usICIC—A Proactive Small Cell Interference Mitigation Strategy for Improving Spectral Efficiency of LTE Networks in the Unlicensed Spectrum

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***Abstract*—The deployment of long term evolution (LTE) in the unlicensed spectrum (LTE-U) has been gaining significant industry momentum in recent months. The US 5-GHz Unlicensed National Information Infrastructure (UNII) bands that are currently under consideration for LTE deployment in the unlicensed spectrum contain only a limited number of 20 MHZ channels. Thus, in a dense multi-operator deployment scenario, one or more LTE-U small cells have to coexist and share the same 20 MHz unlicensed channel with each other and with the incumbent Wi-Fi. In this paper, we present the scenario and demonstrate that in the absence of an explicit interference mitigation mechanism, there will be a significant degradation in the overall LTE-U system performance for LTE-U cochannel coexistence in countries that do not mandate listen-before-talk (LBT) requirements. We then present the unlicensed spectrum intercell interference co-ordination (usICIC) mechanism as a time-domain multiplexing technique for interference mitigation for the sharing of an unlicensed channel by multioperator LTE-U small cells. Through extensive simulation results, we also demonstrate that our proposed usICIC mechanism will result in 40% or more improvement in overall LTE-U system performance.**

***Index Terms*—4G wireless networks, LTE-U, unlicensed spectrum, interference mitigation.**

I. Introduction

THE demand for mobile wireless data is growing at an exponential rate in recent years. Industry is preparing for what is being labeled as the 1000x data traffic growth in the coming years. To meet such a stunning demand a several fold increase in spectrum [15], [16] is needed. The use of unlicensed spectrum is thus critically needed to aid the existing licensed spectrum to meet such a huge mobile wireless data traffic growth demand in a cost effective manner. Currently the unlicensed 5 GHZ band is used by Wi-Fi [13], [18]–[22] capable devices such as smart phones, laptops and tablet PCs. Wi-Fi 802.11 n/ac protocols are suitable for interference free environment, but offer unpredictable Quality of Service (QoS) and degraded performance in interference limiting environment, which are considered far inferior to those offered by licensed cellular wireless technologies such as LTE [14], [17] that offers higher spectral efficiency [10].

The support for LTE in the unlicensed 5 GHZ band [1], [2]where it has to co-exist with Wi-Fi, and where the LTE carrier is transmitted according to the lower transmit power requirements of the unlicensed spectrum, makes it suitable only for Small Cell deployments. A small cell [32] utilizing LTE-L (LTE in licensed spectrum), and LTE-U (LTE in unlicensed spectrum) will therefore significantly reduce the total cost of small cell ownership for the service provider. LTE-U capable small cell will have a lower cost per bit of wireless data transmitted, while providing the additional mobile wireless data offloading capacity from Macro Cell to small cell in LTE Heterogeneous Networks (HetNet).

The basic mode of LTE operations in the unlicensed spectrum is the Supplemental Downlink (SDL) [5]. In this mode of operations the Best Effort (BE) user data in downlink is carried over the unlicensed secondary carrier also known as SCell. All control and uplink user data is carried over the anchor primary LTE licensed carrier also known as PCell. The licensed PCell and the unlicensed SCell are employed by the small cell, and the User Equipments (UEs) in the Carrier Aggregation (CA) mode.

Fig. 1 depicts the single operator wireless HetNet deployment scenario comprising of a Macro Cell, and three Wi-Fi, and LTE-U capable small cells. Wi-Fi coverage area is uplink (UL) limited due to the lower device uplink transmit power requirement in the unlicensed spectrum. On the other hand, LTE-U transmission is Supplemental Downlink (SDL) only, and all uplink control and critical data is transmitted via the anchor licensed LTE-L carrier (PCell), thereby increasing the LTE-U effective coverage area relative to the Wi-Fi coverage area for the same small cell.

The limited number of available 20 MHZ channels in the 5 GHZ unlicensed spectrum will therefore require channel sharing among Wi-Fi APs, and LTE-U small cells in a dense multi operator deployment scenario.

Studies have been published [5]–[7] to demonstrate not only the viability of LTE deployment, but also its harmonious coexistence with Wi-Fi in the unlicensed spectrum. The published LTE and Wi-Fi coexistence performance studies [5], [6], [9], [11], [12] have demonstrated that using carefully designed coexistence mechanism, LTE can be a fair neighbor to Wi-Fi that does not degrade the Wi-Fi AP performance more than when

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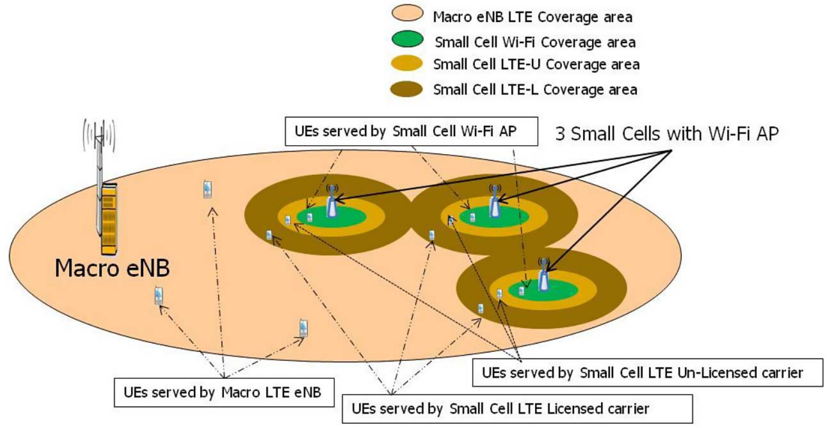

Fig. 1. Single Operator Outdoor LTE-U Deployment Scenario in a Wireless HetNet.

the Wi-Fi AP share and co-exist with another Wi-Fi AP on the same unlicensed channel.

