DYNAMIC REUSE OF UNLICENSED SPECTRUM: AN INTER-WORKING OF LTE AND WIFI

Youjia Chen, Ming Ding, David López-Pérez, Jun Li, Zihuai Lin, and Branka Vucetic

ABSTRACT

The dynamic exploitation of unlicensed spectrum by mobile operators is becoming a trend of future 5G networks, with several efficient solutions being standardized for enabling spectrum sharing. Solutions with various design philosophies diversify the network architectures and protocols. Among them, LAA aims at the physical-layer coexistence of LTE and WiFi within the unlicensed spectrum, while LWA and LWIP focus on aggregating the link capacity of LTE in the licensed spectrum and WiFi in the unlicensed one. In this article, a comprehensive survey of these three spectrum sharing technologies are provided. Moreover, a novel analytical framework is proposed to evaluate the network performance of these technologies by incorporating both spatial and time domain analyses and integrating different types of cells in one network as a whole. Simulation results are provided to compare the system throughput of these spectrum reuse technologies.

INTRODUCTION

The dynamic usage of unlicensed spectrum by mobile network operators has recently attracted considerable attention. It dramatically alleviates the long-standing problem of spectrum scarcity in Long Term Evolution (LTE) systems, and offers user equipments (UEs) larger bandwidth and thus better performance. The unlicensed spectrum band of main interest is around 5 GHz, as it has large bandwidth globally available. However, this band poses a challenge to coexistence for LTE unlicensed operations, due to its wide usage by WiFi.

Unlike LTE, which relies on a base station (BS)-centric scheduled access mechanism, WiFi uses a more distributed one based on carrier sense multiple access with collision avoidance (CSMA/CA). In more detail, all nodes in a WiFi network contend to access the channel using energy detection and a predefined threshold. Data transmissions are only performed when the channel is unoccupied, that is, the detected energy is smaller than the predefined threshold. A maximum channel occupancy time is adopted to reinforce fairness, and an extra backoff period is used to reduce collisions.

This CSMA/CA mechanism, although polite and simple, has been shown to greatly degrade WiFi performance in dense deployments with a large number of devices, as the distributed access becomes inefficient. Moreover, if the current LTE with continuous transmission operates directly in the same spectrum as today's WiFi, there is a strong concern of WiFi starvation and other forms of unfairness, as WiFi would always detect the channel as busy and back off. Simulations and analytical results show that this inter-system interference will greatly limit performance in dense deployments [1].

With these caveats in mind, vendors and operators are actively seeking solutions for the simultaneous usage of the licensed and unlicensed spectrum in cellular operation, while ensuring fair coexistence with WiFi. In this light, the Third Generation Partnership Project (3GPP) has recently standardized a set of new technologies as part of LTE Release 13, that is, licensed-assisted access (LAA) [2], LTE-WLAN aggregation (LWA) [3], and LTE-WLAN radio level integration with IPsec tunnel (LWIP) [3]. These solutions enable radio aggregation of licensed and unlicensed spectrum for operator-controlled access, make the access to unlicensed spectrum transparent to the operator's evolved packet core, and simplify the overall network maintenance by avoiding multiple solutions for network management, security, and authentication.

Generally speaking, the above-mentioned solutions can be classified into two categories, as shown in Fig. 1:

- Those that attempt to adapt the current LTE radio access technology to dynamically reuse the unlicensed spectrum
- Those that attempt to directly reuse the unlicensed spectrum using IEEE 802.11 protocols

Due to this fundamental variation, network architectures, interfaces, and protocols designed for these two kinds of solutions are completely different.

Besides the aforementioned coexistence issues, another major concern is the efficient usage of the spectrum resource to enhance system performance. Solutions with various radio access strategies and dynamic spectrum management schemes diversify the system performance. To obtain a better understanding of the performance of these emerging technologies, characteristics of LTE and WiFi should be comprehensively considered during performance evaluation.

For LTE, its network performance has been analyzed using stochastic geometry theory in recent years, which is a powerful mathematical tool to analyze large-scale wireless networks. By modeling the distributions of BSs and UEs as spatially random point processes, several key performance metrics can be derived, such as coverage probability and average network capacity [4, 5]. For WiFi, howev-

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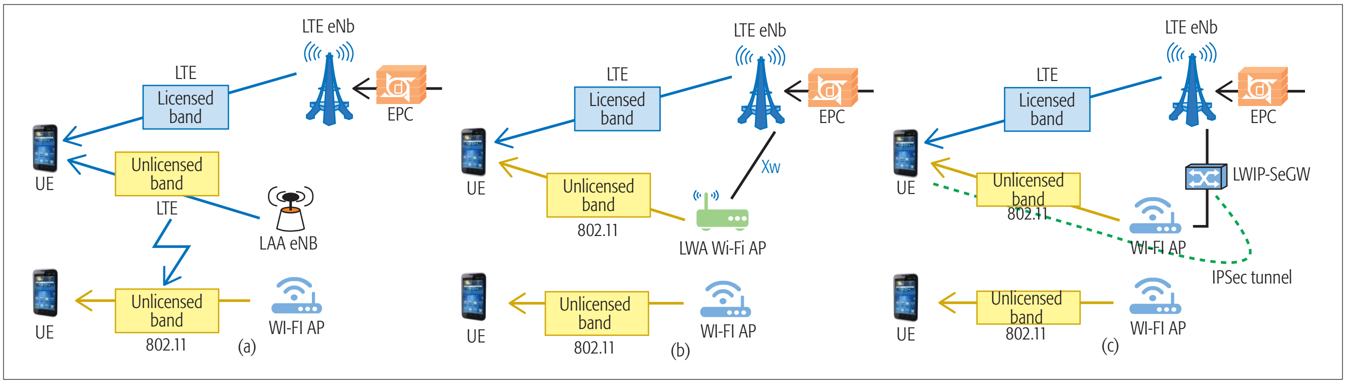

