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Unlicensed Spectra Fusion and Interference Coordination for LTE Systems

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***Abstract*—Unlicensed spectra fusion technology for LTE holds the promise of alleviating the licensed spectra scarcity and enhancing capacity. It allows LTE to effectively utilize the unlicensed spectra distributed over high frequency bands with significant different propagation characteristics from its licensed spectra. However, the interference caused by other systems over unlicensed spectra, particularly the public unlicensed spectra, is viewed as the most serious challenge. In this paper, aiming to guarantee the feasibility in existing LTE systems, we design a novel unlicensed spectra fusion scheme based on the popular standard TDD-LTE systems. To mitigate the interference, we develop an interference coordination scheme which is carried out in two stages: screen the available unlicensed channels for every UE, and allocate unlicensed spectra based on Hungarian algorithm. We have conducted extensive simulation study and demonstrate that our proposed scheme can handle interference coordination effectively and enhance throughput significantly.**

***Index Terms*—Unlicensed spectra fusion, Interference coordination, resource allocation, throughput maximization.**

I. Introduction

Undoubtedly spectrum extension is a straightforward approach for enhancing wireless system capacity. However, radio spectrum is a precious and scarce natural resource and is most often regulated through licensing. Therefore, it is hard for operators to obtain more licensed spectra. Despite spectrum scarcity, various experiments reported that the current fixed spectrum allocation policy has resulted in severely low spectrum utilization in both time and space, even within spectrum-scarce urban areas [1]. To address this issue, US Federal Communication Commission (FCC) published a report prepared by the Spectrum-Policy Task Force, and relaxed the ruling of license usage, stating that "In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access [2]". Thus, in this paper, we focus on the unlicensed spectra fusion mechanism design for LTE systems to enable the use of unlicensed spectra to enhance capacity while guaranteeing communication quality. To avoid the violation of the radio regulation policy for the licensed bands of other systems, we focus on the use of the free public unlicensed spectra, e.g., the ISM bands (2.420-2.4835GHz, 5.725-5.875GHz, 24-24.25GHz, etc in China), and investigate the feasibility of the unlicensed spectra fusion technology for LTE systems.

For engineering implementation, reference [3] designs a cognitive pilot channel (CPC) based backward-compatible network access scheme for LTE-CR to facilitate the application of cognitive radio (CR) in LTE systems. Besides the system procedures related to the initialization access designed in [3], a chain of system procedures, performed after the initialization access, about signal transmission and communication quality maintenance, also referred to as unlicensed spectra fusion, should be designed as well. Haykin [4] puts forward a basic cognitive design for CR, which contains three tasks: radio-status analysis, channel identification and dynamic spectrum management. The first two are carried out at a receiver, and the last one is carried out at a transmitter. Unfortunately, this design procedure could only be implemented in CR, not with LTE because of two main reasons: i) LTE cannot employ the interference strength, so-called interference temperature in CR, but Signal-to-Interference plus Noise Ratio (SINR), as the metric of channel status; ii) Due to the limitation of UE capacity, the dynamic spectrum management must be performed by eNB no matter whether it is the transmitter or receiver, and thus the asymmetric procedure of downlink and uplink should be redesigned to utilize the unlicensed spectra in LTE. To solve these problems, our first contribution in this paper is to address the unlicensed spectra fusion based on the standardized TDD-LTE techniques to ensure its feasibility in LTE. Two main reasons inspire us to adopt the TDD-LTE as the fundamental technologies to perform redesign. First, the system design for TDD-LTE based unlicensed spectra fusion is more challenging than that based on FDD-LTE due to higher system complexity of TDD-LTE. Particularly, as for the system procedures related to the sub-frame distribution, the design for TDD-LTE is much more complex than that for FDD-LTE. Second, most system design procedures for TDD-LTE, which are not related to the sub-frame distribution, can be extended to FDD-LTE, such as physical channel, physical-transport-logical channel mapping, and unlicensed channel-state identification.

According to [5], communication over the public unlicensed spectra, which is free of charge and licensing suffers from interference of other systems whose strength varies in both time and frequency. Obviously, the radio environmental instability makes interference coordination extremely difficult when the unlicensed spectra fusion is deployed in LTE. As for the interference coordination of spectrum sharing, there are many schemes developed for CR so far, which can be classified into two main types according to the way a secondary user accesses the unlicensed spectra. The first one is the opportunistic spectrum access (OSA), also known as the interweaving scheme, under which a secondary user accesses a frequency band only when it is detected not being used by primary users [6]. The second type is the spectrum sharing (SS), also known as the underlaying scheme, under which secondary users coexist with the primary users who are protected from harmful interference [7][8]. There is also a hybrid approach aiming to increase the throughput of the aforementioned two schemes, in which secondary users initially sense a frequency band (as OSA) and then adapt their transmit power, based on the outcome of the spectrum sensing, to avoid causing harmful interference (as SS) [9∼11]. Unfortunately, these schemes for CR are not suitable for LTE that attempts to access the public unlicensed spectra because here there is no distinction among users from LTE and other systems and all of them have the equal priority. In other words, no system has the obligation to make a concession to avoid interference to other systems.

Hence, for interference coordination in public spectra, it has been suggested that multiple systems should cooperate to minimize the interference impact by choosing appropriate power levels and frequency bands [12][13]. This approach may be feasible when different systems are jointly designed with a common goal, or complying with some common agreements. Unfortunately, in a public unlicensed spectra scenario where regulations are more relaxed and systems may compete with each other to gain access to the shared medium, the cooperation between two different systems, such as LTE and 802.11, is hard to achieve. Non-cooperative schemes for the public spectra sharing could be accomplished by means of power control in which systems adjust their transmit power according to the severity level of interference already experienced themselves [14][15]. However, despite no enforced spectrum rules about the upper limit of power over unlicensed bands stated by FCC or other organizations [16], all wireless devices still strictly comply with a maximum power constraint practically. Evidently, it is impossible for LTE to unboundedly raise its power against serious interference.

There is no doubt that the interference from other unlicensed systems is the greatest challenge for LTE over unlicensed spectra under non-cooperative situation. It is notable that, normally, unlicensed systems have small coverage and may cause local interference impact on LTE. In other words, users at different locations experience different channel conditions, a poor channel for one user may be a good channel for another. Furthermore, for any unlicensed channel, LTE system may find a UE which has the desirable channel condition. This is especially true in macro/micro cell environment in LTE systems with large coverage and plenty of UEs. Thus, a judicious unlicensed channel allocation can potentially facilitate the system to implement effective interference coordination over unlicensed spectra. From the discussion above, we have also exploited a computationally efficient unlicensed channel allocation scheme to achieve the functionalities of both interference coordination and throughput maximization under the equal power allocation for all allocated channels. For better interference coordination, the preliminary interference assessment should be done in the unlicensed channel-state identification before performing channel allocation that screens available channels for every UE from all unlicensed channels to ensure that each allocated channel meets the basic reliability requirement.

The rest of paper is organized as follows. In Section II, we design the unlicensed spectra fusion scheme based on the TDD-LTE standard. As the fundamental component of this procedure to realize interference coordination and throughput maximization, the unlicensed channel allocation algorithm is presented in Section III. The analytical model is developed to assess the performance in Section IV and simulation studies are carried out in Section V. Finally, Section VI concludes the paper.

II. Unlicensed Spectra Fusion

To better elaborate our design, we will focus on TDD-LTE systems and present the fusion procedures over unlicensed spectra. Due to the limited capability of UE, the procedures for downlink and uplink are naturally asymmetric, and both consist of five steps as shown in Fig.1 and Fig.2, respectively. In this section, we present these five steps and their mutual relationships in detail:

Step 1: Detection of the SINR over the Unlicensed Spectra

As it is well-known, the periodic detection of SINR is the primary approach to estimate channel quality used for air interface and mobility management in LTE [35]. For implementability, we adopt the same way to sense

