Control/User Plane Decoupled Architecture Utilizing Unlicensed Bands in LTE Systems

Hao Song, Xuming Fang, Li Yan, and Yuguang Fang

Abstract

The explosive growth of wireless traffic demands and the shortage of licensed spectra motivate us to explore the utilization of unlicensed bands (including mmWave bands and opened licensed bands of other wireless systems for the future) in LTE systems, so-called LTE-U. However, since unlicensed spectra are normally distributed over high-frequency bands and may suffer from random and uncontrollable interference, there are many research challenges for LTE-U systems ahead. To tackle these challenges, we propose a C/U decoupled system architecture for LTE-U systems, which has the advantages of lower complexity, higher flexibility, higher reliability, and higher system capacity. Specifically, we first design a framework and the corresponding system procedures for our proposed C/U decoupled LTE-U systems, including network architecture, frame structure, and centralized resource management procedure. Then we put forward the corresponding enabling and supporting technologies to solve the research challenges, including frequent inter-microcell handoffs, available unlicensed spectrum harvesting, and quality of service guarantee for traffic with high reliability requirements. We also conduct a simulation study to demonstrate the performance gain of the unlicensed spectra transmissions in our proposed LTE-U systems. Finally, we discuss several remaining research challenges, which could be potential topics for future research.

Introduction

According to a Cisco study and forecast [1], mobile data traffic is experiencing exponential growth and will increase nearly eight-fold with a compound annual growth rate (CAGR) of 53 percent between 2015 and 2020. Unfortunately, only relying on spectrum efficiency and network density, the current network capacity enhancement strategies will not catch up with this exponential growth. Thus, spectrum extension, as a straightforward solution for capacity enhancement, has attracted tremendous attention recently. However, as scarce and costly resources, licensed spectra are hard to come by for LTE systems. LTE systems may actually search for spectrum extension opportunities on public unlicensed bands, such as industrial, scientific, and medical (ISM) and unlicensed national information infrastructure (UNII) bands. However, the fact that these bands have become crowded and overutilized due to WiFi devices encourages LTE-unlicensed (LTE-U) systems to extend their system bandwidth to other accessible bands, such as unallocated millimeter-wave (mmWave) bands [2]. According to the recent mmWave allocation policy released by the Federal Communications Commission (FCC), 14 GHz of contiguous mmWave bands (57–71 GHz) have been opened up for unlicensed use [3]. Moreover, the experimental tests performed in academia [4, 5] and the measurements conducted in industry [6] reveal that even in the most crowded urban areas, many licensed spectra are extremely underutilized. These caused the FCC to review current static spectrum allocation policy and to open up licensed spectra for dynamic access to the underutilized licensed bands [7], which can also be viewed as unlicensed bands for LTE systems with secondary access priority. In this article, we study the robust network architecture and corresponding enabling technologies for LTE-U systems to facilitate the effective utilization of unlicensed spectra. LTE-U is a standard proposal untapping the use of unlicensed bands at 5.8 GHz. In this article, we use it with a more extended meaning in the sense of an LTE system that can utilize any unlicensed band, including mmWave. In other words, we study LTE-U systems that can access unlicensed and licensed bands simultaneously. Due to the particularity of unlicensed spectra, many challenges have to be considered for LTE-U systems below.

Complex and Dense Heterogeneous Network Architecture: Unlicensed spectra are normally distributed over high-frequency bands with high path loss and should strictly comply with the power constraints that apply to dense microcellular coverage. However, current LTE systems always utilize macro-evolved NodeBs (eNBs) with macrocellular coverage. For compatibility, future LTE-U systems most likely will deploy both macro-eNBs and dense micro-eNBs, which will significantly increase complexity.

Frequent Inter-Microcell Handoffs: Inter-microcell handoffs will increase with the growth of the density of micro-eNBs, and bring more frequent temporary data transmission interruptions due to the hard handoff procedures standardized by LTE specifications [8] and more handoff failures.

Difficult Interference Coordination: Unli-

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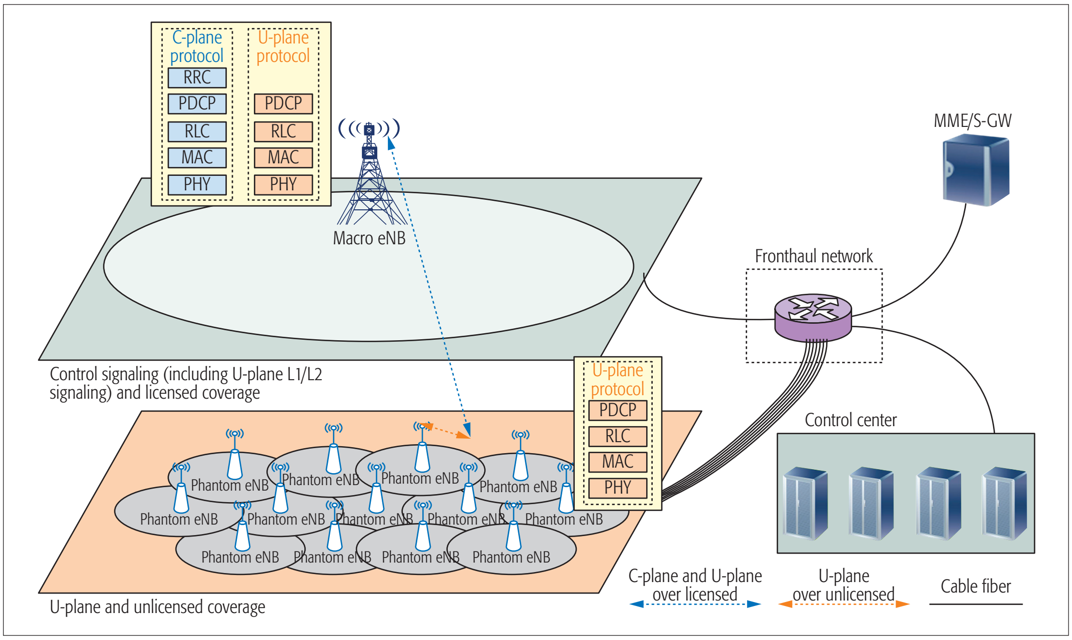

FIGURE 1. C/U decoupling-based LTE-U architecture.

It is apparent that the inherent characteristics of C/U decoupled architecture can assist addressing some of the challenges of LTE-U systems, such as reducing system complexity and realizing centralized resource management. However, there still remain some challenges to be solved.

censed spectra suffer from not only controllable inter-microcell interference, but also uncontrollable interference from the wireless devices of other systems, which makes interference coordination more difficult. For better interference coordination, centralized resource management is necessary for LTE-U systems.

Reasonable Available Unlicensed Spectrum Harvesting: The future LTE-U systems may treat various kinds of unlicensed bands as potential available spectrum. When LTE-U systems perform available unlicensed spectrum harvesting, access priorities and wireless environments of different unlicensed spectra should be taken into account.

Poor Reliability of Unlicensed Spectra: The traffic with high reliability requirements should be carried by reliable licensed spectra rather than interference-susceptible unlicensed spectra. However, the licensed spectra are limited and scarce, and thus unable to carry all the traffic with high reliability requirements, such as control information, and delay-sensitive and interruption-sensitive data traffic. Thus, quality of service (QoS) guarantee is a critical issue for LTE-U systems.