FIGURE 1. Architectures with three different spectrum sharing strategies: a) LAA; b) LWA; c) LWIP.

er, the existing work cannot effectively predict the performance of a large-scale WiFi network. The time-domain analysis of WiFi, based on the Markov chain, only considers a standalone, single-cell WiFi system [6, 7]. The spatial domain analysis of WiFi, based on stochastic geometry, only treats downlink (DL) transmissions, and investigates a snapshot of WiFi access points (APs) that can transmit simultaneously under the CSMA protocol [8, 9]. However, it neglects collisions, exponential backoffs, and most important uplink (UL) transmissions, with the latter being the main source for WiFi performance degradation in real systems. In this circumstance, better network-level analysis is needed for WiFi networks.

In this article, we aim to achieve basic comprehension of the emerging technologies in dynamic spectrum sharing. First, we provide a comprehensive survey of the three main spectrum sharing technologies standardized in the 3GPP. Second, we present a novel evaluation framework, incorporating both time domain and spatial domain analyses, to investigate the network performance of these spectrum sharing technologies. With this framework:

- We theoretically study for the first time a large-scale WiFi system, which is mathematically challenging due to its CSMA/CA protocol, requiring a nontrivial combination of a stochastic geometry analysis in the spatial domain and a Markov chain analysis in the time domain.
- We analyze the co-channel deployment of LTE and WiFi networks in the unlicensed spectrum, where the sub-frame boundary issue in LAA has been considered and the channel contention among different kinds of cells is modeled.
- Most importantly, we systematically investigate the performance of different types of cells, synchronous and asynchronous, scheduling-based and contention-based, thus making the comparison of LAA and LWA/LWIP possible.

Third, we compare these different spectrum sharing technologies in terms of system throughput, thereby shedding new light on the deployment and operation of unlicensed spectrum.

DIVERSE APPROACHES TO SPECTRUM SHARING

In this section, we present the fundamentals of the LAA, LWA, and LWIP in the context of radio channel access.

LAA

The LAA technology is aimed at using LTE-like infrastructure to access the unlicensed band. Thus, its main concern is the harmonious and fair coexistence of these LTE-like deployments with the existing WiFi networks in the unlicensed spectrum. As shown in Fig. 1, LTE and WiFi interwork with each other in the physical layer, with LAA eNodeBs (eNBs) and WiFi APs contending for the unlicensed channel.

Listen-Before-Talk: For fair coexistence, a new feature for channel access is adopted in the LAA, that is, listen-before-talk (LBT). The LBT technique is a procedure whereby radio transmitters first sense the medium and transmit only if the medium is detected to be idle, known as clear channel assessment (CCA). An energy detection (ED) threshold is set beforehand to determine the existence of ongoing transmissions in the channel.

At the same time, a random extended CCA procedure is adopted in LBT before data transmission to mitigate collisions. This LBT scheme, designed for LAA, resembles the medium access control (MAC) protocol used by WiFi in many ways. More specifically, CCA plays the role of CSMA in 802.11, and the eCCA procedure is similar to the exponential random backoff scheme designed for collision avoidance in WiFi.

Figure 2 shows an example of DL data transmission for the LAA in an unlicensed band. If the detected energy is below the ED threshold during the initial CCA, the LAA node begins transmission immediately. Otherwise, the channel is assessed to be busy, and then a defer duration and a backoff period consisting of a random number of additional extended CCA time slots have to pass before a transmission can be attempted again. Once the transmission opportunity is gained, the data transmission is limited by a maximum channel occupancy time (MCOT) for fairness purposes. Different priority classes may correspond to different MCOTs in the LAA.

Frame Structure: Note that the LTE technology works in a synchronous manner, in which data transmissions are aligned among cells. However, the LBT procedure of the LAA may be completed at any time instant. Therefore, the channel access time of an LAA cell is generally not aligned with the LTE subframe boundary, which appears every 1 ms. Since the transmission opportunity can be taken by any other contender, while the LAA eNB is waiting for the coming subframe boundary, a reservation signal is necessary to fill the gap. However, reservation signals contain no information bits, and thus waste time resources and incur additional signal overhead.

