BEYOND COEXISTENCE: TRAFFIC STEERING IN LTE NETWORKS WITH UNLICENSED BANDS

NING ZHANG, SHAN ZHANG, SHAOHUA WU, JU REN, JON W. MARK, AND XUEMIN SHEN

ABSTRACT

In this article, we study how to efficiently utilize heterogeneous network resources for various service provisioning in LTE networks with unlicensed bands. Our focus is on traffic steering, which is to intelligently distribute traffic among heterogenous cells, radio access technologies, and spectrum bands based on the desires of the network or users. We first highlight the significance of traffic steering, and then present the typical applications and approaches for traffic steering. After that, discussions on how to leverage unlicensed bands for traffic steering are provided, followed by case studies to demonstrate the benefits of traffic steering. Finally, some research issues essential for traffic steering in LTE networks with unlicensed bands are identified.

INTRODUCTION

Mobile traffic has dramatically increased and will continue to skyrocket in the next decade, due to the proliferation of devices and emergence of data-hungry applications. It is predicted to grow at a compound annual growth rate (CAGR) of 59 percent and reach 24.3 exabytes per month by 2019 [1]. To accommodate such a mobile traffic surge, more spectrum can be added to boost network capacity. However, spectrum is very scarce and therefore costly. Recently, there is great interest in exploring unlicensed bands to meet the massive traffic demand [2]. This method helps augment the capacity and bandwidth available to LTE systems, lower the network operators' operational expenditure (OPEX), and provide better quality of service (QoS) and quality of experience (QoE) to users.

The key issue for LTE networks to exploit unlicensed bands, especially 5 GHz band, is the coexistence issue with Wi-Fi systems [3]. Wi-Fi is adopting contention-based access and carrier sensing technologies, enabling fair sharing in unlicensed bands. However, LTE is adopting scheduling-based access technology for licensed band operation. Expanding LTE to unlicensed bands will have a detrimental impact on Wi-Fi. To enable fair coexistence between LTE and Wi-Fi, extensive research efforts have been made from both academia and industry. The techniques for harmonious coexistence include channel selection, carrier sensing adaptive transmission (CSAT) in LTE-Unlicensed (LTE-U), and Listen Before Talk (LBT) in licensed assisted access LTE (LAA-LTE). LTE-U is proposed by Qualcomm based on Third Generation Partnership Project (3GPP) Releases 10–12 without modification of the LTE air interface, while LAA-LTE will be standardized in 3GPP Release 13 in 2016 [4].

With the significant research and standardization efforts, the coexistence issue should be resolved [4, 5]. Then operators will face a network featuring multi-dimensional heterogeneity in terms of access technologies, diverse cells, divergent operating spectrum bands (licensed and unlicensed), and traffic distribution with various QoS requirements. In such a network, one fundamental and critical issue is how to make efficient use of diverse network resources while providing satisfactory QoS to users. On one hand, the heterogeneous network provides opportunities to exploit specific advantages of certain technologies or resources for different services. On the other hand, it also results in technical challenges to improve network unitization and user experience due to multi-dimensional heterogeneity and highly dynamic network environments.

As a promising method, traffic steering aims to distribute the traffic load optimally across different network entities and spectrum bands in order to achieve diverse objectives of both network operators and users [6, 7]. Therefore, traffic steering should be granted more attention from both academia and industry. In this article, we first review the state-of-the-art progress in expanding LTE in unlicensed bands. Then we provide our vision for future mobile networks with unlicensed bands, featuring heterogenous cells, radio access technologies (RATs), spectrum bands, as well as traffic types and distribution. In such a network, we highlight the necessity and importance of traffic steering, followed by typical traffic steering applications. In addition, approaches to traffic steering are presented from different perspectives, and a two-layer traffic steering framework is introduced. To fully harvest the benefits of traffic steering, we also discuss how to facilitate traffic steering by exploiting unlicensed bands. Case studies are also carried out to demonstrate the advantages of traffic steering. Finally, research topics are identified and discussed.

