A Modified LBT Mechanism and Performance Enhancement for LTE-U/WiFi Co-Existence

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***Abstract*—Unlicensed spectrum, unlike its licensed counterpart, has to be shared by multiple technologies and hence the performance is heavily impacted by cross-technology interference. In this paper, we focus on the co-existence mechanism design of LTE-U and WiFi in the unlicensed spectrum. We propose a modified-LBT (M-LBT) mechanism for LTE-U coexisting with WiFi in unlicensed band. Moreover, a precoding algorithm is designed to utilize spatial resource. Meanwhile, a user selection scheme can be applied to balance fairness and efficiency of LTE-U users. Simulation results demonstrate that the M-LBT mechanism can improve the total system throughput while guaranteeing fairness between LTE-U and WiFi.**

***Index Terms*—LTE in unlicensed spectrum (LTE-U); WiFi; Co-existence**

I. Introduction

With the exponential growth of smart mobile devices, meeting the enormous traffic demand has become one of the most critical issues in today's wireless networks. Albeit its significant progress over the last decade, the Long Term Evolution (LTE) system has become increasingly limited by the crowded licensed spectrum. In order to improve the capacity, the Third Generation Partnership Project (3GPP) standard group is actively seeking for advanced solutions to boost the network capacity while continually providing better user experience to customers. New solutions such as heterogeneous and ultra-dense networks have been proposed for addressing this challenge. In addition, operators and standard bodies are considering to extend the LTE operations into the unlicensed spectrum, which is referred to as LTE in Unlicensed spectrum (LTE-U) [1]. This is an attractive choice mostly thanks to the availability of large bandwidth in the 2.4GHz and 5GHz bands [2].

In reality, WiFi technology has been widely deployed and become the most popular access technology in the aforementioned unlicensed spectrum. As a result, the LTE-U solution must be compatible with existing WiFi devices to ensure a fair sharing of the spectrum. However, unlike the traditional LTE system where macro-cell and micro-cells are managed by one operator, coordination is difficult for unlicensed networks of different WiFi stations. Due to the fundamental differences in the Physical layer (PHY) and Media Access Control (MAC) layer design between LTE and WiFi, a direct implementation of LTE may impact the opportunistic channel occupancy of co-channel WiFi, especially in some high load scenarios. In [3], an experimental analysis for indoor environment shows that the WiFi system performance would decrease rapidly in the presence of LTE-U, mainly because the LTE system is aggressive in channel access. These challenges have recently attracted much attention from academia and industry, and some analyses and solutions have been reported in the literature. In [4], the authors perform a performance evaluation of co-existence between LTE-U and Wi-Fi systems and summarize some challenges faced by different technologies. In [5], Qualcomm presents an effective channel selection policy based on interference levels. If the interference of the occupied channel exceeds a certain level, LTE-U changes to a new channel which is measured before and during the operation. Furthermore, [5] shows that with their co-existence solution, adding a neighboring LTE-U node does not affect an existing WiFi node more than adding another WiFi node. Thus they argue that LTE-U protects WiFi better than WiFi protects itself. In [6], the authors design a second-price reverse auction mechanism, which enables the LTE provider and the WiFi Access Points (APs) to effectively negotiate the operation mode. In [7], Listen Before Talk (LBT) mechanism is recommended by 3GPP as the baseline approach for downlink transmissions to guarantee a fair sharing of time resource with WiFi devices. In [8], the authors discuss the major challenges for the LTE/WiFi co-existence. They introduce the implementation regulations, principles and typical deployment scenarios of LTE-U. Despite these results, considerable efforts are still needed to seek more effective solutions. According to traditional LBT mechanism, LTE-U do not allow to access channel in the duration of WiFi transmission.

The main contributions of this paper are three-fold. Firstly, we introduce a Modified-Listen Before Talk (M-LBT) mechanism between LTE-U and WiFi systems. Secondly, based on the M-LBT mechanism, we propose a max-min SINR precoding scheme to improve system performance. Lastly, two user selection schemes are applied to balance rate and fairness among LTE-U users.