However, none of the published literature has so far examined the impact on the overall LTE-U system performance due to the interference resulting from multi-operator LTE-U channel sharing. In this paper, we study this key aspect, and quantify and highlight the need for an explicit interference mitigation mechanism for multi-operator LTE-U channel sharing for countries such as U.S., that do not mandate the LBT requirements for operations in the unlicensed spectrum. Our contributions are summarized as follows:

- We present the LTE and Wi-Fi co-existence mechanism as proposed by LTE-U Forum [23], and define the deployment scenario that will result in overall degraded LTE-U system performance as a result of multi-operator LTE-U co-channel co-existence in non-LBT regions.
- We propose an unlicensed spectrum Inter Cell Interference Coordination (usICIC) mechanism to significantly improve the overall LTE-U system performance for multi-operator LTE-U co-channel co-existence in non LBT regions.
- We demonstrate by extensive simulation results that the proposed usICIC mechanism will result in 40% or more improvement in overall LTE-U system performance.

The rest of the paper is organized as follows. We discuss the related work in Section II. In Section III, we present the system model and problem description for multi-operator LTE-U co-channel co-existence scenario that employs the LTE and Wi-Fi coexistence mechanism in the unlicensed spectrum as proposed by the LTE-U Forum. In Section IV, we present our proposed usICIC mechanism for enhancing multi-operator LTE-U co-channel co-existence scenario performance. In Section V, we describe the simulation setup and discuss the results. Finally, we draw conclusions in Section VI.

II. Related Work

The LTE and Wi-Fi coexistence in the unlicensed spectrum has been studied recently. In [6], the benefits of deploying LTE in the unlicensed spectrum and its potential co-existence with Wi-Fi were discussed. In [8], the need for proper co-existence mechanisms was explored to enable Wi-Fi, and LTE co-existence in the unlicensed spectrum. In [9], a Wi-Fi, and LTE co-existence mechanism that consisted of blanking some LTE sub-frames to improve Wi-Fi performance was discussed. In [10], the performance of LTE and Wi-Fi was compared in the unlicensed spectrum to demonstrate that in general, LTE outperforms Wi-Fi in similar scenarios. In [11], the use of LTE UL power control was presented to improve LTE and Wi-Fi coexistence. In [12], the performance of LTE and WLAN in a shared frequency band was evaluated. The study demonstrated that the co-existence has a negative impact on WLAN system performance but it was reasoned that the severity of the impact can be controlled by restricting LTE activities. [12] Called for more careful co-existence mechanism studies to address this issue. [5], [25]–[27] provided in-depth analyses for LTE and Wi-Fi co-existence using carefully designed Carrier Sense Adaptive Transmission (CSAT) gating cycle mechanism for LTE-U transmissions in the unlicensed spectrum. These work that were done under the umbrella of the LTE-U Forum [23] demonstrated via simulation results that the CSAT mechanism will allow LTE to be a fair neighbor to Wi-Fi while sharing the same unlicensed channel by ensuring that the performance of the Wi-Fi AP is no worse than when it shares the same channel with another Wi-Fi AP.

The difference between the work presented in this paper and the other research works has been that the other research works have not studied and performed analysis for multi-operator LTE-U co-existence in the unlicensed spectrum while sharing the same unlicensed channel. The LTE-U Forum work [24]–[27] assumed that for the multi-operator LTE-U deployment scenario, the two LTE-U small cells will use different channels in the unlicensed spectrum. Since there are a limited number of channels in the 5 GHZ unlicensed spectrum, the probability of two LTE-U small cells sharing the same unlicensed channel in a dense multi operator deployment scenario is very high. We have demonstrated via detailed LTE system level simulations that overall system performance degrades significantly when two LTE-U Small cells share the same unlicensed channel without any CSAT gating cycle coordination. We have proposed an unlicensed spectrum Inter Cell Interference Coordination (usICIC) mechanism to allow the multi-operator LTE-U small cells to negotiate orthogonal (non-overlapping) CSAT gating cycles for their respective LTE-U transmissions while sharing an unlicensed channel to drastically improve the overall LTE-U system performance as validated by the simulation results.

Interference migration has been studied in the context of cognitive radios. In [28], the authors surveyed the fundamental capacity limits and associated transmission techniques for different wireless network design paradigms using cognitive radios. Power allocation strategies were proposed in [29], which could be employed for the coexistence of one or more cognitive radios with a primary radio where the cognitive radios transmit in a spectrum allocated to the primary radio. In [30], the authors proposed an underlay spectrum sharing policy for a point-to-point link of cognitive radios to leverage uplink spectrum resource of the primary network, and demonstrated that such an uplink band sharing mechanism could enhance the throughput performance of point-to-point link, while the interference to the primary users could be regulated under the allowed level decided by the primary users. In [31], the authors studied the green cognitive mobile networks with small cells in the smart grid environment. Unlike most existing studies on cognitive networks, where only the radio spectrum is sensed, their proposed cognitive networks sense not only the radio spectrum environment, but also the smart grid environment, based on which power allocation and interference management for multimedia communications are performed to significantly reduce the operational expenditure and CO2 emissions. Unlike cognitive radios, the LTE-U small cell operates in the unlicensed spectrum where there is no concept of the primary user. Upon detecting another node's (Wi-Fi or LTE-U) presence on the unlicensed channel, the LTE-U small cell does not necessarily switch its operation to another unlicensed channel, but rather attempts to co-exist with the other nodes and share the unlicensed channel in TDM fashion.