As shown in Fig. 2, to efficiently utilize radio resources (i.e., lengthen data transmission time) and alleviate the reservation signal overhead, the

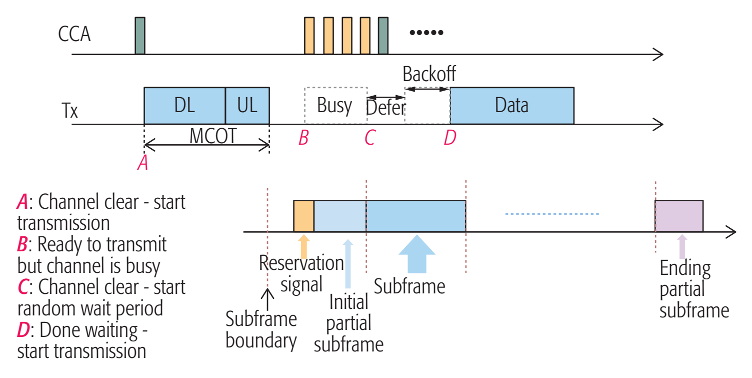

FIGURE 2. An illustration of LAA data transmission.

concept of a partial subframe is introduced into the LAA, including an initial partial subframe and an ending partial subframe. The initial partial subframe with length of 1/2 the normal subframe can start transmission in the middle of an LTE subframe. As illustrated in Fig. 2, if the first subframe boundary comes later than 0.5 ms, an initial partial subframe can be transmitted after the reservation signal. The ending partial subframe can be transmitted to make the most use of the MCOT, whose length can be chosen among {3, 6, 9, 10, 11, 12} orthogonal frequency-division multiple access (OFDMA) symbols. It is used when there is not enough time to transmit a full subframe comprising 14 OFDMA symbols.

Enhanced LAA: In 3GPP Release 13, only DL transmission in unlicensed spectrum is considered, while in Release 14 both DL and UL transmissions are supported, which is also referred to as enhanced LAA (eLAA). In the eLAA, channel access is always driven by the LAA eNB, which contends for the channel. Once the LAA eNB has gained access to the the channel through the aforementioned LBT procedure, the subframes within its MCOT can be assigned to DL or UL transmissions dynamically according to the LAA eNB scheduling decisions. It is important to note that the UEs that are provided with an UL grant and thus may transmit data in unlicensed band should perform an extra CCA prior to transmission to comply with regulations and ensure the idle status of the channel. If the channel is sensed busy, the UE will ignore the UL grant and will not transmit.

Comparison with LTE-U: LTE in unlicensed spectrum (LTE-U) was proposed by the LTE-U Forum. Both LTE-U and LAA use carrier aggregation to augment an existing LTE licensed carrier with an unlicensed one. LTE-U, however, is a simplified scheme without LBT targeted at early deployments. LTE-U operates in accordance with the existing Release 10/11/12 LTE physical (PHY)/MAC standards. The absence of LBT, however, restricts its use to regions such as the United States, where this is not required by government regulations. Instead, LAA has worldwide scope, and thus includes LBT and other features (e.g., minimum bandwidth occupancy, transmit power spectral density) required to conform with, for instance, European and Japanese regulations.

To allow fair coexistence with WiFi and other technologies operating in the unlicensed band, LTE-U adopted CAST, which is based on an On-Off duty cycle. For example, an LTE-U eNB would transmit on every other frame and leave the channel between them idle, yielding a 50 percent On-Off cycle. During the CAST off periods, WiFi nodes have full access to the band. LTE-U uses the MAC channel element activation and deactivation feature of carrier aggregation to activate and deactivate the unlicensed carrier and realize the CAST duty cycle [10].

Since a WiFi device may start transmission at any time during CAST Off periods, if WiFi transmissions do not end before the next CAST On period, collision may occur. CAST has been enhanced with a short CCA to avoid colliding with WiFi transmissions at the duty cycle flip, thus enhancing coexistence [11].

LWA AND LWIP

Different from LAA, as shown in Fig. 1, the LWA and LWIP leverage WiFi infrastructure to access the unlicensed spectrum. Thus, coexistence and regulatory requirements in unlicensed spectrum are not a concern.

Generally speaking, LWA and LWIP integrate LTE and WiFi technology to enhance system performance. By exploiting both LTE and WiFi interfaces in parallel, users can benefit from the best of both technologies, that is, LTE provides reliable connectivity and mobility management, while WiFi boosts data capacity through its large bandwidth. The main difference between LWA and LWIP is the different layers where the integration of LTE and WiFi occur.

LWA: LWA supports link aggregation at the Packet Data Control Protocol (PDCP) layer, as shown in Fig. 3. That is, in DL transmissions, PDCP packet data units (PDUs) of the same IP flow can be independently routed by the LTE eNB through the LTE and WiFi links. The reordering mechanism at the PDCP layer ensures in-sequence data delivery to the upper layers at the UE. Since LWA works at an LTE radio protocol layer and benefits from PDCP radio link statistics, each PDCP PDU split can quickly adapt to radio and traffic fluctuations of LTE and WiFi links.

LWA defines a new interface, *Xw*, between LTE and WLAN, which has similar functions to the X2 interface in LTE and is used to route PDCP PDUs to WiFi APs. Specifically, the *Xw* interface is terminated at the WLAN termination (WT), a newly defined 3GPP logical node, which may be in control of one or more WiFi APs and provides seamless mobility among these WiFi APs. LWA also defines a new Ether-type to identify the PDCP PDUs routed over WLAN, which allows the WiFi APs to differentiate LWA traffic from other WLAN traffic. Note that software or firmware upgrades of legacy WiFi APs to recognize this new Ether-type are needed to enable LWA operation.