As a novel and advanced architecture with the advantages of low complexity, high flexibility, and high data rate, decoupled control/user (C/U) architecture is attracting more and more attention, and has been viewed as a promising technology for fifth generation (5G) systems [9, 10]. To tackle the aforementioned challenges, we propose a framework for the C/U decoupled architecture for LTE-U systems. In this framework, micro-eNBs, also referred to as phantom eNBs, are not fully functional eNBs and are only configured with low-complexity U-plane protocol, while macro-eNBs are in charge of fulfilling C-plane functions for the phantom eNBs. Accordingly, the system complexity and flexibility would be significantly reduced and enhanced when replacing conventional LTE eNBs by the phantom eNBs to build dense small cell networks. Since the C-plane functions of phantom eNBs, such as those for measurement, radio resource control (RRC) connection management, and admission control, are centralized and coordinated by macro-eNB, it is possible to collect the unlicensed spectra state of different microcells and realize centralized resource management and optimization. From the aforementioned analysis, it is apparent that the inherent characteristics of C/U decoupled architecture can assist in addressing some of the challenges of LTE-U systems, such as reducing system complexity and realizing centralized resource management. However, there remain some challenges to be solved. Moreover, due to the particularity of C/U decoupled architecture, the framework and system procedures of C/U decoupled LTE-U systems significantly differ from the existing LTE specifications, which need to be redesigned. As a final remark, the C/U plane separation in the frequency domain is not surprising as it has been done already in traditional cellular system design: in all frequency-division duplex (FDD) systems, a certain number of frequency channels are reserved for control signaling. In fact, in [11], Zhai *et al.* demonstrated that by separating control messages and data messages in the frequency domain in IEEE 802.11 systems, multihop ad hoc networks could significantly lower collisions and boost throughput performance. We expect that future high data rate wireless systems will benefit significantly by utilizing reliable lower-frequency bands to support control signaling to enable high data rate transmissions in high-frequency bands.

The remainder of this article is organized as follows. We begin with the design of the proposed framework and the corresponding system procedures for C/U decoupled LTE-U systems, including network architecture, frame structure, and unlicensed resource management procedure. Then we introduce the enabling and supporting technologies solving or alleviating the negative effects of the aforementioned challenges. Finally, we discuss several remaining research challenges and outline our future potential research directions.

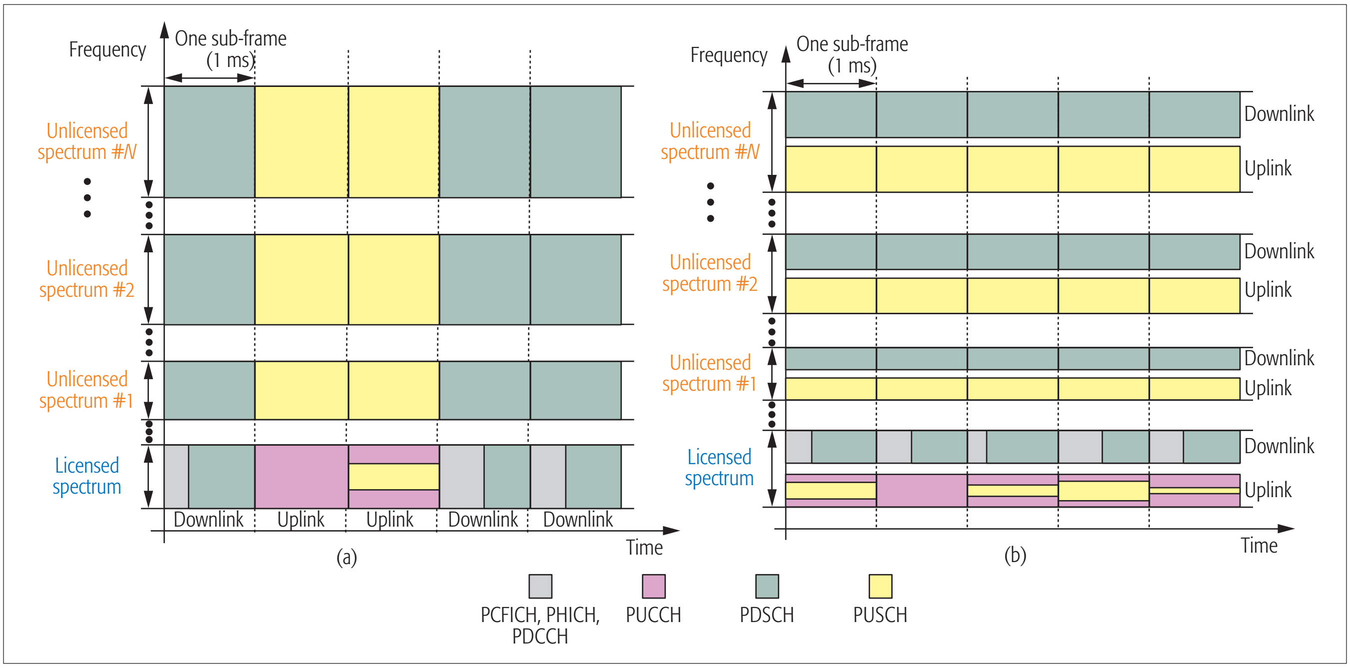

FIGURE 2. Frame structures: a) TDD-LTE-U; b) FDD-LTE-U.

C/U Plane Decoupled LTE-U Architecture

Figure 1 presents our proposed C/U decoupled LTE-U system architecture in which macro-eNBs use superior licensed spectra (normally lower-frequency bands with less interference) to provide macrocell coverage, while dense microcells are covered by dense phantom eNBs with potentially inferior unlicensed spectra (normally higher-frequency bands and more interference) to deal with more severe path loss and power constraints. Due to the negative impact of random and unpredicted interference [12], unlicensed spectra are not suitable for carrying important control messages with high reliability requirements, which include not only the layer 3 (L3) signaling of the C-plane, such as system broadcast, paging, and measurement configuration, but also the L1/L2 signaling of the U-plane, such as scheduling, power control, and hybrid automatic repeat request (HARQ). Therefore, despite U-plane functions implemented at a phantom eNB, the U-plane control information generated at the phantom eNB still needs to be forwarded by a macro-eNB to guarantee reliability. Dense phantom eNBs only provide ultra-wide-bandwidth access for U-plane data traffic on unlicensed spectra. Moreover, if licensed resource is adequate, the U-plane data traffic with high reliability requirements should also be transmitted on licensed spectra. As for the protocol stack, a macro-eNB works as a normal base station with both C-plane and U-plane protocol stacks, while a phantom eNB is only configured with a U-plane protocol stack. For better unlicensed resource utilization, centralized resource management is necessary. However, the huge burden of data management would emerge in this centralized mode. To realize complex resource allocation algorithms and promote computing computational efficiency, we employ a control center in our proposed architecture to manage both the licensed resources of macro-eNBs and the unlicensed resources of phantom eNBs, such as available unlicensed spectrum harvesting and joint licensed/unlicensed resource allocation. It is noticeable that the control center may need to provide the resource management for macro-eNBs and phantom eNBs in multiple macrocells [13, 14]; hence, it should be an individual hardware entity rather than merging into other entities, such as macro-eNB or a mobility management entity (MME)/serving gateway (S-GW). As shown in Fig. 1, fronthaul networks are in charge of establishing the connections among macro-eNB, phantom eNBs, control center, and MME/S-GW, which can be realized by heterogeneous physical media, including wireless point-to-point transmissions, cable, fiber, and so on.

