Extending LTE to Unlicensed Band – Merit and Coexistence

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***Abstract*—Innovations enabling efficient spectrum utilization is a key element to optimize user experience with growing data demand. This paper discusses the approach of extending enhancements in cellular technology like LTE to unlicensed band for higher spectral efficiency and better user experience. A key challenge for such extension is the coexistence with legacy technology such as Wi-Fi. The description herein highlights techniques for effective coexistence. The results include evaluation and lab data that demonstrate how the technology provide benefit to surrounding Wi-Fi deployment and contribute towards enhancing spectral efficiency of the unlicensed band.**

Keywords—LTE; carrier aggregation; unlicensed band; coexistence; fair-sharing; channel sensing; CSAT; Listen-before-talk; WiFi; heterogeneous network

I. Introduction

The past decade has been an era of exciting growth for mobile data demand, with smartphones becoming an essential companion in every part of our lives. The amount of data traffic on mobile networks has been doubling roughly year-over-year such that the growth of mobile traffic over past 10 years is over 1000 times. [1] Such growth is driving innovation to increase capacity of cellular networks while minimizing investment cost. The innovations in general come from three dimensions. The first is physical and MAC layer air interface enhancement towards higher link spectral efficiency (bits/sec/Hz), such as higher-order modulation, large-scale MIMO, and interference cancellation proposed for 3GPP long-term-evolution (LTE) technology. [2] The second aspect is network densification that targets to minimize deployment cost while ensuring optimized network performance as nodes densify. Key techniques include self-organizing networks (SON) and interference coordination (eICIC) across macro-, pico- and femto cells. [3] The third dimension focuses on techniques that enable better use of different types of spectrum for traffic offload, including unlicensed bands. This paper focuses on more efficient utilization of unlicensed spectrum.

The use of unlicensed spectrum to offload mobile network traffic has been a wide practice for the past decade. With the rising value of licensed spectrum, the use of unlicensed spectrum, such as ISM bands at 2.4 GHz and UNII bands at 5 GHz, for offload is very attractive. A widely used technology for mobile traffic offload is 802.11-based wireless LANs (WLANs), [4], or Wi-Fi, which can also be aggregated with cellular link to enhance user experience. Wi-Fi is attractive in multiple ways: it offers lower cost compared to traditional cellular equipment, is easy-to-deploy in an ad-hoc manner, and uses unlicensed spectrum (e.g. 2.4 GHz and 5 GHz). On the other hand, as a tradeoff to the inherent low-cost, Wi-Fi still need improvement to provide high grade of service to users like what LTE offers. Enhancement in coverage, mobility, and network efficiency are key areas of enhancement for high-efficiency Wi-Fi (802.11ax) currently under development [5].

It is important to realize that Wi-Fi is not the only technology in unlicensed band. Given LTE can already support mobility and is robust to variation of radio environment, taking LTE to operate in unlicensed band is a strong candidate that has been proposed in industry forums including 3GPP. [6]. The concept of LTE in unlicensed band, or LTE-U, is a natural extension of LTE carrier-aggregation (CA) [7] to including unlicensed band as a part of secondary carriers, initially targeting 5-GHz UNII band. The essence of the design is to anchor mobility and control procedures on licensed anchor carrier, and opportunistically use the secondary carrier in unlicensed band to offload traffic. This technology extension needs to meet two criterion to be meaningful. The first criteria is whether there is significant merit over Wi-Fi in metrics such as coverage, capacity, and user experience. A few studies on performance for the concept exists[8][9]. The second criteria is that LTE-U must be able to coexist in a fair-sharing manner with other technologies in the band, especially Wi-Fi. Specifically, in a cluster of Wi-Fi nodes being deployed, if an arbitrary number of the access points (APs) are replaced with LTE-U nodes, performance of the remaining Wi-Fi nodes should be comparable to or better than what they were in an all-Wi-Fi scenario. There has been initial evaluations [9][10] showing the performance of coexistence in unlicensed band.