III. System Model and Problem Description

As part of the technical specifications released for the deployment of LTE-U, the LTE-U Forum [23] has proposed CSAT [5], [24], [25] to be used as the non LBT co-existence mechanism for the harmonious co-existence of LTE with Wi-Fi in the unlicensed spectrum. The CSAT mechanism allows the LTE-U small cell share an unlicensed channel with Wi-Fi in a Time-Division-Multiplexing (TDM) manner. In this adaptive transmission scheme, the LTE-U small cell employs a transmission gating cycle T_{CSAT} with a LTE-U ON/OFF duty cycle (Fig. 2) to co-exist with Wi-Fi APs in a fair manner on the same unlicensed channel. The T_{CSAT} gating cycle is divided into Transmission Time Interval (TTI) or timeslots, each of which is a millisecond or sub-frame wide. Thus N timeslots or sub-frames for LTE-U ON (Z_1 msec), and another M timeslots or sub-frames for the LTE-U OFF (Z_2 msec) pattern (Fig. 2). For the case of T_{CSAT} gating cycle with 50% duty cycle, N = M.

The CSAT mechanism works well for LTE and Wi-Fi co-existence, because the co-channel Wi-Fi backs off during the LTE-U ON transmission period of the T_{CSAT} gating cycle due to the Carrier Sense Multiple Access (CSMA) nature of its Medium Access Control (MAC) layer. By using an appropriate duty cycle (e.g., 50%) for the CSAT transmission gating cycle (T_{CSAT}), LTE-U small cell ensures that it leaves at least 50% of the channel for Wi-Fi use thereby ensuring a proper TDM

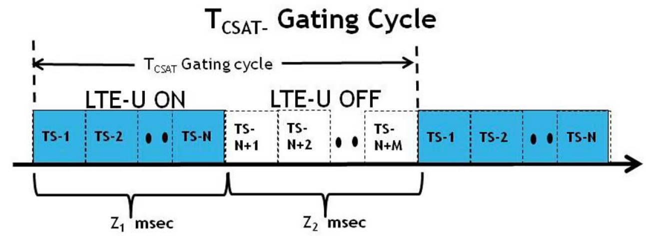

Fig. 2. T_{CSAT} Gating Cycle for LTE-U Channel Sharing with Wi-Fi.

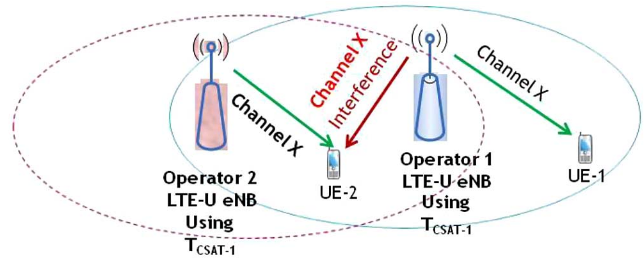

Fig. 3. Multi-Operator LTE-U Co-channel Interference Scenario.

sharing of the channel with Wi-Fi. However, an uncoordinated use of CSAT transmission gating cycle does not work well for multi-operator LTE-U small cells co-channel co-existence scenario, mainly because none of the LTE-U small cells sharing the channel backs off to each other's LTE-U transmissions during their respective LTE-U ON period of the gating cycle. This situation is exacerbated when each of them use overlapping T_{CSAT} gating cycles for their LTE-U operations. If there is no coordination between multi-operator LTE-U small cells for the use of the LTE-U transmission gating cycle T_{CSAT} for co-channel LTE-U co-existence, it will result in overall degraded LTE-U system performance. The two LTE-U small cells that are either co-located or non-co-located with overlapping coverage area may each independently select an overlapping LTE-U transmission gating cycle. This will result in severe interference to their LTE-U users in the overlapping coverage area of the two LTE-U small cells for the duration of the overlapped LTE-U transmission gating cycle.

Fig. 3 depicts such a multi-operator LTE-U small cell deployment scenario, where Operator 1 LTE-U small cell and operator 2 LTE-U small cell each select the same unlicensed 5 GHZ Channel X and also use non-coordinated overlapping LTE-U transmission gating cycle for their LTE-U SDL operations. UE-1 is being served by operator 1 LTE-U small cell, and UE-2 is being served by operator 2 LTE-U small cell. The Operator 1 LTE-U small cell SDL transmission to UE-1 will result in interference to UE-2 during its simultaneous SDL operations with its serving Operator 2 LTE-U small cell for the duration of the overlapped LTE-U T_{CSAT} gating cycle, and will subsequently impact the LTE-U system throughput performance.

Let's denote $\mathbf{S}_{i,j,k,t}$ as the received signal power at the i^{th} user from its serving LTE-U small cell j, of operator k at TTI t of the T_{CSAT} gating cycle, and $\mathbf{N}_{thermal}$ is the thermal noise at i^{th} user. Let's use $\oslash(t)$ to denote the set of interfering nodes (Wi-Fi or LTE-U) transmitting during a TTI t of the T_{CSAT} gating cycle on the unlicensed channel X. A node l is part of the interfering nodes set $\oslash(t)$ only if it is transmitting at TTI t. The aggregate interference $\mathbf{I}_{i.j.k.t}$ or the received signal power from the interfering nodes l in set $\oslash$(t) at the i^{th} user that is being served by LTE-U small cell j of operator k at TTI t can be represented by $\sum_{l \in \oslash(t)} I_{i,j,k,l,t}$.

