Interoperator Opportunistic Spectrum Sharing in LTE-Unlicensed

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***Abstract*—Extending long-term evolution (LTE) to unlicensed bands, termed LTE-unlicensed, is gaining significant interest recently. The coexistence of LTE-unlicensed with the current users of unlicensed bands (such as Wi-Fi) and the interference among LTE-unlicensed users themselves are the two challenges for the success of this new technology. In this paper, we propose a novel distributed online algorithm for opportunistic sharing of unlicensed bands among LTE-unlicensed base stations (BSs) while guaranteeing the quality of service (QoS) of user equipment (UE). We first derive a Lyapunov optimization-based algorithm for BSs to evaluate the true value of unlicensed spectrum, guarantee a maximum delay, and minimize the packet drop rate. We then develop a distributed auction mechanism to maximize the social welfare in each auction and enable optimal spectrum reuse. We prove that BSs bid truthfully with the proposed algorithm, while UEs' QoS requirements on delay and packet drop rate can be guaranteed with bounded optimality gaps. We also reveal an interesting tradeoff between the delay and packet drop rate. The proposed algorithm is validated with simulations.**

***Index Terms*—Distributed auction, long-term evolution (LTE)-unlicensed, LTE licensed-assisted access (LAA), Lyapunov optimization, quality of service (QoS).**

I. Introduction

With the unprecedented growth in wireless data, wireless operators are in critical need of more spectra for higher capacity. To meet the so-called 1000× mobile data challenge [1], extending long-term evolution (LTE) to the unlicensed spectrum, as specified in LTE Rel-10–Rel-13 [2]–[4], has recently gained significant attention [1], [3]–[13]. However, there are two main challenges to the success of the so-called *LTE-unlicensed* technology. First, the unlicensed bands are already occupied by many existing wireless networks (e.g., Wi-Fi). It is essential to enable the coexistence of LTE-unlicensed with existing unlicensed band users, i.e., to avoid significant performance degradation to existing users while achieving high capacity gains with LTE-unlicensed. Second, the interference in unlicensed bands is unpredictable, which is detrimental to the performance of LTE-unlicensed users. Hence, it is important to effectively manage the interference between LTE-unlicensed and existing users, as well as that among LTE-unlicensed users themselves.

To study the coexistence of LTE-unlicensed with existing unlicensed band users, some system-level simulation studies have been reported in several recent works [5], [10], [11]. The simulation results show that the Wi-Fi performance could be significantly degraded, while the LTE performance is only slightly affected. This is because Wi-Fi uses carrier sensing multiple access to compete for channel access, while LTE adopts a centralized channel access control mechanism. Wi-Fi usually keeps silent when sensing a busy channel continuously used by LTE. To protect existing unlicensed band users, requirements for clear channel assessment (CCA) and listen before talk (LBT) are specified by European standardization bodies [7]. In LBT, user equipment (UE) must perform CCA on the operating channel(s) before starting a transmission. The observing duration should be at least 20 μs.

Although the LTE performance may be only slightly affected by Wi-Fi in some coexistence scenarios [10], [11], there could still be significant throughput degradations due to the interoperator interference, when multiple LTE-unlicensed base stations (BSs) of different operators are deployed in the same area [3]. There are two solutions to this problem: 1) Achieve an agreement for the operators to share the unlicensed spectrum; or 2) enable opportunistic access to unlicensed channels. The first solution may not be practical in most countries due to competition among operators and the lack of regulation for unlicensed bands [3], while the second solution is promising for effective unlicensed spectrum sharing.

In this paper, we investigate the problem of opportunistic spectrum sharing among LTU-unlicensed BSs. We consider the license-assisted access (LAA) scenario, in which licensed and unlicensed carrier bands are integrated and used [4]. We also adopt the LBT mechanism for coexistence of LTE-unlicensed and Wi-Fi [7]. For the LTE-unlicensed BSs deployed in the same area on both licensed and unlicensed bands, we propose a novel distributed online algorithm for opportunistic sharing of unlicensed bands among the BSs while guaranteeing the QoS of UEs in the form of bounded worst-case delay and minimized packet drop rate.

Specifically, based on Lyapunov optimization, we first derive an online algorithm for BSs to evaluate the true value of unlicensed spectrum, guarantee a maximum delay, and minimize the packet drop rate. We then develop a distributed auction mechanism to incorporate the Lyapunov optimization based schemes,

Manuscript received December 16, 2015; revised June 26, 2016; accepted August 24, 2016. Date of publication September 26, 2016; date of current version June 16, 2017. This work was supported in part by the U.S. National Science Foundation under Grant CNS-0953513 and Grant CNS-1247955 and in part by the Wireless Engineering Research and Education Center at Auburn University. The review of this paper was coordinated by Prof. C. Zhang.

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Digital Object Identifier 10.1109/TVT.2016.2613444

aiming to maximize the social welfare in each auction and enable optimal spectrum reuse. We prove that all the BSs bid truthfully with the proposed algorithm, while the UEs' QoS requirements on delay and packet drop rate can be guaranteed with bounded optimality gaps. The proposed algorithms are validated with simulations and are shown to outperform two benchmark schemes with considerable gains in all the cases simulated in this paper.

This paper presents a comprehensive and effective solution to the problem of opportunistic spectrum sharing for LTE-unlicensed. Due to the Lyapunov optimization approach, the proposed algorithms are applicable to very general scenarios with different traffic models and service rate distributions. The proposed schemes are also *online* algorithms, i.e., only requiring the current state of the network (e.g., queue backlogs and channel conditions), making them highly suitable for practical implementations. In addition to proving several nice properties of the proposed algorithms, including truthful bidding, utility maximization, social welfare maximization, and packet drop rate minimization, we also reveal an interesting tradeoff between delay and packet drop rate, which provides a useful control knob for operators.

The remainder of this paper is organized as follows. We examine related works in Section II and introduce the system model in Section III. We discuss evaluation of unlicensed spectrum, resource allocation, and drop scheduling in Section IV. We present the proposed auction mechanism and analyze its performance in Section V. Our simulation results are analyzed in Section VI. Section VII concludes this paper.

II. Related Work

The considerable amount of underutilized spectrum in unlicensed bands is the main motivation for operators and researchers to extend LTE, which is a well-designed orthogonal frequency-division multiplexing solution, to unlicensed bands [1], [3]–[14]. One of the biggest challenges is the so-called internetwork spectrum sharing [15] or, more specifically, the coexistence of LTE-unlicensed and Wi-Fi [1], [3], [5]–[11], [13], [16]–[18]. In [10] and [11], system-level simulations were conducted to evaluate the feasibility of LTE/Wi-Fi coexistence. It was shown that such coexistence causes significant degradations to the Wi-Fi performance but only affects the LTE performance slightly. Hence, LBT was introduced to protect the Wi-Fi users in the coexistence scenario [7], [18], where an LTE-unlicensed BS follows a CCA process before accessing the unlicensed spectrum. In [9], an analytical model was presented for evaluating the effectiveness of the simple LBT. The analysis showed that LBT can effectively mitigate the impact of LTE-unlicensed on Wi-Fi, though the performance of LTE-unlicensed would be degraded. Furthermore, experiments [14] show that with LBT or adaptive duty cycle, Wi-Fi can be protected. Therefore, we consider LBT in this paper to address the coexistence issue of LTE-unlicensed and Wi-Fi.

Another challenge in LTE-unlicensed is interference management among LTE-unlicensed BSs [3], while opportunistic spectrum sharing is one of the proposed solutions. In [19], a credit token based spectrum auction scheme was proposed for spectrum leasing among secondary users, while in [20], a revenue generation for truthful spectrum auction in dynamic spectrum access was proposed to render a truthful bidding for spectrum leasing from agencies. In a recent work [21], a socially optimal online spectrum auction was proposed for spectrum sharing among secondary users. However, these works either failed to address the new challenges for spectrum sharing in LTE-unlicensed, or provided no precise evaluation of the value of spectrum based on QoS guarantees in auctions. In [12], a game theoretic approach was proposed to enable spectrum sharing among LTE-unlicensed BSs through power control. However, it did not exploit the potential advantage of spatial reuse of spectrum among the BSs.