LWIP: In contrast to LWA, LWIP provides a more universal solution to access the unlicensed band, realized via legacy WiFi APs (no new Ether-type needed). LWIP supports link switching of IP flows at the IP layer, that is, the IP data is tunnelled from the LTE eNB to UE transparently over legacy WiFi APs relaying on IP connectivity. Such tunnelling is realized via an LWIP-security gateway (SeGW) introduced between the LTE eNB and UE, where IPsec is adopted to guarantee data security when traversing the WLAN network. As shown in Fig. 3, the IP packets transmitted between the LWIP-SeGW and the UE are encapsulated with IPsec. Thus, the path between LWIP-SeGW and UE is also called an IPSec tunnel, illustrated in Fig. 1.

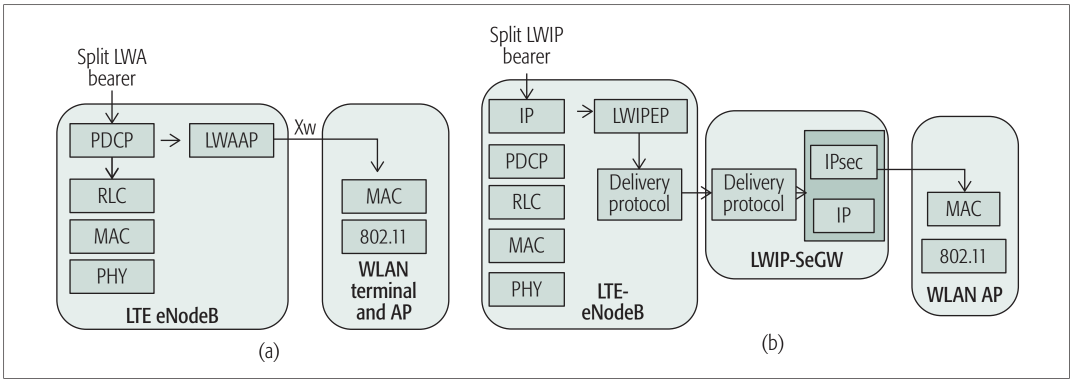

FIGURE 3. Comparison of the protocol architectures of LWA and LWIP: a) protocol architecture of LWA [12]; b) protocol architecture of LWIP [3].

Although LWA and LWIP require less change in existing networks and will become commercially available in a short term, more work is still needed in QoS provisioning, flow control and security to improve performance. Moreover, WiFi specifications continue to evolve, providing higher rates and better mobility.

Different from the link aggregation capacity in LWA, with which PDCP packets of the same data flow can be simultaneously transmitted in both LTE and WiFi links, the IP packets of a data flow can be transmitted through either an LTE or a WiFi link but never over both (no aggregation) in LWIP. This is because TCP cannot cope with the out-of-order delivery of packets transmitted over two radio interfaces, which would lead to poor TCP performance.

SUMMARY

The 3GPP dynamic spectrum sharing technologies (LAA, LWA, and LWIP) allow mobile operators to benefit from additional capacity in the unlicensed band. The main difference between LAA and LWA/LWIP is that LAA uses LTE-like radio access technology in the unlicensed spectrum, while LWA and LWIP directly access the unlicensed spectrum by following IEEE 802.11 specifications.

This fundamental difference leads to different protocol designs and network structures. For LAA, the LTE and WiFi technologies meet and coexist with each other in the unlicensed spectrum through LBT. LWA and LWIP are aimed at aggregating the capacity of LTE and WiFi by reusing WiFi infrastructures. The former aggregates the LTE and WiFi links in the PDCP layer, while the latter does it in the IP layer.

It is important to note that an anchor cell or component carrier (CC) in the licensed spectrum is needed for both LAA and LWA/LWIP, since continuous and periodic presence of reference signals and control channels cannot be guaranteed in unlicensed spectrum. That is, the LTE cell in the licensed band is the primary cell, where a UE communicates and maintains its connection with the network. LAA cells and WiFi cells working in LWA/LWIP can be viewed as secondary cells, which are activated for supplementary bandwidth extension.

CHALLENGES

A number of WiFi operators in different countries have expressed their concerns and approached government regulatory bodies indicating that LAA and LTE-U operations may have a detrimental impact on the existing and future use of unlicensed or shared spectrum. For fair coexistence, it is necessary that deploying an LAA or LTE-U eNB should not impact WiFi services more than adding a WiFi AP. Maximizing the capacity of LTE in unlicensed spectrum in this coexistence spirit still needs more effort. Moreover, since the implementation of LAA and LTE-U will increase the traffic in unlicensed spectrum, how to maintain a balance in unlicensed spectrum, guaranteeing fair access to resources for all other systems, such as WiFi, Bluetooth, and ZigBee, has also raised deep concerns.

Although LWA and LWIP require less change in existing networks and will become commercially available soon, more work is still needed in quality of service (QoS) provisioning, flow control, and security to improve performance. Moreover, WiFi specifications continue to evolve, providing higher rates and better mobility. Such enhancement may require additional optimizations; thus, the collaboration of 3GPP and IEEE may allow LWA to further increase the benefits of these radio access technologies (RATs).

A FRAMEWORK OF PERFORMANCE ANALYSIS FOR LTE AND WIFI INTERWORKING

A key issue when discussing advantages and disadvantages of these different interworking technologies is their performance [13]. Thus, a new framework is required to analyze the system performance of a large-scale network that includes different types of cells in licensed and unlicensed spectrums, such as LTE cells, LAA cells, and WiFi cells. Here, WiFi cells include legacy WiFi cells and those new WiFi cells in which LWA or LWIP is adopted.