Instantaneous signal to interference plus noise (SINR) ratio [24] for a given TTI t reflects instantaneous received signal powers from different transmitting nodes. Unlike Wi-Fi, LTE-U SINR distribution is independent of decoding. Thus, the SINR for the i^{th}user served by LTE-U small cell j of operator k for a TTI t is defined by:

$$\boldsymbol{SINR_{i,j,k,t}} = \frac{\mathbf{S}_{i,j,k,t}}{\mathbf{N}_{thermal} + \sum_{l \in \emptyset(t)} I_{i,j,k,l,t}} \tag{1}$$

Thus for the multi-operator LTE-U co-channel interference scenario depicted in Fig. 3, the higher interference level $\mathbf{I}_{\boldsymbol{i.j.k.t}}$ during the overlapping portion of the LTE-U ON period of the $\mathrm{T_{CSAT}}$ gating cycle of the nearby LTE-U small cells will result in lower $\boldsymbol{SINR_{i,j,k,t}}$, leading to degraded LTE-U system performance.

To address this co-channel LTE-U interference issue, and to enhance the overall LTE-U system performance (throughput gains) in non-LBT unlicensed spectrum, there is a need for an explicit LTE-U Inter Cell Interference Co-ordination mechanism. We present such a mechanism in the next section that will facilitate the coordination and usage of orthogonal non-overlapping LTE-U transmission gating cycles between adjacent multi-operator small cells that co-exist on the same unlicensed channel X (e.g., channel 149 in the 5GHZ band), for their LTE-U SDL operations.

IV. Proposed Unlicensed Spectrum Inter Cell Interference Co-Ordination (usICIC) Mechanism

A. Overview

The main goal of our proposed usICIC mechanism is to reduce the inter-cell interference and enhance the overall system performance for the multi-operator LTE-U co-channel co-existence scenario. When two or more LTE-U small cells with overlapping coverage area, share an unlicensed channel for their respective LTE-U SDL operations, the usICIC mechanism enables them to negotiate with each other, over the backhaul X2 eNodeB signaling interface [3] the use of non-overlapping CSAT transmission gating cycle of appropriate duty cycle. Thus, when one LTE-U small cell is transmitting during its LTE-U ON period of the CSAT transmission gating cycle, the other LTE-U small cells sharing the same channel will be quiet (or OFF) leading to significant reduction in interference ($\mathbf{I}_{\boldsymbol{i.j.k.t}}$) to their users ($i^{th}$ user of serving small cell j of operator K at TTI t of the CSAT gating cycle) throughout the overlapping coverage area of the LTE-U small cells.

When the LTE-U transmission gating cycles of two co-located or near-by multi-operator small cells that share the same channel X, is perfectly aligned, it will result in the worst case interference for LTE-U co-channel co-existence scenario. However, when the small cells employ orthogonal non-overlapping LTE-U transmission gating cycle via an inter cell coordination mechanism such as usICIC it will result in the best case interference mitigation scenario for multi operator LTE-U co-channel co-existence.

Since the small cells of different operators will not be time synchronized across the same sub-frame boundary, during the CSAT gating cycle coordination process the adjacent small cells will also establish the start of each other's transmission gating cycle relative to their own sub-frame boundaries in an attempt to achieve as orthogonal a transmission gating cycles as possible with minimum overlap. For the non-coordinated scenario that does not employ usICIC mechanism, the level of LTE-U transmission gating cycle overlap between the two small cells will be a random distribution between the worst case (perfectly aligned and completely overlapping) and best case (orthogonal non-overlapping) scenarios. Consequently, the actual interference level and the resulting LTE-U system performance will be somewhere within the two extreme boundary conditions of worst case, and best case co-ordination scenarios.

B. Workflow of the Proposed usICIC Mechanism

Figure 4 depicts the event trace diagram of our proposed usICIC mechanism with high level description for each step involved in the usICIC mechanism.

In **Step 1**, operator 1 small cell is performing LTE-U SDL operations with UE 1 on unlicensed channel X (e.g., channel 149 in the 5GHZ band).

In **Step 2**, as operator 2's small cell starts to initiate its LTE-U operations, its channel selection algorithm picks channel X for its LTE-U operations. Upon detecting the presence of other operator (operator 1) LTE-U small cell on the same channel X, operator 2 small cell initiates the usICIC request with Operator 1 small cell over the backhaul eNodeB X2 signaling interface.

In **Step 3**, the two small cells then exchange relevant information (such as number of Wi-Fi AP nodes presence on the channel X, number of LTE-U small cell nodes presence on Channel X, the timing information to notify each other about the start of their sub-frame boundaries etc) over the backhaul X2 eNodeB signaling interface, to negotiate and determine as orthogonal a $\mathrm{T_{CSAT}}$ gating cycle as possible of appropriate duration for their LTE-U operations to share the channel X in time domain.

In **Step 4**, the two small cells notify their respective serving UEs about the beginning and end of the negotiated LTE-U ON period of the CSAT gating cycle from step 3, by the activation/deactivation of the unlicensed secondary carrier (SCell) using existing 3rd Generation Partnership Project (3GPP) standards based MAC (Medium Access control) channel element signaling over the primary carrier that is anchored in the licensed spectrum (PCell). This allows the UEs to know when to expect the LTE-U SDL transmission (LTE-U ON period of the $\mathrm{T_{CSAT}}$ gating cycle) form their serving LTE-U small cell.