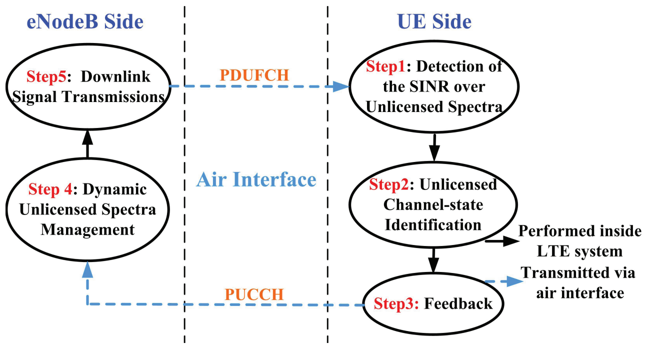

Fig. 1. Downlink unlicensed spectra fusion

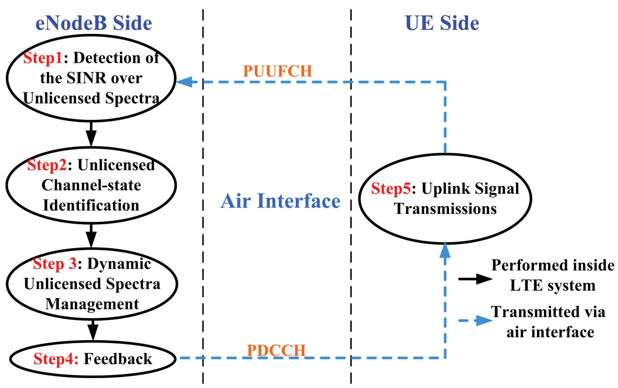

Fig. 2. Uplink unlicensed spectra fusion

the unlicensed spectra under the lack of cooperation in heterogeneous networks. For management tractability and consistency with LTE, channel partition on unlicensed spectra is necessary. We hereby define a novel dedicated channel for unlicensed spectra as Physical Downlink/Uplink Unlicensed Frequency Channel (PDUFCH/PUUFCH). These channels are configured with one Physical Resource Block (PRB) and one sub-frame (1ms) in frequency and time domain separately, both of which could rerun the resource allocation [18], described as in Fig.3. Moreover, to deal with the instability, the unlicensed channel should only support traffic data transmissions, without handling any control information for better radio channel environment, reliability and stability. As a result, there should be only PDUFCH and PUUFCH distributed on unlicensed bands without any other channels.

To perform the frequency-selective scheduling on unlicensed spectra, the SINR of all unlicensed channels on each radio path between eNB and all UEs should be obtained. For consistency, we adopt the same method as in LTE to estimate the channel-state that is needed by the receiver for detection of the Reference Signal (RS) within the channel. The SINR of PDUFCH could be obtained by detecting Common Reference Signal (CRS) [19], and Sounding Reference Signals (SRS)

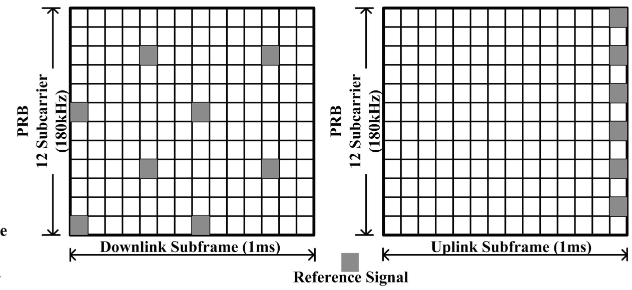

Fig. 3. PDUFCH and PUUFCH

could be used for PUUFCH [20], both of them being full-bandwidth RS. To avoid collision, the SRS of multiple UEs could employ the method of frequency or code division multiplexing (FDM/CDM) simultaneously. In addition, the distribution density of RSs, determined by coherence time and coherence bandwidth [21], is critical for channel estimation because the excessive denseness degrades the data efficiency and the excessive dispersal leads to inaccuracy. Fig.3 shows the RS distribution presented in LTE specification [18] that is applicable to frequency bands around or below 5GHz, but unapplicable to higher frequency bands. For example, with 25GHz, according to the parameters given in Spatial Channel Model and International Telecommunication Union [22$\sim$24], the coherence bandwidth is 770kHz, and the coherence times of downlink and uplink are 0.36ms and 0.18ms, respectively, with Doppler shift of uplink doubling that for downlink. Thus, in terms of higher frequency bands, such as millimeter wave bands above 30GHz, the RS distribution in frequency domain needs denser than that shown in Fig.3 in order to guarantee accuracy.

Unfortunately, the channel sensing granularity of CSMA/CA based systems, like WiFi, might be shorter than the interval between two RSs of LTE. The impact of this fact is that CSMA/CA based systems may access the unlicensed spectra which are being occupied by LTE but no data, while only RSs are transmitting on them. For example, in Fig.3, the interval between CRSs is 142μs or 213μs (two or three symbol times). Hence, there would exist the 142μs or 213μs silence time over an unlicensed channel with only CRSs transmission for LTE. Whereas, according to the specifications of 802.11n [36], the sensing time of 802.11n is from 34μs to 9241μs (from DIFS to DIFS+CWmax). If a 802.11n device begins to detect the channel after a CRS finishing transmission and the sensing time is shorter than the silence time, it would consider this channel to be idle and access it. In order to shun this negative impact, LTE should arrange data delivery on each unlicensed channel used by it, unless the quality of a channel is too poor to support the lowest rate transmission, like BPSK.

In particular, the corresponding physical-transport-logical channel mapping should be redesigned, as presented in Fig.4 and Fig.5 [25]. We redefine a new transport channel, namely Downlink/Uplink Unlicensed Frequency Channel (DL-UFCH/ UL-UFCH), which merely takes the data from Dedicated Traffic Channel (DTCH) and deliver it to PDUFCH/PUUFCH only. Accordingly, the unlicensed physical channels only carry the data from DL-UFCH/UL-UFCH. Moreover, it should be noted that an unlicensed channel is not suitable for supporting delay-sensitive applications because transmission delay may be unpredictable due to uncontrollable strong interference. Another consideration is that licensed and unlicensed spectra, which may be separated significantly further apart in frequency domain with significantly different propagation characteristics, should be configured with different Link Adaptation Techniques (LAT) [17][26]. For instance, higher transmit power is allocated to higher unlicensed bands to cope with higher propagation loss, with different coherence bandwidth and time to adapt to different modulation and coding scheme (MCS) at a proper granularity.

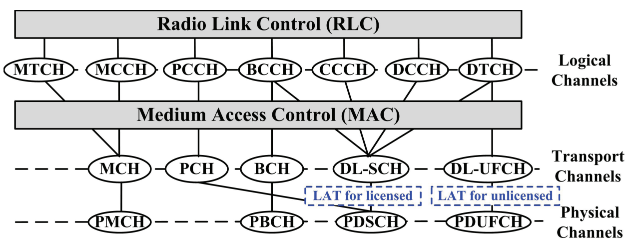

Fig. 4. Downlink physical-transport-logical channel mapping

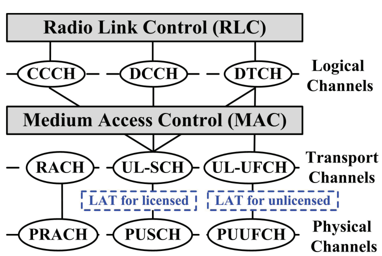

Fig. 5. Uplink physical-transport-logical channel mapping

Step 2: Unlicensed channel-state identification

There are two main tasks in this step. The first task to make LTE complete the preliminary interference coordination is to screen the available channel for every UE from all unlicensed channels to ensure that every UE could be assigned with a channel to meet the basic reliability requirement. Suppose $SINR_{ij}$, obtained in Step 1, denote the SINR value of PDUFCH *j* detected by UE *i* in the downlink or that of PUUFCH *j* detected by eNB from UE *i* in the uplink. The basic communication reliability is assured by choosing a channel with the SINR margin Γ large enough, as a design parameter, under operating conditions all the time. If $SINR_{ij} > \Gamma$, channel *j* is viewed as being available and a candidate potentially allocated to UE *i* in the subsequent channel allocation.

The second task is to convert and simplify the SINR values to the brief channel-state information to alleviate the overhead of feedback and information processing. Like Channel Quality Indication (CQI) employed in LTE, our proposed channel allocation algorithm seeks a strategy for the maximum throughput. We take channel capacity as the channel-state information, defined as Channel Capacity Indication (CCI) given below:

$$cci_{ij} = \begin{cases} round\left[B_c \log_2\left(1+10^{SINR_{ij}/10}\right)\right] & \text{if} SINR_{ij} > \Gamma \\ 0 & \text{if} SINR_{ij} \leq \Gamma \end{cases} \tag{1}$$

where cci_{ij} denotes the channel-state information of channel *j* for UE *i*. If channel *j* is available for UE *i*, the actual channel capacity can be calculated by $B_c \log_2\left(1+10^{SINR_{ij}/10}\right)$, with the unlicensed channel bandwidth B_c=180kHz. $round[\bullet]$ converts the values to positive integer which adjusts to the proposed algorithm. Otherwise $cci_{ij} = 0$.