The objective of this paper is to provide an overview on the conceptual framework of LTE in unlicensed band with associated performance merit and coexistence with Wi-Fi under dense deployment scenarios. Section 2 outlines the key design concept and provides simple analytical insights on coexistence.

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Section 3 provides simulation evaluation results based clustered deployment model and lab results that demonstrate technology merit and coexistence with Wi-Fi in the same band. Section 4 concludes the discussion.

II. CONCEPT OVERVIEW

A. Key concepts of extending LTE to unlicensed band

LTE-U is an extension of the LTE carrier aggregation protocol. The essential idea is for a given LTE connection with primary carrier on a licensed cellular band, if there is additional capacity demand, the base station (eNB) can add a secondary carrier in unlicensed band to serve users. Given the unlicensed bands are usually unpaired, the secondary carrier would be a time-division-duplexed (TDD) carrier or supplementary downlink-only (SDL). The aggregation is based on what is supported in 3GPP R12, FDD+SDL, TDD+TDD, FDD+TDD, and TDD+SDL. The reliability of LTE connection is maintained through the primary carrier, with opportunistic offload in unlicensed band. Figure 2.1 illustrates the CA configuration for LTE-U. Such deployment would target mainly small cells due to the transmit power limitation in unlicensed bands. [14]

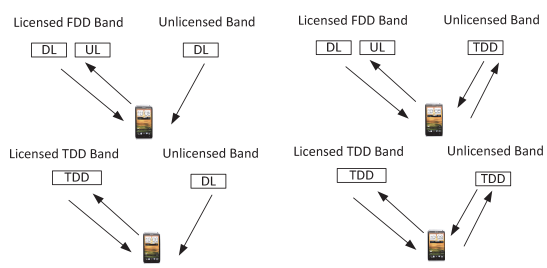


Figure 2.1. LTE Carrier Aggregation with Unlicensed Band

A key requirement for the carrier extension in the unlicensed band is the capability to coexist in fair-sharing manner with other technologies in the same band, mostly Wi-Fi for 5-GHz UNII band. Hereon we specifically focus on the coexistence of LTE with Wi-Fi. Fundamentally, band sharing across technologies can be done with coordinated resource sharing (such as RAN-sharing) or uncoordinated access. For coexistence between LTE and Wi-Fi in the same band would be uncoordinated, while the different LTE eNB and UE of the same operator would be a coordinated scheduling system by nature.

There are at least two basic approaches to uncoordinated medium sharing: frequency-domain avoidance and time-domain sharing. The concept of frequency selection exists for multiple technologies today and can be extended to LTE. An LTE equipment equipped with a network-listen (NL) module would be capable of sensing energy in a band and possibly deciphering Wi-Fi and LTE overhead. Hence LTE eNB would utilize NL to sense the channel and camp on if it has low levels of interference. Once connection is established, the eNB would continue to sense the channel dynamically and be able to move to a new band if the band occupancy situation changes.

In areas of dense deployment, there may be no unoccupied channels available, in which case LTE has to operate with Wi-Fi via time-sharing co-channel. Wi-Fi nodes perform random time-sharing with carrier sensing multiple access, i.e. CSMA, in which case the nodes would listen to the channel and transmit with a limited duration if there is no other transmission heard, or else defer the transmission by a specified time window. [4] For LTE secondary carrier in the unlicensed band, the eNB would perform at least one of two ways. The first mechanism is called channel sensing adaptive transmission (CSAT). [15] The eNB would sense the medium and compute a long-term medium utilization based on number of nodes heard, duty cycle of other nodes, and received energy associated with each node. The eNB then determines a transmission duty cycle for subsequent transmissions. Channel sensing is performed whenever the unlicensed carrier is turned off. CSAT works with LTE release 10 and later version where secondary carriers can be enabled with MAC activation and deactivation. The on/off time can vary from 10s to 100s of msec, while the most recent released coexistence specification from LTE-U forum specifies maximum of 50-ms. [14] During on time, data punctured subframes can also be inserted with a periodic pattern. Longer duty cycle provides higher capacity due to less overhead in carrier activation, and periodic data punctured gaps minimizes latency impact to delay sensitive traffic (e.g. VoIP) on Wi-Fi. The second mechanism of time-sharing is similar to the listen before transmit procedures for Wi-Fi. For example, in ETSI EN 301 893 specification for UNII band [11] there is a specific listen-before-talk (LBT) waveform specified with a frame-based mechanism, where the medium sensing happens at fixed frame boundary, and a load-based scheme with dynamic sensing and linear backoff. The air interface of LTE needs to change to include LBT as in [11]. The corresponding standardization in 3GPP is now a study item for R13. [6] Figure 2.2 illustrates the CSAT as well as LBT as co-channel fair-sharing mechanisms.