III. System Model

A. LTE-Unlicensed Network Model

We consider the LAA scenario, in which licensed and unlicensed carrier bands are integrated and used [4]. This can be enabled by carrier aggregation (CA) defined in LTE Rel-10–Rel-13 [3], [4]. With LAA, LTE on licensed band serves as a backbone and the CA of unlicensed bands boosts the downlink (FDD) or both downlink and uplink (TDD) capacity [1]. Considering the asymmetric uplink and downlink traffic, we focus on the downlink transmission of LAA in the FDD scenario. Due to the low power constraint on unlicensed spectrum imposed by regulations (e.g., Wi-Fi standards) and the relatively higher frequency of unlicensed bands (i.e., 5 GHz), it is expected to have coverage holes in unlicensed band with cosite deployment of licensed and unlicensed bands. Hence, we consider noncosite deployment of licensed and unlicensed bands in this paper.

Specifically, we consider a system with M BSs operating in the LTE-unlicensed mode, which is denoted as $\mathcal{M} = \{1, 2, \ldots, M\}$. The BSs could be several macro evolved NodeBs of different operators operating on both licensed and unlicensed bands, and/or piconodes working on unlicensed bands. We also assume a high-speed backhaul for coordinating the operation of the BSs, e.g., intercell interference coordination (ICIC) and bidding information exchange as in our proposed scheme. Define the interference index variable for BS i and j as[1]

$$I_{i,j} = \begin{cases} 1, & \text{if BS } i \text{ and } j \text{ interfere with each other} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Let $\mathcal{U}^m = \{1, 2, \ldots, U^m\}$ denote the set of UEs served by the LTE-unlicensed BS m, which maintains a queue for each UE i, denoted as Q_i^m. Let $\mathcal{C} = \{1, 2, \ldots, C\}$ be the set of orthogonal channels, each of which has an identical bandwidth as the corresponding Wi-Fi channel. Furthermore, there is no overlap between two different channels and none of the channels overlaps with more than one Wi-Fi channels (i.e., they are "aligned"). We

[1]LTE uses ICIC to maintain the links under interference. We adopt the protocol model rather than the physical model in this paper [22]. Since, in LTE-U, the typical deployment scenario is small cell and LBT is becoming a requirement, the protocol model is adequate, given such Wi-Fi-like operation behavior. In our future work, we plan to consider the more sophisticated resource allocation schemes with ICIC, as well as suitable models for adjacent channel interference [23] for LTE-U.

adopt the LBT mechanism for LTE-unlicensed/Wi-Fi coexistence [7]. Moreover, any transmission of an LTE-unlicensed BS must be followed by an idle period of the channel to avoid starvation of Wi-Fi users. The transmission time of LTE-unlicensed BSs should be confined to one frame to limit the impact on coexisting Wi-Fi users.

B. Transmission and Qeueing Model

We consider the UEs covered by LTE with both licensed and unlicensed bands.[2] LTE on licensed bands provides relatively reliable data transmissions. We assume that for UE i, BS m provides a data rate on licensed bands that transmits $R_i^m(t)$ packets in frame t. With the LBT mechanism, an LTE-unlicensed BS needs to wait for an available frame on unlicensed bands and bid for transmission opportunity on the frame to avoid collision among the BSs. If BS m wins the transmission opportunity on an unlicensed channel $c \in \mathcal{C}$ in frame t, then it can provide an extra data rate for UE $i \in \mathcal{U}^m$, denoted as $R_{ic}^m(t)$. We also have $R_{ic}^m(t) = \varphi_{ic}^m(t) e_{ic}^m(t)$, where $\varphi_{ic}^m(t)$ is the number of resource blocks (RBs) assigned to UE i, and $e_{ic}^m(t)$ is the expected data rate provided by an RB in packets per frame, which depends on the condition of channel c between BS m and UE i.[3]

For each UE i, $A_i^m(t)$ data packets arrive at BS m during frame t. We assume that the arriving packets follow a certain process with a bounded maximum rate, i.e., $A_i^m(t) \leq (A_i^m)^{\max}$. The queue at BS m for UE i is maintained as

$$Q_i^m(t+1) = \max\{Q_i^m(t) - R_{ic}^m(t) - R_i^m(t) - d_i^m(t), 0\} + A_i^m(t) \tag{2}$$

where $Q_i^m(0) = 0$ and $d_i^m(t)$ are the number of packets dropped at frame t due to violating the maximum delay requirement.

C. Spectrum Auction and LBT on Unlicensed Band

The success of LTE on unlicensed bands hinges upon the coexistence of LTE-unlicensed with other wireless networks on the same bands. LBT is introduced to enable the coexistence of LTE-unlicensed and Wi-Fi. Before an LTE-unlicensed transmission, the BS should follow a CCA procedure and wait for an idle frame before claiming the channel to transmit. The CCA process of LBT can effectively prevent collision between LTE-unlicensed and Wi-Fi. However, if more than one LTE-unlicensed BSs, within an interference range, claim and transmit on the same idle channel, there will still be collision among themselves. A channel bidding mechanism among LTE-unlicensed BSs is thus needed right after LBT.

Spectrum auction takes place among the LTE-unlicensed BSs that are interested in transmitting on an idle channel. After CCA, if a BS identifies an idle channel $c \in \mathcal{C}$, it may bid for the transmission opportunity. Other BSs can bid for the same channel following the first bid in the bidding window. All bids should be submitted to the auction session initiated by the first bidder, denoted as the *auction initiator*, in its interference range.

[2]For UEs with no coverage of LTE licensed band, LTE-unlicensed is not available due to the absence of a control channel. For UEs with no coverage of LTE-unlicensed band, the regular LTE service can be offered.

[3]We assume negligible frequency selective fading in each of the channels.

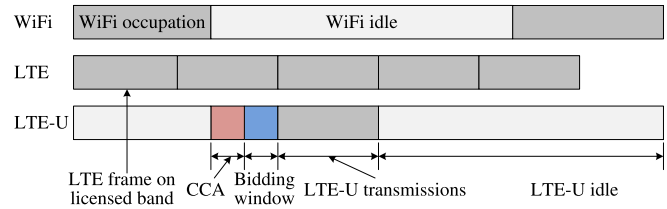

Fig. 1. Frame structure of the proposed auction scheme, where LTE-unlicensed and Wi-Fi share the same unlicensed channels.

If there is no BS in an active auction session for channel c in the interference range of a BS, the BS itself will become the auction initiator.[4] The auction is denoted as $S_c^{m^*}(t)$, where m^* is the auction initiator, t is the frame that the winner BS/BSs access, c is the channel for auction, and $\{i \in S_c^{m^*}(t)\}$ are the BSs that participate in the auction. The frame structure of the auction is shown in Fig. 1. The auction can be conducted in the following *three* steps.

Step 1: Any BS $m \in \mathcal{M}$ interested in transmitting on channel c evaluates the value of transmitting on channel c for frame t, denoted as $\tilde{b}_c^m(t)$. It then submits a bid $b_c^m(t)$ to the auction session for transmission on the next frame.[5] Note that each BS aims to maximize its own utility in the auction, and therefore, it may try to manipulate the auction by submitting a bid deviating from its true value, i.e., $\tilde{b}_c^m(t) \neq b_c^m(t)$. We aim to design a strategy-proof auction to force BSs to bid truthfully.

Step 2: At the end of each bidding window, the auction session makes the channel assignment decision $\alpha_c^{m^*}(t)$, i.e., the set of auction winners to access channel c in the following transmission frame. Notice that the set of auction winners should be beyond the interference range of each other [i.e., $I_{i,j} = 0$, for all $i, j \in \alpha_c^{m^*}(t)$]. The auction session decides the payment $\hat{b}^m(t)$ of all the BSs participating in the auction. Auction losers do not need to make a positive payment.

Step 3: At the beginning of transmission frame t, the winner BSs make decisions on transmitting or dropping packets.

D. Utility Function and Social Welfare

We consider selfish BSs, each aiming to maximize its utility during each bidding cycle. The utility of BS $m \in \mathcal{M}$ depends on the QoS of the UEs it serves, including the drop rate and packet delay. The BS decides to bid when there is a potential transmission opportunity on channel c starting at frame t. If BS m participates in an auction of channel c that is available at frame t, its utility function is defined as

$$\phi_c^m(t) = \sum_{i \in \mathcal{U}^m} \{-\beta_i^m d_i^m(t)\} - \hat{b}_c^m(t) \tag{3}$$

where β_i^m is the penalty of dropping a packet of UE i served by BS m. Note that we do not include the delay constraint in the utility function, which, however, will be considered in the design of a dropping policy in the next section. The transmission on the licensed band is not included in the utility function

[4]The auction initiator serves as a virtual holder. The actual auction is processed at a back-end server to reduce the cost on the auction initiator and to prevent cheating.