The remainder of this paper is organized as follows. The system model is described in Section II. In Section III, we describe the M-LBT mechanism between LTE-U and WiFi. In Section IV-A, we proposed a precoding scheme that utilizes

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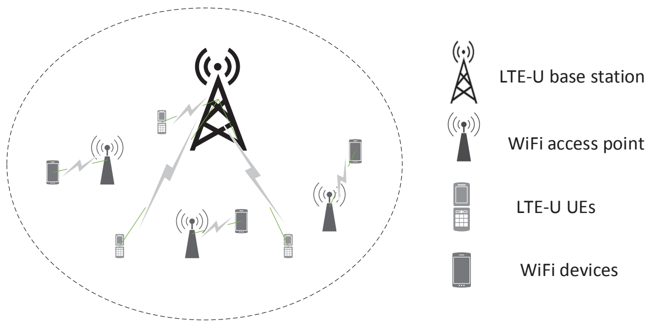

Fig. 1: Co-Existence Network of LTE-U and WiFi

the spatial resource more effectively in the co-existence phase. In Section IV-B, a selection scheme is applied to improve the cellular throughput of LTE-U. In section V, a similar method is applied in exclusive phase. In section VI, we report the simulation results and evaluate the performance of the proposed solutions. Section VII concludes this paper.

II. System Model

We consider the downlink transmission of a cellular network, as shown in Fig. 1, where a cellular BS is deployed to operate in the unlicensed band, and communicate with its set of connected cellular User Equipments (UEs) $\mathcal{B}_s$. On the same unlicensed frequency band, WiFi devices also exist and both systems need to share the spectrum. We assume that the BS is equipped with N antennas, and simultaneously serves K cellular UEs, where $K = |\mathcal{B}_s|$. For WiFi, $\mathcal{B}_w$ is used to denote the set of WiFi devices. We assume that all WiFi devices transmit with a constant power P_w. Both UEs and WiFi devices are equipped with one antenna. Without loss of generality, we assume the same symbol duration for cellular and WiFi transmissions. The signal $y_i^{\text{lte-u}} \in \mathbb{C}$ received by UE i can be expressed as:

$$\begin{aligned} y_i^{\text{lte-u}}[m] =& h_i^H w_i s_i[m] + \sum_{j=1, j\neq i}^{K} h_i^H w_j s_j[m] + \\ & \sqrt{P_w} g_{(i,l)} s_l[m] + \eta[m], \end{aligned} \tag{1}$$

where $h_i \in \mathbb{C}^{N\times 1}$ denotes the channel vector between BS and UE i, $g_{(l,i)} \in \mathbb{C}$ denotes the channel coefficient between WiFi device l and UE i, $l \in \mathcal{B}_w$ is index of the WiFi transmitting device. Vector $w_i \in \mathbb{C}^{N\times 1}$ is the precoding vector from BS to UE i, $s_i \in \mathbb{C}$ and $s_l \in \mathbb{C}$ are the unit-variance signal transmitted by BS and WiFi l, respectively. $\eta[m] \sim \mathcal{CN}(0, \sigma^2)$ represents the thermal noise. Note that the WiFi devices with traditional LBT mechanism is incompatible with other WiFi devices in term of sharing time resources. As a result, only one device is active at a time via CSMA/CA. Meanwhile, the signal $y_l^{\text{wifi}} \in \mathbb{C}$ received by WiFi device l can be expressed as

$$y_l^{\text{wifi}}[m] = \sqrt{P_w} q_{(l,j)} s_j[m] + \sum_{i=1}^{K} g_{(bs,l)}^H w_i s_i[m] + \eta[m], \tag{2}$$

where $q_{(l,j)} \in \mathbb{C}$ denotes the channel coefficient between WiFi received device l and WiFi transmitted device j, $g_{(bs,l)} \in \mathbb{C}^{N\times 1}$ denotes the channel vector between WiFi receiving device l and LTE-U BS. The resulting signal to interference plus noise ratio (SINR) $\text{sinr}_i^{\text{lte-u}}$ at UE i, is given by

$$\text{sinr}_i^{\text{lte-u}} = \frac{||h_i^H w_i||^2}{\sum_{j=1, j\neq i}^{K} ||h_j^H w_j||^2 + P_w ||g_{(i,l)}||^2 + \sigma^2}. \tag{3}$$

Furthermore, the interference caused by UEs at WiFi receiving device l can be expressed as $\sum_{i=1}^{K} ||g_{(bs,l)}^H w_i||^2$. A constraint of the total transmitting power [9] should be satisfied which can be expressed by

$$\sum_{k=1}^{K} \|w_k\|^2 \leq P_0. \tag{4}$$

III. Modified LBT

The principle of the traditional LBT mechanism is based on discontinuous transmission. If the channel is sensed as busy, the device should keep silent and sense the channel periodically in the following subframe till the channel is idle for a distributed interframe space (DIFS) duration. Therefore the interference from other UEs and WiFi devices is avoided. However, the traditional LBT mechanism is not efficient when multiple technologies co-exist, as the resources are not utilized effectively. In principle, if LTE-U can have more information of the WiFi transmission, a more efficient co-existence mechanism can be achieved.

