

Qualcomm Research

LTE in Unlicensed Spectrum:

Harmonious Coexistence with Wi-Fi



March 2014



Qualcomm Technologies, Inc.

5775 Morehouse Drive

San Diego, CA 92121

U.S.A.

©2014 Qualcomm Technologies, Inc.

All Rights Reserved.

This technical data may be subject to U.S. and international export, re-export or transfer (“export”) laws. Diversion contrary to U.S. and international law is strictly prohibited.

Qualcomm is a trademark of QUALCOMM Incorporated, registered in the United States and other countries. All QUALCOMM Incorporated trademarks are used with permission. Other product and brand names may be trademarks or registered trademarks of their respective owners.



Contents

1. Introduction	4
2. LTE-U Coexistence Considerations for Markets without LBT Requirements	5
2.1 Coexistence Mechanisms.....	5
Channel Selection.....	6
Carrier-Sensing Adaptive Transmission (CSAT).....	7
Opportunistic SDL.....	8
2.2 Simulation Results.....	8
2.3 Lab Demo	12
3. LTE-U Coexistence Considerations for Markets with LBT Requirements.....	15
3.1 LBT Requirements	15
3.2 LTE design modifications for LBT	15
3.3 Simulation Results.....	16
4. Conclusion	19



1. Introduction

Today a number of access technologies such as 802.11 (WiFi), 802.15.1 (Bluetooth) and 802.15.4 (ZigBee) are used in 2.4GHz ISM (Industrial, Scientific and Medical) and 5GHz U-NII (Unlicensed National Information Infrastructure) bands. These bands are also collectively known as ‘Unlicensed’ or ‘Licensed-Exempt’ bands. Data offload in unlicensed band today is primarily carried out using WiFi which is designed in the premise of trading off performance for low cost and simple implementation for spectrum sharing. The unlicensed bands have traditionally been unsuitable for use with access technologies designed primarily to operate in “licensed” frequencies, like LTE, that focus on maximizing spectral efficiency and optimizing user experience. However, for the first time LTE features such as Carrier Aggregation (CA) have made it possible to operate these technologies in unlicensed bands as well. In a companion publication (‘Extending LTE Advanced to unlicensed Spectrum’, Qualcomm Inc. December 2013) Qualcomm Inc. has introduced such a system, known as LTE-U (‘LTE in Unlicensed band’), which enables data offload initially in unlicensed U-NII band, leveraging LTE CA and SDL(Supplemental Downlink) protocols. LTE operation in unlicensed band has the potential to offer significantly better coverage and higher spectral efficiency comparing to WiFi, while allowing seamless flow of data across licensed and unlicensed in a single core network. From the user perspective, this means an enhanced broadband experience, higher data rates, seamless use of both licensed and unlicensed bands, with high reliability and robust mobility through licensed anchor carrier.

A critical element of the design for LTE in unlicensed band is to ensure LTE-U co-exists with current access technologies such as WiFi on “fair” and “friendly” bases. There are many features to achieve such friendly coexistence, i.e. all-in-all to be a “good-neighbor” to Wi-Fi when using the same channel. At the same time, the operation in unlicensed band also needs to factor in the regulatory requirements of a given region. In some markets, like Europe and Japan, a specific waveform requirement on supporting LBT (Listen-Before-Talk) at milliseconds scale is required which would need changes in LTE air interface. In other markets, like US, Korea and China, there are no such requirements. Techniques that enable coexistence with WiFi can be realized for LTE Release 10/11 without changing LTE air interface protocol, and hence enable mobile operators to deploy the technology early in markets that do not require LBT at milliseconds scale. In markets where LBT is required, LTE in unlicensed operation can be further optimized through air interface enhancement with the introduction of LBT feature potentially in 3GPP Release 13. Regardless of the market and mode of operation, it is ensured that any LTE-U deployment can co-exist with incumbent access technologies such as WiFi on “fair” and “friendly” bases.