[5]If there is more than one channel available, then the BS can randomly choose *one* to bid.

because we aim to limit the modification on the current LTE system and assume that the transmission on licensed band is not affected by the transmission on unlicensed band. However, the transmissions on licensed band do have a great influence on the queue length and packet drop rates of the UEs, which will be considered in the algorithm design.

The objective of the auction design is to maximize the social welfare of each auction. The social welfare of an auction on transmission opportunity at frame t on channel c should be the total utility of all anticipating BSs in auction $S_c^{m^*}(t)$. As payments are made among the participants, so the total payment should always be 0. Hence, the social welfare of auction $S_c^{m^*}(t)$ is defined as follows:

$$\sum_{m\in S_c^{m^*}(t)} \phi_c^m(t) = \sum_{m\in S_c^{m^*}(t)} \sum_{i\in\mathcal{U}^m} \{-\beta_i^m d_i^m(t)\}. \tag{4}$$

IV. Lyapunov Optimization Based Valuation and Scheduling

A. Virtual Queue and Delay Bound

In each auction, a BS needs to dynamically evaluate the value of spectrum resource in LTE-unlicensed, and decide the resource allocation and packet drop scheme according to the channel condition and the queue length of each UE it serves. In this section, we apply Lyapunov optimization to derive an online algorithm for resource allocation and packet drop control to guarantee the maximum delay of packets [24]–[26].

We adopt the ϵ-persistence queue model [24] to guarantee the maximum delay requirement. The BS maintains the following*virtual queue* for each UE it serves:

$$\begin{aligned} Z_i^m(t+1) = \ & \max\big\{Z_i^m(t) + \epsilon_i^m \cdot 1_{\{Q_i^m(t)>0\}} - R_i^m(t) \\ & -R_{ic}^m(t) - d_i^m(t) - Z_i^m(t)\cdot 1_{\{Q_i^m(t)=0\}}, 0\big\} \end{aligned} \tag{5}$$

where $\epsilon_i^m > 0$ is a prescribed constant; $1_{\{\cdot\}}$ is an indicator function; and $Z_i^m(0) = 0$. When $Q_i^m(t) > 0$, the virtual queue $Z_i^m(t)$ has the same departure process $R_{ic}^m(t) + R_i^m(t) + d_i^m(t)$ as $Q_i^m(t)$, but its arrival rate is a constant ϵ_i^m. When $Q_i^m(t) = 0$, $Z_i^m(t)$ will be reset to 0. In fact, $Z_i^m(t)$ approximately tracks the packet delay of queue Q_i^m. A larger $Z_i^m(t)$ indicates a longer delay of packets in the traffic queue $Q_i^m(t)$. An algorithm that stabilizes $Z_i^m(t)$ and $Q_i^m(t)$ will ensure a bounded maximum delay, as given in the following Fact [24].

Fact 1 (Upper Bound of Delay [24]): Suppose $Q_i^m(t)$ and $Z_i^m(t)$ maintained by an algorithm satisfy the following constraints for all $t \in \{0, 1, 2, \ldots\}$: $Q_i^m(t) \le (Q_i^m)^{\max}$ and $Z_i^m(t) \le (Z_i^m)^{\max}$, where $(Q_i^m)^{\max}$ and $(Z_i^m)^{\max}$ are finite constants. Then, the maximum delay of packets can be bounded with a finite constant $(W_i^m)^{\max}$, i.e., a packet will be either transmitted or dropped within $(W_i^m)^{\max}$. If packets are served in the first-in-first-out (FIFO) manner, according to the ϵ-persistence queue analysis in [24], the delay bound can be written as

$$(W_i^m)^{\max} = \lceil ((Q_i^m)^{\max} + (Z_i^m)^{\max})/\epsilon_i^m \rceil \tag{6}$$

where $\lceil\cdot\rceil$ is the ceiling function.

B. Lyapunov Optimization

Let $\Theta^m(t)$ be a vector of all $Q_i^m(t)$ and $Z_i^m(t)$, $i \in \mathcal{U}^m$. We define the *L*yapunov function $L(\Theta^m(t))$ as

$$L(\Theta^m(t)) \doteq \frac{1}{2}\sum_{i\in\mathcal{U}^m} \{(Q_i^m(t))^2 + (Z_i^m(t))^2\}. \tag{7}$$

We also define a one-step sample path *Lyapunov drift* as

$$\Delta_1(\Theta^m(t)) \doteq L(\Theta^m(t+1)) - L(\Theta^m(t)). \tag{8}$$

The *drift-plus-penalty* used in Lyapunov optimization [24] is obtained by adding the penalty of spectrum bidding cost. The penalty includes the payments and cost of dropped packets as $-V^m\phi^m(t) \doteq V^m b_c^m(t) + V^m \sum_{i\in\mathcal{U}^m} \beta_i^m d_i^m(t)$, where $V^m > 0$ indicates BS m's concern on the price it needs to pay, and β_i^m is the penalty of dropping a packet of UE i, $i \in \mathcal{U}^m$. Hence, the one-frame *drift-plus-penalty* can be written as $\Delta_1(\Theta^m(t)) + V^m b_c^m(t) + \sum_{i\in\mathcal{U}^m} V^m \beta_i^m d_i^m(t)$. If BS m bids for transmission opportunity on channel c at frame t, the problem can be formulated as follows:

$$\min: \ \Delta_1(\Theta^m(t)) + V^m b_c^m(t) + \sum_{i\in\mathcal{U}^m} V^m \beta_i^m d_i^m(t) \tag{9}$$

$$\text{s.t.} \ \sum_{i\in\mathcal{U}^m} \varphi_{ic}^m(t) = \varphi, \quad \text{for } c \in \mathcal{C} \tag{10}$$

$$\varphi_{ic}^m(t) \ge 0, \ \text{for } i \in \mathcal{U}^m, \quad c \in \mathcal{C} \tag{11}$$

$$R_{ic}^m(t) + R_i^m(t) + d_i^m(t) \le Q_i^m(t) \quad \text{for } i \in \mathcal{U}^m, c \in \mathcal{C} \tag{12}$$

$$\epsilon_i^m \ge (A_i^m)^{\max}, \quad \text{for } i \in \mathcal{U}^m \tag{13}$$

$$(d_i^m)^{\max} \ge (A_i^m)^{\max}, \ d_i^m(t) \ge 0, \quad \text{for } i \in \mathcal{U}^m \tag{14}$$

where φ is the total amount of RBs on channel c. In the formulation, (10) and (11) are resource allocation constraints, while constraint (12) guarantees that the packets transmitted and dropped in slot t are no greater than $Q_i^m(t)$.

We can rewrite the *drift-plus-penalty* as follows:

$$\begin{aligned} &\Delta_1(\Theta(t)) + V^m b_c^m(t) + \sum_{i\in\mathcal{U}^m} V^m \beta_i^m d_i^m(t) \\ &\quad \le B^m + V^m b_c^m(t) + \sum_{i\in\mathcal{U}^m} V^m \beta_i^m d_i^m(t) \\ &\quad - \sum_{i\in\mathcal{U}^m} Q_i^m(t)(R_{ic}^m(t) + R_i^m(t) + d_i^m(t) - A_i^m(t)) \\ &\quad + \sum_{i\in\mathcal{U}^m} Z_i^m(t)\epsilon_i^m 1_{\{Q_i^m(t)>0\}} - \frac{1}{2}(Z_i^m(t))^2 1_{\{Q_i^m(t)=0\}} \\ &\quad - \sum_{i\in\mathcal{U}^m} Z_i^m(t)(R_{ic}^m(t) + R_i^m(t) + d_i^m(t)) \\ &= B^m - \frac{1}{2}(Z_i^m(t))^2 1_{\{Q_i^m(t)=0\}} + \sum_{i\in\mathcal{U}^m} Q_i^m(t)A_i^m(t)) \\ &\quad + \sum_{i\in\mathcal{U}^m} Z_i^m(t)\epsilon_i^m 1_{\{Q_i^m(t)>0\}} - \Phi_{(1)}^m(t) - \Phi_{(2)}^m(t) \end{aligned} \tag{15}$$

where

$$\begin{cases} \Phi^m_{(1)}(t) = \sum_{i\in\mathcal{U}^m}(R^m_{ic}(t)+R^m_i(t))(Q^m_i(t) \\ \quad +Z^m_i(t)) - V^m b^m_c(t) \\ \Phi^m_{(2)}(t) = \sum_{i\in\mathcal{U}^m} d^m_i(t)(Q^m_i(t)+Z^m(t)-V^m\beta^m_i) \\ B^m \doteq \dfrac{1}{2}\sum\limits_{i\in\mathcal{U}^m}\{[(R^m_{ic}+R^m_i+d^m_i)^{\max}]^2 \\ \quad +2[(A^m_i)^{\max}]^2+[(\epsilon^m-R^m_{ic}-R^m_i-d^m_i)^{\max}]^2\}. \end{cases} \tag{16}$$

With Lyapunov optimization [24], we can derive an online algorithm to minimize the *drift-plus-penalty*, which will yield policies for resource allocation, valuation of spectrum, and packet dropping.