The remainder of this article is organized as follows. The unlicensed band exploitation

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Candidate	Features	Merits	Demerits
Carrier Wi-Fi	Deploys operators' own Wi-Fi network	Easy to deploy	Lacks the performance benefits from LTE in unlicensed bands
LTE-U	LTE operates in unlicensed bend using CSAT	Unified management mechanism; higher spectrum efficiency	Applicable in restricted areas
LAA-LTE	LTE operates in unlicensed band using LBT	Unified management mechanism; higher spectrum efficiency; global standard	New standard R13 required; longer for commercialization
LWA	LTE in licensed band aggregated with carrier Wi-Fi	Easy to implement; quick commercial-ization	Lack the performance benefits from LTE in unlicensed bands

TABLE 1. Comparison among approaches for unlicensed operation.

LTE-U was proposed in 2013, based on 3GPP Release 10–12. It employs CSAT to ensure co-channel coexistence. In CSAT, LTE devices sense the channel for a longer duration (around tens of milliseconds to 200 ms) and, based on the observed activities, define a duty cycle consisting of ON and OFF durations with a certain percentage.

in LTE networks is reviewed. A new vision for LTE-U is provided along with the challenges and necessity of traffic steering. Typical applications and approaches of traffic steering are introduced, respectively. A discussion of how to exploit unlicensed bands to facilitate traffic steering is presented. Future research topics and conclusions are then given, respectively.

State-of-the-Art Unlicensed Bands Exploitation in LTE Networks

In this section, we present the state-of-the-art unlicensed bands exploitation, paying particular attention to the coexistence issue when operating in unlicensed bands.

Carrier Wi-Fi

Network operators can deploy their own Wi-Fi access points (carrier Wi-Fi) to offload traffic, reduce congestion, and provide Internet access. Carrier Wi-Fi can be considered as the first step for a mobile network operator to move into unlicensed bands. However, carrier Wi-Fi adopts different access and management mechanisms from LTE networks, such as access control and authentication, leading to inefficiency for network management. In addition, carrier Wi-Fi cannot have the high spectrum efficiency obtained from LTE techniques.

Recently, mobile operators also strive to expand LTE in unlicensed bands, where Wi-Fi systems exist. For harmonious coexistence, the requirement for LTE networks is to keep the impact on existing Wi-Fi systems not greater than that of a Wi-Fi access point. To this end, different solutions have been designed, such as LTE-U and LAA-LTE.

LTE-Unlicensed

LTE-U was proposed in 2013, based on 3GPP Releases 10–12. It employs CSAT to ensure co-channel coexistence. In CSAT, LTE devices sense the channel for a longer duration (around tens of milliseconds to 200 ms) and, based on the observed activities, define a duty cycle consisting of ON and OFF durations with a certain percentage. In ON duration, LTE devices can transmit, while they keep silent in OFF duration to allow a Wi-Fi system access. Since LTE-U does not employ the LBT mechanism, it can only be used in limited regions, such as the United States, China, and Korea.

License Assisted Access LTE

The regulation bodies in Europe and Japan require LBT to periodically check the channel occupancy before transmission on a millisecond scale. LAA-LTE adopts LBT for coexistence. LAA-LTE exploits unlicensed bands opportunistically for capacity improvement while utilizing licensed bands for control signaling. For the channel of interest, the LTE device first listens to check whether there is any ongoing transmission. If the channel is clear, it starts to transmit for a period of time and then performs backoff to re-check the channel availability. If the channel is identified as busy, it does not transmit and keeps listening. The LTE device selects another channel if the current channel remains unavailable after several attempts.

LTE + Wi-Fi Link Aggregation

As an alternative to LTE-U and LAA-LTE, LWA leverages existing Wi-Fi access points to improve indoor cellular performance by integrating Wi-Fi transmission into the cellular radio access network. In LWA, LTE runs in the licensed bands, with no impact on the unlicensed band. LWA splits LTE data and tunnels some traffic over Wi-Fi while the rest is sent over LTE. The LTE data over Wi-Fi is tunneled in 802.11 medium access control (MAC) frames and collected at Wi-Fi access points, and then tunneled back to LTE small cells. LWA is very easy to implement by software upgrading Wi-Fi to support LWA.

A comparison among the above solutions is provided in Table 1.