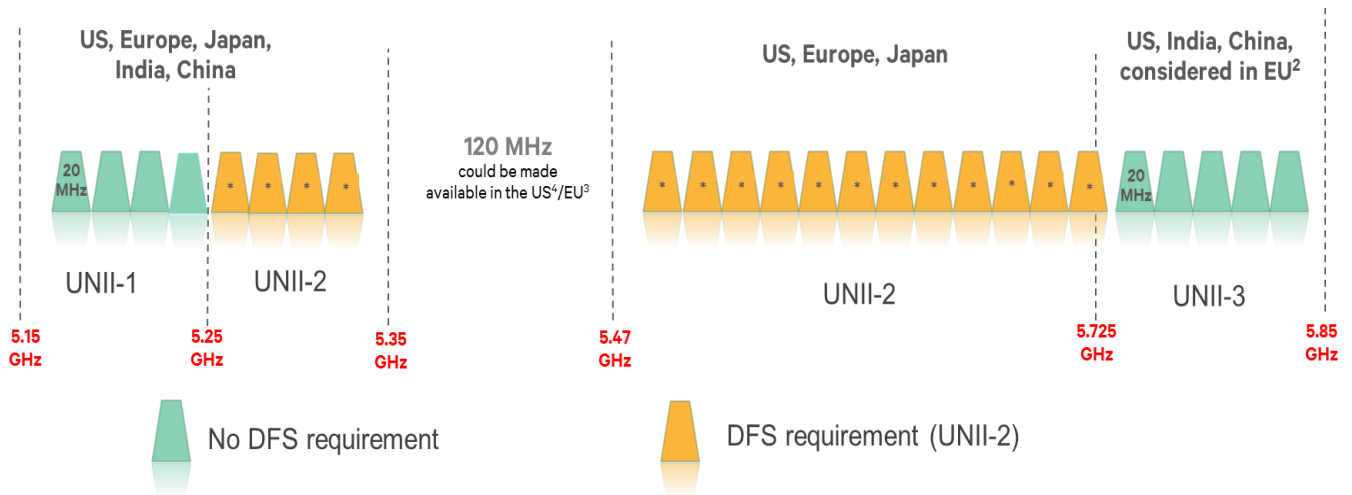


Figure 1-1: 5 GHz spectrum allocation

This whitepaper discusses LTE-U coexistence algorithms and design changes, that are required to operate in markets with and without LBT, together with evaluation/verification tests and performance simulation results.

2. LTE-U Coexistence Considerations for Markets without LBT Requirements

In countries such as the United States, China and South Korea, there is no regulatory requirement for “Listen-Before-Talk” (LBT) waveform for the unlicensed bands. In these countries, with carefully design coexistence mechanisms realizable by software to ensure peaceful coexistence with WiFi, operators can deploy LTE in unlicensed bands that are compatible with Rel. 10/11 3GPP LTE standards. It allows fast-time-to-market launch of small cells and UEs that can aggregate unlicensed carrier as a SDL with a primary carrier in licensed bands. New RF band (e.g. 5GHz) support is needed at both small cells and UEs for the operation. Moreover, carefully designed mechanisms are used to ensure harmonious co-existence with Wi-Fi.

2.1 Coexistence Mechanisms

Without modifying Rel. 10/11 LTE PHY/MAC standards, three mechanisms can be used to safeguard that LTE is a “good neighbor” in unlicensed bands (Figure 2-1). First, ‘Channel Selection’ enables small cells to choose the cleanest channel based on Wi-Fi and LTE measurements. This ensures the interference is avoided between the small cell and its neighboring Wi-Fi devices and other LTE-U small cells, provided an unused channel is available. The Channel Selection algorithm monitors the status of the operating channel on an on-going base, and if needed will select a more suitable one and change.