Fortunately, we can achieve this goal by a slight modification of the transmission mechanism of WiFi. Inspired by the Request to Send/Clear to Send (RTS/CTS) mechanism [10], the transmission behavior of LTE-U BS can be made to depend on the analysis of CTS frames from WiFi devices. Furthermore, pilot information can be added to CTS/RTS frame, which can help the LTE-U BS collect WiFi channel state information (CSI) to determine the cross-technology interference. With this new information, new schemes of better spatial utilization can be applied. The proposed Modified LBT (M-LBT) co-existence mechanism is shown in Fig 2.

For WiFi devices, they do not send data frame right away but send a RTS subframe to the destination device, which responds with a CTS subframe that adds pilot information. If WiFi devices decode a RTS subframe from another device and it is not the destination of the RTS subframe, it will keep silent. For LTE-U UEs, there are two phases which are the *co-existence phase* and the *exclusive phase*. The exclusive phase is the same as the traditional LBT where BS occupies the channel exclusively for the time duration of a data frame, and acquires the CSI of each UE via pilot information. In the co-existence phase, BS acquires the CSI of WiFi via analyzing

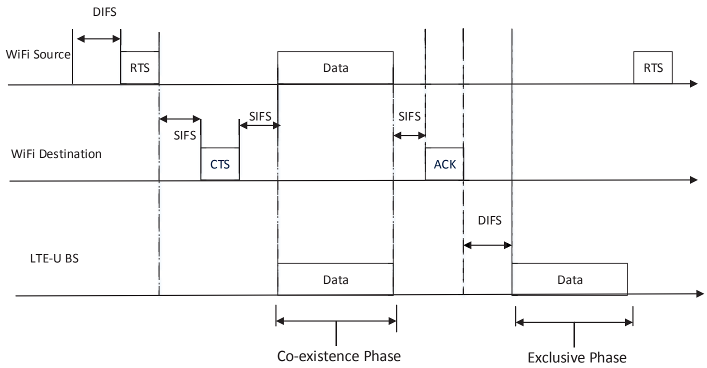

Fig. 2: M-LBT Mechanism

RTS/CTS subframes from WiFi devices. Then LTE-U BS can co-exist with WiFi by applying spatial reuse.

A fairness principle among all UEs is also considered. In the exclusive phase, BS will select a group of UEs by evaluating their average rates during a time period. We define $R_k(t)$ as the rate of UE k in during t-th time slot, which can be updated as

$$\begin{cases} \frac{1}{R_k(t)} = (1-\frac{1}{T})\frac{1}{R_k(t-1)} + \frac{\overline{R_k(t)}}{T}, & k \in \mathcal{B}_s \\ \frac{1}{R_k(t)} = (1-\frac{1}{T})\frac{1}{R_k(t-1)} & k \notin \mathcal{B}_s, \end{cases} \quad (5)$$

where T is the window size of evaluation period, and $\overline{R_k(t)}$ is the supported data rate of UE k in t-th time slot.

The procedures of M-LBT co-existence can be summarized as

1) LTE-U BS senses the channel state and CTS/RTS frame.
2) If the channel state is idle, LTE-U BS accesses the channel with an exclusive phase. Otherwise, BS accesses the channel with a co-existence phase.
   - In the exclusive phase, BS acquires channel vector h of BS to all UEs, and serves a selected group of UEs with low rate.
   - In the co-existence phase, BS acquires channel vector $g_{(bs,l)}$ of BS to WiFi receiving device l. Then BS co-exists with WiFi stations using spatial reuse.
3) Update the rate of UEs with Eq. 5.
4) Back to step 1 and loop.

We also assume that unlicensed LTE-U control messages are sent via the licensed spectrum. This means that Quality of Service (QoS) of LTE-U can be ensured.