Future Mobile Networks with Unlicensed Bands

Although 3GPP mainly focuses on LTE in unlicensed 5 GHz band, LTE networks actually can expand to other bands as well, such as TV white space (TVWS) and 3.5 GHz. This section presents the LTE networks with unlicensed bands, along with the challenges and solutions.

Network Architecture

Multi-tier heterogeneous networks have been considered as the dominant network architecture for next generation wireless networks [8], where lower-power and short-range small cell base stations are deployed densely and overlaid with the macrocell base station, as shown in Fig. 1. Moreover, LTE networks will overlay the existing second/third generation (2G/3G) infrastructures.

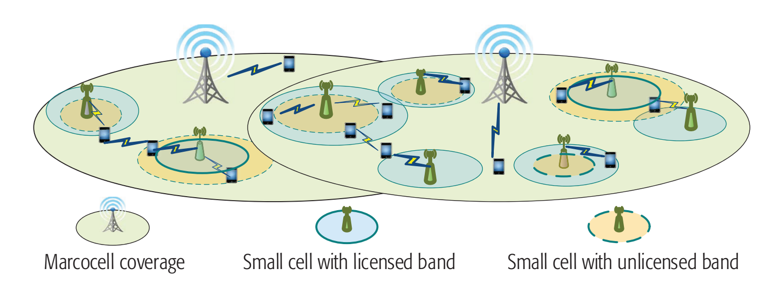

Figure 1. LTE networks with unlicensed bands.

Additionally, diverse types of Wi-Fi access points are also deployed, including carrier Wi-Fi.

Besides the allocated spectrum bands, cells can also explore the unlicensed spectrum bands, such as TVWS ranging from 572 to 698 MHz, 2.4 GHz, and millimeter-wave frequency spectrum around 60 GHz. In addition, with the advancement of dynamic spectrum access [9, 10], unused spectrum from other systems can also be explored. Those spectrum bands have divergent characteristics in terms of bandwidth and availability, as well as features of propagation and penetration. For instance, the TVWS has good building penetration and can support larger coverage. In contrast, spectrum in high frequency bands has larger bandwidth and can provide higher data rate. With those unlicensed spectra, the cellular network is referred to as an LTE network with unlicensed bands.

In addition to the heterogeneity of cells and spectrum resources, mobile traffic is also heterogeneous in terms of spatio-temporal distributions and QoS requirements. Mobile users are non-uniformly distributed across the network, and the distribution may change dynamically with user mobility, leading to various loads at different locations and time instants. Furthermore, the traffic types are heterogenous, such as voice and video, with different QoS requirements in terms of delay, data rate, and reliability.

In summary, LTE networks with unlicensed band are characterized by:

- **Heterogeneous RAT/cells:** different access technologies, overage and service capacities
- **Heterogeneous spectrum:** divergent available spectrum over different locations and time
- **Heterogeneous traffic:** diverse traffic types with different QoS requirements and time-varying traffic non-uniformly distributed across the network

Opportunities and Challenges

Expanding LTE into unlicensed bands, an additional layer of opportunity as well as complexity is provided simultaneously. The exploitation of unlicensed spectrum can significantly improve network throughput and user performance. LTE with unlicensed bands also provides more dimensions of network resources to explore for meeting the diverse needs of users. Specific advantages of access points or spectrum bands can be leveraged for particular services. Integration of different cells, RATs, as well as licensed and unlicensed bands helps the network operator select the most suitable set of resources to satisfy QoS requirements.

It is also a great challenge to efficiently utilize the diverse spectrum resource due to the following reasons:

- The non-uniform distribution of wireless traffic load leads to unbalanced traffic load among different cells, degrading the utilization of network resource.
- The multi-dimensional heterogeneity of RATs/cells, spectrum, and traffic demand makes it hard to satisfy the differentiated QoS requirements.
- The network operation might have varying objectives over time and locations.

For instance, in peak hours, it is important to balance traffic to avoid cell overload, while energy saving is concerned when lightly loaded cells keep running.

Traffic Steering: What and Why

Traffic steering is a network functionality to intelligently manipulate and manage the traffic/users across the network units and spectrum bands, aiming to achieve the desires of the network operators or end users. It can be performed for different objectives, such as to increase the overall resource utilization; to optimize user satisfaction while considering user preference and service differentiation; and to minimize signaling overhead and handset power consumption.[1]

Traffic steering is of great importance to the network operators and users, because:

- It enables control and management of the traffic load across various access entities and spectrum bands, enabling efficient use of the network resources.
- It improves the user experience by properly assigning access entities and spectrum bands.