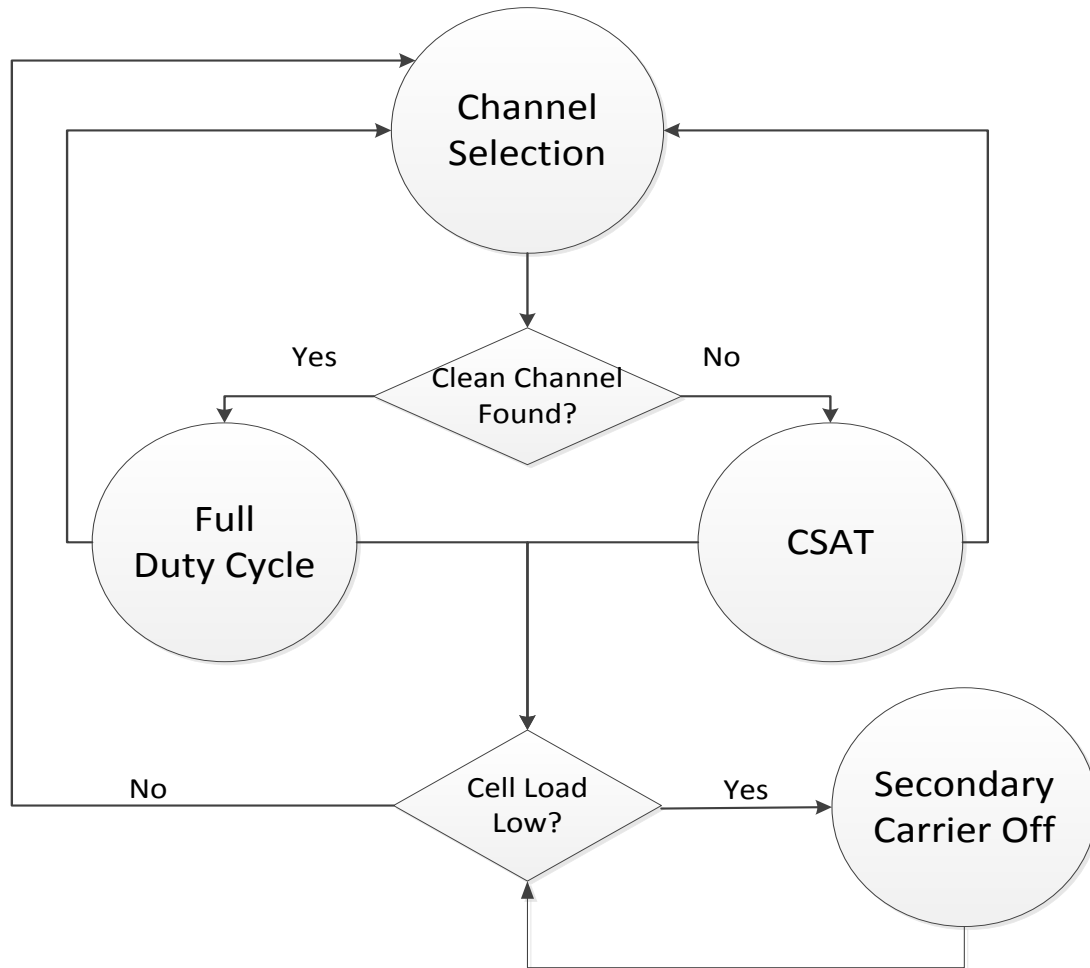


Figure 2-1 Co-existence Algorithms flow chart for LTE-U in markets without LBT requirements

In the event that no clean channel is available, Carrier-Sensing Adaptive Transmission (CSAT) algorithm is used to apply adaptive TDM transmission to LTE-U small cells, based on long-term carrier sensing of co-channel Wi-Fi activities. CSAT ensures that even in very dense deployments, LTE-U nodes can share the channel fairly with the neighboring Wi-Fi APs.

In addition, the SDL transmissions can be made opportunistically, based on the traffic demand. If the small cell is lightly loaded, the secondary component carrier in the unlicensed band can be turned off to avoid transmission of overheads such as CRS signals, which further reduces the interference to neighboring Wi-Fi APs. This is possible because the primary carrier is always operating in the licensed band.

Channel Selection

LTE-U small cells will scan the unlicensed band and identify the cleanest channels for the SDL carrier transmission. The measurements are performed at both the initial power-up stage and later periodically at SDL operation stage. If interference is found in the operating channel and there is another cleaner channel available, the SDL transmission will be switched to the new channel using



LTE Rel. 10/11 procedures. For most Wi-Fi and LTE-U small cell deployments channel selection is usually sufficient to meet the coexistence requirements.

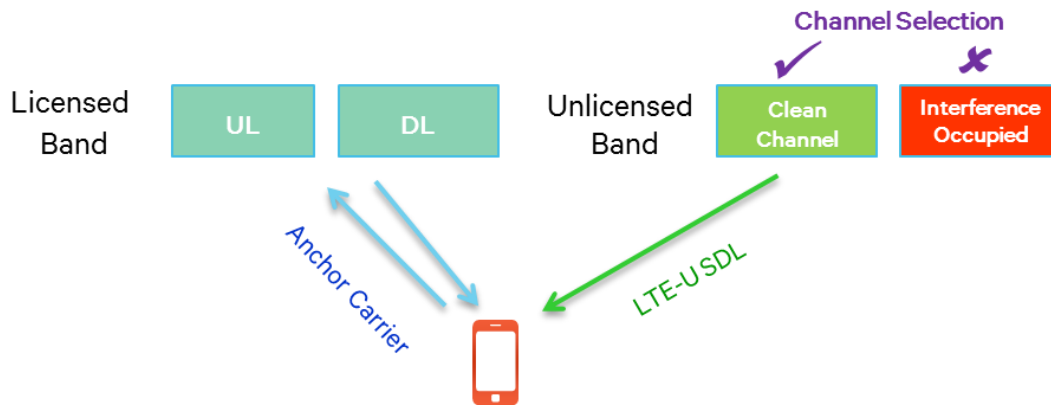


Figure 2-2 Channel selection for LTE-U SDL transmission

The interference level in a channel is initially measured by energy detection, which is agnostic to the interfering types and the number of interfering sources. Technology-specific measurements are also used to improve interference detection sensitivity and additional information collection. For example, Wi-Fi preambles are detected to identify and estimate the number of neighboring Wi-Fi APs operating in a given channel. Similarly, a LTE network listening module is used to detect neighboring LTE-U's PSS, SSS and PBCH channel. In addition, device-assisted enhancements, such as 802.11k and UE measurements, can be used to address the hidden node effect and thus help to select a better channel.