Undoubtedly, keeping C-plane protocol in macro-eNBs will significantly increase the signaling overhead of macro-eNBs, since the macro-eNBs need to provide system broadcast information transmissions for all phantom eNBs and C-plane signaling transmissions for all users covered by it. However, it can also bring in more advantages. First, low complexity, high flexibility, low cost, low energy consumption, and efficient operation could be achieved, which have been discussed above. Second, by centralized radio bearer control in macro-eNBs, an LTE-U network can effectively control the load of each microcell to achieve network-level load balance. Third, due to suffering from interference, the signaling messages transmitted by macro-eNBs with licensed spectra will be more reliable than by phantom eNBs with unlicensed spectra. Finally, centralized C-plane control performed by macro-eNBs can make mobility management more efficient, as discussed below. Because of these benefits, the C/U decoupled architecture with C-plane protocol only deployed in macro-eNBs has been widely regarded as a promising technology for 5G mobile networks [9, 10, 13].

It is noteworthy that the unlicensed spectra used in our proposed LTE-U systems may consist of multiple noncontinuous unlicensed bands with different bandwidth. Thus, the corresponding frame structure would significantly differ from that standardized by recent LTE specifications [15]. Figures 2a and 2b show the frame structures of C/U decoupled time-division duplex (TDD)-LTE-U and FDD-LTE-U, respectively. We assume that the licensed bands of LTE-U systems are continuous. It can be seen that there are only physical downlink shared channel (PDSCH) and physical uplink shared channel (PUSCH) distributed in the subframe of unlicensed spectra with only U-plane data traffic delivery. All sub-frames on licensed spectra should contain both control zone — physical control format indicator channel (PCFICH), physical HARQ indicator channel (PHICH), and physical downlink control channel (PDCCH) for downlink and physical uplink control channel (PUCCH) for uplink — and data zone (PDSCH and PUSCH) to carry all control information and part of the U-plane data traffic. To facilitate resource management and ensure the instantaneity of scheduling and decoding U-plane data traffic, the licensed and unlicensed sub-frames should maintain synchronization in the time domain with the same length. In addition, to carry the extra control information used to manage unlicensed spectra, more licensed resources for control signaling may be employed. For example, the control format indicator of a licensed downlink sub-frame may be more than four orthogonal frequency-division multiplexing (OFDM) symbols, the maximum value standardized in [16], to carry more acknowledgment (ACK)/negative ACK (NACK), scheduling, and power control signaling for unlicensed channels. More or even only PUCCHs are distributed on licensed uplink subframes to carry more ACK/NACK and channel quality information (CQI).

Figure 3 presents our designed unlicensed spectrum management which is divided into two main parts, available unlicensed spectrum harvesting, and joint licensed/unlicensed resource allocation. First, phantom eNB performs periodic or regular spectrum sensing to identify the state of unlicensed spectra and issues the corresponding spectrum sensing report to control center. According to this report, the available unlicensed spectrum harvesting is executed in the control center. After that, the control center sends the spectrum harvesting results to macro-eNB where measurement reconfigurations are performed for all harvested available unlicensed spectra. Second, according to the measurement reconfiguration results from the macro-eNB, phantom eNB transmits reference signal (RS) on unlicensed bands. Meanwhile, the macro-eNB also needs to inform UEs of the results to allow the UEs to measure the RS transmitted by the phantom eNB. After the measurement by a UE, it feeds back a measurement report to the macro-eNB over PUCCH on licensed spectra, which contains the measured CQI of both licensed and unlicensed spectra. After then, all the measurement reports of all UEs are forwarded to the control center via macro-eNB, according to which the centralized joint licensed/unlicensed resource allocation is carried out. Upon receiving the joint resource allocation results, the macro-eNB and the phantom eNB adjust their parameters to transmit on licensed and unlicensed spectra, respectively.

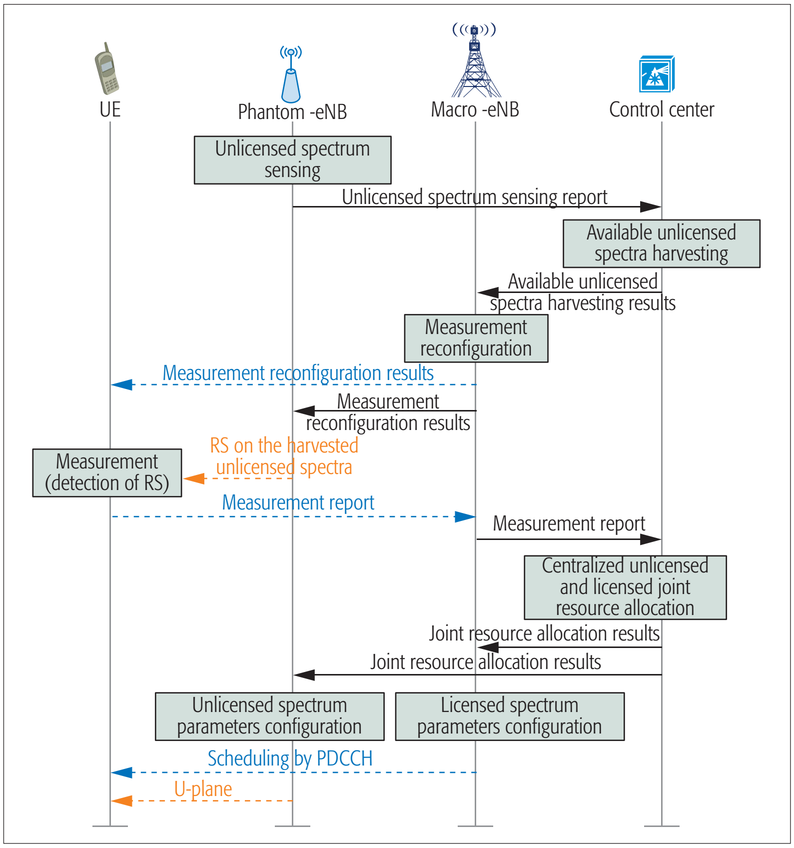

FIGURE 3. Unlicensed spectrum management.

Moreover, based on the allocation results for unlicensed spectra, the macro-eNB provides the corresponding scheduling signaling delivery over PDCCH to enable UE to decode the U-plane data traffic transmitted on unlicensed sub-frames.

Enabling and Supporting Technologies

In this section, we present the enabling and supporting technologies to address the aforementioned design challenges for our proposed C/U decoupled network architecture for LTE-U systems.

Mobility Management

More frequent temporary data transmission interruptions and more handoff failures will be induced with frequent inter-microcell handoff. To tackle this issue, we propose a phantom–phantom seamless handoff scheme based on our proposed LTE-U architecture, illustrated in Fig. 4 and described below. With C/U decoupled architecture, all the radio resource control (RRC) signaling messages related to the handoff procedure are generated in macro-eNBs. In the preparation stage, a user equipment (UE) periodically feeds back its measurement report to its macro-eNB based on the parameter set in the measurement configuration from the macro-eNB. Once the macro-eNB decides to trigger the phantom–phantom handoff according to the measurement report, it delivers the handoff request to the target phantom eNB to inform it of the upcoming handoff and let it perform admission control, namely, preparing and reserving required resources for the UE. Then the target phantom eNB issues the handoff request ACK, carrying the admission

Since the macro-eNB replaces the source phantom-eNB to transmit U-plane data traffic on licensed spectra when handoff is executed, it can avoid the data transmission interruption caused by hard handoff and keep U-plane data traffic transmissions during the whole phantom-phantom handoff procedure, so-called seamless handoff.