Step 3 and Step 4: Feedback information and dynamic unlicensed spectra management

Feedback information is delivered in air interface. Thus, to protect feedback from the unstable radio environment, we configure feedback channel with licensed bands, which is normally not interfered by other systems. On the other hand, LTE achieves the various features by dynamic unlicensed spectra management, such as channel allocation, power control and so on. In this paper, we only focus on channel allocation by which we further complete the interference coordination and throughput maximization for unlicensed spectra. Considering UE capability, dynamic unlicensed spectra management must be carried out at eNB. For downlink operation, spectrum management can only be executed after eNB receives the feedback information from feedback channel PUCCH (Physical Uplink Control Channel), where feedback information is CCI. On the other hand, in uplink, eNB can immediately fulfill spectrum management following Step 2 at eNB, and then send the feedback information, namely scheduling signaling of PUUFCH, to UEs, by feedback channel PDCCH (Physical Downlink Control Channel).

It is apparent that part of steps, depending on air interface, would be restricted by the distribution of downlink/uplink sub-frame with Time Division Duplexing of TDD-LTE. To facilitate management, we expect

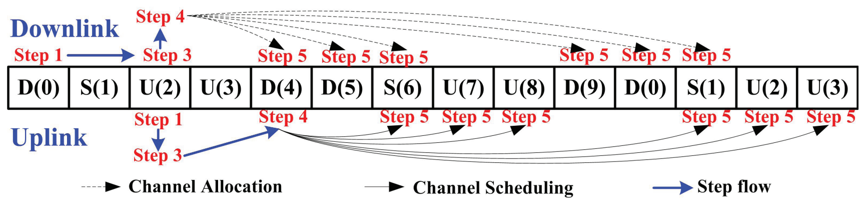

Fig. 6. Distribution cycle

to design a reasonable distribution cycle on sub-frame to match the existing sub-frame distribution configuration of TDD-LTE. At first, an appropriate cycle length should be selected to adapt to the time-varying conditions of radio channel environment, while reducing system burden. Therefore, we choose 10ms, the duration of one radio frame and a typical length of TDD-LTE, as the cycle length to give a design example with one of the sub-frame distribution configurations standardized by TDD-LTE specifications shown in Fig.6 [18]:

In Fig.6, sub-frames from 0^{th} to 10^{th} constitute a radio frame in which D, U and S represent downlink, uplink and special sub-frame, respectively. Special Sub-frame is located in the 1^{th} and 6^{th} sub-frames and involves Downlink and Uplink Pilot Time Slot (DwPTS and UpPTS) as well as Guard Period. Downlink cycle starts with detection of SINR performed on the first downlink sub-frame D(0), and then UEs send feedback information to eNB via PUCCH of the first uplink sub-frame U(2). According to the feedback information, eNB is in charge of all PDUFCH signaling from D(4) to the S(1) of the next radio frame and carries out the resource allocation. In terms of uplink, the SINR of PUUFCH is detected in U(2), followed by Step 2 (channel-state identification), and Step 3 (spectrum management) is carried out at eNB. Afterwards, eNB transmits the feedback information to UEs on PDCCH in D(4) to schedule all PUUFCH within from S(6) to U(3) of the next radio frame. If PDCCH resources in D(4) are insufficient, eNB could also utilize other downlink sub-frames, like D(4) and D(9), to schedule the PUUFCH at later sub-frames. Once one cycle finishes, the system shall start a new cycle with the SINR detection of D(0) and U(2) in the new radio frame. Since few symbols are used for data transmission in special sub-frame (especially only 1 or 2 symbols are allocated for UpPTS), and some special control information, such as primary synchronized signals and random access signallings, are delivered by that, special sub-frame would not need to undertake any feedback information delivery normally. It is possible that unlicensed spectra may suffer from the uncertain and abrupt interference from CSMA/CA based systems, like WiFi. Therefore, for the future evolution, the gap between SINR detection and the transmission based on that should be as short as possible to mitigate the negative impact due to abrupt interference. Accordingly, after a new SINR detection, receivers should feedback the detection results as soon as possible. In the best case, the minimum gap between SINR detection and the feedback is one sub-frame (1ms). However, the minimum gap is determined by the sub-frame distribution configuration adopted by LTE. For our design based on the sub-frame distribution configuration shown in Fig.6, we configure the gap between SINR detection and the feedback with two sub-frames, the minimum value which can be achieved, rather than four in the current release of LTE specifications [37]. Moreover, the sub-frames, like D(0), S(1), U(2) and U(3), which cannot be allocated based on the latest SINR detection, would transmit based on the last SINR detection to avoid any blank sub-frame. As a result, according to CSMA/CA mechanism, CSMA/CA based systems cannot access the unlicensed spectra and cause interference until LTE releases them.

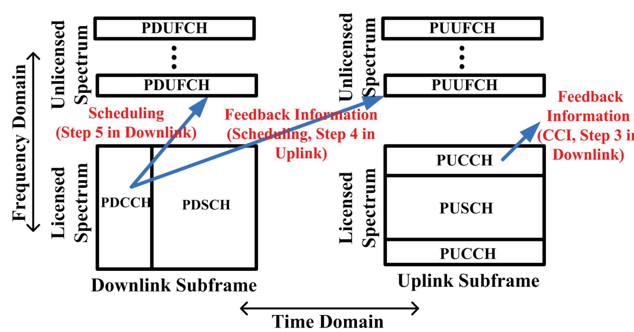

Fig. 7. Frame structure

Step 5: Signal transmission

Fig.7 presents the frame structure of unlicensed spectra, in which the downlink transmission of PDUFCH signaling complies with the channel allocation from Step 4 and are scheduled by the PDCCH within the same downlink sub-frame. For uplink, UEs send uplink signal on PUUFCHs indicated by the feedback information in PDCCH of the previous downlink sub-frame. It is noteworthy that the issue on whether an unlicensed channel has successful transmission or not is determined by not only the quality of the channel, but also that of licensed channels. For example, the feedback channel outage will terminate the whole fusion procedure, and the outage of the scheduling channel PDCCH in downlink indicates

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that UEs cannot distinguish and demodulate their own transmitted data. Thus, to assess the unlicensed channel transmission performance, the quality of the corresponding licensed channels should be treated as one of the decision factors.

III. Unlicensed Channel Allocation Algorithm

As discussed in Section II, unlicensed channel allocation, executed in dynamic spectrum management, should play a role in the interference coordination by enabling each UE to have the channel with the preferable link quality. Besides, it should also consider the features of maximizing throughput and preserving fairness.

Let x_{ij} denote the status variable for the unlicensed channel allocation: $x_{ij} = 1$ if channel *j* is allocated to UE *i*, otherwise $x_{ij} = 0$. To ensure that the unavailable channels for one UE are unlikely to be assigned for this UE, the algorithm should set the corresponding CCI to be small enough in a maximum assignment problem. Therefore, we should have the first constraint.

$$x_{ij}{=}0, \quad \text{for any } cci_{ij} = 0. \tag{2}$$

The capacity of each unlicensed channel is determined based on the assumption that each UE has abundant data to proceed with full-load transmission on the unlicensed channel assigned to the UE. When channel *j* has been allocated to UE *i*, the actual capacity of channel *j* can be calculated as $c_{ij} = B_c \log_2\left(1 + 10^{SINR_{ij}/10}\right)$. Moreover, the total throughput of the whole unlicensed bands is equal to the value of adding up the capacity of all unlicensed channels and can be obtained with $\sum_{i=1}^{M}\sum_{j=1}^{N} c_{ij}x_{ij}$. In addition, it is noticeable that the most straightforward way to guarantee the fairness between different UEs is to equally allocate the number of channels to each UE under the constraint (2). Assuming that the total numbers of UEs and the unlicensed channels are *M* and *N*, respectively, the corresponding constraint is given below:

$$\sum_{j=1}^{N} x_{ij} \begin{cases} \leq 1, & M > N \\ =1, & M = N \\ \leq p+1, & M < N \text{ and } \left\lfloor \frac{N}{M} \right\rfloor = p \end{cases} \quad i{=}\ 1,2,\cdots,M \tag{3}$$

where $p = 1, 2, \cdots, N$, and $\sum_{j=1}^{N} x_{ij}$ represents the total number of channels allocated to UE *i*. If *M*=*N*, the system allocates one channel to one UE; if *M* > *N*, at least (*M*-*N*) UEs would not be assigned any channels; and if *M* < *N* and $\left\lfloor \frac{N}{M} \right\rfloor = p$, $(N - Mp)$ UEs can obtain $(p + 1)$ channels, while others get p channels. Furthermore, each channel can only be assigned to one UE, accordingly, the constraint is given below:

$$\sum_{i=1}^{M} x_{ij} = 1, \quad \text{for any } j. \tag{4}$$

To improve spectrum efficiency, we adopt the throughput maximization in each allocation as the optimization target with the throughput maximum optimization problem formulated as

$$\begin{aligned} &\text{maximize} && \sum_{i=1}^{M}\sum_{j=1}^{N} c_{ij}x_{ij} \\ &\text{subject to} && (2)(3)(4) \end{aligned} \tag{5}$$