IV. The Co-Existence Phase

In this section, we focus on how LTE-U co-exists with WiFi in the same band. The LTE-U BS must guarantee the performance of the WiFi receiver. One way to address this issue is to enforce a power constraint, which can be expressed as

$$\sum_{k=1}^{K} \|w_k g_{(bs,l)}^H\|^2 \leq P_{\text{thr}}, \quad (6)$$

where P_{thr} is the threshold for the aggregated received power at the WiFi device from LTE-U BS. WiFi data frame can be transmitted successfully if the interference power is below P_{thr}.

A. Max-Min SINR Precoding

The performance of a system usually can be quantified by the SINR, in particular the worst-case SINR. Therefore, we intend to obtain the optimal precoding that maximizes the SINRs. This optimal problem can be formulated as

$$\begin{aligned} \max_{W} \min_{i \in \mathcal{B}_s} \quad & \frac{||h_i^H w_i||^2}{\sum_{j=1,j\neq i}^{K} |||h_i^H w_j||^2 + N_i^2} \\ \text{s.t.} \quad & \sum_{k=1}^{K} \|w_k\|^2 \leq P_0 \\ & \sum_{k=1}^{K} \|w_k g_{(bs,l)}^H\|^2 \leq P_{\text{thr}} \end{aligned} \quad (7)$$

where $N_i^2 = P_w||g_{(i,l)}||^2 + \sigma^2$ is the interference from WiFi plus the noise. It is worth noting that problem (7) is a quasiconvex problem [11], which can be solved by finding a feasible solution of problem (8). The bisection method [12] can be applied to (8). The overall procedure is summarized in Algorithm 1.

In our proposed algorithm, SINR_{min} and SINR_{max} define a range of relevant SINRs for a specific application, and κ is the accuracy of the optimal solution. Notice that the constraints of the problem (8) can be expressed in the standard semidefinite form [13]. We now recast the constraints in standard form. Rearranging the constraints and using matrix notations, the constraints yield

$$(1+\frac{1}{\gamma_0})||h_i w_i^H||^2 \geq || \begin{bmatrix} W^H h_i \\ N_i \end{bmatrix} ||^2 \quad i \in \mathcal{B}_s. \quad (9)$$

Since $||w_i^H h_i|| \geq 0$ for all $i \in \mathcal{B}_s$, we can take the square root of both sides, resulting in

$$\sqrt{1+\frac{1}{\gamma_0}}||w_i^H h_i|| \geq || \begin{bmatrix} W^H h_i \\ N_i \end{bmatrix} || \quad i \in \mathcal{B}_s, \quad (10)$$

Algorithm 1 The SINR optimal algorithm

Initialization: Set $\gamma_{\text{min}} = \text{SINR}_{\text{min}}$, $\gamma_{\text{max}} = \text{SINR}_{\text{max}}$

repeat
  Let $\gamma_0 = (\gamma_{\text{max}} + \gamma_{\text{min}})/2$
  Solve the following feasibility problem

$$\begin{aligned} \text{Find} \quad & W \\ \text{s.t.} \quad & \frac{||h_i^H w_i||^2}{\sum_{j=1,j\neq i}^{K} ||h_i^H w_j||^2 + N_i^2} \geq \gamma_0 \qquad i \in \mathcal{B}_s \\ & \sum_{k=1}^{K} \|w_k\|^2 \leq P_0 \\ & \sum_{k=1}^{K} \|w_k^H g_{(bs,l)}\|^2 \leq P_{\text{thr}}, \end{aligned} \tag{8}$$

  if the problem is feasible, **then**
    $\gamma_{\text{min}} = \gamma_0$
  else
    $\gamma_{\text{max}} = \gamma_0$
  end if
until $(\gamma_{\text{max}} - \gamma_{\text{min}}) < \kappa$

Return: a feasible solution W^* from problem (8)

which can be written in a semidefinite form

$$\begin{bmatrix} \sqrt{1+\frac{1}{\gamma_0}} w_i^H h_i & [W^H h_i N_i] \\ \begin{bmatrix} W^H h_i \\ N_i \end{bmatrix} & \sqrt{1+\frac{1}{\gamma_0}} w_i^H h_i \mathbf{I} \end{bmatrix} \succeq 0 \quad i \in \mathcal{B}_s, \tag{11}$$

where the notation $\succeq$ denotes the positive semidefinite generalized inequality. Similarly, the other constraints can be reformulated using the vector operator as $||\text{vec}(W)|| \leq \sqrt{P_0}$ and $||\text{vec}(W^H g_{(bs,l)})|| \leq \sqrt{P_{\text{thr}}}$, which are equivalent to the semidefinite form