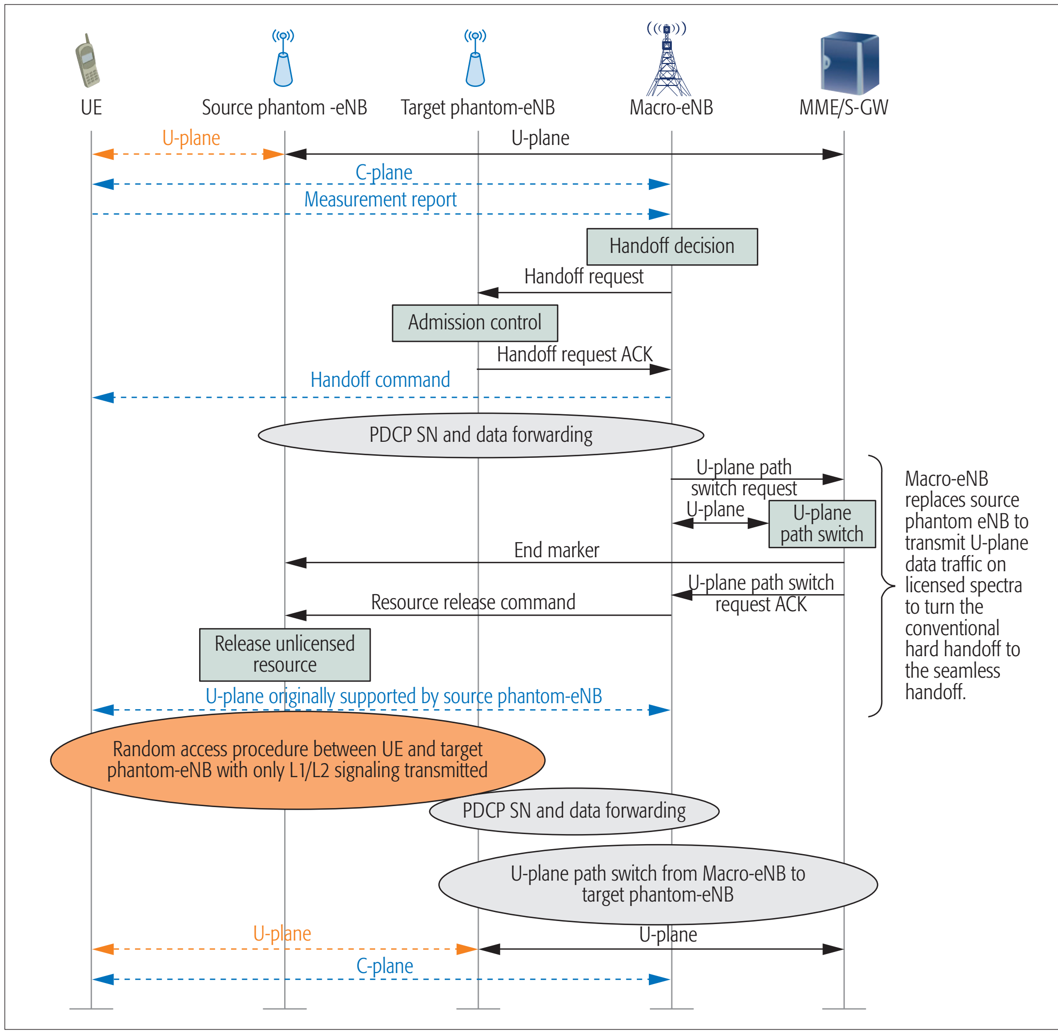

FIGURE 4. The proposed phantom–phantom seamless handoff procedure.

control information, toward the macro-eNB who needs to transparently forward all the admission control information without any modification to the UE in the handoff command. Meanwhile, the macro-eNB and the source phantom eNB exchange Packet Data Convergence Protocol (PDCP) sequence numbers (SNs) with each other to prevent out-of-order packet delivery, duplication, and loss. After that, the macro-eNB asks the corresponding MME/S-GW to switch the U-plane path from the source phantom eNB to the macro-eNB, and replaces the source phantom eNB to transmit U-plane data traffic on licensed spectra. It is noticeable that the UE still resides at the original macrocell after the inter-microcell handoff. Therefore, there is no RRC connection reconfiguration performed in the phantom–phantom handoff, which can be ignored by the RRC layer and regarded as more efficient and less complicated L1/L2 handoff with brief signaling and short latency. Accordingly, the random access between the UE and the target phantom eNB barely possesses an L1/L2 signaling switch; only the physical (PHY) and medium access control (MAC) layers are involved. If the random access succeeds, the handoff execution stage is completed and the completion stage begins, in which the PDCP SNs are exchanged between the target phantom eNB and the macro-eNB, and the U-plane path switching from the macro-eNB to the target phantom eNB is performed. During the handoff procedure, all the signaling messages among the macro-eNB, the phantom eNB, and the MME/S-GW must be transmitted via the fronthaul networks.

Since the macro-eNB replaces the source phantom eNB to transmit U-plane data traffic on licensed spectra when handoff is executed, it can avoid the data transmission interruption caused by hard handoff and keep U-plane data traffic transmissions during the whole phantom–phantom handoff procedure, so-called seamless handoff. Furthermore, even if a phantom–phantom handoff fails, the U-plane data traffic transmission is still preserved by connecting the macro-eNB until an unlicensed link is reestablished. Thus, our proposed phantom–phantom seamless handoff scheme can effectively address the frequent inter-microcell handoff issue. Although the seamless handoff can also be achieved by the dual connection in LTE systems, this seamless handoff is still an L3 handoff with a complex RRC control procedure and more RRC signaling messages transmitted [17]. Compared to that, our proposed seamless handoff is a simpler and more efficient L1/L2 handoff with briefer signaling and shorter latency. As for the inter-macrocell handoff, the macro–macro handoff should first be executed to establish C-plane link connection. Then the phantom–phantom handoff is executed to establish U-plane link connection under the control of the target macro-eNB. Song, Fang, and Yan [18] conducted a detailed design of the inter-macrocell handoff procedure of C/U decoupled architecture, which is not described in this article for brevity.

Spectrum Harvesting

There are two main purposes of spectrum harvesting. The first is to screen out the accessible spectra, complying with government regulations, and the second is to screen out the spectra with better wireless environments. Current schemes for spectrum harvesting can be generally classified into two categories: spectrum sensing and statistical analysis. However, the individual spectrum sensing and the individual statistical analysis can only reflect current and historical average spectrum state, respectively, which cause inaccurate spectrum state identification [19]. Thus, the unlicensed spectrum harvesting schemes should be determined by both spectrum sensing and statistical analysis. In this subsection, we design the spectrum harvesting scheme with both spectrum sensing and statistical analysis considered, which could be practically utilized in our proposed C/U decoupled LTE-U systems. Moreover, notice that, as mentioned before, LTE-U only attempts to utilize the public unlicensed bands at 5.8 GHz. Here, we intend to make it more general by including other unlicensed bands, such as mmWave bands and open licensed bands of other wireless systems. However, most existing spectrum harvesting schemes with both spectrum sensing and statistical analysis considered are proposed to harvest the licensed bands of other systems in cognitive radio systems [19]. For feasibility, we extend this spectrum harvesting method to two other types of unlicensed spectra, namely, unallocated and public unlicensed spectra.