Apparently, this problem can be viewed as a maximum assignment problem with c_{ij} as the cost coefficient. Therefore, we can solve the problem using Hungarian Algorithm [34] after substituting c_{ij} with $cci_{ij}{=}$ round (c_{ij}) to meet the requirement of Hungarian Algorithm for the cost coefficient. This process, namely channel-state information generation, is complemented in Step 2. It is well known that this algorithm can achieve throughput maximization and fairness, while the effectiveness for interference coordination, the greatest challenge for communicating over unlicensed spectra, has not been proven under non-cooperative heterogeneous networks, which would be validated by simulation in Section V. The coefficient matrix is defined as

$$CCI_{M\times N}{=}\begin{bmatrix} cci_{11} & cci_{12} & \cdots & cci_{1N} \\ cci_{21} & cci_{22} & \cdots & cci_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ cci_{M1} & cci_{M2} & \cdots & cci_{MN} \end{bmatrix} \tag{6}$$

However, Hungarian algorithm is usually used to solve the minimum problem. Thus, with respect to the maximum problem, the coefficients should carry out the second transformation from cci_{ij} to $a_{ij}{=}m - cci_{ij}$, where *m* is the largest element in $CCI_{M\times N}$. Meanwhile $CCI_{M\times N}$ is changed into $A_{M\times N}{=}\ (a_{ij})_{M\times N} = (m - cci_{ij})_{M\times N}$, whose minimum problem shares the same optimal solution with the maximum problem of $CCI_{M\times N}$. Another issue that must be considered is that the number of UEs and channels would be different in most practical cases while the Hungarian Algorithm only applies to the standard case of $M = N$ with the square coefficient matrix. As for the nonstandard cases, relevant solutions have been known as well, nevertheless, the existing common methods are inappropriate for $M < N$ case in this paper, which should be improved. The detailed solution is described below.

If $M = N$, we can immediately solve the problem by Hungarian algorithm and obtain the optimal solution matrix, the process of which can be presented as

$$X = \text{Hungarian}(A_{M\times N}) \tag{7}$$

If $M > N$, the number of UEs exceeds the number of channels by $(M-N)$. We firstly extend $A_{M\times N}$ with $(M-N)$ columns to a square matrix as $B_{M\times M} = \left[A_{M\times N} \ (0)_{M\times(M-N)}\right]$, then solve it by Hungarian algorithm and obtain the optimal solution matrix $X' = (x_{ij})_{M\times M}$.

$$X' = \text{Hungarian}(B_{M\times M}) \tag{8}$$

Finally, we retain the first N columns and remove the rest columns of X' to turn it into an $M \times N$ matrix $X = (x_{ij})_{M\times N}$. Apparently, X is the optimal solution matrix of $A_{M\times N}$.

If $M < N$, the number of channels exceeds the number of UEs by $(M-N)$. Suppose that $N = pM + q$ ($p = 1, 2, \cdots$; $q = 0, 1, \cdots$; and $q \neq 0$ if $p = 1$). In order to make the algorithm to satisfy the constraints, a reasonable solution with low complexity consists of three steps as shown below:

Step 1: Extend $A_{M\times N}$ for $A^1_{(p+1)M\times N} = \begin{bmatrix} A_{M\times N} \\ A_{M\times N} \\ \vdots \\ A_{M\times N} \end{bmatrix}$

which means that each of UEs is replaced by the $(p+1)$ identical UEs with the same cost coefficient. After extension, there would exist $(p+1)\cdot M$ UEs represented by $(p+1)\cdot M$ rows and there still exist N channels represented by N columns in the new matrix. At this moment, because the number of UEs exceeds the number of channels by $(p+1)\cdot M - N = M - q$, fill $(M-q)$ columns 0 to $A^1_{(p+1)M\times N}$ to form a $(p+1)M\times(p+1)M$ square matrix

$$A^2_{(p+1)M\times(p+1)M} = \begin{bmatrix} A_{M\times N} & 0\cdots 0 \\ A_{M\times N} & 0\cdots 0 \\ \vdots & \vdots \ \ddots \ \vdots \\ A_{M\times N} & \underbrace{0\cdots 0}_{\substack{(M-q)\\ \text{columns}}} \end{bmatrix} \tag{9}$$

Step 2: Obtain the optimal solution matrix of $A^2_{(p+1)M\times(p+1)M}$ by Hungarian Algorithm

$$X'_{(p+1)M\times(p+1)M} = \text{Hungarian}(A^2_{(p+1)M\times(p+1)M}) = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1,(p+1)M} \\ x_{21} & x_{22} & \cdots & x_{2,(p+1)M} \\ \vdots & \vdots & \ddots & \vdots \\ x_{(p+1)M,1} & x_{(p+1)M,2} & \cdots & x_{(p+1)M,(p+1)M} \end{bmatrix} \tag{10}$$

and then remove the latter $(M-q)$ columns from $X'_{(p+1)M\times(p+1)M}$ as

$$X''_{(p+1)M\times N} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1,N} \\ x_{21} & x_{22} & \cdots & x_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ x_{(p+1)M,1} & x_{(p+1)M,2} & \cdots & x_{(p+1)M,N} \end{bmatrix} \tag{11}$$

Step 3: Start with the first row, and extract every sequential M rows from $X''_{(p+1)M\times N}$ to obtain $(p+1)\cdot M\times N$ matrices.

$$X^n_{M\times N} = \begin{bmatrix} x_{(n-1)M+11} & x_{(n-1)M+12} & \cdots & x_{(n-1)M+1N} \\ x_{(n-1)M+21} & x_{(n-1)M+22} & \cdots & x_{(n-1)M+2N} \\ \vdots & \vdots & \ddots & \vdots \\ x_{nM1} & x_{nM2} & \cdots & x_{nMN} \end{bmatrix} \quad n = 1, 2, ..., p+1 \tag{12}$$

Then add up all of the $M \times N$ matrices to obtain the solution matrix $X_{M\times N}$ of $A_{M\times N}$.

$$X_{M\times N} = \sum_{n=1}^{p+1} X^n_{M\times N} \tag{13}$$

The LTE system could rely on the above-introduced algorithm to obtain the optimal solution matrix $X = (x_{ij})_{M\times N}$, based on which the channel allocation is conducted.

IV. System Model and Performance Analysis

In this section, we show the effectiveness of our proposed scheme in terms of interference coordination and throughput enhancement by comparing the received SINR of unlicensed channels and system throughput before and after employing the proposed scheme. Therefore, we firstly analyze how to compute the received SINR of unlicensed channels in both downlink and uplink. In addition, with the aforementioned analysis, the transmission failure over an unlicensed channel is related not only to the quality of the unlicensed channel, but also to that of the corresponding licensed channels. We also redefine the unlicensed channel transmission failure probability under this new transmission system and give the calculation process in this section.

A. SINR on an unlicensed channel interfered by other systems

Assume that the interference source is from 802.11 devices in 5GHz bands, referred to Access Points (APs). The propagation between a transmitter and a receiver in urban cellular scenario is regarded as Non Line-of-Sight (NLOS) case and the small-scale

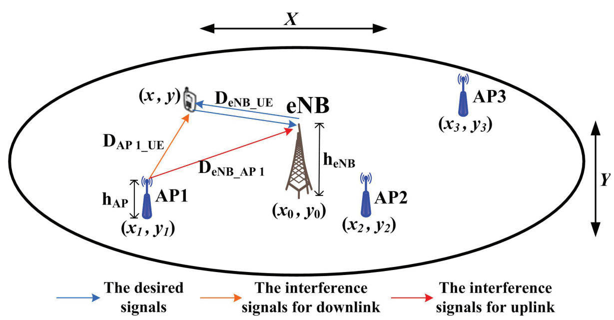

Fig. 8. System model

fading obeys Rayleigh fading [24]. As shown in Fig.8, on the X-Y two-dimensional coordinates, (x_0, y_0) and (x, y) are the position coordinates of eNB and a UE. Again, assume there are three APs within the coverage of an eNB, each of which occupies different unlicensed bands, and (x_i, y_i) represents the position coordinate of AP_i, $i = 1, 2, 3$. h_{eNB} and h_{AP} are the heights of eNB and AP, and the heights of all APs are the same for simplicity. Hence, the distances from eNB to the UE, from AP_i to the UE, and from eNB to AP_i can be expressed as $D_{\text{eNB\_UE}} = \sqrt{(x-x_0)^2+(y-y_0)^2+\text{h}_{\text{eNB}}^2}$, $D_{\text{AP}_i\text{\_UE}} = \sqrt{(x-x_i)^2+(y-y_i)^2+\text{h}_{\text{AP}}^2}$ and $D_{\text{eNB\_AP}_i} = \sqrt{(x_0-x_i)^2+(y_0-y_i)^2+(\text{h}_{\text{eNB}}-\text{h}_{\text{AP}})^2}$ respectively. Then from [24], the corresponding path loss can be given by:

$$\begin{aligned} PL_{\text{eNB\_UE}}[\text{dB}] = \overline{PL(\bar{x})} + 10n\log_{10}\frac{D_{\text{eNB\_UE}}}{\bar{x}} \\ +10n\log_{10}\frac{f_c}{5.0} + \varepsilon_{\text{eNB\_UE}} \end{aligned} \tag{14}$$

where f_c stands for the carrier frequency of the unlicensed channel, $\overline{PL(\bar{x})}$ is the path loss at reference distance $\bar{x}$ evaluated by Hata Model for the urban scenario, n is the path-loss exponent which depends on the frequency, antenna heights and propagation environment. $\varepsilon_{\text{eNB\_UE}}$, $\varepsilon_{\text{AP}_i\text{\_UE}}$ and $\varepsilon_{\text{eNB\_AP}_i}$ denote, respectively, the shadow fading in dB and all of them are assumed to obey Gaussian distribution with mean 0 and standard deviation σ. Similarly, $PL_{\text{AP}_i\text{\_UE}}$ and $PL_{\text{eNB\_AP}_i}$ can be derived from (14).

OFDM (Orthogonal Frequency Division Multiplexing) is employed [27][28]. Suppose there are totally C sub-carriers. In one symbol duration, the baseband signal received by the UE from the eNB in the downlink can be expressed as:

$$\begin{aligned} r_{\text{eNB\_UE}} = pl_{\text{eNB\_UE}} \cdot sh_{\text{eNB\_UE}} \cdot h_{\text{eNB\_UE}}(t) \\ \otimes \sum_{m=0}^{C-1} d_m e^{j2\pi s\Delta f t} + n_{\text{eNB\_UE}}(t) \end{aligned} \tag{15}$$

where $pl_{\text{eNB\_UE}}^2$ denotes the path loss, $sh_{\text{eNB\_UE}}^2$ represents the log-normally distributed shadow fading, $|pl_{\text{eNB\_UE}} \cdot sh_{\text{eNB\_UE}}|^2 = 10^{-PL_{\text{eNB\_UE}}/10}$; $h_{\text{eNB\_UE}}(t) = \sum_{l=0}^{L-1} h_{\text{eNB\_UE}}^l \delta(t-\tau_{\text{eNB\_UE}}^l)$ is the microscopic multiple Rayleigh fading, L is the number of resolvable multipath components; d_m is the desired data transmitted by sub-carrier m with the transmitted power $Pd_{\text{eNB}}[dBm] = 10\log_{10}(E\left[|d_m|^2\right])$; $t \in [0, T_g + T_s]$, T_g and T_s represent the time duration of Cyclic Prefix (CP) and effective OFDM symbol, respectively; Δf is the sub-carrier spacing; $n_{\text{eNB\_UE}}(t)$ stands for the zero-mean Additive White Gaussian Noise.

Assume that the length of CP is longer than the maximum delay spread $T_d (T_g > T_d)$, resulting in no Inter-symbol Interference. Thus, the output signal on $\hat{m}^{th}$ sub-carrier at the receiver in the k^{th} time chip duration can be calculated as [30][31]:

$$\begin{aligned} & Y_{\text{eNB\_UE}}^{\hat{m}}(k) = \frac{1}{T_s}\int_{kT}^{kT+T} r_{\text{eNB\_UE}}(t) \\ & \quad \cdot e^{-j2\pi f_{\hat{m}}(t-kT)} p(t-kT)dt \\ & = \underbrace{pl_{\text{eNB\_UE}} sh_{\text{eNB\_UE}} d_m \lambda_{\hat{m}}^{\hat{m}}(k)}_{the\ desired\ signal} \\ & + \underbrace{\sum_{m \neq \hat{m}}^{C-1} pl_{\text{eNB\_UE}} sh_{\text{eNB\_UE}} d_m \lambda_{\hat{m}}^{m}(k)}_{ICI(Inter-carrier\ Interference)} + \underbrace{N_{\text{eNB\_UE}}(k)}_{noise} \end{aligned} \tag{16}$$

where $T = T_g + T_s$ is the time duration of OFDM symbol, $p(t)$ is the pulse shaping function. $H_{\text{eNB\_}UE}(k) = pl_{\text{eNB\_UE}} sh_{\text{eNB\_UE}} \lambda_{\hat{m}}^{\hat{m}}(k)$ is the channel fading gain on the desired signal with

$$\lambda_{\hat{m}}^{\hat{m}}(k) = \frac{1}{T_s}\sum_{l=0}^{L-1} e^{-j2\pi\frac{\hat{m}l}{C}} \cdot \int_0^{T_s} h_{\text{eNB\_}UE}^l(t+kT)dt \tag{17}$$

and $G_{\text{eNB\_UE}}(k) = pl_{\text{eNB\_UE}} sh_{\text{eNB\_UE}} \lambda_{\hat{m}}^{m}(k)$ represents the Inter-carrier Interference (ICI) for $\hat{m}$ sub-carrier contributed from m sub-carrier with

$$\begin{aligned} \lambda_{\hat{m}}^{m}(k) = \frac{1}{T_s}\sum_{l=0}^{L-1} e^{-j2\pi\frac{ml}{C}} \\ \cdot \int_0^{T_s} h_{\text{eNB\_}UE}^l(t+kT) e^{j2\pi\frac{m-\hat{m}}{T_s}t} dt \end{aligned} \tag{18}$$

Then the desired received signal power on downlink within one Resource Element (one sub-carrier×one OFDM symbol) can be derived as:

$$\begin{aligned} & Pr_{\text{eNB\_}UE}[\text{dBm}] = 10\log_{10}(E\left[|d_m|^2\right] \\ & \quad \cdot |pl_{\text{eNB\_UE}} \cdot sh_{\text{eNB\_UE}}|^2 \cdot E\left[\left|\lambda_{\hat{m}}^{\hat{m}}(k)\right|^2\right]) \\ & = 10\log_{10}\left(E\left[|d_m|^2\right]\right) + 10\log_{10}\left(|pl_{\text{eNB\_UE}} \cdot sh_{\text{eNB\_UE}}|^2\right) \\ & \quad +10\log_{10}\left(E\left[\left|\lambda_{\hat{m}}^{\hat{m}}(k)\right|^2\right]\right) \\ & = Pd_{\text{eNB}} - PL_{\text{eNB\_UE}} + \Omega_{\text{eNB\_UE}} \end{aligned} \tag{19}$$

where $\Omega_{\text{eNB\_UE}}=10\log_{10}\left(E\left[\left|\lambda_{\hat{m}}^{\hat{m}}(k)\right|^2\right]\right)$. For $E\left[\left|\lambda_{\hat{m}}^{\hat{m}}(k)\right|^2\right]$, we offer the calculation details in Appendix A.

Since both LTE and 802.11 adopt OFDM as the fundamental technologies, based on calculation illustrated above, we can similarly obtain the received desired signal power of uplink $\Pr_{\text{UE\_eNB}}$.

$$Pr_{\text{UE\_eNB}}[\text{dBm}] = Pd_{\text{UE}} - PL_{\text{eNB\_UE}} + \Omega_{\text{UE\_eNB}} \tag{20}$$

where Pd_{UE} denote the transmit power of UE within 15kHz bandwidth, with the unit of dBm. $\Omega_{\text{UE\_eNB}}$ stand for the small-scale fading channel gain of UE-eNB links. As stated in [32][33], we normally set transmit power of eNB at 43dBm/1MHz, and the power of 15kHz bandwidth approximately to $Pd_{\text{eNB}}=10\log_{10}^{(10^{43/10}\times 15\text{kHz}/1\text{MHz})} \approx 25\text{dBm}$. Suppose that the power of the UE is set to $Pd_{\text{UE}}= 16\text{dBm}$ due to its battery limitation.

Thus, the received signal SINRs for the downlink and the uplink can be computed, respectively, as follows:

$$SINR_{DL}[\text{dB}] = Pr_{\text{eNB\_UE}}[\text{dBm}] - 10log_{10}\left(I_{UE}^{tot}\right) \tag{21}$$

$$SINR_{UL}[\text{dB}] = \Pr_{\text{UE\_eNB}}[\text{dBm}] - 10log_{10}\left(I_{eNB}^{tot}\right) \tag{22}$$

where I_{UE}^{tot} and I_{eNB}^{tot} represent the total power of the mixed signal of the interference and noise experienced by UE and eNB, respectively. By sensing unlicensed channel, systems can only obtain the overall power of interference and noise but cannot distinguish them.