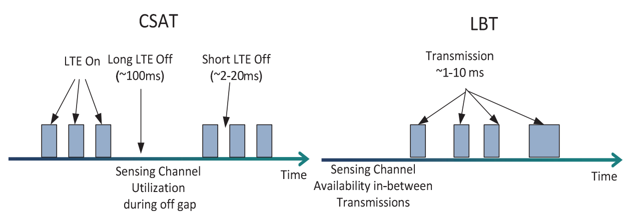


Figure 2.2. Illustration of CSAT and LBT Operation

B. First-order Analysis on LTE and WiFi Throughput

We develop a simple analysis to illustrate how coexistence between LTE and Wi-Fi can be achieved on the same 20 MHz channel. We first consider downlink of two pairs of nodes, access point (AP) 1 serving device 1 and AP 2 serving device 2, with cross-link interference as shown in Figure 2.3. We consider two scenarios. In scenario 1, both APs would be able to hear each other and transmit accordingly to ensure proper time-sharing of the spectrum. This would apply to the case where both are Wi-Fi nodes performing CSMA, or one node is Wi-Fi and second node is LTE with CSAT or LBT where its signal can reach Wi-Fi within CCA-ED threshold (-62 dBm) [4].

With proper design of LBT or CSAT on/off, ignoring the access overhead and imperfect rate control, the pair of nodes can achieve the downlink data rate in scenario 1 as follows:

$$R_1 = \alpha \cdot C(\frac{E_1 \cdot L_{1,1}}{N_0}) = \alpha \cdot C(SNR_1) \quad \text{(Eq. 2.1)}$$

$$R_2 = (1-\alpha) \cdot C(\frac{E_2 \cdot L_{2,2}}{N_0}) = (1-\alpha) \cdot C(SNR_2)$$

where R_1 and R_2 denote the achievable rate at device 1 and 2, respectively; E_1 and E_2 denote the transmitted signal energy at device 1 and 2 from access points 1 and 2 with N_o being the noise floor, respectively; $L_{i,j}$ denotes the path loss from AP i to device j; $C(.)$ denotes the constraint capacity function with 3 dB gap to capacity; SNR_i denotes the signal-to-noise ratio for the ith node; α denotes the fraction of time AP and device 1 uses the air link. In the case of equal time sharing this fraction is 0.5 for each pair. In practice, however, even when both APs are Wi-Fi, α is dependent on parameter settings of each Wi-Fi AP as TxOP and contention window, which varies across vendors. [12]

In scenario 2, AP 2 will be able to hear AP 1 and ensure a proportional time to be allocated to the other pair, while AP 1 will not hear AP 2. This resembles the likely case where AP 1 is a Wi-Fi AP and AP 2 is a LTE small cell with coexistence mechanisms built-in. The path loss between the two is such that the signals of one arriving at the other at energy below -62 dBm but above Wi-Fi preamble detection threshold, i.e. ~-82 dBm. In such case Wi-Fi will follow CCA-ED and not back off to LTE, while LTE with proper network listening can hear Wi-Fi and will share channel fairly. The pairs of nodes can achieve downlink data rate in scenario 2 as follows:

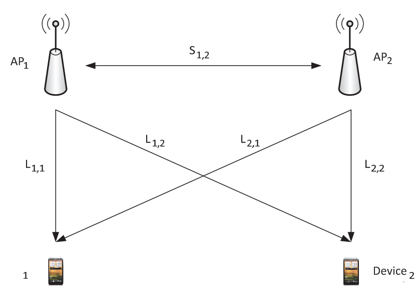
$$R_1 = \alpha \cdot C(\frac{E_1 \cdot L_{1,1}^2}{N_0}) + (1-\alpha) \cdot C(\frac{E_1 \cdot L_{1,1}^2}{E_2 \cdot L_{2,1}^2 + N_0}) \quad \text{(Eq. 2.2)}$$

$$R_2 = (1-\alpha) \cdot C(\frac{E_2 \cdot L_{2,2}^2}{E_1 \cdot L_{1,2}^2 + N_0})$$

Or equivalently Eq. 2.2 can be denoted as:

$$R_1 = \alpha \cdot C(SNR_1) + (1-\alpha) \cdot C(SINR_1) \quad \text{(Eq. 2.3)}$$

$$R_2 = (1-\alpha) \cdot C(SINR_2)$$



For analytical insight we assume a simple case where $SNR_1 = SNR_2 = 30$ dB, and $SINR_1 = SINR_2 = 15$ dB, the achievable rate for each pair as a function of α is shown in Figure 2.4. In scenario 1, a ratio of $\alpha=0.5$ is the point where each link achieves equal time access. This case applies to Wi-Fi and LTE with coexistence where signals of each AP can be heard by each other above CCA-ED threshold. In scenario 2, AP 1 (Wi-Fi) would not back off to LTE node, while the LTE node, with proper coexistence algorithms like CSAT, would attempt to provide gaps to allow Wi-Fi node to transmit for fair sharing. For a given link sharing ratio the Wi-Fi AP and device would achieve higher throughput in scenario 2 than that in scenario 1, while LTE performance would suffer in latter case due to Wi-Fi interference. This is a result of how Wi-Fi treats non-Wi-Fi node differently from another Wi-Fi node (20 dB difference in back-off threshold). Note that results here assume LTE and Wi-Fi have the same link efficiency. In practice, LTE performance in scenario 2 can still be better than Wi-Fi due to inherent link and MAC efficiency such as hybrid ARQ, better channel estimation, scheduling gains, and optimized coexistence techniques.

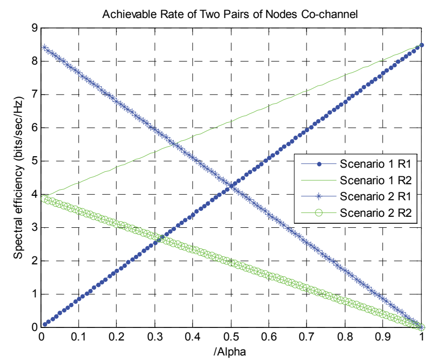


Figure 2.4: Achievable Rate for Each Pair in Scenarios 1 and 2.

As the number of pairs of APs and devices increases, assuming the same link efficiency, the performance of LTE comparing to Wi-Fi would improve substantially if all LTE nodes are from the same operator. This is because of the inherent reuse gains, i.e. all LTE nodes can operate synchronously, which is not the case for Wi-Fi. Similar insights have been developed in [13]. Consider three cases with N pairs of APs and devices: case 1 assumes each node transmits 1/N-th time without interference from others (resembles an ideal Wi-Fi network), case 2 assumes that all nodes are transmitting synchronously (as the case of LTE network), and case 3 assumes that half of the nodes behave like Wi-Fi and the other half behaves like LTE, and that all APs are beyond range of -62 dBm from each other but within the range of -82 dBm. To calculate the SINR distribution in each scenario, consider a two dimensional Poisson process with intensity λ. In all three scenarios, N APs are dropped with Poisson distribution in an area A. Similarly N devices are dropped randomly in the same area. The device will try to connect to the nearest AP from the same network. The rest of the APs in the network will be a source of interference to this device.