Licensed Spectra of Other Wireless Systems: In spite of the licensed spectra restriction being relaxed by the FCC, an LTE-U system, as a secondary user (SU), can access a licensed band only if it is detected to be unoccupied by primary users (PUs). For this reason, the function of spectrum sensing is to investigate whether a licensed band is busy or idle. However, it is important to note that even if a licensed band is detected to be idle before LTE-U systems access it, it is still possible to cause interference to PUs. This is because the PUs may access the frequency band between the latest spectrum sensing completion and the next spectrum sensing start. Therefore, the control center should set a high priority on selecting the licensed spectra with low traffic load from PUs, or PU load for short. A simple and effective metric can be adopted by the control center to assess the PU load, that is, the ratio of the number of sensed idle licensed bands to the total amount of spectrum sensing needed within a period of time. Obviously, a larger ratio means a lower PU load.

Unallocated Unlicensed Spectra: By checking global spectrum allocation, we find that there is a vast amount of unallocated spectra, particularly on the mmWave spectra between 6 GHz and 300 GHz, which can be used for unlicensed access. Over these spectra, all wireless devices have equal priority to access; therefore, the key factor in spectrum harvesting is the interference environment. First, by spectrum sensing, we can screen out clean spectra based on judgment of whether the sensed interference power of an unlicensed band is lower than a given threshold. To guarantee transmission quality, LTE-U systems should have priority to access the unlicensed spectra with low probability of suffering from abrupt and unpredicted interference, which is proportional to the load level. Thus, second, the control center can adopt the ratio of the number of unlicensed bands sensed to be clean to the total number of spectrum sensing within a period of time to estimate the load level.

Public Unlicensed Spectra (e.g., 2.4 GHz, 5.8 GHz, 24 GHz, 60 GHz ISM Bands, and 5.4–5.7 GHz UNII Bands): As the most critical issue, the coexistence between LTE-U and WiFi systems must be considered when designing spectrum harvesting schemes for public unlicensed spectra. According to [20], due to the specific carrier sense multiple access with collision avoidance (CSMA/CA) mechanism used for WiFi systems, once an LTE-U device transmits on an unlicensed band, all WiFi devices under the coverage of the LTE-U device would not access the unlicensed band anymore. Since public unlicensed spectra are opened up for each wireless device with equal priority, continuous occupancy by LTE-U devices will not violate any law or regulation, but will not be fair for other devices accessing this band via other protocols, such as IEEE 802.11 MAC protocols for WiFi systems. Therefore, LTE-U systems should also opportunistically access and proactively release the public unlicensed spectra for WiFi systems for fairness. Song and Fang [20] put forward a coexistence scheme that can achieve this goal. For engineering implementation, a novel WiFi detection module is also designed, which can enable eNBs in LTE-U systems to carry out signal detection during the 802.11 PHY frame and transmit the 802.11 PHY frame. The coexistence scheme can be described as follows. When the status of a public unlicensed band turns from busy to idle, initial spectrum sensing is performed by the WiFi detection module. If the band stays in idle status until the spectrum sensing is over, the eNB accesses this band and broadcasts LTE-U occupancy time information to all WiFi devices in the form of an 802.11 PHY frame. If the existing WiFi devices attempt to access the band, the eNB shall not access this band and decodes the 802.11 PHY frame header with the WiFi detection module to obtain frame length information, after which it reruns the spectrum sensing. It is worth noting that the length of the spectrum sensing determines the priority for LTE-U devices with respect to WiFi devices, which gradually decreases with the increase of spectrum sensing time. According to [21], WiFi devices would not access the frequency band that has been occupied. Thus, based on the coexistence scheme in [20], the public unlicensed spectrum harvesting can be determined only through spectrum sensing.

QoS Guaranteed Spectrum Allocation

Apparently, traffic with high reliability requirements is more suited to be carried by licensed spectra than by unlicensed spectra. Unfortunately, finite and scarce licensed resources cannot carry

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Without question, all kinds of control messages should be ranked highest in priority. Thus, a coarse priority classification from high to low can be control messages: U-plane data traffic with high QoS and that with low QoS. A fine priority classification should consider other performance metrics, such as traffic types and economic aspects.

all that traffic, part of which needs to be offloaded to the unlicensed spectra with preferable reliability. In this subsection, we study a joint licensed/unlicensed spectra allocation scheme to guarantee the QoS of each kind of traffic with as high reliability as possible. For this purpose, we need to address the QoS-based traffic priority classification and the unified reliability utility criterion for all unlicensed and licensed channels.

QoS-Based Traffic Priority Classification: Reliable transmissions of control messages directly impact normal network access, link quality maintenance, and network performance optimization, which is also a fundamental requirement for effective U-plane data traffic transmissions. Without question, all kinds of control messages should be ranked highest in priority. Thus, a coarse priority classification from high to low can be control messages: U-plane data traffic with high QoS and that with low QoS. A fine priority classification should consider other performance metrics, such as traffic types and economic aspects. For instance, different kinds of control messages are classified with different priorities based on traffic types. Another example is that the traffic from high-cost UE should have higher priority than that from UE pursuing low cost.

Unified Reliability Utility for Unlicensed and Licensed Bands: Ideally, the utility of channel reliability should be determined by actual channel state [22, 23]. However, in practical operation, when resource allocation needs to be made, the actual channel state is always unknown and can only be estimated based on the measured one. As for a licensed channel, it can be assumed that no interference exists, and the measured channel state is approximate to the actual one under the assumptions of low mobility and flat fading channel. Therefore, the reliability utility of that can be determined solely by the current measured channel state. However, on an unlicensed channel with uncontrollable interference, abrupt and unpredictable interference may cause a significant gap between the actual channel state and the measured one. This gap may make resource allocation unable to reach the planned transmission performance, even causing high bit error rate (BER) and link outage [24]. Hence, we define a reliability utility for unlicensed channels that considers both the current measured channel state and the potential gap between the measured and actual channel state, also referred to as channel instability.

$$U_{reliability} = \underbrace{10 \cdot \log_{10}(1+SINR_{RS}(t))}_{\substack{\text{reward function with the current}\\ \text{measured channel state}}} - \varepsilon \cdot \underbrace{\frac{\sum_{t=T-W_\tau}^{T} \log_2\left(1+\frac{|I(t)-I(t-\tau)|}{\Delta I_{ref}}\right)}{W+1}}_{\substack{\text{pricing function with the statistical}\\ \text{channel instability degree}}} \quad (1)$$

where $I(t)$ and $SINR_{RS}(t)$ represent the received interference power and signal-to-interference-plus-noise ratio (SINR) on an unlicensed channel at time t obtained from spectrum sensing and RS measurement, respectively. Assume that T is the current time, and the resource allocation for the signal transmissions at t is carried out based on the channel measurement at $t - \tau$. According to [25], proper utility functions should exhibit three main properties, including twice differentiability, monotonicity, and concavity/convexity. The logarithmic functions can meet all these properties, which will be used to form the reliability utility in this article. The first term in Eq. 1 is dependent on the current measured channel state. In the second term, we employ

$$\log_2\left(1+\frac{|I(t)-I(t-\tau)|}{\Delta I_{ref}}\right)$$

as the channel instability criterion to characterize the difference degree between measured and actual channel state, which experiences logarithmic increase with the growth of $|I(t) - I(t - \tau)|$. ΔI_{ref} is a referenced gap, which should be different for different kinds of traffic. For example, traffic with high reliability requirements should get small ΔI_{ref}, with QoS more sensitive to channel reliability. As a long-term statistic, we define the channel instability degree, namely, the second term in Eq. 1, as the arithmetic mean of the channel instability criteria within a period of $W + 1$. It is apparent that the first term in Eq. 1 stands for a channel reliability estimation based on current measured channel state, while the second term could reflect the potential risk for the accuracy of that. Thus, the first term and the second term are taken as the reward and pricing function, respectively. ε is a weight to adjust pricing factor.