$$\begin{cases} \begin{bmatrix} \sqrt{P_0} & \text{vec}^H(W) \\ \text{vec}(W) & \sqrt{P_0}\mathbf{I} \end{bmatrix} \succeq 0 \\ \begin{bmatrix} \sqrt{P_{\text{thr}}} & \text{vec}(W^H g_{(bs,l)}) \\ \text{vec}^H(W^H g_{(bs,l)}) & \sqrt{P_{\text{thr}}}\mathbf{I} \end{bmatrix} \succeq 0, \end{cases} \tag{12}$$

where operator $\text{vec}(\mathbf{X})$ represents stacking the elements of matrix $\mathbf{X}$ in one long column vector.

Thus, the problem (8) can be reformulated as the following semidefinite program (SDP)

$$\begin{aligned} \text{find} \quad & W \\ \text{s.t.} \quad & \begin{bmatrix} \sqrt{1+\frac{1}{\gamma_0}} w_i^H h_i & [W^H h_i N_i] \\ \begin{bmatrix} W^H h_i \\ N_i \end{bmatrix} & \sqrt{1+\frac{1}{\gamma_0}} w_i^H h_i \mathbf{I} \end{bmatrix} \succeq 0 \quad i \in \mathcal{B}_s \\ & \begin{bmatrix} \sqrt{P_0} & \text{vec}^H(W) \\ \text{vec}(W) & \sqrt{P_0}\mathbf{I} \end{bmatrix} \succeq 0 \\ & \begin{bmatrix} \sqrt{P_{\text{thr}}} & \text{vec}(W^H g_{(bs,l)}) \\ \text{vec}^H(W^H g_{(bs,l)}) & \sqrt{P_{\text{thr}}}\mathbf{I} \end{bmatrix} \succeq 0, \end{aligned} \tag{13}$$

Therefore, many standard packages [14] can be used to obtain the feasible solution. We make the sinr value rise if the feasible solution exists. Otherwise we make sinr value down. After enough iteration count, we can find a feasible solution which is the optimal solution original problem (7). As a result, a optimal precoding matrix is obtained by our algorithm.

B. UEs Selection

In the previous design, we do not consider the interference from WiFi devices. LTE-U BS should protect WiFi transmission with low interference. However, WiFi devices may not protect transmission of LTE-U UEs. Hence, cellular downlink rate may degrade as a result of WiFi devices. This means that the coverage area of BS may be limited, and only UEs which sufficiently close to BS or away from WiFi transmitting device should be scheduled in the unlicensed band. Therefore, an UEs selection scheme is applied to address this issue. Firstly, UEs can report their SINRs information to BS via licensed band. So BS can determine which UEs can be selected. Then, a pre-selection rule is applied that BS selects part of UEs with low SINRs as candidate UEs. Finally, a greedy algorithm is applied to select UEs from candidate UEs for better cellular throughput. Detailed implementation procedures can be summarized in Algorithm 2. Note that $\mathcal{B}_c$ is the candidate set of UEs in cellular.

Algorithm 2 UE selection in the co-existence phase

Initialization: Set $\mathcal{B}_s = \emptyset$, $\mathcal{B}_c = \emptyset$

Select a part of UEs as candidate users $\mathcal{B}_c$ from $\mathcal{B}$ with low SINRs, where $|\mathcal{B}_c| = \min[2N, K]$
repeat
  for $i \in \mathcal{B}_c \backslash \mathcal{B}_s$ **do**
    Select potential user i
    Update precoder matrix W of all selected users
    Compute system sum rate R_{sum}
  end for
  Add one new user which make sum rate maximum
  Update $\mathcal{B}_s$
until Sum rate does not increase any more

Return: $\mathcal{B}_s$, W

V. The Exclusive Phase

Similar to the traditional LBT mechanism, LTE-U transmission will occupy unlicensed band exclusively in the exclusive phase. In this case, the precoding matrix can be designed without considering WiFi devices. The new optimization problem can be formulated as

$$\begin{aligned} \max_{W} \min_{i \in \mathcal{B}_s} \quad & \frac{||h_i^H w_i||^2}{\sum_{j=1,j\neq i}^{K} ||h_i^H w_j||^2 + \sigma^2} \\ \text{s.t.} \quad & \sum_{k=1}^{K} \|w_k\|^2 \leq P_0. \end{aligned} \tag{14}$$

TABLE I: Parameter Configuration

Parameter	Description
BS tx power	30dBm
WiFi tx power	24dBm
Number of WiFi	6
Number of UE	30
Carrier frequency	5.15GHz
Cell radius	30m
Threshold P_{thr}	-62dBm
System bandwidth	20MHz
Thermal noise	-174 dBm/Hz spectral density
Path loss	3GPP RRC [15]

It is easy to see that the optimization problem (14) is a weakened form of problem (7). As a result, the optimal precoding matrix can be solved with Algorithm 2.