Traffic steering helps make use of all the network resources to the maximum, while at the same time delivering service with better QoS/QoE.

Traffic Steering Applications

QoS/QoE Enhancement: Enabled by carrier aggregation (CA), integration of different spectrum bands can significantly improve users' throughput. Moreover, with more spectrum bands to select, small cells can steer traffic intelligently to different portions of spectrum bands (5 GHz bands and other available bands), aiming to meet the specific needs of different users, based on the traffic types, QoS requirements, and spectrum transmission characteristics. For instance, delay-tolerant traffic can be steered to unlicensed bands for opportunistic transmission, while delay-sensitive traffic could be served by licensed bands. Additionally, high-mobility users can be steered to the low-frequency TVWS bands, which can provide larger coverage for service connectivity due to low path loss.

Network Resource Utilization Improvement: Traffic steering can also help improve network utilization significantly. It has the potential to deal with the dynamics in traffic and unbalanced traffic load among different cells [11]. Due to the traffic dynamics, some cells with limited capacities may serve more users than their capacities, while other cells might waste their resources due to fewer associated users. Traffic steering can re-distribute traffic across the network, for example, steer traffic from heavily loaded cells to lightly loaded

[1] Different from the conventional traffic offloading originally proposed to deal with the overload issue, traffic steering has a much broader range of applications. To some extent, traffic offloading can be considered as a special case of traffic steering.

cells such that users' QoS can be provisioned. By doing so, traffic steering among different cells helps improve network utilization to better serve users.

Operational Cost Reduction: Considering the variation in traffic demand, cells might not need to always be in ON mode, which constantly consumes energy and increases energy costs. In certain scenarios, traffic can also be steered from a lightly loaded cell to neighboring cells such that the lightly loaded cell can be turned off for saving energy [12]. For instance, in an LTE network with unlicensed bands, the cell can zoom in (enlarge its convergence) by choosing a low-frequency band to help serve users beyond the coverage such that the neighboring cell can be turned off.

Traffic Steering Approaches

Traffic Steering from the RAN Perspective: Traffic can be steered over different cells or RATs, based on traffic load, QoS requirements, and service capacities. For instance, voice traffic can be steered to 3G base stations, while data traffic can be served by LTE/LTE-Advanced (LTE-A) base stations.

- **Inter-cell traffic steering:** Traffic is steered among different cells based on the load and service capacity of each cell. It can be further categorized into *inter-tier traffic steering* and *intra-tier traffic steering*, respectively. In inter-tier traffic steering, traffic is steered from an upper tier to a lower tier, such as from macrocell to femtocell (e.g., for higher throughput). In contrast, traffic can also be steered from a lower tier to an upper tier, such as from a femtocell to a microcell (e.g., for connectivity). In intra-tier traffic steering, traffic is steered among the neighboring cells with the same type, capacity, and coverage.
- **Intra-cell traffic steering:** Within a cell, traffic can be further steered to different channels in the same spectrum band, to different spectrum bands, and to different time slots. The traffic steering decision usually considers different traffic types, available spectrum bands, channel capacities, and so on. In addition, for certain cells with multiple modes, traffic can be steered to different RATs.

Traffic Steering from the Spectrum Perspective: Due to integration of unlicensed bands into the system, available spectrum bands vary in both the spatial and temporal domains. Considering different availability, as well as propagation and penetration features, traffic can be steered from one spectrum band to other(s), to fulfill the desires of users and the network.

- **Intra-band traffic steering:** Traffic can be steered within the same operating frequency band with the same transmission features. One example is to steer the traffic from one carrier to another to avoid interference if the neighboring cell uses the same channels.
- **Inter-band traffic steering:** Traffic can also be steered among different operating frequency bands to exploit different transmission features to satisfy specific users' needs. For instance, a moving user can be tuned to a lower spectrum to maintain longer connectivity and reduce handover frequency.