Joint Licensed/Unlicensed Resource Allocation: With our proposed reliability utility, the control center can normalize all unlicensed and licensed channels to the unified wireless resources with different reliability performance to perform joint licensed/unlicensed resource allocation. The joint resource allocation can be divided into two consecutive steps. The first step is channel scheduling under the assumption of equal power distribution across all channels, described as follows. First, the control center calculates the reliability utility value for each UE on each licensed channel and each harvested unlicensed channel, respectively. Then it finds the packet with highest-priority traffic in the transmission queue, and schedules the packet transmission with the channel that has the largest reliability utility for the intended UE. The allocation process is repeated until the allocated channels can satisfy the traffic requirements. When all the packets in the queue have been scheduled, the first step is complete. After that, the second step is to distribute power to the allocated channels with proportional reliability and traffic requirement constraints. The basic idea is to allocate adequate power to meet the reliability constraint of each type of traffic, particularly the traffic allocated the lower reliability utility channels, aiming to achieve the proportional fairness among the traffic while maintaining the QoS guarantee of each traffic type. Note that since the packets with lower priority may be allocated lower reliability utility channels, multiple retransmissions may be needed due to high BER and link outage. For fairness, after every transmission failure, the priority of the failed packet should be raised properly. In this way, more reliable channels will be allocated to the retransmitted packet in the next resource allocation round to improve transmission success probability.

Performance Evaluation

In this section, we conduct a simulation study to investigate the link robustness for our proposed C/U decoupled LTE-U systems. In the simulation, the link transmission performance of a user is investigated under different transmission distances and received interference power. Moreover, we also consider the C/U coupled LTE-U systems to make comparisons, in which control information and U-plane data traffic are supported by the same eNB and transmitted on the same frequency band. In LTE-U systems, the essential condition to ensure that the U-plane data traffic transmitted over PDSCH on unlicensed spectra is successfully received by UE is that the control information, such as scheduling signaling transmitted over PDCCH, is successfully received first [26]. Since control information always contains lower data volume, and adopts a low-rate modulation and coding scheme (MCS) to guarantee reliable transmissions, we can assume that the control information would be successfully transmitted if the received SINR exceeds a predefined threshold. Accordingly, we can calculate the effective spectral efficiency of U-plane data traffic by

$$C_{U-plane}^{effective} = P(SINR_{control} > \eta) \cdot \log_2(1 + SINR_{U-plane}),$$

where η, $SINR_{U\text{-}plane}$ and $SINR_{control}$ denote the predefined threshold, the received signal SINR of U-plane data traffic, and the corresponding control information, respectively. As for delay, it can be calculated by

$$D = \sum_{i=1}^{\infty} i \cdot \bar{D} \cdot (1 - P_{success})^{i-1} \cdot P_{success} = \bar{D}/P_{success},$$

where

$$P_{success} = P(SINR_{control} > \eta) \cdot P(SINR_{U\text{-}plane} > \gamma)$$

represents the successful transmission probability of one-round U-plane data transmissions. γ and $\bar{D}$ denote the received signal SINR threshold that can ensure successful U-plane data transmissions and the average delay caused by one round, respectively. In the simulation, the computations of $P(SINR_{control} > \eta)$ and $P(SINR_{U-plane} > \gamma)$ adopt the method provided in [18]. The main simulation parameters are listed in Table 1.

Parameters	Values
Transmit power on licensed spectra	46 dBm/10 MHz
Transmit power on unlicensed spectra	30 dBm/10 MHz
Path loss model for urban macrocell	$39 + 26 \cdot \log_{10}(d[\mathrm{m}]) + 20 \cdot \log_{10}(f_c[\mathrm{GHz}]/5)$
Path loss model for urban microcell	$41 + 22.7 \cdot \log_{10}(d[\mathrm{m}]) + 20 \cdot \log10(f_c[\mathrm{GHz}]/5)$
Log-normally distributed shadow fading deviation for macrocell	6 dB
Log-normally distributed shadow fading deviation for microcell	3 dB
Licensed carrier frequency	2 GHz
Unlicensed carrier frequency	6 GHz
η	–6 dB
γ	0 dB
$\bar{D}$	5 ms
N_0	–174 dBm/Hz

TABLE 1. Simulation parameters [27, 28].

Figure 5 presents the effective spectral efficiency of the unlicensed spectra, which are used to carry U-plane data traffic, vs. received interference power. Assume that in C/U coupled LTE-U systems, U-plane data traffic and the corresponding control information are all transmitted by a micro-eNB on the same unlicensed band, while they are transmitted by a phantom eNB on unlicensed band and a macro-eNB on licensed band, respectively, in our proposed C/U decoupled LTE-U systems. Figure 5a shows that the effective unlicensed spectral efficiency of the C/U coupled LTE-U systems is always lower and more sensitive to the growth of received interference power than that of the C/U decoupled LTE-U systems. This is because the interference on unlicensed spectra brings in the negative impact on not only the received signal SINR of U-plane data traffic, but also the transmission success probability of control information in the C/U coupled way, while the C/U decoupled LTE-U systems can effectively alleviate this negative impact by transmitting control information on reliable licensed spectra. From Fig.5b, we can see that with the growth of received interference power, the effective unlicensed spectral efficiency of the C/U coupled LTE-U system rapidly declines. When the received interference power is raised to $3.5 \times 10_{-7}$ mW/10 MHz, the effective unlicensed spectral efficiency of the C/U coupled LTE-U system becomes lower than that of the C/U decoupled LTE-U system, which has experienced high propagation loss on licensed spectra (at 1500 m distance between a UE and the macro-eNB). Both Figs .5a and 5b demonstrate that our proposed C/U decoupled LTE-U systems could achieve significantly higher spectral efficiency in strong interference environments. The same conclusion can also be drawn from Fig. 6, which illustrates the transmission delay of U-plane data traffic caused by transmission failures and retransmissions vs. received interference power. Obviously, with transmitting control information on reliable licensed spectra, the transmission success probability of control information is higher than that transmitted on unlicensed spectra, which results in higher transmission success probability of U-plane data traffic and fewer retransmissions. Hence, the U-plane data traffic delay of our proposed C/U decoupled LTE-U systems is always lower than that of the C/U coupled LTE-U systems, and the delay increase is slower with the growth of received interference power, especially in strong interference environments.