To involve the analysis of different RATs in one framework, their different characteristics should be considered. Generally, stochastic geometry is a powerful math tool for the performance analysis of large-scale networks in the spatial domain. However, unlike the well-scheduled LTE systems, the CSMA or CSMA-like protocols adopted in unlicensed spectrum make time domain analysis indispensable. Besides, the interactions between the spatial domain analysis and the time domain analysis cannot be neglected. Moreover, the interactions between different types of cells when they coexist in the same spectrum should be covered too. We present such a framework in the following.

PERFORMANCE METRICS

As one important performance parameter, the signal-to-interference-plus-noise ratio (SINR) of a typical UE can be formulated as

$$\mathrm{SINR} = \frac{P\cdot\zeta(r)\cdot h}{I_{\mathrm{agg}}+N_0}, \tag{1}$$

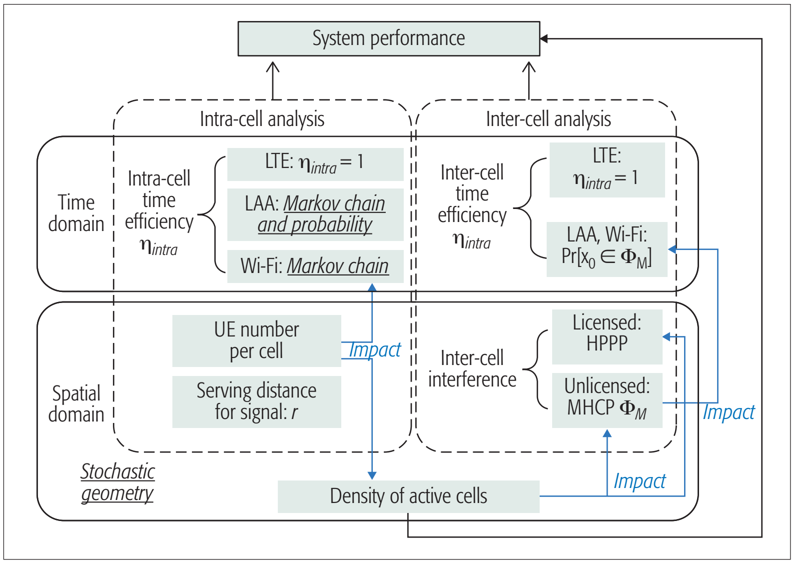

FIGURE 4. The proposed analysis framework.

where P, h, and N_0 denote the transmission power, channel gain, and additive white Gaussian noise power, respectively. Moreover, $\zeta(\cdot)$ denotes the path loss function, and I_{agg} denotes the cumulative interference, which comes from the transmitters in other co-channel cells. Note that, different link directions or cell types may have different transmission powers, path loss functions, and cumulative interference.

The coverage probability is defined as the probability that SINR is above a determined threshold γ_0, that is, $\Pr[\mathrm{SINR} > \gamma_0]$. Moreover, the SINR-dependent area system throughput (AST) in bits per second per square kilometer can be calculated as

$$\mathrm{AST} = B \cdot \tilde{\lambda}_s \cdot \eta \cdot \log_2(1 + \mathrm{SINR}), \tag{2}$$

where B denotes the bandwidth allocated, $\tilde{\lambda}_s$ denotes the density of active cells with transmissions, and η denotes the time efficiency (i.e., the time fraction spent on data transmissions). In the proposed analysis framework, η is divided into two parts: $\eta = \eta_{\mathrm{intra}} \cdot \eta_{\mathrm{inter}}$, that is, intra-cell and inter-cell time efficiency.

Before the detailed interpretation of the proposed analysis framework, a diagram is plotted in Fig. 4 to illustrate its major components and the targeted parameters that impact the system performance.

DENSITY OF AN ACTIVE CELL

In practice, an LTE eNB/WiFi AP will mute its transmission if there is no UE connected to it, aiming to reduce interference and energy consumption. Considering the increasing densities of eNBs and APs deployed in current and future networks, the common assumption that all the cells are active is no longer appropriate.

Modeling the distribution of eNBs/APs as a homogeneous Poisson point process (HPPP) with density λ_s and the distribution of its UEs as another HPPP with density λ_u, the density of active cells, denoted by $\tilde{\lambda}_s$, can be derived by the probability that there is at least one UE inside each cell. where $0 < \tilde{\lambda}_s < \lambda_s$, and a larger λ_u leads to a larger $\tilde{\lambda}_s$.

Note that only active cells contribute to system throughput and inter-cell interference in the network. Moreover, channel contention only occurs among the active cells in unlicensed bands. The calculation of the density of an active cell, $\tilde{\lambda}_s$, is presented in the following subsection.

INTRA-CELL ANALYSIS

The intra-cell analysis mainly includes two parts: the spatial domain analysis and the time domain analysis.

Spatial Domain: First, the distance r in Eq. 1, between the typical UE and its serving eNB/AP, determines the received signal power necessary to compute the UE SINR. No matter the type of cell, LTE, LAA, or WiFi, the distribution of such serving distance, r, can be derived from the density of eNBs/APs and the association criteria adopted.