B. Transmission failure probability on an unlicensed channel

According to the analysis in Section II, we know that a transmission failure on an unlicensed channel happens when either the unlicensed channel itself or its corresponding licensed channels, used for feedback or scheduling, experience outage. As it is well-known, the outage probability characterizes the situation that the received signal is too weak to be properly decoded and maintain normal link connection. It is assumed that if the received signal quality is lower than a threshold γ (dB), the outage would happen. Since LTE has the sole ownership on its licensed spectra, it could be assumed that there is no external interference on it and employ Signal-to-Noise Ratio (SNR) as the metric of licensed channel quality. Moreover, to simplify calculation, we assume that the same transmit power is allocated to the unlicensed and the licensed spectra, and all licensed channels have the same carrier frequency. With the aforementioned assumptions, the received signal SNR of licensed channel in the downlink and the uplink can be expressed as:

$$\begin{aligned} SNR_{DL}^{licensed}[\text{dB}] = Pd_{\text{eNB}}[\text{dBm}] - PL_{\text{eNB\_UE}}^{licensed}[\text{dB}] \\ +\Omega_{\text{eNB\_UE}}^{\text{licensed}} - 10\log_{10}\left(B\times 10^{N_0/10}\right) \end{aligned} \tag{23}$$

$$\begin{aligned} SNR_{UL}^{licensed}[\text{dB}] = Pd_{\text{UE}}[\text{dBm}] - PL_{\text{eNB\_UE}}^{licensed}[\text{dB}] \\ +\Omega_{\text{UE\_eNB}}^{\text{licensed}} - 10\log_{10}\left(B\times 10^{N_0/10}\right) \end{aligned} \tag{24}$$

where $\Omega_{\text{eNB\_UE}}^{\text{licensed}}$ and $\Omega_{\text{UE\_eNB}}^{\text{licensed}}$ represent the small-scale fading gains of licensed channels, and $PL_{\text{eNB\_UE}}^{licensed}$ signifies the path loss with carrier frequency f_0:

Thus, the outage probability of the licensed channel, including downlink and uplink, is shown as:

$$P_{DL\_outage}^{licensed} = P[SNR_{DL}^{licensed} < \gamma] \tag{25}$$

$$P_{UL\_outage}^{licensed} = P[SNR_{UL}^{licensed} < \gamma] \tag{26}$$

which can be calculated as follows:

$$\begin{aligned} P_{DL\_outage}^{licensed} &= P[Pd_{\text{eNB}} - PL_{\text{eNB\_UE}}^{licensed} + \Omega_{\text{eNB\_UE}}^{\text{licensed}} \\ &\quad -10\log_{10}\left(B\times 10^{N_0/10}\right) < \gamma] \\ &= P[\varepsilon_{\text{eNB\_UE}} > Pd_{\text{eNB}} - \overline{PL(\bar{x})} - 10n\log_{10}\frac{D_{\text{eNB\_UE}}}{\bar{x}} \\ &\quad -10n\log_{10}\frac{f_0}{5.0} + \Omega_{\text{eNB\_UE}}^{\text{licensed}} - 10\log_{10}\left(B\times 10^{N_0/10}\right) - \gamma] \\ &= 1 - \Phi\{[Pd_{\text{eNB}} - \overline{PL(\bar{x})} - 10n\log_{10}\frac{D_{\text{eNB\_UE}}}{\bar{x}} \\ &\quad -10n\log_{10}\frac{f_0}{5.0} + \Omega_{\text{eNB\_UE}}^{\text{licensed}} - 10\log_{10}\left(B\times 10^{N_0/10}\right) - \gamma]/\sigma\} \end{aligned} \tag{27}$$

Similarly, $P_{UL\_outage}^{licensed}$ can be obtained by the same calculation process. Equally, the outage probability of unlicensed channels are

$$P_{DL\_outage}^{unlicensed} = P[SINR_{DL} < \gamma] \tag{28}$$

$$P_{UL\_outage}^{unlicensed} = P[SINR_{UL} < \gamma] \tag{29}$$

whose detailed calculation processes could refer to (27).

Apparently, the calculation of unlicensed channel transmission failure probability on the downlink and the uplink would be different due to different spectra fusion procedures. In the downlink procedure, there are three essential conditions that must be satisfied to guarantee the transmission success: 1) no outage happens in the PUCCH for the feedback; 2) no outage happens in the PDCCH when used for delivering the scheduling information on PDUFCH; 3) no outage happens in the PDUFCH used for transferring the traffic information. Based on the unlicensed spectra fusion cycle illustrated in Fig.6, the time lag among the aforementioned three events within one cycle is less than 10ms, even if events 2) and 3) occur simultaneously in the same downlink sub-frame. Thus, it is reasonable for UE in urban scenario with low mobility to assume that these events occur when the UE is located in the same position. The three events are mutually independent. Consequently,

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the downlink transmission failure probability on the unlicensed channel can be calculated as:

$$P_{DL\_failure}^{unlicensed} = (1 - P_{UL\_outage}^{licensed}) \times (1 - P_{DL\_outage}^{licensed}) \times (1 - P_{DL\_outage}^{unlicensed}) \tag{30}$$

In the case of the uplink, two basic conditions must be satisfied for a successful transmission are: 1) no outage happens in the feedback channel PDCCH; 2) no outage happens in the PUUFCH in order to support the traffic delivery. Hence the uplink transmission failure probability on the unlicensed channel can be calculated as:

$$P_{UL\_failure}^{unlicensed} = (1 - P_{DL\_outage}^{licensed}) \times (1 - P_{UL\_outage}^{unlicensed}) \tag{31}$$

V. Simulation Results

In this section, we conduct simulation study for the interference coordination, throughput enhancement and fairness performance of the proposed unlicensed spectra fusion scheme. To make comparisons, we also consider the Proportional Fair Scheduling (PFS) used on unlicensed spectra as the reference scheme. PFS is a classical algorithm and known in [38][39] to provide an efficient throughput-fairness tradeoff in OFDMA-based systems. The key principle is that channel j is assigned to user $i^* = \arg\max_{\mathcal{M}} \frac{R_{i,j}}{\overline{R_i}(t-1)}$, $i \in \mathcal{M}$, where $\mathcal{M}$ is the set of UE, $R_{i,j}$ is the achievable rate of user i on channel j, and $\overline{R_i}(t-1)$ is the average rate of user i over the time window in the past and defined as

$$\overline{R_i}(t) = (1 - \frac{1}{T_w})\overline{R_i}(t-1) + \frac{1}{T_w}\sum_{j \in \mathcal{N}_i} R_{i,j} \tag{32}$$

where T_w is the window size and is equal to 2s in our simulation, $\mathcal{N}_i$ is the set of the channels assigned to UE i. Since PFS works effectively in terms of the time-average fairness and throughput, the simulations for unlicensed channel allocation based on our proposed and the reference scheme should perform multiple times with once per 10ms.

The simulation parameters are presented in Table I, the cell is situated on the X-Y two-dimensional coordinate with 3km radius, and the eNB is located at (3,3). In order to thoroughly evaluate our proposed scheme, we deploy 3 APs in the cell each of which is located at different location and occupy different unlicensed bands. Moreover, because APs are generally used for small coverage and may be employed by different systems with different power configurations, we assume that the power of APs is lower than eNB, but higher than UE, and use three values in this paper, namely, 22dBm, 20dBm and 18dBm, respectively, for our study. Thus, LTE would suffer from the interference of one specific unlicensed channel caused only by one AP. Moreover, 2000 UEs are spread all over the cell in different positions with uniform distribution. Additionally, for the unlicensed spectra simulation layout, we assume that LTE coexists with 3 APs on a continuous unlicensed band with the center frequency at 5GHz. Because we regard APs as 802.11 devices which communicate through constant bandwidth channel (20/40MHz for 802.11n, 20/40/80/160MHz for 802.11ac, etc), it is reasonable to assume that no matter how much the bandwidth of the unlicensed band is, AP1, 2 and 3 occupy the lower, medium and higher part of this band, respectively, and the bandwidth taken by each of them is uniformly distributed.