Resource Allocation: Maximizing $\Phi^m_{(1)}(t)$ defined in (16), we can derive the optimal allocation of RBs and obtain the transmission policy. Note that the first term in $\Phi^m_{(1)}(t)$ is valid only when BS m wins the auction and makes the payment and the value of the second term does not affect the maximization of $\Phi^m_{(1)}(t)$. We, thus, solve the following problem:

$$\begin{aligned} \max: \quad & \sum_{i\in\mathcal{U}^m}(R^m_{ic}(t)+R^m_i(t))(Q^m_i(t)+Z^m_i(t)) \\ \text{s.t.} \quad & \text{Constraints (10)–(12).} \end{aligned} \tag{17}$$

The objective function (17) can be rewritten as

$$\begin{aligned} &\sum_{i\in\mathcal{U}^m}(R^m_{ic}(t)+R^m_i(t))(Q^m_i(t)+Z^m_i(t)) \\ &\quad = \sum_{i\in\mathcal{U}^m}\varphi^m_{ic}(t)e^m_{ic}(t)(Q^m_i(t)+Z^m_i(t)) \\ &\qquad + \sum_{i\in\mathcal{U}^m}R^m_i(t)(Q^m_i(t)+Z^m_i(t)). \end{aligned} \tag{18}$$

Recall that $\varphi^m_{ic}(t)$ is the number of RBs in spectrum c allocated to UE i by BS m. We focus on resource allocation on the unlicensed spectrum and do not consider optimization of the rate from licensed band [i.e., $R^m_i(t)$]. Hence, we can tune $\varphi^m_{ic}(t)$ to maximize (17). Specifically, we apply a greedy algorithm to allocate more RBs to UE i with a higher $e^m_{ic}(t)(Q^m_i(t)+Z^m_i(t))$ under constraints (10)–(12).

True Value of Channel: To find the highest price that BS m is willing to pay for unlicensed channel c, i.e., $\tilde{b}^m_c(t)$, we can compare $\Phi^m_{(1)}(t)$ when a bid is successful for spectrum c, with that when no bid is made. Since $\tilde{b}^m_c(t)$ is the highest price that BS m is willing to pay for channel c, it is also the *true value* of channel c to BS m.

If the bid is successful, we have

$$\begin{aligned} \Phi^m_{(1)}(t)' = &\sum_{i\in\mathcal{U}^m}(R^m_{ic}(t)+R^m_i(t))(Q^m_i(t) \\ &+ Z^m_i(t)) - V^m b^m_c(t). \end{aligned} \tag{19}$$

Otherwise, if BS m does not bid for channel c, we have

$$\Phi^m_{(1)}(t)'' = \sum_{i\in\mathcal{U}^m}R^m_i(t)(Q^m_i(t)+Z^m_i(t)). \tag{20}$$

When BS m pays the highest price, we have $\Phi^m_{(1)}(t)' - \Phi^m_{(2)}(t)'' = 0$, from which we can solve for $\tilde{b}^m_c(t)$ as

$$\begin{aligned} \tilde{b}^m_c(t) &= \frac{1}{V^m}\Bigg\{\max\sum_{i\in\mathcal{U}^m}(R^m_{ic}(t)+R^m_i(t))\times(Q^m_i(t) \\ &\qquad + Z^m_i(t)) - \sum_{i\in\mathcal{U}^m}R^m_i(t)(Q^m_i(t)+Z^m_i(t))\Bigg\} \\ &= \frac{1}{V^m}\max\Bigg\{\sum_{i\in\mathcal{U}^m}R^m_{ic}(t)(Q^m_i(t)+Z^m_i(t))\Bigg\} \\ &\quad \text{s.t. Constraints}(10)-(12). \end{aligned} \tag{21}$$

Packets to Drop: By maximizing $\Phi^m_{(2)}(t)$ defined in (16), we can obtain the amount of packets to drop as follows:

$$d^m_i(t) = \begin{cases} (d^m_i)^{\max}, & Q^m_i(t)+Z^m_i(t) > V^m\beta^m_i \\ 0, & \text{otherwise} \end{cases} \tag{22}$$

where $(d^m_i)^{\max}$ is a constant, i.e., a predefined limit for d^m_i. To satisfy the maximum delay requirement, packets are dropped as in (22) in each frame, whether or not there is addition transmission opportunity on unlicensed bands.

C. Maximum Delay Guarantee

In this section, we first derive upper bounds on the real and virtual queue lengths. We then translate the backlog bounds to an upper bound on queueing delay.

Lemma 1: With the drop decision (22) and assuming $0 \le \epsilon^m_i \le (d^m_i)^{\max}$ and $0 \le (A^m_i)^{\max} \le (d^m_i)^{\max}$, the proposed resource allocation and dropping policies ensure the following upper bounds on the real and virtual queues:

$$(Q^m_i(t)+Z^m_i(t))^{\max} = V^m\beta^m_i + (A^m_i)^{\max} + \epsilon^m_i \tag{23}$$

$$(Z^m_i)^{\max} = V^m\beta^m_i + \epsilon^m_i. \tag{24}$$

Proof: We first prove (23) with *induction*. Since the real and virtual queues are all initially empty, we have $Q^m_i(0) + Z^m_i(0) \le V^m\beta^m_i + (A^m_i)^{\max} + \epsilon^m_i$. Then, we assume that (23) holds for some $t_0 \ge 0$, and prove that (23) also holds for (t_0+1).

If $Q^m_i(t_0)+Z^m_i(t_0) \le V^m\beta^m_i$, it follows from (2) and (5) that

$$\begin{aligned} &Q^m_i(t_0+1)+Z^m_i(t_0+1) \\ &\quad \le Q^m_i(t_0)+Z^m_i(t_0)+(A^m_i)^{\max}+\epsilon^m_i \\ &\quad \le V^m\beta^m_i+(A^m_i)^{\max}+\epsilon^m_i. \end{aligned}$$

Otherwise, if $V^m\beta^m_i \le Q^m_i(t_0)+Z^m_i(t_0) \le V^m\beta^m_i + (A^m_i)^{\max} + \epsilon^m_i$, then we have $d^m_i(t) = (d^m_i(t))^{\max}$, according to

(22). Hence

$$\begin{aligned} &Q_i^m(t_0+1) + Z_i^m(t_0+1) \\ &\quad \le Q_i^m(t_0) - R_{ic}^m(t_0) - R_i^m(t_0) - (d_i^m)^{\max} + A_i^m(t_0) \\ &\qquad + Z_i^m(t_0) + \epsilon_i^m - R_{ic}^m(t_0) - R_i^m(t_0) - (d_i^m)^{\max} \\ &\quad \le Q_i^m(t_0) + Z_i^m(t_0) + A_i^m(t_0) + \epsilon_i^m - 2(d_i^m)^{\max} \\ &\quad \le V^m \beta_i^m + (A_i^m)^{\max} + \epsilon_i^m. \end{aligned}$$

Thus, (23) also holds for the case of (t_0+1), and we conclude that (23) is true for all t. The proof for (24) is similar to that in [24] and is omitted for brevity. ■

Theorem 1: With the proposed resource allocation and packet dropping polices and the FIFO service discipline, the queueing delay is upper bounded by $(W_i^m)^{\max}$. That is, any packet is either transmitted or dropped within $(W_i^m)^{\max}$, given by

$$(W_i^m)^{\max} = 2 + (2V^m \beta_i^m + (A_i^m)^{\max})/\epsilon_i^m. \tag{25}$$

Proof: According to Fact 1, we have

$$(W_i^m)^{\max} = ((Q_i^m)^{\max} + (Z_i^m)^{\max})/\epsilon_i^m.$$

It follows Fact 1 and Lemma 1 that

$$\begin{aligned} (W_i^m)^{\max} &\le ((Q_i^m + Z_i^m))^{\max} + (Z_i^m)^{\max})/\epsilon_i^m \\ &= 2 + (2V^m \beta_i^m + (A_i^m)^{\max})/\epsilon_i^m. \end{aligned}$$