Second, the distribution of the number of UEs in a cell, n, is known to follow a negative binomial distribution, that is,

$$n \sim \mathrm{NB}\left(\frac{\lambda_u}{\lambda_u + K\lambda_s}\right),$$

where K is a distribution parameter. Thus, the distribution of the number of UEs in an active cell, $\tilde{n}$, follows a truncated negative binomial distribution. $\Pr[n \neq 0]$ can be used to calculate $\tilde{n}$ and thus $\tilde{\lambda}_s$.

Time Domain: The intra-cell time efficiency, η_{intra}, is the focus here, which reflects the time fraction used for data transmission when considering the cell as a standalone system:

- Inside an active LTE cell, due to centralized scheduling and exclusive use of licensed spectrum, the time resource is fully used in full buffer scenarios (i.e., $\eta_{\mathrm{intra}}^{\mathrm{LTE}} = 1$).
- Inside an active WiFi cell, due to the CSMA/CA protocol, statuses can be differentiated: idle, transmission, and collision. Since data can only be transmitted in the transmission status, the time resource is not fully used, and $\eta_{\mathrm{intra}}^{\mathrm{WiFi}}$ should be carefully studied. In this case, we adopt the existing Markov chain framework in [6, 7]. Note that $\eta_{\mathrm{intra}}^{\mathrm{WiFi}}$ depends not only on the parameters adopted in CSMA/CA, but also on the UE number inside the cell (i.e., $\tilde{n}$).
- The calculation of $\eta_{\mathrm{intra}}^{\mathrm{LAA}}$ should consider two aspects. First, a similar Markov chain model can be used to analyze the time efficiency of the CCA/eCCA procedure adopted in LAA. However, different from WiFi cells, there are only idle and transmission statuses inside LAA cells. Intra-cell collisions do not take place as traffic is scheduled. Second, the time in MCOT occupied by reservation signals should be excluded from the effective transmission time.

INTER-CELL ANALYSIS

In large-scale networks, especially with dense deployments, inter-cell interference, I_{agg}, greatly degrades the system performance. Since in licensed spectrum all active LTE cells can transmit simultaneously, I_{agg} comes from all other active cells. However, in unlicensed spectrum where contention-based channel access is adopted, the inter-cell interference only comes from the cells that grab the chance to transmit at that time instance. Moreover, due to channel contention, one cell cannot always access the channe;, thus, the inter-cell time efficiency, η_{inter}, should also be investigated in unlicensed spectra.

According to these differences, in the following, we discuss the inter-cell analyses for licensed spectrum and unlicensed spectrum, respectively.

Licensed Spectrum — Spatial Domain Analysis: As mentioned earlier, the inter-cell interference for an active LTE cell comes from other active LTE cells. Moreover, because LTE works in a synchronous manner, no matter if in frequency-division duplex (FDD) or time-division duplex (TDD) mode, the interference for an LTE DL transmission only comes from the DL transmissions in other active LTE cells, while that for an LTE UL transmission only comes from the UL transmissions. In our modeling, the spatial distribution of DL interference sources follows an HPPP with density $\tilde{\lambda}_s^{LTE}$, and that of UL interference sources can also be approximately modeled as an HPPP [5].

Unlicensed Spectrum — Joint Spatial and Time Domain Analysis: In traditional networks, only WiFi cells are deployed in the unlicensed spectrum. When the LAA strategy is engaged, LAA cells and legacy WiFi cells coexist in the unlicensed band. When the LWA or LWIP strategy is adopted, new WiFi cells join in, which essentially work in the same way as legacy WiFi cells. In unlicensed spectrum, channel contention not only occurs inside a cell, but also occurs among the nodes in different cells. Therefore, we conclude that:

- Not all of the active cells in the unlicensed spectrum can transmit simultaneously. In other words, each cell can use part of the time resource, defined as inter-cell time efficiency η_{inter}.
- The inter-cell interference in one time instance is generated only from the active cells that successfully grab the transmission opportunity at that time.

To investigate η_{inter} and the spatial distribution of the inter-cell interference, three major steps are taken to model the inter-cell channel contention in a tractable way:

- Each cell in the contention is abstracted to a spatial point with a specific location and power. Specifically, the center of the cell (i.e., the location of its eNB/AP) can be used to represent its location. Moreover, the expected transmission power inside this cell represents its power. This abstraction is sufficiently accurate because the distance between two co-channel cells is much larger than the average cell coverage, especially when the number of channels in unlicensed spectrum is large. Besides, the usage of the expected transmission power is reasonable due to the comparable transmission powers of an AP(LAA eNB) and a UE [14].
- The contention domain or the contention range is defined based on the CCA threshold. In more detail, cell *A* will be inside the contention domain of cell *B* if the received power from *A* to *B* is higher than the pre-determined CCA threshold.
- We use the Matérn hard-core point process (MHCP), Φ_M, to model the channel contention among cells:
  - –An independent random mark is tagged onto each contending cell in an HPPP, representing the minimum backoff time in this cell.
  - –All cells that have a neighbor cell with a smaller mark and within its contention domain are removed, which means these cells do not acquire the transmission opportunity in the channel contention.