The SINR distribution at a given node for case 2 can be calculated as follows

$$SINR_2 = \frac{P r_1^{-\theta}}{P \sum_{n=2}^{N} r_n^{-\theta} + N_o}$$

Where r_n denotes the distance to the nth neighbor. The mean distance to the nth neighbor could be approximated as [16]

$$E[r_n] = \gamma \sqrt{\frac{n}{\lambda}}$$

For simplicity, the average SINR expression will be computed by replacing the vector of distances $\{r_i\}$ with the average distance $\{E[r_i]\}$. Therefore the average SINR for case 2 can then be approximated as (absorbing the constant γ in the SNR)

$$E[SINR_2] = \frac{P}{P\sum_{n=2}^{N} n^{\frac{-\theta}{2}} + N_o \lambda^{\frac{-\theta}{2}}}$$

where the first term in the denominator denotes the interference from the same LTE network, and hence considering interference from the second neighbor.

For case 3, the average SINR of a Wi-Fi node during CSAT on can be given by

$$E[SINR_{3W}] = \frac{P}{P\sum_{n=1}^{N/2} n^{\frac{-\theta}{2}} + N_o \left(\frac{\lambda}{2}\right)^{\frac{-\theta}{2}}}$$

where the first term of the summation represents the interference from the LTE-U network to a Wi-Fi node during LTE on, which takes into account the first interference neighbor n=1, reflecting the near-far problem. Since each network in case 3 has N/2 nodes, the node density is given by $\lambda/2$.

The average SINR in case 3 for an LTE-U node can be given by

$$E[SINR_{3L}] = \frac{P}{P\sum_{n=2}^{N/2} n^{\frac{-\theta}{2}} + \frac{2P}{N}\sum_{k=1}^{N/2} k^{\frac{-\theta}{2}} + N_o \left(\frac{\lambda}{2}\right)^{\frac{-\theta}{2}}}$$

For case 1, when all N nodes are Wi-Fi, the throughput can be expressed as

$$R_1 = \frac{1}{f(N)} C\left(\frac{P\lambda^{\frac{\theta}{2}}}{N_o}\right)$$

Where f(N) denotes the number of nodes, which is a function of the node density and the pathloss model, within CCA-CS (preamble detection) range and hence will TDM with each other. For case 2, when all N nodes are LTE-U

$$R_2 = C(E[SINR_2])$$

For case 3, when N/2 of the nodes are Wi-Fi, and N/2 of the nodes are LTE-U, the throughput of a Wi-Fi node and LTE-U node could be give respectively as

$$R_{3W} = \frac{2}{f(N)} C\left(\frac{P\lambda^{\frac{\theta}{2}}}{N_o}\right) + \frac{2}{f(N)} C(E[SINR_{3W}])$$

$$R_{3L} = \frac{1}{2} C(ESINR_{3L})$$

Figure 2.5 illustrates the performance of the difference scenarios analyzed. The numerical analysis assumes a transmit power of 30dBm, noise floor of -95dBm, and varying the node density per sqkm. The propagation pathloss assumed is 2. From the figure, it is clear that as network density increases, LTE-U network capacity scales better than Wi-Fi capacity. This is due to the fact that as node density increases, CSMA has poor network capacity scaling as degrees of freedom drops proportionally to node density. On the other hand, LTE-U is a scheduled system that operates in reuse 1. As network density increases, the capacity scales up as desired signal gains due to devices getting closer to serving APs overweigh interference increase.