Moreover, the UE selection scheme can be used to balance rates and fairness. On one hand, an excess number of served UEs may degrade the cellular rate. On the other hand, UEs which are rarely selected in the co-existence phase need more access opportunity to guarantee fairness. Due to these these considerations, a different pre-selection rule is applied before a greedy selection algorithm. The pre-selection rule is that BS will select a group of UEs with low average rate. Then the same greedy selection algorithm like the co-existence phase is applied in the exclusive phase. Detailed implementation procedures can be found in Algorithm 3.

Algorithm 3 UE selection in the exclusive phase

Initialization: Set $\mathcal{B}_s = \emptyset$, $\mathcal{B}_c = \emptyset$

1: Select a part of UEs as candidate users $\mathcal{B}_c$ from$\mathcal{B}$ with low rate, where $|\mathcal{B}_c| = \min[2N, K]$
2: **repeat**
3: **for** $i \in \mathcal{B}_c \backslash \mathcal{B}_s$ **do**
4: Select potential user i
5: Update precoder matrix W of all selected users
6: Compute system sum rate R_{sum}
7: **end for**
8: Add one new user which make sum rate maximum
9: Update $\mathcal{B}_s$
10: **until** Sum rate does not increase any more

Return: $\mathcal{B}_s$, W

VI. Simulation Resluts

In this section, different simulation results are provided to demonstrate the performance of the proposed solutions in a range of settings. We perform simulations according to the scenario and methodologies described in Table I. The transmission rate of WiFi is assumed to be 30 Mbps regardless of packet collisions.

For evaluation, we compare the performance of the traditional LBT mechanism and the M-LBT mechanism in unlicensed band under different conditions. Fig. 3 shows the average data rates of the BS and each WiFi device under various number of BS antennas. The following observations can be made from Fig. 3. First, M-LBT mechanism will not degrade the performance of WiFi comparing to traditional LBT mechanism. The WiFi devices rates stay constant because both traditional LBT and M-LBT mechanisms attempt to eliminate the effect of interference. In the traditional LBT mechanism, different devices are divided into different time slots. In the M-LBT mechanism, different devices are separated into different spatial directions. Second, the number of BS antennas is an important parameter for the LTE-U BS rate in both M-LBT and traditional LBT. The rate of BS increases with the number of antennas in both mechanisms. The reason is that spatial resource is utilized more effectively with an increasing number of antennas.

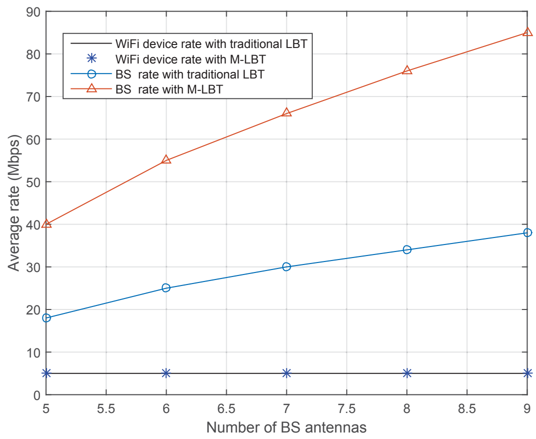

Fig. 3: Performance evaluation with different number of antennas.

VII. Conclusion

In this paper, we consider a co-existence downlink cellular system, where LTE-U and WiFi devices operate in the same unlicensed spectrum. We have introduced the M-LBT mechanism, which improves upon the traditional LBT and fits better with LTE-U/WiFi co-existence. Furthermore, a max-min SINR precoding schemes are applied for better system rate. User selection schemes are applied for different operating phases to balance rate and fairness. Simulation results show that our proposed M-LBT mechanism is better than the traditional LBT mechanism. In our future work, we plan to extend the performance study by considering multi-cellulars LTE-U systems with WiFi networks operating in multiple unlicensed channels.

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