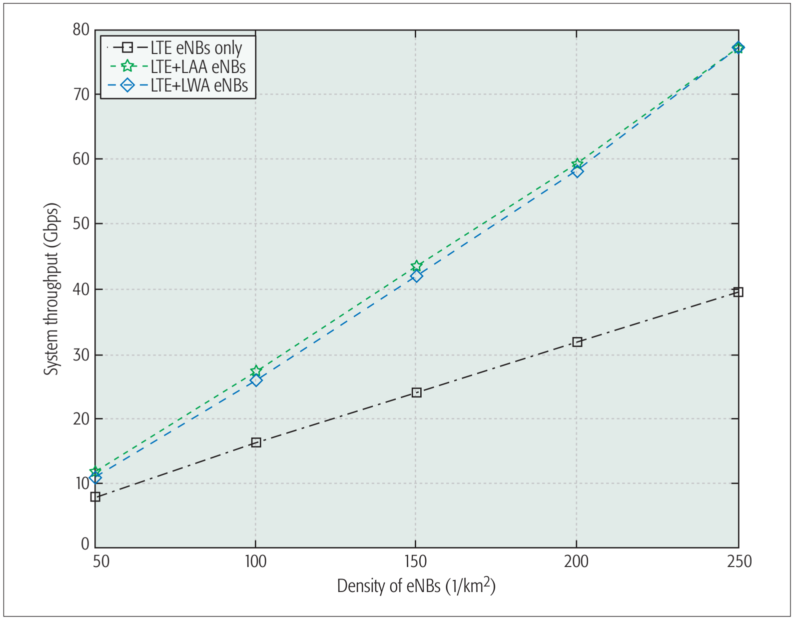

FIGURE 5. Throughput gain with different strategies.

Through these three steps, the spatial distribution of interfering cells for typical cell x_0 can be formulated as $\phi^I = \{x_i : x_i \in \Phi_M \,|\, x_0 \in \Phi_M, x_i \neq x_0\}$. Also, the inter-cell time efficiency can be calculated by the probability that the typical cell is retained in the MHCP (i.e., $\eta_{inter} = \Pr[x_0 \in \Phi_M]$).

PERFORMANCE STUDIES

In this section, we analyze the system performance with the various spectrum sharing strategies discussed.

First, we establish the baseline performance from the traditional network with a clear cut of LTE and WiFi, where LTE eNBs are deployed in licensed spectrum and WiFi APs are deployed in unlicensed spectrum. Second, two spectrum sharing technologies are considered: LAA and LWA/LWIP. That is, the operator with LTE infrastructures deploys LAA eNBs or LWA APs to dynamically reuse unlicensed spectrum. These newly deployed LAA eNBs and LWA APs will contend for the spectrum resource with legacy WiFi networks, which are assumed to belong to another operator.

In Fig. 5, we present the performance gain that an operator can achieve by deploying LTE eNBs and employing spectrum sharing strategies. When only LTE eNBs are deployed in licensed spectrum, the system capacity almost linearly increases when the density of LTE eNBs increases from 50/km^2 to 250/km^2 under the single-slope path loss model. The higher deployment density results in shorter serving distance and stronger received signals, which counterbalance the stronger interference. The idle mode also plays a role in the higher system throughput.

To boost system performance, two different strategies are considered: LAA and LWA (LWIP). In more detail, one LAA eNB or LWA AP is co-located with every LTE eNB to use the unlicensed spectrum. In this way, the operator obtains a performance improvement due to the extra spectrum resource in the unlicensed band. Generally speaking, the performance gains achieved by LAA and LWA are similar. The difference is shown in more detail in Fig. 6.

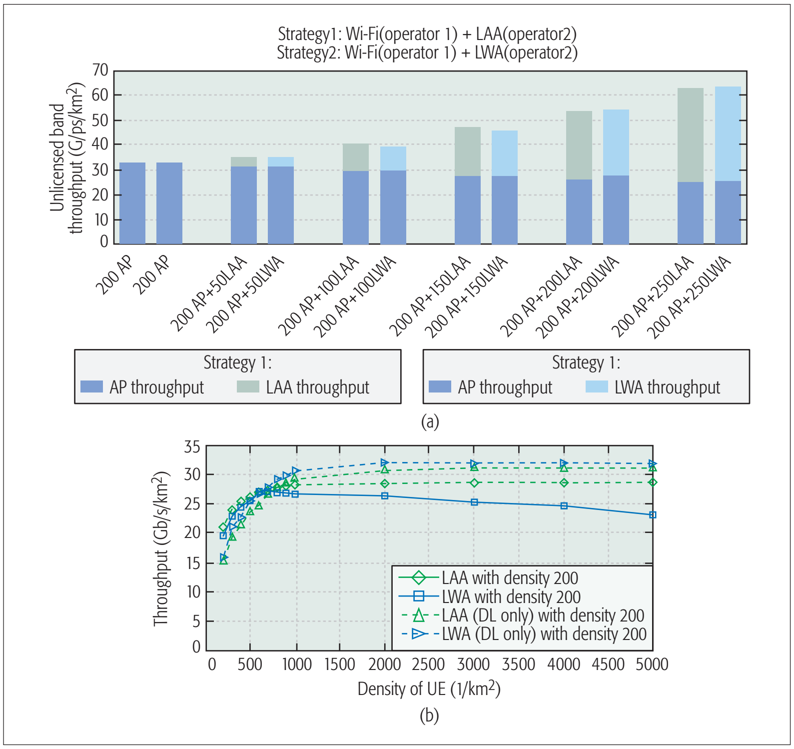

FIGURE 6. Throughput comparison of LAA and LWA: a) throughput in unlicensed spectrum with different numbers of LAA and LWA cells; b) throughput of LAA and LWA cells with different UE densities.