Moreover, Wi-Fi performance is boosted when replacing half of the Wi-Fi nodes with LTE-U nodes. The rationale is that LTE-U nodes use CSAT which is a sharing mechanism in which nodes calculate long term channel utilization statistics of neighbor nodes and adapts their transmission duty cycle accordingly by deterministically backing off to other Wi-Fi nodes, to share the medium with neighbor nodes in a fair manner. Wi-Fi on the other hand uses CSMA/CA which is a random access contention based mechanism that does not work efficiently as node density increases. In particular, as node density increases collision increases with random access, an aspect that is not considered in this analysis which therefore presents an optimistic model of CSMA/CA. In summary, the sum capacity of the unlicensed band increases with deploying LTE-U nodes including the capacity of existing Wi-Fi networks.

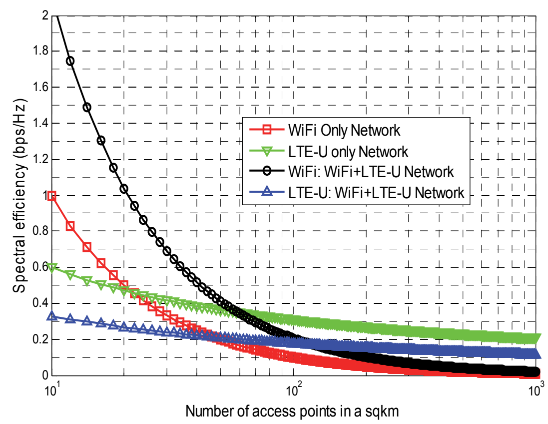


Figure 2.5. Wi-Fi and LTE Efficiency with Larger Number of Nodes in Cases 1, 2, and 3.

III. PERFORMANCE EVALUATION

The performance of LTE in unlicensed band and its impact to Wi-Fi for more realistic deployment scenarios has been evaluated in a large-scale system simulation. The evaluation focus on Rel-10-based LTE-U in SDL mode that uses CSAT and frequency selection, as Rel-13 based on LBT is still under progress in 3GPP. The evaluation framework is based on 3GPP evaluation methodology with 21-cell wrap-around [15] extended to cover unlicensed band. The deployment assumes dense hotspot deployment, where each macro cell has one dense hotspot that contains 8 or 16 APs (or pico cells) within an area of 50-m radius, with 160 user devices. Such density is comparable to 1000-2000 APs per km^2 with over 10000 devices. Only downlink traffic and associated uplink overhead is assumed. Within each hotspot, the total number of APs and devices are equally divided into two groups, with all APs and devices in each group using the same family of technology in 5-GHz UNII band, either Wi-Fi (802.11ac) or LTE-U SDL with coexistence. One way to view the partition is that there are two operators within the hotspot each using either Wi-Fi or LTE-SDL in 5-GHz band, while noting that the Wi-Fi APs need not be from the same operator as they operate independently. There is also a common 10-MHz licensed carrier with LTE supported at both macro cell and hotspot APs. Further detailed simulation assumptions are listed in Table 3.1.

Parameters	Wi-Fi	LTE in Unlic Band
Frequency	5 GHz	5 GHz
Bandwidth	40 MHz (2x20)	40 MHz (2x20)
# of Channels	8	8
Antenna Config	2x2	2x2
AP/eNB TxPwr (include EIRP)	27 dBm	27 dBm
Noise Figure	9 dB	9 dB
TxOP (Wi-Fi) / TTI (LTE)	3 ms	1 ms