Discussion and Future Challenges

Clearly, despite many disadvantages in using unlicensed bands in LTE systems, with proper novel design, such as deploying C/U decoupled network architecture and innovative enabling tech-

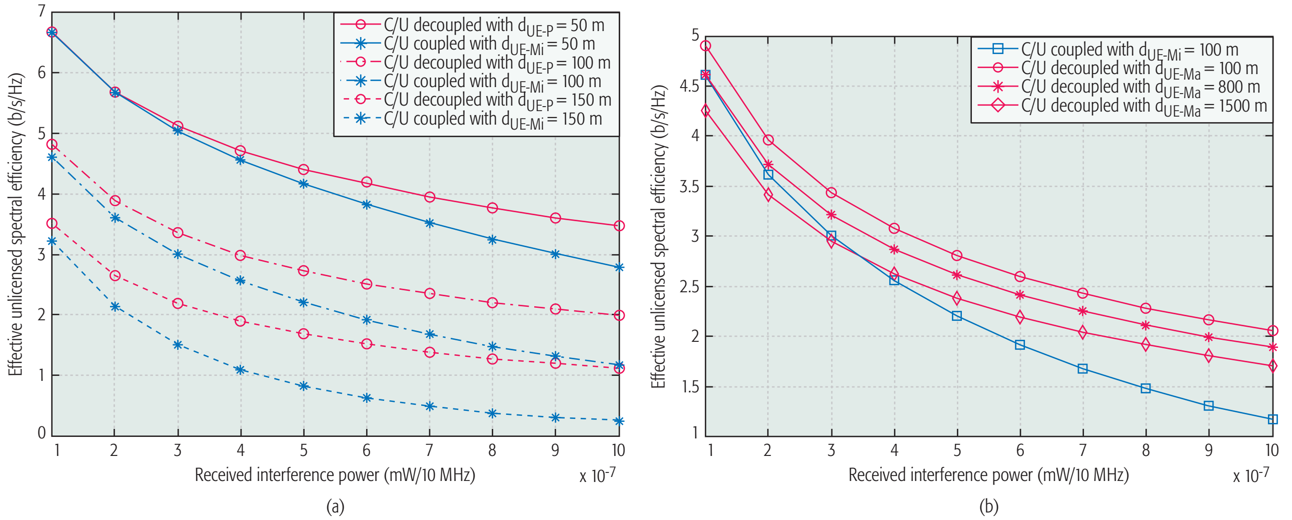

FIGURE 5. Effective unlicensed spectral efficiency vs. received interference power: a) for different UE-phantom/micro distances d_{UE-P}/d_{UE-Mi} with a fixed UE-macro distance 500 m; b) for different UE-macro distances d_{UE-Ma} with a fixed UE-phantom /micro distance 100 m.

nologies, we can bring in tremendous capacity enhancement to LTE-U systems. However, both C/U decoupled architecture and unlicensed spectra opportunistic access have been viewed as the promising key technologies of 5G mobile networks. Therefore, apart from two most fundamental performance indicators (i.e., spectral efficiency and transmission delay), more 5G required key performance indicators should also be evaluated for our proposed C/U decoupled LTE-U systems, such as latency caused by signaling congestion, handoff latency, connection density, and traffic volume density. Moreover, some challenges are still unresolved and need more comprehensive and deeper studies to make our design effective for practical use. Here, we discuss the remaining challenges, which could be our future research issues.

Interference coordination is a big and inevitable challenge for each dense microcell network. Network-level centralized resource allocation is an effective way to perform interference coordination among microcells. However, the computation complexity of centralized resource allocation algorithms may be high, which would pose design challenges for engineering implementation. Beamforming technologies used in phantom eNBs to carry out interference coordination were introduced in [9]. Besides higher received SINR brought by beams, strong directional transmissions can effectively suppress the interference to other users. Moreover, new issues are also emerging; for example, in mobility management, how to measure the beam signal of adjacent phantom eNBs to trigger handoff, and how to perform accurate and efficient beam training in handoff.

The frequency of resource re-allocation should be high enough to promptly adapt to radio environment variation. However, frequent centralized resource re-allocation can greatly increase signaling overhead and system burden. Hence, how to find a reasonable resource re-allocation triggering mechanism to effectively reduce the frequency of resource re-allocation, while ensuring the resource re-allocation to be promptly triggered to adapt to radio environment variation, is an important issue. To address this, we propose a semi-opportunistic and semi-periodic resource re-allocation triggering mechanism described as follows. By using unlicensed spectrum harvesting, if the control center finds that the available channel set of each phantom eNB has changed, new channels have been harvested, or old channels have been eliminated, the centralized resource re-allocation is triggered immediately. This can make LTE-U systems opportunistically trigger the resource re-allocation according to the variations of interference environments to reduce the frequency of that. If no change happens in the available channel sets, the resource re-allocation will not be triggered until the change happens in later spectrum harvesting, or the countdown of the resource re-allocation timer goes to zero. When a resource re-allocation procedure is finished, the timer goes to an initial value. It is easy to see that even if the resource re-allocation cannot be triggered by the variations of interference environments, it will also be triggered at least once within the duration of the timer, which can let LTE-U systems promptly adjust resource allocation parameters to adapt to the variations of radio environments caused by user mobility. In future research, we will improve our proposed mechanism by optimizing the unlicensed spectrum harvesting cycle and resource re-allocation timer based on interference environments and user mobility.

Three main performance indicators impact quality of experience (QoE): data rate, cost, and the relevant indicators related to reliability, such as signal error probability and link outage probability. Both lowering cost and boosting reliability can improve the QoE. However, the enhancement of one of them always causes the deterioration of the other. This is because lowering cost always means more unlicensed channels used to support data transmissions with low reliability, while boosting reliability always needs to use more costly licensed channels. Thus, maximizing global QoE could be a good optimization objective for joint unlicensed/licensed resource allocation to find an excellent

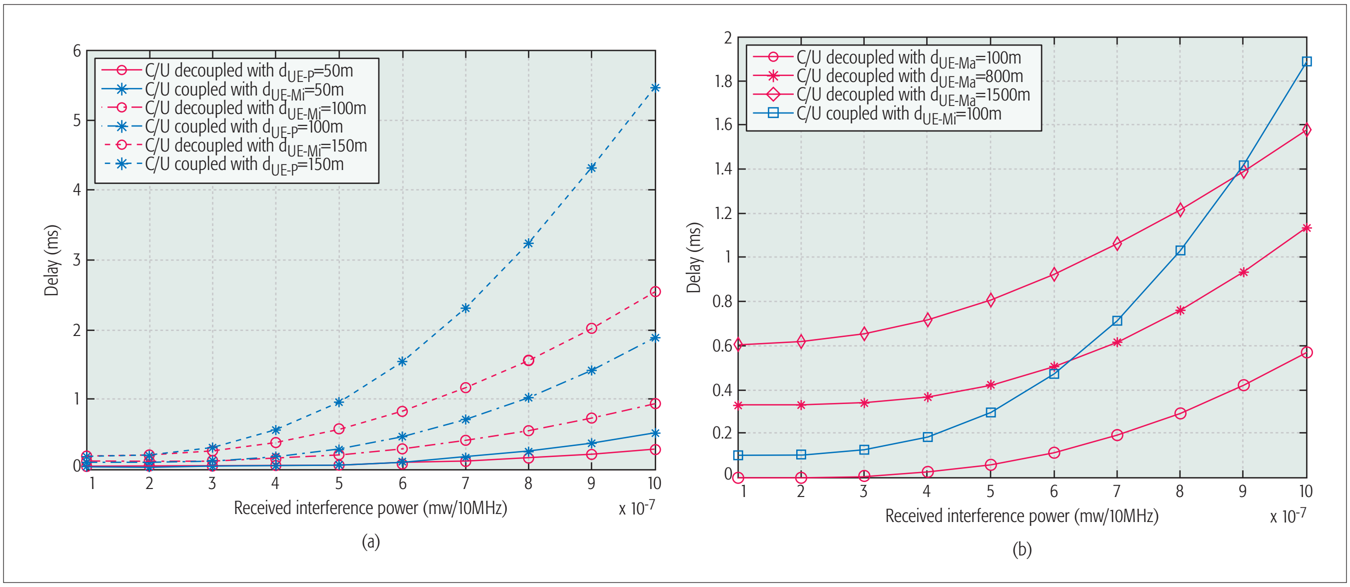

FIGURE 6. Delay vs. received interference power: a) for different UE-phantom/micro distances d_{UE-P}/d_{UE-Mi} with a fixed UE-macro distance 500m; b) for different UE-macro distances d_{UE-Ma} with a fixed UE-phantom/micro distance 100m.

balance between cost and reliability, which is a potential research topic.