From Theorem 1, we see that there is an approximately linear relationship between the maximum delay and $V^m \beta_i^m/\epsilon_i^m$. ■

V. Auction and Pricing

A. Determine the Auction Winner

During the auction, the same spectrum can only be allocated to a set of BSs with no mutual interference. A set of BSs with no mutual interference can be denoted as a noninterfering bidding set. In each auction, the auction session determines the bidding set $\alpha_c^{m^*}(t)$ that wins the auction and obtains the opportunity of transmission in frame t. The objective of the auction is to maximize the sum of bids in $\alpha_c^{m^*}(t)$. It follows that

$$\max_{\{\alpha_c^{m^*}(t)\}} \; : \; G_c(t)|_{\{S_c^{m^*}(t)\}} \doteq \sum_{m \in \alpha_c^{m^*}(t)} b_c^m(t) \tag{26}$$

$$\text{s.t.} \quad I_{i,j} = 0, \quad \text{for all } i,j \in \alpha_c^{m^*}(t). \tag{27}$$

Recall that $S_c^{m^*}(t)$ is the set of BSs that bid in the auction. Constraint (27) guarantees that there is no mutual interference among the winner BSs. It is possible that the solution to problem (26) is not unique. Then, the auction session will randomly choose one noninterfering set as a winner set.

To solve problem (26), we could use a brute-force approach to examine all the BS combinations for the optimal noninterfering bidding set, which has a complexity of $\mathcal{O}(2^n - 1)$, where $n = |S_c^{m^*}(t)|$ is the number of BSs participating in the auction. In fact, this is a *maximum weighted independent set problem* in graph theory [27], which is NP-complete. Wu *et al.* [28] proposed an approximation solution with a polynomial complexity by relaxing the objective function. Fortunately, in the auction design of this paper, the number of BSs in a noninterfering bidding set is limited.

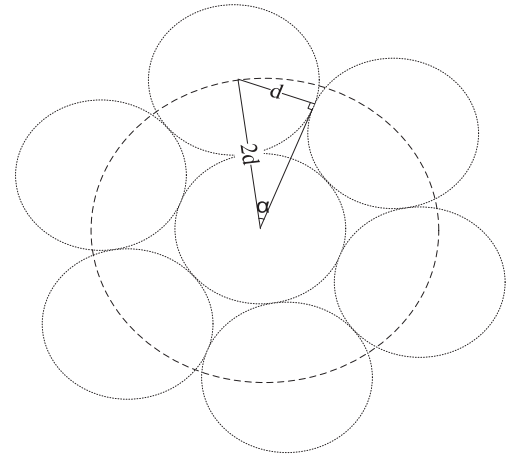

Fig. 2. Illustrate the maximum independent set.

Algorithm 1: WINNERSET$\big(S_c^{m^*}(t)\big)$

Input: Information about participating BS's, $S_c^{m^*}(t)$ and $I_{i,j}(t)$, and all the bids made for channel c, $b_c^m(t)$, for $i,j,m \in S_c^{m^*}(t)$
Output: The Optimum Non-interfering Bidding Set

```
G^max = 0 ;
α = ∅ ;
for each BS m ∈ S_c^{m*}(t) do
    S = S_c^{m*}(t) ;
    Delete BS m and all BS's interfering with BS m from S ;
    α' = WINNERSET(S) ∪ m ;
    Compute G' as the sum of all bids in α' ;
    if G' > G^max then
        G^max = G' ;
        α = α' ;
    end
end
Return α ;
```

Lemma 2: If the interference range of each BS is shaped as disks with an identical diameter, the maximum number of BSs in a noninterfering bidding set is seven.

Proof: Recall that all the bidding BSs are in the interference range of the auction initiator. Hence, the distance between any two BSs is no more than $2d$, where d is the interference range of a BS. If the interference range of each BS is shaped as a disk with diameter d, then the maximum independent bidding set should be formed as shown in Fig. 2. As $\alpha = \pi/6$, there are six disks in the outer layer and the size of the independent set is seven. ■

We propose a recursive algorithm WINNERSET$\big(S_c^{m^*}(t)\big)$ to solve problem (26), to find the maximum sum of bids of a noninterfering bidding set. As shown in Algorithm 1, the recursive algorithm WINNERSET$(\cdot)$ works as follows. The goal is to obtain the maximum noninterfering bidding set among all the sets that contain BS m, for $m \in S_c^{m^*}(t)$. The maximum noninterfering bidding set containing BS m is BS m plus the

maximum noninterfering bidding set α' in $S_c^{m^*}(t)$, after deleting BS m and all its interfering BSs, and α' can be obtained recursively.

The algorithm has a complexity of $\mathcal{O}(n(k-1)!)$, where k is the maximum depth of the recursive algorithm, which is equal to the maximum number of BSs in a noninterfering bidding set. The overall complexity can be calculated from two perspectives: complexity of the auction and that of each BS. For each auction, first, the winner set should be determined, with a complexity of $\mathcal{O}(n(k-1)!)$. Then, the secondary winner set is determined, with a complexity of $\mathcal{O}(n(k-1)!)$. Finally, the payments are computed with complexity $\mathcal{O}(n)$. The overall complexity of the auction is, thus, $\mathcal{O}(n(k-1)!)$. For BS m, the complexity can be written as $\mathcal{O}(\mathcal{U}^m \log(\mathcal{U}^m))$ as it needs to sort the users for channel assignment, where $\mathcal{U}^m$ is the number of the users served by BS m.

B. Determine the Payments

In our auction design, all bidders are equal. Hence, we introduce the second-price strategy in second-price sealed-bid auctions (i.e., *Vickrey auctions*) [28], [29], in which the auction winner pays the second highest bid among the bidders. Applying this strategy, the winning BS set $\alpha_c^{m*}(t)$ pays for the maximum sum bids of the noninterfering bidding sets among the losers [i.e., the maximum independent set in $S_c^{m^*}(t)\backslash\alpha_c^{m^*}(t)$, denoted as the *secondary winner set* $\alpha_c^{m^*}(t)'$].

Unlike the traditional second-price strategy, there may be multiple winners in a single auction in our design. Hence, we need to split the payment among the winners, which is given by

$$\sum_{m\in\alpha_c^{m^*}(t)} \hat{b}_c^m(t) = G_c(t)|_{\{S_c^{m^*}(t)\backslash\alpha_c^{m^*}(t)\}} \tag{28}$$

where $G_c(t)|_{\{S_c^{m^*}(t)\backslash\alpha_c^{m^*}(t)\}}$ is the maximum sum bids of the secondary winner set. To effectively split the payment among winners, a Nash bargaining solution is introduced in [28], aiming to maximize $\sum_{m\in\alpha_c^{m^*}(t)}(b_c^m(t)-\hat{b}_c^m(t))$. However, the solution in [28] ignores the constraint $b_c^m(t)-\hat{b}_c^m(t)\geq 0$, for $m\in\alpha_c^{m^*}(t)$. Actually, we could obtain a truthful bidding if $0\leq\hat{b}_c^m(t)\leq b_c^m(t)$ (as given by Theorem 2 in Section V-C). Hence, we propose the following pricing scheme:

$$\hat{b}_c^m(t) = \begin{cases} b_c^m(t)\dfrac{G_c(t)|_{\{S_c^{m^*}(t)\backslash\alpha_c^{m^*}(t)\}}}{G_c(t)|_{\{S_c^{m^*}(t)\}}}, & m\in\alpha_c^{m^*}(t) \\ -b_c^m(t), & m\in\alpha_c^{m^*}(t)' \\ 0, & \text{otherwise.} \end{cases} \tag{29}$$

C. Proposed Lyapunov-Based Multiwinner Auction (LMWA) Algorithm and Performance Analysis

With the proposed schemes for resource allocation, valuation of spectrum, packet dropping, and auction, we develop an integrated algorithm for the LTE-unlicensed system, named LMWA, which is presented in Algorithm 2. In Line 10 of LMWA, no bid would be made to avoid the hidden node problem.