Table 3.1. System Simulation Parameter for Wi-Fi and LTE-U

The simulation results are shown in Figure 3.1 and 3.2 for the case of 8 and 16 APs per hotspot area, respectively. The baseline is the case where all APs within a hotspot use Wi-Fi 802.11ac, including the prevalent use of LDPC codes. For each device connected to the hotspot AP, bearer selection between licensed LTE band and Wi-Fi is assumed. The second case is a mixed case where one group is Wi-Fi and the other is LTE with frequency selection and CSAT. The benchmark for proper coexistence here is that the performance of Wi-Fi users in the mixed case should be at least comparable to that in the baseline case. We observe that in the mixed case, both the median and 5% tail of Wi-Fi user throughput are at least maintained with CSAT, and in fact the median throughput of Wi-Fi users is slightly better by 10-40% in the case of LTE being a neighbor comparing to when Wi-Fi is a neighbor. This is contributed partly to insights in IIb that when LTE is the neighbor, with 802.11ac protocol today, Wi-Fi can actually achieve more chances of transmission and hence receive higher throughput. In the same case, the performance of LTE devices on the UNII band provides a significant performance merit (2 to 3 times) over baseline Wi-Fi users in the same group, thereby enhancing the overall spectral efficiency in the unlicensed band by benefiting both LTE and Wi-Fi users. We also observe that if both groups are deploying LTE with coexistence mechanisms, the overall user experience can be further enhanced.

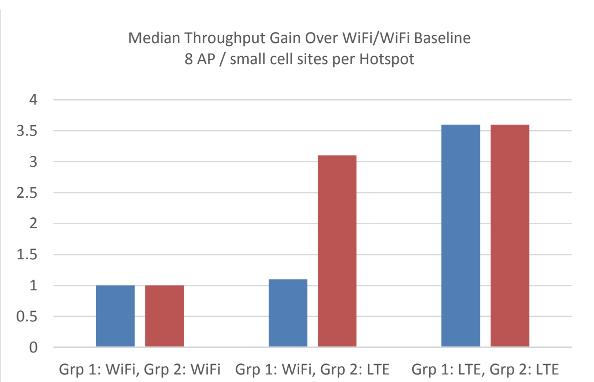


Figure 3.1 UNII-band Performance with Wi-Fi and LTE with 8 APs in the Hotspot.

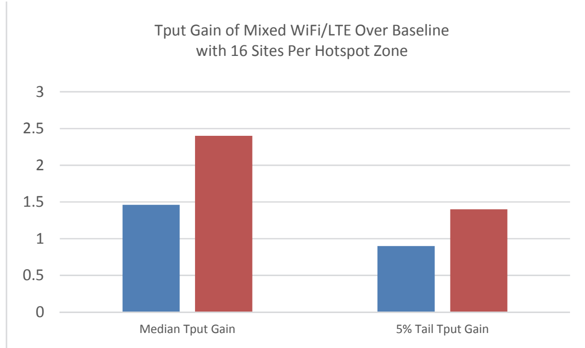


Figure 3.2 UNII-band Performance with Wi-Fi and LTE with 16 APs in the Hotspot.

Simulation evaluation assumes behavior of Wi-Fi APs are entirely compliant to 802.11ac specification with minstrel rate control algorithm [15]. In reality, the performance of commercial Wi-Fi APs tend to vary significantly depending on realization techniques. In order to thoroughly study the coexistence between Wi-Fi and LTE with CSAT in the same channel, further lab tests with commercial Wi-Fi APs are conducted. At R&D lab in Qualcomm, a dense Wi-Fi chamber with 8 reference Wi-Fi APs each paired with a given station are set up as shown in Figure 3.3. A Wi-Fi AP or LTE eNB under test will be the 9th transmitter in the dense chamber with a corresponding station or UE. All 9 pairs of transmissions occur over-the-air in the 5 GHz UNII-3 band over the same single 20-MHz channel. The most challenging aspect of the setup is actually the significant variation of throughput of baseline Wi-Fi when different Wi-Fi brands are used in the same environment. Such fact often makes LTE to appear to be a much better neighbor than Wi-Fi. To provide a more strict criteria for LTE to coexist with Wi-Fi, we proceed with illustration in the case where all Wi-Fi access in the chamber are from the same commercial vendors. The results are also comparable when we test across different commercial Wi-Fi brands, as long as all of the APs in the test-bed have the same brand.