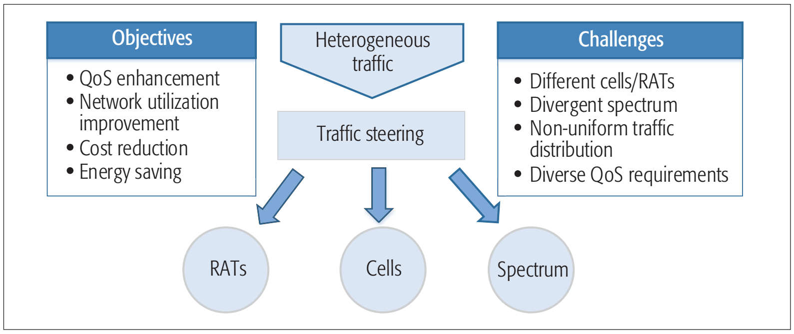

FIGURE 2. Traffic steering in LTE with unlicensed bands.

Two-Layer Traffic Steering Framework

Due to the divergent needs of network operators for traffic steering based on location, time, and event, and the multi-dimensional heterogeneity, traffic steering is complex. By exploiting the multi-tier architecture, we introduce a two-layer traffic steering framework. The upper layer mainly distributes traffic to different cells, based on network load and service capacities, aiming to avoid overload and fully utilize network infrastructure. The lower layer traffic at each cell manipulates traffic to different spectrum bands, based on users' QoS requirements and divergent spectrum characteristics in terms of bandwidth, propagation, penetration, and availability. The two layers can be jointly optimized, but this requires a global view of the network in terms of load, available capacities, spectrum availabilities, and so on. This could be achieved through network monitoring and software defined networking (SDN).

Extending Traffic Steering in LTE with Unlicensed Bands

Traffic steering typically requires cells to have overlapping coverage. In this section, we leverage unlicensed bands to fully harvest the benefits of traffic steering, making it a more attractive and flexible solution to improve network utilization and users' experience.

Spectrum-Based Cell Zooming for Traffic Steering

With the diverse propagation characteristics of spectrum bands, the transmission distance of a cell can be adjusted by adopting different spectrum. Therefore, cell zooming can be enabled by selecting a suitable spectrum band for particular users. The cell can enlarge the coverage by selecting bands in low spectrum and shrink its coverage by selecting bands in high spectrum, with a fixed transmission power. With spectrum-enabled cell zooming, traffic can be steered among cells more flexibly. As shown in Fig. 3a, cell 1 is overloaded, while cell 2 is lightly loaded. Since users in cell 1 are beyond the coverage of cell 2, cell 2 can enlarge its coverage by choosing suitable low spectrum bands dedicated to serving the users in cell 1. Moreover, transmission power of cells can also be properly adjusted for cell zooming, which can be combined with spectrum selection to enable more flexible and agile traffic steering. Mixed-integer programming techniques can be employed to formulate the spectrum and power

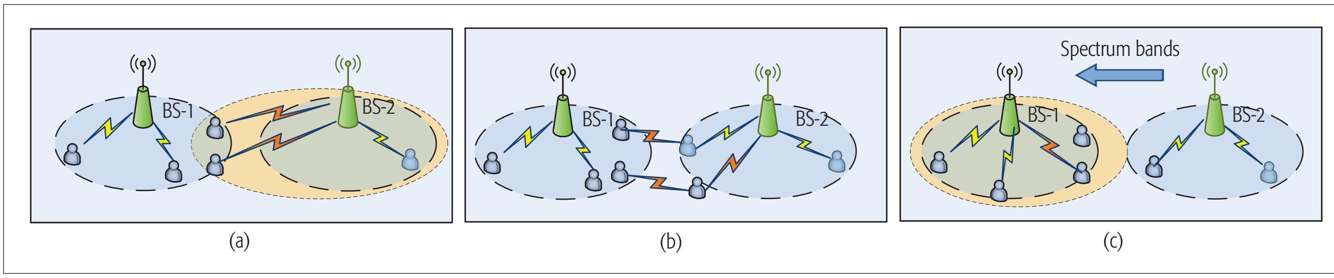

FIGURE 3. Traffic steering scenarios in LTE networks with unlicensed bands: a) spectrum-based cell zooming for traffic steering; b) unlicensed-band-based D2D assisted traffic steering; c) spectrum-sharing-based traffic steering.

selection problem to balance traffic load among different cells.