Algorithm 2: The Proposed LMWA Algorithm

```
1  for each BS m idle on unlicensed bands do
2      if a set of channels C' on unlicensed bands are sensed idle
       at frame t then
3          Randomly select a channel c from C' ;
4          Compute R_ic^m(t) as in (17), b̃_c^m(t) as in (21), and
           d_i^m(t) as in (22) ;
5          if a BS in the interference range is the auction initiator
           of channel c then
6              Submit b_c^m(t) = b̃_c^m(t) to the auction initiator ;
7          else if no BS in the interference range is bidding for c
           then
8              BS m becomes the auction initiator and broadcasts
               a message to hold channel c ;
9          else
10             Continue ;
11         end
12     end
13 end
14 Each auction session decides the winner BS set with Alg. 1 ;
15 Each auction session decides the actual price b̂_c^m(t) as in (29) ;
16 for each BS m, at the beginning of frame t do
17     Drop d_i^m(t) packets as in (22) in frame t ;
18     if BS m wins a bid then
19         Schedule transmission on channel c with R_ic^m(t) in
           frame t ;
20     end
21 end
```

We have the following theorems on the performance of LMWA about truthful bidding, utility, and social welfare maximization, as well as the QoS of UEs.

Theorem 2 (Truthful Bidding): The pricing scheme in (29) guarantees the truthfulness of bidding, i.e., $b_c^m(t)=\tilde{b}_c^m(t)$.

Proof: With the proposed pricing scheme (29), the payment of a winner $\hat{b}_c^m(t)$ is a complicated function of bid $b_c^m(t)$. It also depends on other BSs bids, which are unknown to BS m before submitting its bid. Hence, a bidder cannot predict the payment during the auction. If $b_c^m(t)>\tilde{b}_c^m(t)$, then it may be charged with a price $\hat{b}_c^m(t)>\tilde{b}_c^m(t)$. If $b_c^m(t)<\tilde{b}_c^m(t)$, then it has a lower chance to win the auction. Hence, $b_c^m(t)=\tilde{b}_c^m(t)$ is always the best bidding strategy.

The proposed pricing scheme (29) is also resistant to the version of shill bidding, where a buyer uses multiple identities in the auction in order to maximize its profit [30]. In shill bidding, one identity of a buyer submit a price high enough to ensure winning the auction and the another identity of the same buyer submit a price high enough to be the second highest price. In this case, the buyer will win the auction and only pay to itself. In this paper, two or more BSs from the same operators may form multiple identities of the buyer (the operator). However, in the proposed pricing scheme (29), BSs from the same operator have no clue of whether there would be any other BSs in the secondary winner set without knowing the overall interfering matrix and all bids from other BSs. If they apply shill bidding as in [30] and there is any other BS in the secondary winner set, they would need to make a higher payment to other BSs in the secondary winner set. ■

Theorem 3 (Utility Maximization for Individual BS): If the compound process $\{A_i^m(t), e_{ic}^m(t)\}$ is independent identically distributed (i.i.d.) over frames for any UE i served by BS m, the proposed LMWA algorithm achieves the following lower bound on the utility of BS m:

$$\mathbb{E}\{\phi_c^m(t)\} \geq \{\phi_c^m\}^{\text{opt}} - B^m/V^m \tag{30}$$

where $\phi_c^m(t)$ is the utility of BS m defined in (3), B^m is defined in (16), and $(\phi_c^m)^{\text{opt}}$ is the maximum utility BS m can achieve without knowing the bids of others in an auction.

Proof: According to (15), we have

$$\begin{aligned}
&\Delta_1(\Theta(t)) + V^m b_c^m(t) + \sum_{i\in\mathcal{U}^m} V^m \beta_i^m d_i^m(t) \\
&\quad \leq B^m + V^m b_c^m(t) + \sum_{i\in\mathcal{U}^m} V^m \beta_i^m d_i^m(t) \\
&\quad + \sum_{i\in\mathcal{U}^m} Q_i^m(t)(A_i^m(t) - R_{ic}^m(t) - R_i^m(t) - d_i^m(t)) \\
&\quad + \sum_{i\in\mathcal{U}^m} Z_i^m(t)(\epsilon_i^m 1_{\{Q_i^m(t)>0\}} - R_{ic}^m(t) - R_i^m(t) - d_i^m(t)).
\end{aligned} \tag{31}$$

Then, for any (possibly randomized) feasible schedule, we have

$$\begin{aligned}
&\min\{\Delta_1(\Theta(t)) - V^m \phi_c^m(t)\} \leq B^m + V^m \phi_c^{m*}(t) \\
&\quad + \sum_{i\in\mathcal{U}^m} Q_i^m(t)(A_i^m(t) - R_{ic}^{m*}(t) - R_i^{m*}(t) - d_i^{m*}(t)) \\
&\quad + \sum_{i\in\mathcal{U}^m} Z_i^m(t)(\epsilon_i^m 1_{\{Q_i^m(t)>0\}} - R_{ic}^{m*}(t) \\
&\quad - R_i^{m*}(t) - d_i^{m*}(t))
\end{aligned} \tag{32}$$

where $R_{ic}^{m*}(t)$, $R_i^{m*}(t)$, and $d_i^{m*}(t)$ are the terms corresponding to the feasible schedule. Now, we consider a randomized scheduling policy that achieves the following for each application $i \in \mathcal{U}^m$:

$$\mathbb{E}\{\phi_c^{m*}(t)\} = \{\phi_c^m(t)\}^{\text{opt}} \tag{33}$$

$$\mathbb{E}\{A_i^m(t) - R_{ic}^{m*}(t) - R_i^{m*}(t) - d_i^{m*}(t)\} \leq 0 \tag{34}$$

$$\mathbb{E}\{\epsilon_i^m 1_{\{Q_i^m(t)>0\}} - R_{ic}^{m*}(t) - R_i^{m*}(t) - d_i^{m*}(t)\} \leq 0 \tag{35}$$

where $\{\phi_c^m(t)\}^{\text{opt}}$ is the maximum utility BS m can achieve in a stable system, and (34) and (35) stabilize the queues.

As the LMWA algorithm minimizes (32), we have

$$\begin{aligned}
&\mathbb{E}\{\Delta_1(\Theta(t)) - V^m \phi_c^m(t)|t\} \leq B^m - V^m\{\phi_c^m(t)\}^{\text{opt}} \\
&\quad + \mathbb{E}\left\{\sum_{i\in\mathcal{U}^m} Q_i^m(t)(A_i^m(t) - R_{ic}^{m*}(t) - R_i^{m*}(t) - d_i^{m*}(t))\right\} \\
&\quad + \mathbb{E}\left\{\sum_{i\in\mathcal{U}^m} Z_i^m(t)(\epsilon_i^m 1_{\{Q_i^m(t)>0\}} - R_{ic}^{m*}(t) - R_i^{m*}(t)\right. \\
&\quad \left. - d_i^{m*}(t))\right\} \leq B^m - V^m\{\phi_c^m(t)\}^{\text{opt}}
\end{aligned}$$

where

$$\mathbb{E}\left\{\sum_{i\in\mathcal{U}^m} Q_i^m(t)(A_i^m(t) - R_{ic}^{m*}(t) - R_i^{m*}(t) - d_i^{m*}(t))\right\} \leq 0$$

$$\begin{aligned}
&\mathbb{E}\left\{\sum_{i\in\mathcal{U}^m} Z_i^m(t)(\epsilon_i^m 1_{\{Q_i^m(t)>0\}} - R_{ic}^{m*}(t) - R_i^{m*}(t)\right. \\
&\quad \left. - d_i^{m*}(t))\right\} \leq 0.
\end{aligned}$$

Then, we have

$$\mathbb{E}\{\Delta_1(\Theta(t)) - V^m \phi_c^m(t)|t\} \leq B^m - V^m\{\phi_c^m(t)\}^{\text{opt}}$$

for the proposed LMWA algorithm. Notice that $\sum_{t=0}^{T-1}\mathbb{E}\{\Delta_1(\Theta(t))|t\} = \mathbb{E}\{L(\Theta(t))\} < \infty$ for a stable system. It follows that

$$\begin{aligned}
&\limsup_{t\to\infty} \frac{1}{T}\sum_{t=0}^{T-1}\mathbb{E}\{\Delta_1(\Theta(t))|t\} - \limsup_{t\to\infty}\frac{V^m}{T}\sum_{k=0}^{T-1}\mathbb{E}\{\phi_c^m(t)\} \\
&\quad = 0 - \limsup_{t\to\infty}\frac{V^m}{T}\sum_{k=0}^{T-1}\mathbb{E}\{\phi_c^m(t)\} \\
&\quad \leq B^m - V^m\{\phi_c^m(t)\}^{\text{opt}}.
\end{aligned}$$

Then, we conclude that Theorem 3 holds true. ■

It follows that with LMWA, each BS can achieve an average utility with a gap of B^m/V^m from the optimal average utility.

