SBSs in the proposed method

1.99% more rate on average than LTE-A, LTE-U(NC), LTE-U(Rand), and LTE-U(BG) respectively.

In Fig. 5, we reveal the comparison of unsatisfied users among different methods. It shows that the percentage of unsatisfied users is less in the proposed method than other methods. It also shows that the median of unsatisfied users are 57.36%, 57.36%, 40.60%, 57.34%, and 35.08% respectively for LTE-A, LTE-U(NC), LTE-U(Rand), LTE-U(BG), and LTE-U(Proposed) respectively, and the proposed method achieves 63.51%, 63.51%, 15.74%, and 63.45% better than LTE-A, LTE-U(NC), LTE-U(Rand), and LTE-U(BG) respectively.

In Fig. 6, we find the comparison of fairness among different methods. It shows that most of the fairness scores for LTE-A and LTE-U(NC) reside between 70% ~ 75.50% whereas the same scores for LTE-U(Rand), LTE-U(BG), and LTE-U(Proposed) fall within 75% ~ 80%, 76% ~ 82%, and 75.5% ~ 81% respectively. On average, this fairness score of the proposed method is 6.74%, 6.74% and 0.63% better than LTE-A, LTE-U(NC), and LTE-U(Rand) respectively, and 1.20% lower than LTE-U(BG).

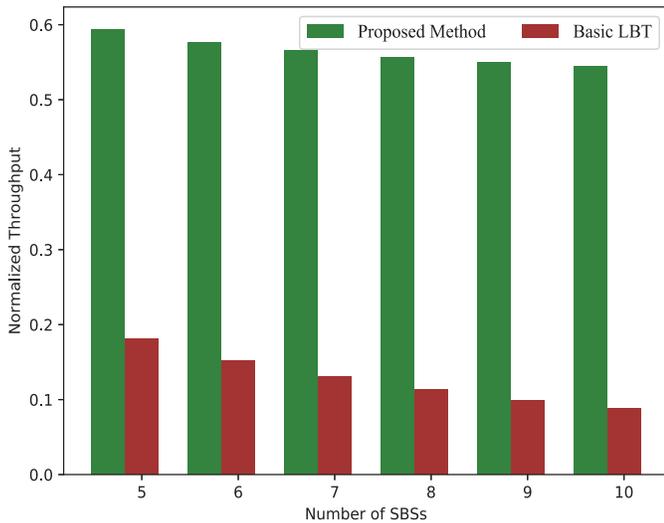


Figure 8: Comparison of normalized throughput of Wi-Fi user

In Fig. 7, we show the comparison of fairness among the SBSs when they use a single unlicensed channel in the proposed method. It reveals that most of this fairness scores reside between 77% to 81% for all the SBSs and the median of these scores are almost same (78.50%) for all the SBSs. It indicates that the division of unlicensed resources is fair among the SBSs.

In Fig. 8, we show the comparison of normalized throughput of Wi-Fi user between the proposed method and basic listen-before-talk (LBT) with the varying number of SBSs. It represents that the proposed method shields Wi-Fi user better than basic LBT does in all cases. With the increasing number of SBSs, the outputs reduce for both the proposed method and LBT as it increases the competition among the APs. The proposed method can guarantee 69.59%, and 83.85% more throughput than basic LBT in 5 SBSs and 10 SBS cases correspondingly. Moreover, the proposed method protects Wi-Fi users better than basic LBT in more dense deployment.

## V. CONCLUSIONS

In this paper, we have tried to meet the QoS requirements of the users by augmenting unlicensed spectrum with licensed one in the LTE-A network known as LTE-U after taking care of co-existence issue with WAPs. Here, we have solved the problem by utilizing the NBG, and heuristic algorithm. Simulation results show that opportunistic use of the unlicensed spectrum in the proposed method can provide better per user average achieved rate, and user satisfaction than LTE-A, LTE-U(NC), LTE-U(Rand), and LTE-U(BG) methods. The same trend also follows for fairness except for the LTE-U(BG). Moreover, we find that the proposed method can protect Wi-Fi users fur better way than basic LBT does. In the future, we will try to meet the QoS requirement of all the users by designing the mechanism carefully.

## ACKNOWLEDGMENT

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