Unlicensed D2D-Assisted Traffic Steering

Device-to-device (D2D) communication [13, 14] with unlicensed bands can also be leveraged to allow traffic steering when cells have no overlapping coverage. As shown in Fig. 3b, with D2D communication, user devices can act as a relay to forward the traffic from one cell to the other [15]. For instance, D2D communication can be used to move the traffic in a heavily loaded cell to a lightly loaded cell. To mitigate the interference caused by the concurrent transmission in cells and D2D communication, D2D communication can utilize an orthogonal unlicensed band to relay the traffic. With two-hop or multihop D2D communication, the opportunities of traffic steering can be greatly improved by bridging traffic among cells. It can enable dynamic and flexible traffic to flow among different cells across the network, thereby significantly extending the use scenarios. D2D-assisted traffic steering can help to improve network performance, while consuming resources of the relay users such as power. Therefore, network operators need to give users incentives to encourage them work as D2D relays. The cooperation between users and operators can be modeled as games for analysis.

Spectrum-Sharing-Based Traffic Steering

Since the network has a richer spectrum pool for use, spectrum sharing can also facilitate traffic steering. Specifically, full spectrum reuse is usually adopted to boost network capacity, which results in inter-cell interference. To manage interference, neighboring cells dynamically occupy different spectrum bands for operation. In the scenario shown in Fig. 3c, cell 1 has heavier traffic than cell 2, or users in cell 1 require a higher level of QoS. However, cell 1 does not possess sufficient spectrum, while cell 2 has more spectrum resource than it needs. Cell 2 can grant certain spectrum bands to allow cell 1 for access. Then cell 1 either uses granted spectrum bands to serve its traffic, or aggregates the granted spectrum with its own spectrum to improve users' throughput. This procedure can be performed through either centralized coordination or negotiation among cells.

Case Studies

We present case studies to demonstrate the necessity and benefits of traffic steering in terms of throughput and delay performance. As for the throughput performance, a simple network setting is considered, which consists of two cells with licensed band (1800 MHz) and TVWS (600 MHz, to be available with certain probability). Cell 1 has three users to serve in its coverage, while cell 2 only has one user. The users are distributed with different distances to the respective base stations. Cell 2 can help serve one user from cell 1 through inter-cell traffic steering, while both cells can allocate suitable bands for their own users through intra-cell traffic steering. Transmission power and noise power are set to 1 W and –80 dB, respectively. Figure 4 shows the throughput achieved through traffic steering. It can be seen that the network throughput is increased by about 50 percent through intra-cell traffic steering, compared to that using no traffic steering. With inter-cell and intra-cell traffic steering enabled, it is further increased by about 100 percent. This significant performance gain achieved through proper traffic steering demonstrates the benefits of traffic steering.

In terms of delay performance, a single cell is considered, which distributes real-time and best effort traffic to either LTE licensed band or unlicensed band shared with a Wi-Fi network. The cell can randomly distribute traffic to either licensed or unlicensed bands, without service differentiation. It can also steer traffic based on the traffic type (service differentiation); for example, all real-time traffic is steered to LTE licensed band while the best effort traffic is steered to unlicensed band. The real-time arrival rate ranges from 0.2 to 2, while the arrival rate for best effort traffic is set to 2. The arrival rates for Wi-Fi traffic can be 0.5 and 1.5. Figure 5 shows the service delay for real-time traffic with different policies. It can be seen that service-differentiation-based traffic steering can achieve lower delay. Furthermore, there is an optimal traffic steering policy that can significantly reduce the service delay. The optimal traffic steering depends on the traffic types and the respective arrivals, as well as the load and service capacities of each band.

Research Issues

In this section, further research topics are discussed on traffic steering in LTE networks with unlicensed bands.