Theorem 4 (Social Welfare Maximization or Weighted Dropping Minimization): If $V^m \doteq V$ is a constant for all BSs, and the compound process $\{A_i^m(t), e_i^m(t)\}$ is i.i.d. over frames, for BS $m \in S_c^{m^*}(t)$ and UE $i \in \mathcal{U}^m$, then for each auction the following inequality holds true:

$$\begin{aligned}
&\sum_{m\in S_c^{m^*}(t)}\sum_{i\in\mathcal{U}^m}\mathbb{E}\{\beta_i^m d_i^m(t)\} \\
&\quad \leq \mathbb{E}\left\{\sum_{m\in S_c^{m^*}(t)}\sum_{i\in\mathcal{U}^m}[\beta_i^m d_i^m(t)]\right\}^{\text{opt}} + B/V
\end{aligned} \tag{36}$$

where $B = \sum_{m\in S_c^{m^*}(t)} B^m$, B^m is given in (16), and $\mathbb{E}\{\sum_{m\in S_c^{m^*}(t)}\sum_{i\in\mathcal{U}^m}[\beta_i^m d_i^m(t)]\}^{\text{opt}}$ is the expected minimum weighted dropping penalty that can be achieved in an auction.

Proof: As in (26), the proposed LMWA algorithm maximizes $\sum_{m\in\alpha_c^{m^*}(t)} b_c^m(t)$ in the auction part. According to (21) and Theorem 2, we have

$$\begin{aligned}
\sum_{m\in\alpha_c^{m^*}(t)} b_c^m(t) &= \sum_{m\in\alpha_c^{m^*}(t)} \tilde{b}_c^m(t) = \frac{1}{V^m}\sum_{m\in\alpha_c^{m^*}(t)} \\
&\quad \times \max\left\{\sum_{i\in\mathcal{U}^m} R_{ic}^m(t)(Q_i^m(t) + Z_i^m(t))\right\}.
\end{aligned}$$

As R_{ic}^m, $Q_i^m(t)$, and $Z_i^m(t)$ are independent among different BSs at frame t, LMWA maximizes $\sum_{m\in\alpha_c^{m^*}(t)}\sum_{i\in\mathcal{U}^m}\{R_{ic}^m(t) + R_i^m(t)\}(Q_i^m(t) + Z_i^m(t))$ in each auction, by enforcing the interference constraint. Based on Theorem 3,

we have

$$\mathbb{E}\left\{\sum_{m\in S_c^{m\,*}(t)}\sum_{i\in\mathcal{U}^m}\left[-\hat{b}_i^m(t)-\beta_i^m d_i^m(t)\right]\right\}$$
$$\geq \mathbb{E}\left\{\sum_{m\in S_c^{m\,*}(t)}\sum_{i\in\mathcal{U}^m}\left[-\hat{b}_i^m(t)-\beta_i^m d_i^m(t)\right]\right\}^{\text{opt}}-\frac{B}{V}. \tag{37}$$

Since $\sum_{m\in S_c^{m\,*}(t)}\hat{b}_i^m(t)=0$ according to the auction design, the above inequality (37) can be simplified as

$$-\sum_{m\in S_c^{m\,*}(t)}\sum_{i\in\mathcal{U}^m}\mathbb{E}\{\beta_i^m d_i^m(t)\}$$
$$\geq \mathbb{E}\left\{\sum_{m\in S_c^{m\,*}(t)}\sum_{i\in\mathcal{U}^m}\left[-\beta_i^m d_i^m(t)\right]\right\}^{\text{opt}}-\frac{B}{V}. \tag{38}$$

Thus, we conclude that (36) holds true. ■

In the special case with $\beta_i^m=\beta$ for all UEs and BSs involved in the auction, we have

$$\sum_{m\in S_c^{m\,*}(t)}\sum_{i\in\mathcal{U}^m}\mathbb{E}\{d_i^m(t)\}-\mathbb{E}\left\{\sum_{m\in S_c^{m\,*}(t)}\sum_{i\in\mathcal{U}^m}[d_i^m(t)]\right\}^{\text{opt}}$$
$$\leq B/(V\beta). \tag{39}$$

In this special case, it can be seen that the optimality gap for packet drop rate is proportional to $1/(V\beta)$. If $V\beta\to\infty$, the proposed LMWA algorithm can achieve the minimum drop rate in each auction. Furthermore, according to Theorem 1, the maximum delay is proportional to $V\beta$. There is clearly a tradeoff between packet drop and delay here.

VI. Simulation Validation

In this section, we use MATLAB simulations to evaluate the performance of the proposed algorithms with a typical outdoor small cell scenario. We used two simple schemes as benchmarks: 1) single winner that selects only one winner during an auction and 2) random access that randomly selects a winner during the bidding stage. The configuration of simulation parameters is based on [31], as summarized in Table I. Specifically, we set $\epsilon_i^m=8$ and $(d_i^m)^{\max}=8$ for all UEs, which are both normalized to the time scale of 1 s. We also set $\beta_i^m=\beta$ to better reveal its impact. The network area of 200×200 m^2 is covered with LTE macrocells in licensed bands and the average data rate provided by the LTE Macro cell is 4 MB/s for all UES. Six LTE-unlicensed BSs are deployed in the area, each serving ten UEs. Two channels on the LTE-unlicensed band are available.

We adopt a truncated Poisson traffic model in the simulations, which is a Poisson process with arrival rate λ and the maximum number of arrival packets is bounded with 2λ. The packet size is 2 MB (a file in the application and can be separated two smaller packets to fit the MAC layer packet size [7]). In this paper, we focus on the coordination among LTE-unlicensed users, and therefore, the evaluation of Wi-Fi performance is not included.

TABLE I
Simulation Parameters

Parameter	Scenario for Outdoor Small Cells
Carrier frequency	5 GHz
Bandwidth	20 MHz
Number of RBs	100
Frame duration	10 ms
BS height	10 m, below rooftop
Mobile device height	1.5 m
Antenna configuration	2Tx-2Rx
Transmit power	30 dBm
UE noise figure	7 dB
Channel model	UMi outdoor
BS antenna configuration	Omnidirectional, 0 dBi gain
UE antenna gain	0 dBi
Thermal noise	−174 dBm/Hz
LBT threshold	−85 dBm
Traffic model	Poisson
Packet size	2 MB

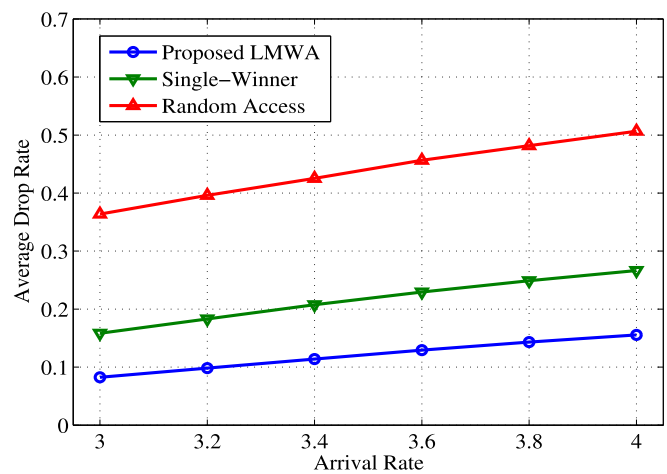

Fig. 3. Packet arrival rate versus average drop rate. $V\beta=20$ for all UEs.

We adopt the *COST 231 Hata* model for metropolitan areas in the simulations [32], as

$$L(d)=\ 46.3+33.9\log_{10}(f_c)-13.82\log_{10}(h_b)-\alpha(h_m)$$
$$+(44.9-6.55\log_{10}(h_b))\log_{10}(d)+3 \tag{40}$$

where $\alpha(h_m)=3.2(\log_{10}(11.75))^2-4.75$, f_c, h_b, and h_m are the central frequency, height of the BS, and height of the mobile device, respectively.

In Fig. 3, we present the relationship between arrival rate of packets and the average packet dropping rate. We find that the average dropping rate is increasing as the arrival rate grows. The proposed LMWA algorithm outperforms the two other schemes with a considerably smaller dropping rate. This is because that under the proposed LMWA algorithm, spectrum in unlicensed bands can be spatially reused, and the lower dropping rate is enabled by an higher throughput due to spectrum reuse. We can also see that the dropping rate of single winner is also considerably lower that of random access, which indicates that the auction enables the BS with a higher utility to win the unlicensed spectrum.