In **Step 5**, the two small cells initiate their LTE-U SDL operations with their respective users (UEs) while causing minimal to no interference to each other's LTE-U SDL operations with users in their overlapped coverage area.

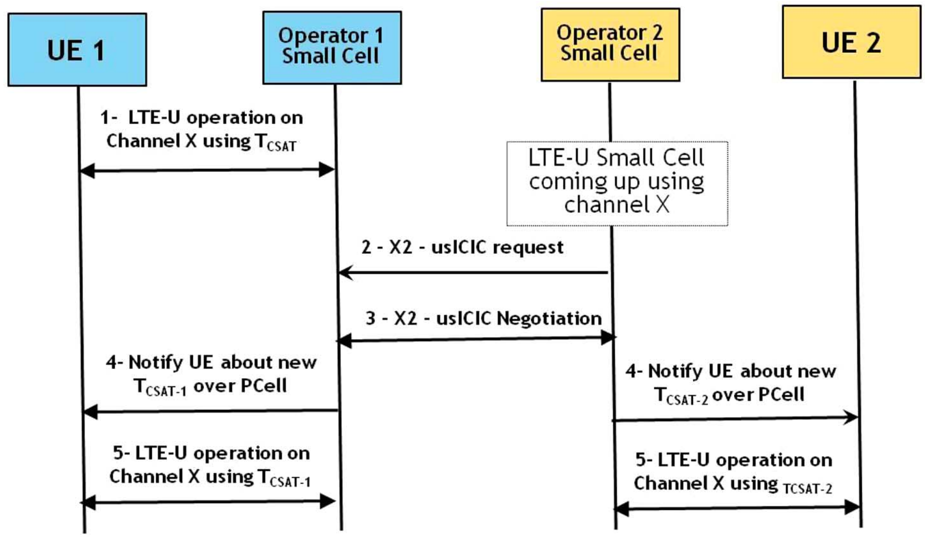

Fig. 4. Event Trace Diagram for the proposed usICIC Mechanism.

If channel X is only shared by two LTE-U small cells, the negotiated orthogonal (non-overlapping) T_{CSAT} gating cycles for the two LTE-U small cells cannot use the entire 100% time duration of channel X. Some portion of the channel usage time has to be left free of any LTE-U activity to allow a nearby Wi-Fi AP to sneak in, and share the channel as well. In such a case, the number of nodes sharing channel X will change from 2 to 3 (Two LTE-U small cells, and one Wi-Fi AP). This change in channel node usage will trigger another round of usICIC negotiations between the two LTE-U small cells that would result in the two LTE-U small cells using orthogonal CSAT gating cycle that use one third of the available channel time.

The usICIC mechanism applies equally for the scenario where the same unlicensed channel is shared by more than two LTE-U small cells, such as the case where an unlicensed channel is shared e.g., by three LTE-U small cells, and a Wi-Fi AP. Using the usICIC mechanism the three LTE-U small cells may each negotiate the use of their respective orthogonal non overlapping CSAT gating cycle that use one fourth of the available channel time, while leaving 25% of the channel time exclusively for use by the Wi-Fi AP, thereby reducing interference for all nodes sharing the unlicensed channel.

The goal of our proposed interference mitigation usICIC mechanism is to minimize $\mathbf{I}_{i.j.k.t}$ by reducing the interference caused by two or more co-channel LTE-U small cells to each other's LTE-U SDL operations. The use of the orthogonal non- overlapping CSAT transmission gating cycle by each co-existing LTE-U small cell on the same unlicensed channel will result in better SINR distribution, which will lead to higher user (50^{th} percentile, Average, 95^{th} percentile) and small cell system throughputs on the unlicensed carrier. The improvement in SINR distribution results from the fact that when one LTE-U small cell j is transmitting during a TTI t of its LTE-U ON transmission gating cycle, the other LTE-U small cells that share the same unlicensed channel X, will not be simultaneously transmitting, and will thus not cause interference to the users served by the LTE-U small cell j of operator k.

The usICIC handshake mechanism is triggered only when a new LTE-U small cell starts to share an unlicensed channel with another LTE-U small cell, or if there is a change in the number of nodes sharing the unlicensed channel. Therefore, once the orthogonal CSAT duty cycle duration, and start, and end time is negotiated, the LTE-U small cell may continue to use it for its LTE-U SDL transmission. If there is a change in the CSAT duty cycle duration, and start, and end time as a result of a new usICIC handshake mechanism that is being done in parallel with the on-going LTE-U SDL transmissions, the LTE-U small cell will start using the new settings once they become available after the successful conclusion of the new usICIC handshake mechanism.

The SINR distribution, user (50^{th} percentile, Average, 95^{th} percentile) and small cell average throughput are the three key performance indicators (KPIs) that we have utilized in our LTE system level simulations to evaluate the performance of our proposed usICIC mechanism for the multi-operator LTE-U co-channel co-existence scenario.

The LTE-U small cells average throughput is dependent upon Channel Resource Utilization [24], Channel Loading [24], and Channel Congestion [24] metrics. Better SINR distribution resulting from the use of our proposed usICIC mechanism will result in better channel conditions so the small cell will be able to complete its LTE-U SDL transmissions to its UEs much faster, thereby reducing the channel loading and congestion metrics and improving the LTE-U small cell average throughput.