TABLE I
SIMULATION PARAMETERS[31][32]

Parameters		Value
Cell Radius (R)		3km
Outage Threshold (γ)		-20dB
Available Unlicensed Channel Threshold (Γ)		6dB
Path Loss Parameter (n)		4
Shadow Fading Deviation (σ)		4dB
Unlicensed Channel Center Frequency		5GHz
Licensed Channel Carrier Frequency		2GHz
Thermal Noise Density (N_0)		-174dBm/Hz
Antenna Pattern		Omni
Channel Bandwidth (B_c)		180kHz
eNB	Location	(3,3)
	Transmit Power	25dBm/15kHz
	Antenna Height	30m
AP1	Location	(1.5,4.5)
	Transmit Power	22dBm/15kHz
	Antenna Height	10m
AP2	Location	(2.5,2.5)
	Transmit Power	20dBm/15kHz
	Antenna Height	10m
AP3	Location	(4,1)
	Transmit Power	18dBm/15kHz
	Antenna Height	10m
UE	Quantity (M)	2000
	Distribution	Uniformly-spaced
	Transmit Power	16dBm/15kHz
	Antenna Height	1.5m

First, we investigate the interference coordination performance by SINR distribution. In these simulations, LTE shares the 4.83-5.17GHz unlicensed band, containing 2000 unlicensed channels, with 3 APs. However, UEs may be allocated with no, one or more than one channel in one allocation with PFS, while each UE can only obtain one channel with Hungarian Algorithm when the number of channels and UEs is equal. For comparison, the average SINR of each UE is employed, calculated by $\overline{SINR_i} = \frac{\sum_{k=1}^{K}\sum_{j \in \mathcal{N}_i^k} SINR_i^k(j)}{K}$, where K is the total number of channels allocated, $\mathcal{N}_i^k$ is the set of the channels assigned to UE i in k^{th} allocation, and $SINR_i^k(j)$ denotes the SINR value of the channel j.

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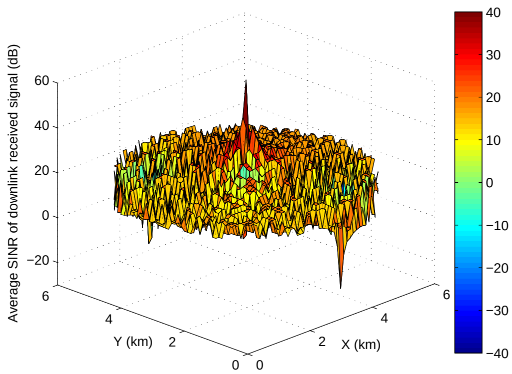
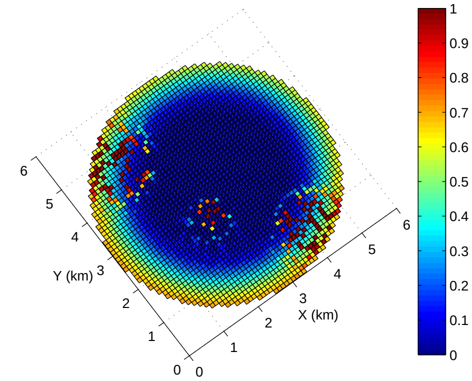


(a)

(b)

Fig. 9. Downlink average SINR distribution: (a) based on reference scheme, (b) based on our proposed scheme.



(a)

(b)

Fig. 10. Downlink transmission failure probability: (a) based on reference scheme, (b) based on our proposed scheme.

Fig.9 (a) and (b) present the downlink average SINR distribution of the reference scheme and our proposed scheme, respectively, where a point represents a position with one UE. It can be seen that the UEs closer to AP have lower average SINR in Fig.9 (a). The reason is that, though not much, there still exists opportunity to assign an unlicensed channel to the UE closer to the AP that communicates on this channel by PFS. In this case, UE would experience strong co-channel interference, which degrades the average SINR. Whereas from Fig.9(b), all UEs within the cell have higher average SINR by our proposed scheme, and the entire surface of Fig.9(b) appears to be smooth, which indicates that the main impact factor of average SINR distribution is the path loss and the impact from APs does not exist to some extent. Therefore, the comparison between Fig.9(a) and (b) directly illustrates that our proposed scheme has significantly better performance attained from the downlink interference coordination. Moreover, this conclusion can be verified by comparing the simulations of our proposed scheme with the reference scheme in terms of the downlink transmission failure probability. As shown in Fig.10(a) and (b), the reference scheme causes higher transmission failure probability for UEs around APs, while our proposed scheme could eliminate this kind of harmful impact effectively.

Second, we simulate the average SINR and transmission failure probability for the uplink under the same radio environment. Apparently, Fig.11(b) and Fig.12(b) show that our proposed scheme makes all UEs attain high-grade uplink transmission quality, higher SINR and lower transmission failure probability than the reference scheme. This is because our proposed scheme only allocates a channel to the UE that has superior propagation condition over the channel. For example, a channel occupied by an AP should be allocated to the UE with shorter distance to the eNB than that AP under the condition that the power of the UE is lower than that of the AP to ensure higher uplink received power against interference. Unfortunately, in the reference scheme, systems may assign a channel to the UE with the inferior propagation condition. Undoubtedly,

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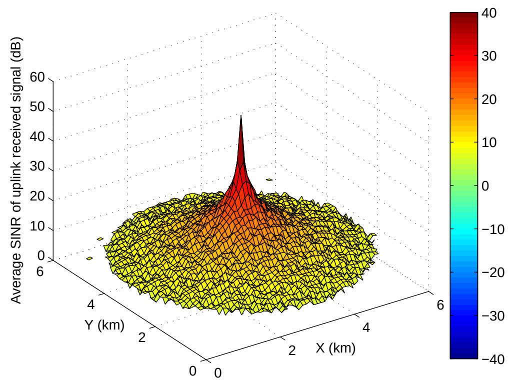
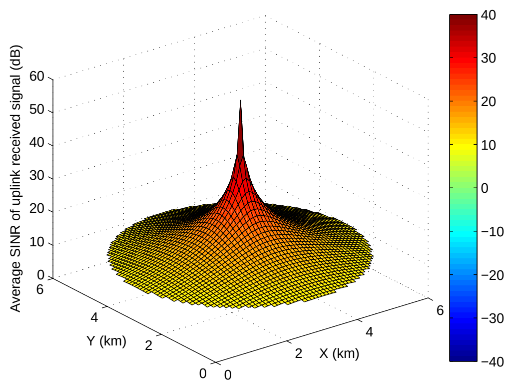
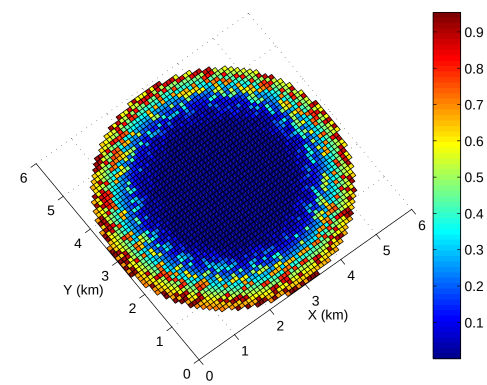


(a)

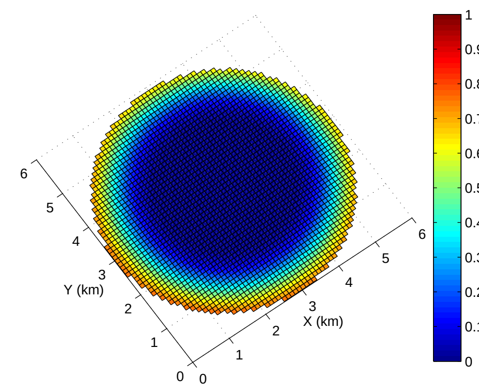


(b)

Fig. 11. Uplink average SINR distribution: (a) based on reference scheme, (b) based on our proposed scheme.



(a)



(b)

Fig. 12. Uplink transmission failure probability: (a) based on reference scheme, (b) based on our proposed scheme.

our proposed scheme can perform uplink interference coordination better over the unlicensed spectra.