Centralized vs. Distributed Traffic Steering

To enable traffic steering among cells, cell coordination is required, and necessary information regarding the load and serving capacities of each cell needs to be exchanged. Centralized coordination can achieve the optimal performance, but requires real-time control of cells. Moreover, the traffic steering should be adapted to different scenarios based on current needs. This can be achieved by the promising SDN platform, which allows for real-time management by controlling network entities through a logical central controller. However, SDN is still in its infancy in wireless networks. Compared to the centralized way, traffic steering can also be performed in a distributed fashion, where neighboring cells decide the optimal traffic steering strategies based on local information. Research efforts are required for both solutions, and comparison is also an interesting topic to reveal the best option for particular network scenarios.

User-Centric vs. Network-Centric Traffic Steering

Traffic steering can be performed from the perspectives of either the network operator or users. Network-centric and user-centric traffic steering aim to improve network resource utilization or QoS/QoE of users, respectively. However, when improving network performance, users' interests may be compromised. For instance, a user is scheduled from a lightly loaded cell to a heavily loaded cell to turn off a cell for energy saving, which reduces user throughput. Therefore, it is of significance to study how to balance the network utility and users' performance.

Traffic Steering among Different Operators

In the same region, several networks owned by different network operators usually coexist. From time to time, the traffic load in each network varies. By enabling traffic steering among operators, the operators can cooperate to relieve the network burden and combat bursty peak traffic load. The operators can make a contract or occasionally trade for infrastructure sharing. It is an interesting topic to study how to enable traffic steering among operators from the business point of view, based on the traffic profile and the capacities of each network.

SON-Based Automated Traffic Steering

Due to the large network scale and the need for agile network operation, automated traffic steering is desired to minimize manual intervention. Automated traffic steering can be performed in near real time, quickly adapting to different needs and network status such as time-varying variations in network loads and link failures. To this end, self organizing network (SON) functions can be introduced, which encompass self-configuration, self-optimization, and self-healing. Developing SON-based algorithms can simplify traffic steering and therefore are urgently needed.

Concluding Remarks

In this article, a vision of traffic steering in LTE networks with unlicensed bands has been provided to improve network utilization and users' experience. Traffic steering approaches and applications have been presented. Additionally, exploitation of unlicensed bands to harvest the benefits of traffic steering has been discussed. It is anticipated that traffic steering will play a very important role in future wireless networks for better service provisioning by fully exploring network resources. To facilitate traffic steering in LTE networks with unlicensed bands, further research efforts should be made.

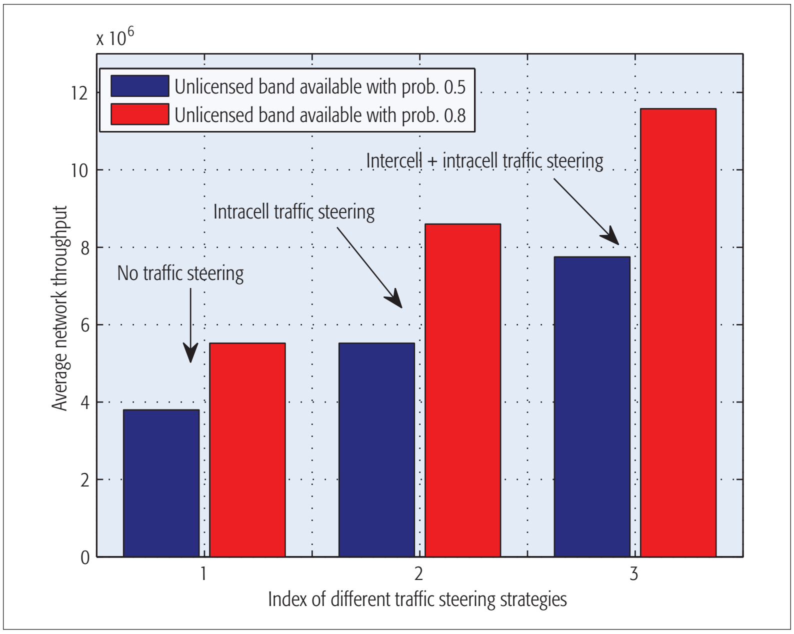

Figure 4. Aggregate throughput through traffic steering.