Channel Congestion metric $\boldsymbol{C}_{j,k}$ for the LTE-U small cell j of operator k, is a function of the Channel Resource Utilization $U_{j,k}$ and Channel Loading $\boldsymbol{L}_{j,k}$, and is defined as follows:

$$\boldsymbol{C}_{j,k} = 1 - \left(\frac{U_{j,k}}{L_{j,k}}\right) \tag{2}$$

If T is the set of TTIs over a given period of time, such that

$$T = \{t_1,\ t_2,\ \ldots,\ t_n\} \tag{3}$$

Let $\mho$ denote the set of users served by LTE-U small cell j of operator k within its coverage area of the 5 GHz unlicensed spectrum. Then the Channel Resource utilization $\boldsymbol{U}_{\boldsymbol{j},\boldsymbol{k}}$ for the LTE-U small cell j of operator k is defined as the fraction of time the LTE-U small cell is transmitting to one of its users in set $\mho$ over the unlicensed channel X. It is thus represented as follows:

$$\boldsymbol{U}_{\boldsymbol{j},\boldsymbol{k}} = \left(\frac{\sum_t 1\left(P_{j,k,t}\right)}{T} \right) \tag{4}$$

Where the indicator function $\mathbf{1}\left(\mathbf{P}_{\boldsymbol{j},\boldsymbol{k},\boldsymbol{t}}\right)$ is defined as follows:

$$1\left(\boldsymbol{P}_{\boldsymbol{j},\boldsymbol{k},\boldsymbol{t}}\right) = \begin{cases} 1 & \textit{If small cell j, k is transmitting in TTI t} \\ 0 & \textit{If small cell j, k is Not Transmitting in TTI t} \end{cases} \tag{5}$$

LTE-U small cell unlicensed Channel Loading $\boldsymbol{L}_{\boldsymbol{j},\boldsymbol{k}}$, may be defined as the fraction of the time LTE-U small cell j of operator k has data to transmit (non empty queues) to its users defined by set $\mho$ within its coverage area. Let $\mathbf{q}_{\boldsymbol{i},\boldsymbol{t}}$ be the size of the queue for the i^{th} user in the set $\mho_{\boldsymbol{j},\boldsymbol{k}}$ at Transmission Time Interval (TTI) t.

An indicator function $\mathbf{1}\left(\mho_{\boldsymbol{i},\boldsymbol{t}}\right)$ is defined on the set $\mho$ such that the value of the indicator function is 1, if the small cell j of operator k has a non empty queue at TTI t for its i^{th} user or element of user set $\mho$. The value of the indicator function $\mathbf{1}\left(\mho_{\boldsymbol{i},\boldsymbol{t}}\right)$ will otherwise be 0.

$$1\left(\mho_{i,t}\right) = \begin{cases} 1 & \textit{if } q_{i,t} > 0 \textit{ at TTI t} \\ 0 & \textit{if } q_{i,t} = 0 \textit{ at TTI t} \end{cases} \tag{6}$$

Then, the Channel Loading $\boldsymbol{L}_{\boldsymbol{j},\boldsymbol{k}}$ over the unlicensed 5 GHZ unlicensed spectrum for each LTE-U small cell j of operator k may therefore be represented as follows:

$$\boldsymbol{L}_{\boldsymbol{j},\boldsymbol{k}} = \left(\frac{\sum_t \sum_{i \in \mho} 1\left(\mho_{i,t}\right)}{T} \right) \tag{7}$$

So using equations (2) - (7), the overall congestion metric of an unlicensed channel is defined as follows:

$$\boldsymbol{C}_{\boldsymbol{j},\boldsymbol{k}} = 1 - \left(\frac{\sum_t 1\left(P_{j,k,t}\right)}{\sum_t \sum_{i \in \mho} 1\left(\mho_{i,t}\right)} \right) \tag{8}$$

The LTE-U small cell continues to monitor the channel conditions (Wi-Fi activity, number of co-existing Wi-Fi, and LTE-U Small Cell) of other unlicensed channels during its LTE-U OFF period of the CSAT transmission gating cycle. This is done to identify a candidate set of unlicensed channels to switch the LTE-U operation if the current unlicensed channel condition continues to yield degraded system performance. Thus by monitoring the Congestion metric $\boldsymbol{C}_{\boldsymbol{j},\boldsymbol{k}}$ in addition to the system throughput, the LTE-U small cell may easily decide when to switch its LTE-U operations to an alternative cleaner unlicensed channel if the degraded system performance persists for a pre-defined period of time. Additionally the small cell may utilize these metrics to determine when to turn its LTE-U SDL operations off while dealing with light traffic that could easily be handled by the licensed LTE carrier, This opportunistic turning off of the small cell LTE-U SDL operations [24] will make it a fair neighbor to other nodes sharing the unlicensed channel, because by doing so it makes the unlicensed channel available to other transmitting nodes to use completely.

TABLE I
SIMULATION PARAMETERS & ASSUMPTIONS

Parameter	Value
Layout	21 Macro Cells layout
Macro Cell Inter Site Distance (ISD)	500 m
Number of Licensed Carriers	2 (2 GHz for licensed carriers)
Number of Unlicensed Carrier	1 (5 GHz for unlicensed carrier)
LTE-U System Bandwidth	10 MHz
Number of Operators	2
Number of small cell Clusters Per Macro Cell	1
Number of Small Cells Per Operator per cluster	1
Number of UEs	30 per macro cell per operator
UE Dropping	2/3 UEs randomly and uniformly dropped within the clusters, 1/3 UEs randomly and uniformly dropped throughout the macro cell coverage area that contained the cluster
Tx Power on Unlicensed	30 dBm over licensed carrier, and 24 dBm over unlicensed carrier
Cell Selection or Association Criteria	Reference Signal Received Power (RSRP) based on the licensed carrier
Antenna Configuration	1Tx, 1 Rx
Traffic Model	Full Buffer
LTE-U T_{CSAT} Duty Cycle	50%
LTE-U ON Period	100 msec
LTE-U OFF Period	100 msec

V. PERFORMANCE EVALUATION

In this section, we present the simulation setup, scenarios, results, and the corresponding analysis.