Third, Fig.13 and Fig.14, respectively, illustrate the reachable average throughput on downlink and uplink when our proposed scheme works in two extremely opposite interference environment. In these two figures, X and Y axes express, respectively, the number of channels and the average throughput of the whole system bandwidth, containing all the unlicensed channels. Besides, the line with circle denotes that the LTE is operating in the most severe interference environment when all APs transmit with full power over the unlicensed channels they have occupied. On the other hand, the line with star denotes the best interference environment with no interference. As for reference, the line with diamond and square represents the reference scheme under the most hostile environment and the best environment, respectively. From the figure, we observe that the throughput with our proposed scheme, no matter whether it is for the uplink or downlink, is significantly higher than that for the reference scheme in the worst

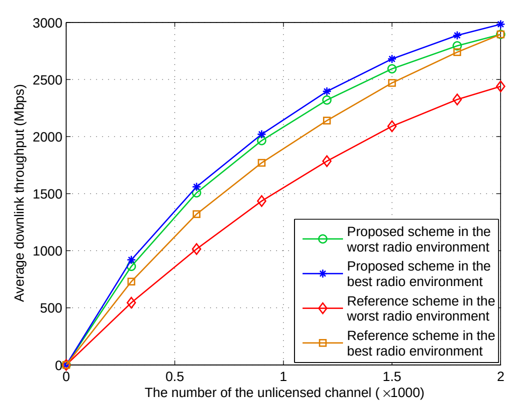


Fig. 13. Average downlink throughput over unlicensed spectra

interference environment. Moreover, in the best interference environment, our proposed scheme can also bring in higher throughput than the reference scheme. It shows that our proposed scheme has significantly better performance for throughput enhancement, especially in the bad interference environment. Moreover, it is noteworthy that

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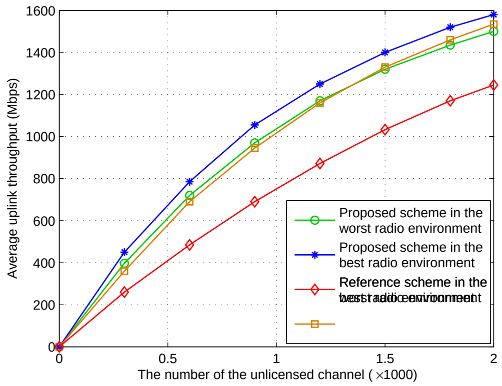

Fig. 14. Average uplink throughput over unlicensed spectra

the throughputs of our proposed scheme in the worst and the best interference environment are extremely similar, which could directly reveal that the interference has less impact on throughput. Meanwhile, it demonstrates the excellent performance due to the interference coordination in our proposed scheme. However, there still exists the significant gap for the throughputs of the reference scheme between in the best interference environment and in the worst interference environment. This implies that the interference coordination of our proposed scheme is much better than the reference scheme.

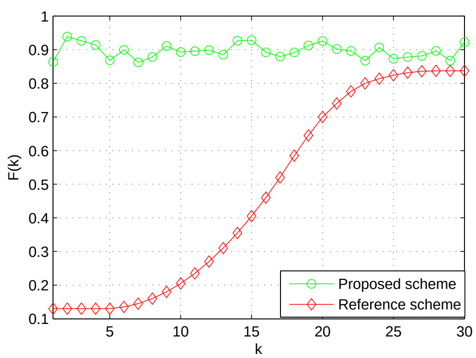

Fig. 15. Jain's fairness index for downlink

Finally, the Jain's index for the rate fairness scheme will be adopted to evaluate the fairness performance of our proposed scheme. This fairness metric is introduced by WiMAX Forum [40] and has been widely used in relevant works [38]. It is defined as

$$F(k) = \frac{\left(\sum_{i=1}^{M} r_i(k)\right)^2}{M \sum_{i=1}^{M} r_i^2(k)} \tag{33}$$

where $r_i(k)$ is the achievable rate of UE i after k^{th} allocation. The index is lower-bounded by $1/K$, corresponding to the most unfair case, and upper-bounded by 1. In Fig.15 and Fig.16, the Jain's index of downlink and uplink is given under $M = 2000$, $N = 2000$ and $K = 30$. The results show that the fairness metric of our proposed scheme is always better than the reference scheme with PFS. Furthermore, the fairness performance for PFS in the initial and previous allocation is extremely bad, while that of our proposed scheme is always excellent at the beginning.

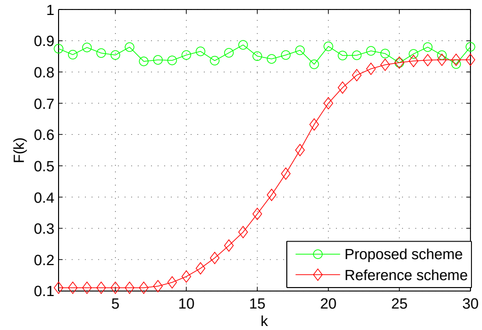

Fig. 16. Jain's fairness index for uplink

VI. Conclusion, Discussion and Future Research

In this paper, we have developed a novel unlicensed spectra fusion scheme for LTE that can significantly improve the system capacity and effectively perform interference coordination. Because of the particularity of the public unlicensed spectra, the system procedures in our spectra fusion scheme differs from the existing LTE and have not been designed. Thus, one of our main contributions is to design the system procedures of the unlicensed spectra fusion based on the popular standard TDD-LTE. Based on these procedures, the interference coordination scheme is developed in two stages: 1) To ensure that every UE is assigned a channel with link quality satisfying the basic reliability requirement; 2) To maximize the system throughput with guaranteed fairness in the unlicensed channel allocation scheme based on the Hungarian algorithm. Finally, we have conducted extensive simulation studies and show that our proposed scheme could make every unlicensed channel allocated to the UE that has preferable link quality with higher received signal SINR and lower transmission failure probability. It has been demonstrated that our proposed scheme could achieve interference coordination on the unlicensed spectra remarkably well. In addition, the simulation results on throughput confirm that our proposed scheme possesses the outstanding performance on both interference coordination and throughput enhancement.

For the coexistence environment in unlicensed spectra, fairness between an LTE system and an 802.11 WLAN is extremely important. However, due to the poor interference cancellation ability in the "listen-before-talk" protocol to access spectra, 802.11 WLANs are in the absolutely inferior position of the competition with LTE-U on unlicensed spectra, which are the only available medium being proposed for Wi-Fi systems. In our recent work [41], we have proposed a solution to addressing the fairness between LTE-U and 802.11 WLANs. We proposed an unlicensed channel access mechanism, also referred to as spectrum etiquette protocol, for LTE-U where LTE-U should regard 802.11 WLANs as the "primary user" with higher priority and can access an unlicensed band only if it is detected not being used by 802.11 WLAN devices, or no harmful interference is caused to 802.11 WLAN devices, just as done in cognitive radio networks [42]. For engineering implementation, we design an LTE-802.11 fusion protocol stack with corresponding frame structure and system procedures designed. Moreover, for spectral efficiency maximization, we also study the problem on maximizing the ergodic throughput for LTE-U to obtain the optimal transmit power and the optimal unlicensed channel access time length under our proposed spectrum etiquette. From [41], we observe that LTE-U could proactively release the unlicensed resource for 802.11 WLAN devices and only opportunistically use the unlicensed spectra to guarantee the fairness. This paper is our follow-up works of [41] on how to perform unlicensed spectra fusion when LTE-U has already occupied the unlicensed spectra.

Due to the inherent disadvantages of unlicensed spectra which suffer from higher propagation loss and uncontrolled interference, LTE-U systems are almost impossible to provide reliable transmission for each UE if solely depending on unlicensed bands. Therefore, based on the present research in this paper, it is reasonable to come up with a sound unlicensed and licensed joint channel allocation scheme to support the unlicensed and licensed joint access service to meet the QoS requirement for each UE. This issue will be investigated in the future.

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Appendix A
Calculation Details of (19)

If Doppler Shift exists, the autocorrelation function of the l^{th} path can be obtained by $J_0(\cdot)$, the zeroth-order Bessel function of the first kind defined as in [29]:

$$\begin{aligned}\varphi_l(\Delta t) &= E\left[h^l_{\mathrm{eNB}\_UE}(t+\Delta t)\cdot h^{l\,*}_{\mathrm{eNB}\_UE}(t)\right] \\ &= \sigma_l^2 \cdot J_0(2\pi f_D \Delta t)\end{aligned} \tag{34}$$

where $\sigma_l^2 = E\left[\left|h^l_{\mathrm{eNB\_UE}}(t)\right|^2\right]$, the maximum Doppler Frequency Shift is $f_D = v f_c / c$, where v and c represent the velocity of receiver and light, respectively.

Assume that ICI could be averaged out and has no effect on the final signal strength, then the channel gain of a small-scale fading signal could be obtained as:

$$\begin{aligned}E\left[\left|\lambda^{\hat{m}}_{\hat{m}}(k)\right|^2\right] &= E\left[\left|\frac{1}{T_s}\sum_{l=0}^{L-1} e^{-j2\pi\frac{\hat{m}l}{M}}\right.\right. \\ &\qquad \left.\left. \cdot \int_0^{T_s} h^l_{\mathrm{eNB}\_UE}(t+kT)dt\right|^2\right] \\ &= \frac{1}{T_s^2}\int_0^{T_s}\int_0^{T_s}\sum_{l=0}^{L-1}\sigma_l^2 \cdot J_0(2\pi f_D(t_1-t_2))dt_1 dt_2 \\ &= \sum_{l=0}^{L-1}\sigma_l^2 \cdot \int_{-1}^{1} J_0\left(2\pi f_D T_s x\right)\left(1-|x|\right)dx\end{aligned} \tag{35}$$

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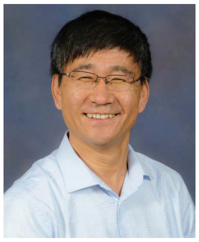

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