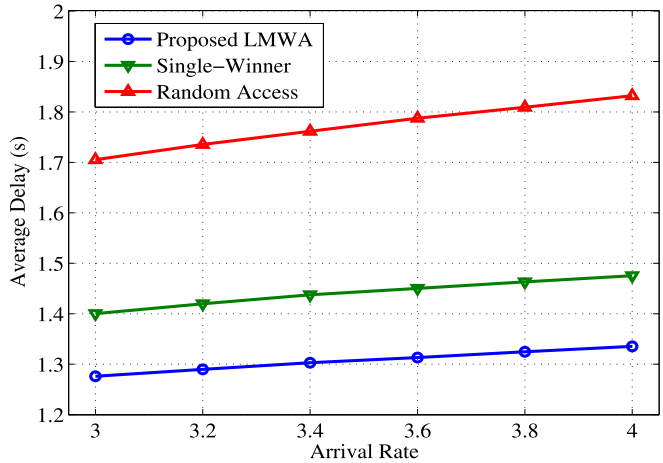

Fig. 4. Packet arrival rate versus average delay: $V\beta = 20$ for all UE.

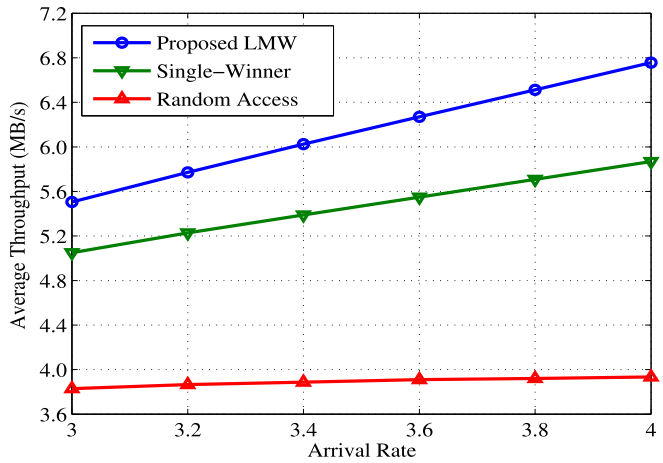

Fig. 5. Packet arrival rate versus average throughput: $V\beta = 20$ for all UE.

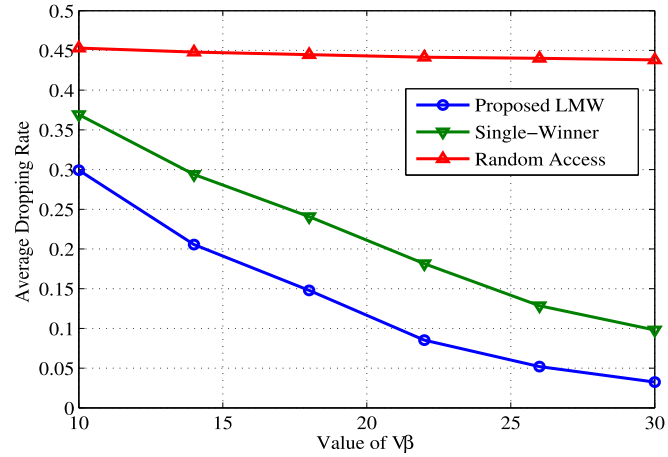

Fig. 6. $V\beta$ versus average drop rate: $A_i^m = 3.5$ for all UE.

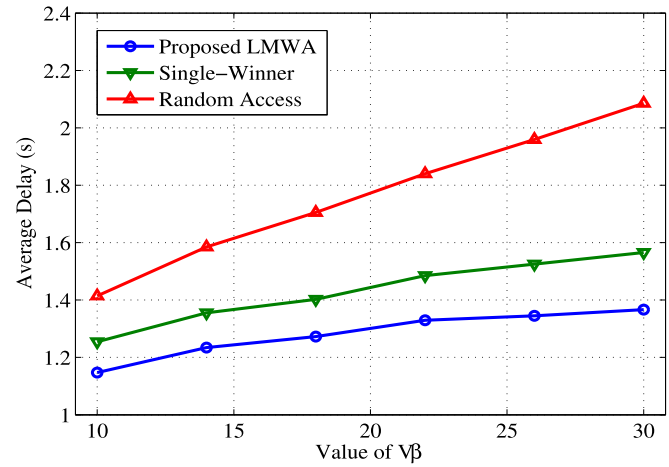

Fig. 7. $V\beta$ versus average delay: $A_i^m = 3.5$ for all UE.

In Fig. 4, we present the relationship between packet arrival rate and average queueing delay. The simulation shows that there is a linear relationship between the arrival rate and average delay, thus validating Theorem 1. The increased arrival rate do not cause a surge in delay. Hence, even if the arrival rate is really high, LMWA can still guarantee that the QoS requirement that a packet is dropped or transmitted within a limited time. As in the previous case, the proposed LMWA algorithm outperforms the two benchmarks with considerable gains, while the single winner also outperforms random access.

In Fig. 5, we present the relationship between the traffic arrival rate and the average throughput. The figure shows that throughput increases with the increasing of the arrival rate for all three algorithms, while the curve for random access is pretty flat.

In Fig. 6, we present the relationship between $V\beta$ and the average dropping rate. The simulation confirms the $O(1/V\beta)$ bound of dropping packets. For the proposed LMWA and single winner algorithm, the average dropping rate decreases as $V\beta$ grows, and the $O(1/V\beta)$ bound of dropping packets can be observed. Hence, we can choose $V\beta$ to better tradeoff between the QoS requirements on dropping rate and delay in practice. For random access, we find that the dropping rate does not decrease significantly with increased $V\beta$. This is because that the arrival rate is much higher than the provided throughput and dropping of many packets is unavoidable, even with a loosen delay requirement. Obviously, this simulation shows similar gap among the performance of the three schemes as in Figs. 3–5.

In Fig. 7, we show the relationship between $V\beta$ and average delay. The simulation confirms the bound of delay and $V\beta$ as in Theorem 1. Although Theorem 1 is about the upper bound of the maximum delay, we can still see that there is an approximately linear relationship between average delay and $V\beta$ in all the three curves, which all adopt the proposed dropping policy. In addition, the proposed algorithm outperforms single winner, and single winner outperforms random access in this simulation again.

In Fig. 8, we present the relationship between $V\beta$ and the average throughput. The simulation shows that throughput increases with increased arrival rate for all three algorithms. The

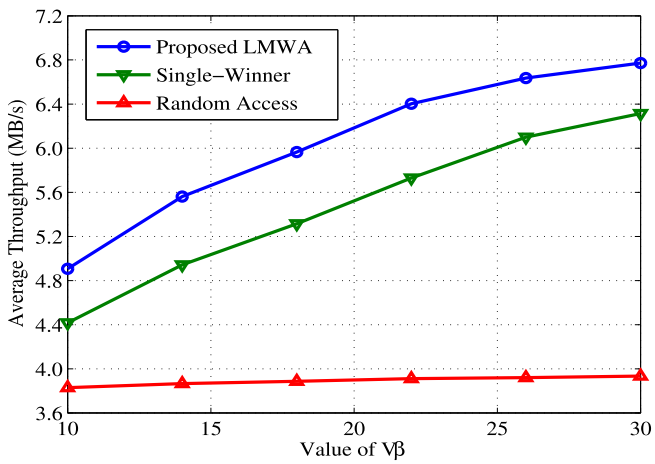

Fig. 8. $V\beta$ versus average throughput: $A_i^m = 3.5$ for all UE.

simulation shows similar gap among the performance of the three schemes as in Fig. 5.

VII. Conclusion

We studied distributed online auction for sharing unlicensed bands among LTE-unlicensed BSs to maximize the social welfare in each auction while achieving the dual goal of minimizing the expected packet dropping rate and guarantee a maximum delay. Specifically, we proposed the Lyapunov optimization based schemes to evaluate the true value of unlicensed spectrum, to allocate RBs on unlicensed bands and to decide when to drop packets based on current channel condition, queue lengths, and delay of packets. We also proposed a truthful auction mechanism to integrate the schemes, which can maximize the overall social welfare and guarantee bounded drop rate and delay. The superior performance of the proposed algorithms over two benchmark schemes was validated with simulations.

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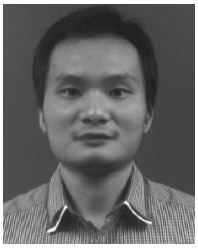

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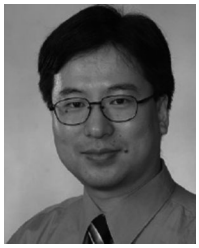

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