Conclusions

Utilizing unlicensed spectra in LTE-U systems holds the promise of alleviating licensed spectra scarcity and enhancing capacity. However, how to efficiently utilize unlicensed spectra to boost performance is challenging and of paramount importance. In this article, we first analyze the challenges encountered in the actual applications of LTE-U systems. To address these challenges, we have proposed a C/U decoupled LTE-U system, which significantly differs from the popular standard LTE-U systems in terms of the utilization of licensed spectra and unlicensed spectra. For feasibility, we design a novel framework and the corresponding system procedures for our proposed C/U decoupled LTE-U systems, including network architecture, frame structure, and centralized resource management. To further improve and optimize our proposed C/U decoupled LTE-U systems, we also put forward the enabling and supporting technologies, including a phantom–phantom seamless handoff scheme, spectrum harvesting for different types of unlicensed bands, and QoS guaranteed joint licensed/unlicensed resource allocation. Our extensive simulations show that our proposed C/U decoupled LTE-U systems could achieve significantly better performance on both effective unlicensed spectral efficiency and transmission delay than C/U coupled LTE-U systems. Finally, we discuss several remaining research challenges, which could be our future research issues.

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References

[1] CISCO Whitepaper, "CISCO Visual Networks Index: Global Mobile Data Traffic Forecast Update 2015–2020," Feb. 2015.

[2] H. Zhang *et al.*, "Coexistence of WiFi and Heterogeneous Small Cell Networks Sharing Unlicensed Spectrum," *IEEE Commun. Mag.*, vol. 53, no. 3, Mar. 2015, pp. 158–64.

[3] http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0714/DOC-340310A1.pdf

[4] S. Yin *et al.*, "Mining Spectrum Usage Data: A Large-Scale Spectrum Measurement Study," *IEEE Trans. Mobile Comp.*, vol. 11, no. 6, June 2012, pp. 1033–46.

[5] S. M. Mishra *et al.*, "A Real Time Cognitive Radio Testbed for Physical and Link Layer Experiments," *Proc. DySPAN 2005*, Baltimore, MD, Nov. 2005, pp.562–67.

[6] M. A. McHenry *et al.*, "Chicago Spectrum Occupancy Measurements and Analysis and A Long-term Studies Proposal," *Proc. TAPAS 2006 Conf.*, Boston, MA, Aug. 2006.

[7] FCC, "Spectrum Policy Task Force Report," Et docket, No. 02-135, Nov. 2002.

[8] 3GPP TS 36.331, "A Radio Resource Control (RRC) Protocol Specification, v10.0.0," Mar. 2013.

[9] J. G. Andrews *et al.*, "What Will 5G Be?" *IEEE JSAC*, vol. 32, no. 6, June 2014, pp.1065–82.

[10] C. L. I *et al.*, "New Paradigm of 5G Wireless Internet," *IEEE JSAC*, vol. 34, no. 3, Mar. 2016, pp. 474–82.

[11] H. Zhai, J. Wang, and Y. Fang, "DUCHA: A New Dual-Channel MAC Protocol for Multihop Ad Hoc Networks," *IEEE Trans. Wireless Commun.*, vol. 5, no. 11, Nov. 2006, pp. 3224–33.

[12] Y. M. Shobowale and K. A. Hamdi, "A Unified Model for Interference Analysis in Unlicensed Frequency Bands," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, Aug. 2009, pp. 4004–13.

[13] S. Zhou *et al.*, "Software-Defined Hyper-Cellular Architecture for Green and Elastic Wireless Access," *IEEE Commun. Mag.*, vol. 54, no. 1, Jan. 2016, pp. 12–19.

[14] P. Demestichas *et al.*, "5G on the Horizon: Key Challenges for the Radio-Access Network," *IEEE Vehic. Tech. Mag.*, vol. 8, no. 3, July 2013, pp. 47–53.

[15] 3GPP TS 36.211, "Physical Channels and Modulation, v11.4.0," Sept. 2009.

[16] 3GPP TS 36.212, "Multiplexing and Channel Coding, v11.2.0," Feb. 2013.

[17] M. C. Chuang and M. C. Chen, "NASH: Navigation-Assisted Seamless Handover Scheme for LTE-A Smallcell Networks," *Proc. 2015 IEEE ICC*, London, U.K., June 2015, pp. 3952–57.

[18] H. Song, X. Fang, and L. Yan, "Handover Scheme for 5G C/U Plane Split Heterogeneous Network in High-Speed Railway," *IEEE Trans. Vehic. Tech.*, vol. 63, no. 9, Apr. 2014, pp. 4633–46.

[19] M. Pan *et al.*, "Spectrum Harvesting and Sharing in Multi-Hop CRNs under Uncertain Spectrum Supply," *IEEE JSAC*, vol. 30, no. 2, Feb. 2012, pp. 369–78.
[20] H. Song and X. Fang, "A Spectrum Etiquette Protocol and Interference Coordination for LTE in Unlicensed Bands (LTE-U)," *Proc. IEEE ICC 2015 Wksp. LTE in Unlicensed Bands: Potentials and Challenges*, London, U.K., June 2015, pp. 2338–43.
[21] E. Perahia and R. Stacey, *Next Generation Wireless LANs Throughput, Robustness, and Reliability in 802.11n*, Cambridge Univ. Press, 2008.
[22] W. Q. Xu *et al.*, "Distributed Optimal Rate-Reliability-Lifetime Trade-off in Time-Varying Wireless Sensor Networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 9, July 2014, pp. 4836–47.
[23] J. W. Lee, M. Chiang, and A. R. Calderbank, "Price-Based Distributed Algorithms for Rate-Reliability Trade-Off in Network Utility Maximization," *IEEE JSAC*, vol. 24, no. 5, May 2006, pp. 962–76.
[24] M. Assaad, "Reduction of the Feedback Delay Impact on the Performance of Scheduling in OFDMA Systems," *Proc. IEEE VTC-Fall 2009*, Anchorage, AK, Sept. 2009, pp. 1–4.
[25] Q. T. Nguyen-Vuong *et al.*, "Multicriteria Optimization of Access Selection to Improve the Quality of Experience in Heterogeneous Wireless Access Networks," *IEEE Trans. Vehic. Tech.*, vol. 62, no. 4, Dec. 2012, pp. 1785–1800.
[26] 3GPP TS 25.321, "Medium Access Control (MAC) Protocol Specification, v11.0.0," Dec. 2011.
[27] 3GPP TR 36.814, "Further Advancements for E-UTRA Physical Layer Aspects, v9.0.0," Mar. 2010.
[28] WINNER II Channel Models Part II, "Radio Channel Measurement and Analysis Results," D1.1.2, V1.2, Dec. 2007.

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