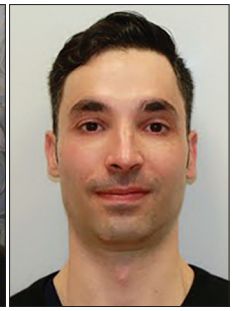
LTE IN UNLICENSED SPECTRUM





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Fifth generation (5G) cellular networks will face a rigorous challenge in the ever increasing data rate requirement. To meet such anticipated data growth demand, the industry and academia have developed many cutting edge techniques to improve spectrum utilization. However, the scarcity of spectral resources is still a fundamental bottleneck for network capacity enhancement. Recently, the rich available bandwidth on the 5.8 GHz unlicensed national information infrastructure (U-NII) spectrum has stimulated substantial interest from cellular operators to use the unlicensed spectrum for LTE. In 2015, the LTE-Unlicensed (LTE-U) Forum formally launched the LTE-U specification, and the Third Generation Partnership Project (3GPP) has pushed the standardization of licensed assisted access (LAA) into its Releases 13 and 14. However, the LTE-U technology is still in its infancy, and there are lots of challenges that need to be solved, such as network coexistence among different radio access technologies, unlicensed spectrum sharing and access, and quality of service (QoS) provision on unlicensed spectrum. This Feature Topic aims to provide a comprehensive overview of this appealing technology, harmonizing recent results and key challenges, as well as highlighting future important directions.

Our Call for Papers received a large number of high-quality worldwide submissions. After a rigorous review process, the eight best papers were finally selected for this Feature Topic. These articles cover various design issues such as network architecture, protocol development, network coexistence, unlicensed spectrum access, and practical implementation.

The article "Comprehensive Spectrum Management for Heterogeneous Networks in LTE-U," by T. Maksymyuk *et al.*, introduces a novel unlicensed spectrum access protocol, carrier sense LTE unlicensed access (CASLUA). The significance of this proposal is that it can be implemented in the standalone LTE-U mode, which is found to be a formidable hurdle in many other coexistence mechanisms. Moreover, it can also deal with the challenging task of utilizing the unlicensed spectrum for multi-tier heterogeneous networks including macrocells, small cells, and even device-to-device (D2D) communications. Related issues of deploying CASLUA in practical heterogeneous LTE networks are discussed in detail in this article.

The next three articles investigate various coexistence issues of LAA and WiFi. The article "Share in the Commons: Coexistence between LTE Unlicensed and Wi-Fi," by J. Li *et al.*, analyzes the network performance of LAA and WiFi coexistence. The merit of this work lies in introducing the stochastic geometry tool for network coexistence analysis, whereas most current works focus on simulation test. The results reveal that the energy detection threshold in the Listen Before Talk (LBT) protocol is essential for both throughput maximization and fair coexistence of LAA and WiFi. In addition, some important challenges related to the stochastic-geometry-based analytical approach are also highlighted in this article.

The article "Design and Evaluation of Licensed Assisted Access LTE in Unlicensed Spectrum," by L. Falconetti *et al.*, focuses on the performance evaluation of the LBT protocol in an LAA and WiFi coexistence network. Extensive performance evaluation results are given in various network coexistence scenarios. The results highlight that it is important to dynamically adapt the LBT parameters, such as the energy detection threshold and the freeze period, to ensure fair network coexistence. Furthermore, the extension of LBT protocols to support multiple and uplink unlicensed channel access is also discussed in this article.

The article "Configurable 3GPP Licensed-Assisted Access to Unlicensed Spectrum," by S.-Y. Lien *et al.*, deals with the transmission inefficiency and radio access inefficiency of LAA and WiFi coexistence. Four formidable obstacles for deploying LTE-Advanced networks on the unlicensed spectrum are illustrated in this article. To deal with the LAA-WiFi hidden terminal problem, a configurable transmission and radio access protocol based on the measurement results of WiFi radio activity is proposed. In addition, a game-theoretic pricing strategy on the licensed and unlicensed bands is introduced to improve the resource utilization of unlicensed spectrum sharing. The work suggests that the LAA performance can be significantly enhanced by utilizing the measured WiFi radio activity.

The article "Beyond Coexistence: Traffic Steering in LTE Networks with Unlicensed Bands," by N. Zhang *et al.*, provides a new vision of exploiting unlicensed spectrum to improve the network utilization from the perspective of upper-layer traffic steering. After reviewing the state-of-the-art unlicensed spectrum sharing techniques, the application and detailed approach of applying traffic steering to the LTE-U network are discussed. Through a comprehensive case study, the performance in terms of network throughput and service delay can be dramatically improved by proper traffic steering strategies. Some future

research challenges are also highlighted later in this article.

The article "Fronthauling for 5G LTE-U Ultra Dense Cloud Small Cell Networks," by H. Zhang *et al.*, investigates the fronthaul technology in LTE-U-based ultra-dense cloud small cell networks. The advantages and challenges for various candidate fronthaul technologies, including optical fiber, millimeter-wave unlicensed spectrum, WiFi unlicensed spectrum, sub-6-GHz licensed spectrum, and free-space optical unlicensed spectrum, are highlighted. This article reveals that utilizing unlicensed millimeter-wave or unlicensed WiFi spectrum can bring benefits for fronthaul capacity improvement and deployment cost reduction.

Due to the lack of an inter-operator coordinator, distributed resource allocation among multiple systems is an important issue for LTE-U implementation. To this end, the last two articles introduce game theoretical approaches to analyze the network coexistence and resource allocation of LTE-U networks. The article "LTE-Unlicensed Coexistence Mechanism: A Matching Game Framework," by Y. Gu *et al.*, presents a matching game framework to deal with the coexistence of LTE and WiFi in the same unlicensed spectrum. Through comprehensive case studies, the work demonstrates the great potential of match games in solving the coexistence problem. Practical implementation details and future directions are also illustrated in this article.

The article "A Multi-Game Framework for Harmonized LTE-U and WiFi Coexistence over Unlicensed Bands," by K. Hamidouche *et al.*, introduces a multi-game framework to model resource allocation problems in LTE-U networks. Different from single games, multi-games can capture all the specific characteristics of the complicated coexisting network and therefore show good capability in dealing with various LTE-U resource allocation problems. After introducing the main idea and algorithmic solutions, this work further illustrates how to apply multi-game models for LTE-U and presents some key results from a detailed case study.

Finally, we would like to thank all authors for their submissions and all reviewers for their timely and professional reviews. We also acknowledge the guidance from the Editor-in-Chief of *IEEE Wireless Communications* and the support from the publication staff.

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