A. Simulation Setup

We performed LTE system level simulations that were based on the scenario #1 of 3GPPTR 36.872 [4]. The MATLAB based LTE system level simulator employed for this simulation work has been developed in Bell Labs, Alcatel-Lucent, which provides LTE protocol stack support at the PHY (layer 1), and the MAC (layer 2) with complete scheduling functions. All Simulation parameters and assumptions are summarized in Table I. The Simulations employed two operators, one small cell per operator, and 30 users per operator in 21 macro cell layout with Inter Site Distance (ISD) of 500 meters. Three carriers were employed in the simulation: 2 licensed carriers at 2 GHz (one licensed carrier or PCell per operator), and 1 unlicensed carrier SCell for LTE-U SDL operations with a bandwidth of 10 MHz at 5 GHz (shared by the small cells of two operators). One transmit and one receive antenna configuration was used at each small cell with transmit power of 30 dBm used for licensed carrier (PCell) and 24 dBm for unlicensed carrier (SCell).

In the LTE system level simulation, the 21 macro cell layout was achieved by 7 macro cell sites, with 3 sectors per site.

Within each of these 21 macro cells coverage areas a cluster of small cells was deployed. In each cluster, one small cell was deployed for each operator, so that there were two small cells per macro cell cluster for evaluating the performance of a multi-operator unlicensed spectrum Inter Cell Interference coordination (usICIC) mechanism.

The simulation employed 30 UEs for each operator's Small cell dropped within each of the 21 macro cell coverage area. Two-thirds of these UEs were randomly and uniformly dropped within the cluster, and the remaining one-third UEs were randomly and uniformly dropped throughout the macro cell coverage area that contained the cluster. Cell selection or association was based on the licensed carrier reference signal received power (RSRP) criteria. A full buffer traffic model was employed in the simulation to ensure that the small cell utilized the entire duration of its LTE-U ON period of its T_{CSAT} transmission gating cycle. For performance evaluation, two types of multi-operator small cell layouts within a macro cell cluster were considered:

- Non co-located multi operator small cells that were 80 meters apart.
- Co-located multi operator small cells that were 3 meters apart.

B. Simulation Scenarios

Four scenarios were simulated to evaluate the performance of our proposed usICIC mechanism compared to the non coordinated case using the three key performance indicators (SINR distribution, user throughput, and small cell average throughput). In each scenario the T_{CSAT} gating cycle with 100 msec LTE-U ON, and 100 msec LTE-U OFF intervals (i.e. 50% duty cycle) was employed. In this section, we first describe the simulation scenarios, and then provide simulation results and comparison analysis of the three key performance indicators for the four scenarios, to highlight and quantify the LTE system performance enhancements achieved by our proposed usICIC mechanism.

- **Scenario # 1 (Worst Coordination) Non Co-Located small cells –** Non Co-Located (80 meters apart) Multi-operator LTE-U small cells sharing the same unlicensed channel X, and using the same fully time aligned T_{CSAT} gating cycle for their LTE-U SDL transmission.
- **Scenario # 2 (Worst Coordination) Co-Located small cells –** Multi-operator Co-located (3 meters apart) LTE-U small cells sharing the same unlicensed channel X, and using the same fully time aligned overlapping T_{CSAT} gating cycle for their LTE-U SDL transmission.
- **Scenario # 3 (Best Coordination) Co-Located small cells –** Multi-operator Co-located (3 meters apart) LTE-U small cells sharing the same unlicensed channel X and employing our proposed usICIC mechanism to use orthogonal non overlapping T_{CSAT} gating cycle for their LTE-U SDL transmission.
- **Scenario # 4 (Random No Coordination) Co-Located small cells –** Multi-operator co-located (3 meters apart) LTE-U small cells sharing the same unlicensed channel X, and using randomly partially aligned overlapping T_{CSAT} gating cycle for their LTE-U SDL transmission. Typically the small cells of two operators are not time synchronized and aligned on the same sub-frame boundary. So in the case of non coordinated multi-operator small cells (Scenario #4), the level of T_{CSAT} gating cycle (LTE-U ON interval) overlap will be a random distribution between [0,..,100] msec. Therefore, for Scenario #4 (Random No Coordination case), the simulations were repeated 10 times with randomly generated T_{CSAT} overlapping gating cycle patterns for each simulation run, and the LTE-U performance averaged across these 10 runs to achieve statistically meaningful result.

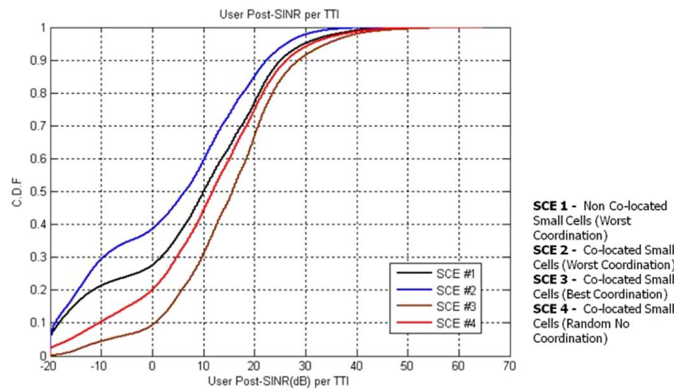

Fig. 5. LTE-U SINR Distribution Comparison for the four simulated scenarios.