Figure 3.3 Dense Wi-Fi Chamber Setup for Coexistence Test

The key lab results are shown in Figures 3.4 and 3.5. Figure 3.4 illustrates the performance of the eight reference Wi-Fi connections in the case of when the 9th transmission is a Wi-Fi AP and when the transmitter is LTE with CSAT instead. As observed, the average throughput performance of the 8 reference

Wi-Fi pairs are slightly better when the 9th node is LTE with CSAT compared to the case of when the 9th node is another Wi-Fi AP of the same brand. This confirms our conjecture from section IIB as well as the observation from simulation evaluations in Figure 3.1 and 3.2. As a by-product, we also observe that LTE in this case demonstrates significantly higher throughput compared to Wi-Fi. Further, Figure 3.5 illustrates what would happen to the average reference Wi-Fi throughput if more nodes in the same chamber are changed from Wi-Fi to LTE with CSAT instead. We observed that as more nodes are changed to LTE, the average Wi-Fi throughput for the remaining connections actually improve further. This case illustrates the effect of LTE with CSAT being a good neighbor to near-by Wi-Fi deployments even under such dense environment, and that by adding LTE to the unlicensed band with proper coexistence mechanisms, the spectral efficiency of the entire unlicensed band such as 5 GHz UNII band has the potential to be significantly enhanced, as it helps both Wi-Fi and LTE users in terms of user experience.

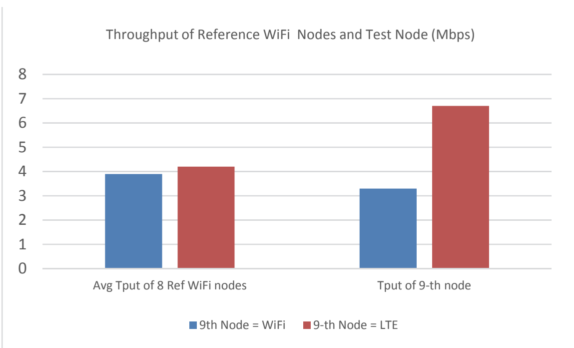


Figure 3.4 Throughput of Reference Wi-Fi Connection and AP/LTE node under Test

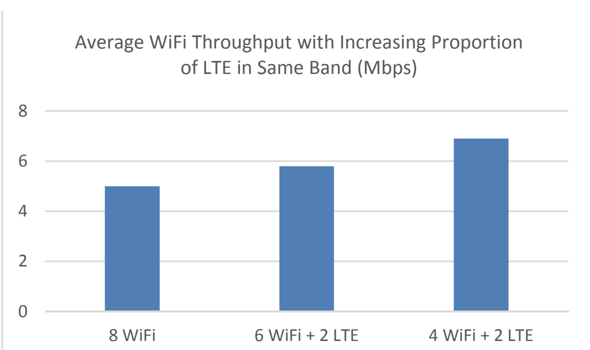


Figure 3.5 Average Throughput of Reference Wi-Fi Connection as More Nodes Become LTE with CSAT

IV. Concluding Remarks

In summary, with an overview on extending LTE to unlicensed band, through first-order analysis, simulation evaluation, and over-the-air in-door test, we observe with properly designed coexistence mechanisms LTE can coexist with Wi-Fi at the same level or better than existing Wi-Fi neighbors. It is also important to note that there are multiple ways for such coexistence mechanisms to be desired. Examples of time-domain coexistence include CSAT or via short LBT waveform, as long as there is channel sensing embedded in the LTE eNB. The observations of the evaluation also show that by deploying LTE in the unlicensed band, mobile users are going to be able to enjoy significantly better experience, and the spectral efficiency of the entire unlicensed band can be improved even in the case of mixed deployment of LTE and Wi-Fi in the same band. Based on the presented evaluation, it also becomes clear that proper coexistence between LTE and Wi-Fi in unlicensed band can be achieved by more than one set of procedures. The demonstrated test scenarios can help to establish a benchmark for the industry to develop a set of commonly accepted fair-sharing criterion for unlicensed band.

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