Moreover, when comparing the performance of LTE only with that of LTE plus LAA or LWA in Fig. 6a, it can be seen that the capacity of an LAA/LWA cell is less than that of an LTE cell when the density is low (from 50/km^2 to 150/km^2), while the capacity in the unlicensed band is comparable to the capacity in the licensed band when the density increases. The main reason is that the transmission powers of LTE eNB and LTE UE are both larger than those of LAA and LWA cells. Thus, when the cell coverage is large, the signal quality in LTE cells is better than in LAA and LWA cells. However, when the density is high, LTE suffers from severe inter-cell interference, while the interference for LAA or LWA cells is limited by the channel contention.

Moreover, Fig. 6a draws the corresponding throughput in the unlicensed spectrum when different densities of LAA eNBs or LWA APs are deployed. As expected, the overall throughput in unlicensed spectrum increases with the deployed number of serving nodes (LAA eNBs, LWA APs, and WiFi APs). However, the throughput of a legacy WiFi network whose density keeps 200/km^2 decreases in this process. From the perspective of the legacy WiFi network, the newly deployed LAA or LWA cells also contend for the spectrum resources, which were occupied by them before. Under the CSMA/CA access scheme, the more nodes contend for the channel, the less chance to access, and thus lower throughput.

In Fig. 6b, we compare the capacity of LAA with that of LWA as the UE density varies. Generally speaking, the performance of LAA is slightly better than that of LWA. This is because LWA cells, which are also WiFi cells, use two energy detection (ED) thresholds, while LAA cells use only one ED threshold. That is, the nodes in WiFi have to satisfy two thresholds: virtual carrier sensing CCA, –82 dBm, and CCA ED, –62 dBm. The first threshold limits the received interference from any other WiFi device to be less than –82 dBm, and the second threshold limits the overall interference power level. In contrast, the nodes in LAAs adopt a CCA ED threshold of –72 dBm. With such configurations, the –82 dBm threshold makes WiFi nodes more sensitive than LAA nodes. Thus, when LAA is used, the spatial reuse is larger, which leads to better performance.

In Fig. 6b, it is also important to note that when the UE density is very low, it can be observed that the throughputs of both LAA and LWA cells are small. The main reason is that some LAA/LWA cells have no UE in their coverage, which makes no contribution to system throughput. However, when the UE density keeps increasing to a relatively large value, the performance of LWA cells starts to decrease while that of LAA cells does not. This is because when the UE density increases, the UE number in each LWA cell also increases. In LWA cells, which are basically WiFi cells, the growth of the contending nodes gives rise to the probability of collision and thus more overhead. Thus, as in legacy WiFi cells, the system performance degrades when a large number of devices are involved.

We further plot the performance of LAA and LWA cells when only DL transmissions are supported as standardized in LTE Release 13, shown by the dashed lines in Fig. 6b. In such scenarios, first, there is little performance degradation in LWA cells caused by collisions, since DL transmissions are scheduled in APs. Second, the system performance of both LAA and LWA cells is better than that when UL transmissions are involved. The main reasons for this phenomenon is the lower contention and the larger transmission power in the DL, which results in higher transmission rate. Third, the performance of LWA is slightly better than that of the LAA when only DL transmissions are supported, due to the extra synchronous cost in LAA cells. It is worth noting that the performance difference depends on the parameters adopted in LWA and LAA cells, such as MCOT in the LAA, maximum backoff stages, and basic contention window size in 802.11.

Compare these two different scenarios, one joint UL and DL transmissions and the other only DL transmissions: LAA performs better than LWA in the first scenario, because the collisions existing in LWA degrade its performance; however, LWA performs better in the second scenario, because in this scenario both LWA and LAA have no collisions while LAA has extra cost on frame synchronicity.

CONCLUSIONS

Unlicensed spectrum sharing by mobile operators is a hot research topic for future 5G networks. Currently, three major approaches have been proposed to enable this spectrum reuse. LAA aims at the coexistence of LTE and WiFi in the physical layer of unlicensed spectrum, while LWA and LWIP focus on aggregating licensed spectrum in LTE and unlicensed spectrum in WiFi. Considering these different strategies, LTE cells, LAA cells, and WiFi cells are incorporated into one network as a whole. From our simulation results, we conclude that the performance gains achieved by LAA and LWA are similar, which present more than one option for mobile operators to unlock the benefits of unlicensed spectrum. However, in scenarios with a large number of UEs, LAA provides better performance than LWA because contention and collision are removed inside the LAA cells. Moreover, we confirm that these newly deployed cells in unlicensed spectrum will degrade the performance of legacy WiFi networks. Nevertheless, the performance impact brought by these newly deployed cells is no more than that from additional legacy WiFi nodes.

Unlicensed spectrum sharing by mobile operators is a hot research topic for future 5G networks. Currently, three major approaches have been proposed to enable this spectrum reuse. The LAA aims at the coexistence of LTE and WiFi in the physical layer of unlicensed spectrum, while the LWA and LWIP focus on aggregating licensed spectrum in LTE and unlicensed spectrum in WiFi.

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