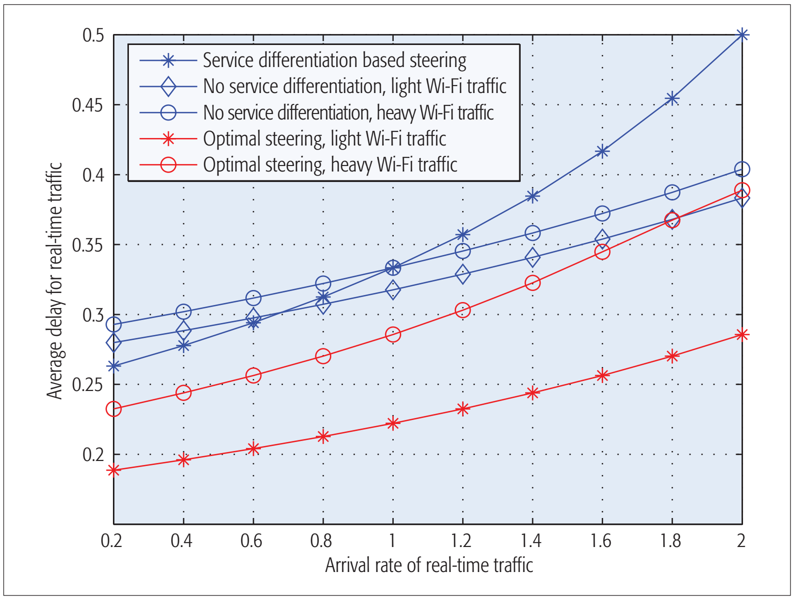

Figure 5. Delay performance through traffic steering.

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References

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast," white paper, 2014.
[2] R. Zhang *et al.*, "LTE-Unlicensed: The Future of Spectrum Aggregation for Cellular Networks," *IEEE Wireless Commun.*, vol. 22, no. 3, June 2015, pp. 150–59.
[3] H. Zhang *et al.*, "Coexistence of Wi-Fi and Heterogeneous Small Cell Networks Sharing Unlicensed Spectrum," *IEEE Commun. Mag.*, vol. 53, no. 3, Mar. 2015, pp. 158–64.
[4] Qualcomm, "LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi," white paper, 2014.
[5] F. M. Abinader *et al.*, "Enabling the Coexistence of LTE and Wi-Fi in Unlicensed Bands," *IEEE Commun. Mag.*, vol. 52, no. 11, Nov. 2014, pp. 54–61.

[6] P. Munoz *et al.*, "Mobility-Based Strategies for Traffic Steering in Heterogeneous Networks," *IEEE Commun. Mag.*, vol. 51, 2013, pp. 54–62.
[7] Nokia, "Business Aware Traffic Steering," white paper, 2014.
[8] N. Zhang *et al.*, "Cloud Assisted Hetnets toward 5G Wireless Networks," *IEEE Commun. Mag.*, vol. 53, no. 6, June 2015, pp. 59–65.
[9] Y. Wu *et al.*, "Revenue Sharing Based Resource Allocation for Dynamic Spectrum Access Networks," *IEEE JSAC*, vol. 32, no. 11, 2014, pp. 2280–96.
[10] J. Ren *et al.*, "Dynamic Channel Access to Improve Energy Efficiency in Cognitive Radio Sensor Networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, 2016, pp. 3143–56.
[11] F. Liu *et al.*, "Small-Cell Traffic Balancing over Licensed and Unlicensed Bands," *IEEE Trans. Vehic. Tech.*, vol. 64, no. 12, 2015, pp. 5850–65.
[12] S. Zhang *et al.*, "Energyaware Traffic Offloading for Green Heterogeneous Networks," *IEEE JSAC*, vol. 34, no. 5, 2016, pp. 1116–29.
[13] L. Song *et al.*, "Game-Theoretic Resource Allocation Methods for Device-to-Device Communication," *IEEE Wireless Commun.*, vol. 21, no. 3, June 2014, pp. 136–44.
[14] P. Li *et al.*, "Fine-Grained Resource Allocation for Cooperative Device-to-Device Communication in Cellular Networks," *IEEE Wireless Commun.*, vol. 21, no. 5, Oct. 2014, pp. 35–40.
[15] H. Nishiyama, M. Ito, and N. Kato, "Relay-by-Smartphone: Realizing Multihop Device-to-Device Communications," *IEEE Commun. Mag.*, vol. 52, no. 4, Apr. 2014, pp. 56–65.

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