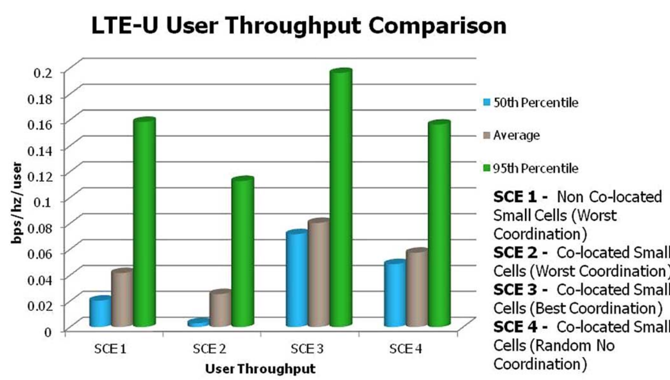

Fig. 6. LTE-U User Throughput Comparison for the four simulated scenarios.

C. Comparative Analysis of the Simulation Results

The LTE-U SINR distributions comparison for the four simulated scenarios is shown Figure 5. Scenario #3 (Co-Located small cells - Best Coordination using our proposed usICIC mechanism) has the best SINR distribution that is even better than that of Scenario #1 (Non Co-located small cells), where the cells were non co-located, and thus had smaller overlapping LTE-U coverage area that limited the impact of interference each small cell LTE-U transmissions would have caused to their respective users. This highlights the fact that the multi-operator small cells that are either co-located or non co-located, and share the same channel X with overlapping coverage area for their LTE-U SDL operations will benefit with better LTE-U SINR

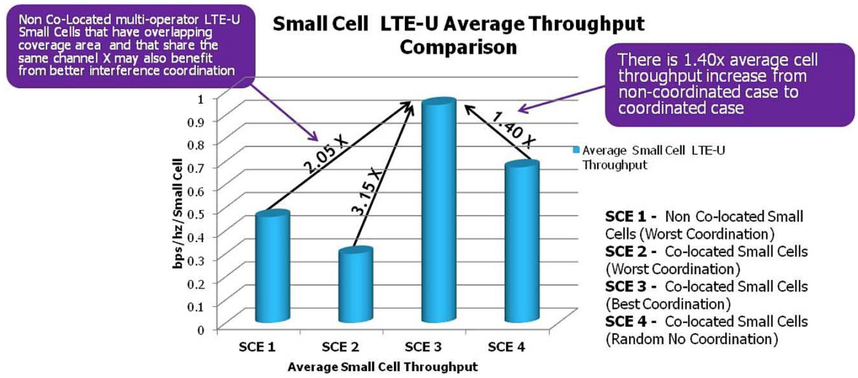

Fig. 7. LTE-U Small Cell Average Throughput Comparison for the four simulated scenarios.

distribution leading to improved overall LTE-U system performance from using our proposed usICIC mechanism.

The LTE-U user throughput (50^{th} percentile, Average, and 95^{th} percentile) comparison for the four simulated scenarios is shown in Figure 6. Scenario #3 (Co-Located small cells – Best Coordination that employed our proposed usICIC mechanism) has the best user throughput results, and demonstrate that the use of our proposed usICIC mechanism will result in substantial LTE-U system performance enhancement.

The LTE-U small cell average throughput comparison for the four simulated scenarios is shown in Figure 7. The results demonstrate that performance of the Scenario # 4 (random no co-ordination) will lie somewhere between [Worst Coordination Performance (Scenario #2), Best Coordination Performance (Scenario # 3)]. Scenario # 3, that employed our proposed usICIC mechanism had the best overall LTE-U system performance, and yielded a performance improvement by a factor of 1.4 (or 40%) compared to Scenario # 4 (Random No multi-operator coordination), and a performance improvement by a factor of 3.15 (0r 215%) compared to that of Scenario # 2 (Worst coordination).

The simulation results also demonstrate that Scenario #3 (Co-located Cells) that employed our proposed usICIC mechanism has a performance that is 2.05 times (or 105%) better than that of the Scenario #1 (Non Co-located Cells) that employed no coordination. Thus, even the overall LTE-U system performance of non co-located multi-operator small cells that share the same channel X and have some overlapping coverage area will also benefit from the use of our proposed usICIC mechanism.

VI. Conclusion

In this paper, we have studied the CSAT co-existence mechanism proposed by the LTE-U Forum for the harmonious co-existence of LTE and Wi-Fi in the unlicensed spectrum. We defined and presented a deployment scenario that highlighted the fact that even though using this CSAT co-existence mechanism will make LTE a fair neighbor to Wi-Fi, it will result in significant degraded overall system performance when multi-operator LTE-U small cells share the same unlicensed channel without any CSAT gating cycle co-ordination for LTE-U transmissions. We proposed an unlicensed spectrum Inter Cell Interference Coordination (usICIC) mechanism to address this issue. We demonstrated via extensive simulation results that our proposed usICIC mechanism will result in 40% or more improvement in overall LTE-U system performance.

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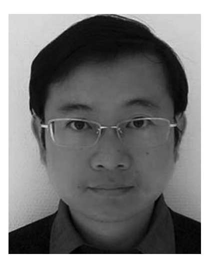

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