Carrier-Sensing Adaptive Transmission (CSAT)

In hyper-dense deployment of WiFi and LTE-U small cells, there is a possibility that no clean channel can be found. In such cases, LTE-U can share the channel with neighboring Wi-Fi or another LTE-U system by using CSAT algorithm. Typical Co-channel coexistence techniques in unlicensed bands such as LBT regulations and CSMA (carrier sense multiple access) used by WiFi are based on the concept of contention based access. In these techniques, transmitters are expected to sense the medium and make sure is clean before transmission. The goal of these algorithms then is to provide coexistence across different technologies in a TDM fashion. LTE Advanced in unlicensed spectrum uses a third mechanism (CSAT) that is in-line with the same concept of TDM coexistence based on medium sensing. In CSAT, the small cell senses the medium for longer (than LBT and CSMA) duration (around 10s of msec to 200msec) and according to the observed medium activities, the algorithm gates off LTE transmission proportionally. In particular, CSAT defines a time cycle where the small cell transmits in a fraction of the cycle and gates off in the remaining duration. The duty cycle of transmission vs gating off is dictated by the sensed medium activity of other technologies. CSAT in spirit is similar to CSMA except that it has longer latency, an impact that is mitigated by avoiding channels where WiFi APs use for discovery signals and QoS traffic (i.e. primary channels)."

CSAT ensures fair and efficient channel sharing, with the impact of a LTE-U node to its neighboring



Wi-Fi APs no worse than a neighboring Wi-Fi AP..

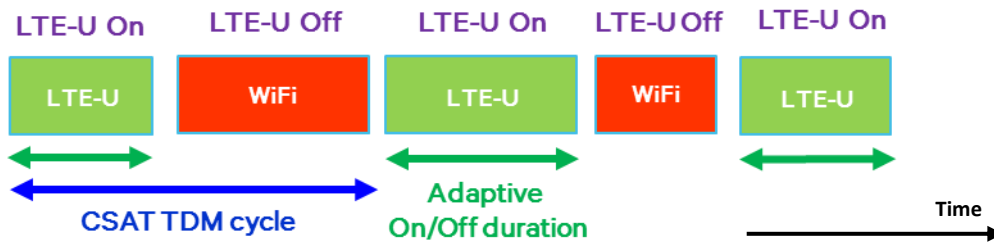


Figure 2-3 CSAT enables LTE-U and Wi-Fi to share the same channel

The LTE-U, which is on the secondary cell, is periodically activated and de-activated using LTE MAC Control Elements. The procedures and timeline are carefully chosen to ensure compatibility with Rel. 10/11 UE behavior. During the LTE-U off period, the channel is clean to neighboring Wi-Fi which can resume normal Wi-Fi transmissions. The small cell will measure Wi-Fi medium utilization during the LTE-U off period, and adaptively adjust On/Off duty cycle accordingly. The TDM cycle can be set to a few hundreds of *msec*, which can effectively accommodate the activation/de-activation procedures while controlling the data transmission delay.

Opportunistic SDL

Since the anchor carrier in license band is always available, the SDL carrier in unlicensed band can be used on an opportunistic base. When the DL traffic of the small cell exceeds a certain threshold and there are active user within the unlicensed band coverage area, the SDL carrier can be turned on for offloading. When the traffic load can be managed by the primary carrier alone, or there is no user within the unlicensed band coverage area, the SDL carrier is turned off. Opportunistic SDL mitigates the interference from continuous RS transmission from LTE-U in unlicensed channel, reducing the interference in and around a given channel.

2.2 Simulation Results

The performance of LTE-U coexistence is shown by system simulations. An outdoor Pico scenario is considered. It is assumed that there are two operators (A and B) deploy their macros and Picos in the same area. Each operator has its own 2x10MHz (FDD) carrier in licensed band of 2GHz shared between Macro and Picos using LTE-Advanced HetNet FeIC/IC techniques. The Picos from both operators also support unlicensed carriers in the same band, either as a Wi-Fi AP or LTE-U SDL.

3GPP model from TR 36.872 is adopted, with 500 meter Macro Inter-Site Distance. In the clustered Pico model, there is one hotspot cluster with 50 meter radius per Macro cell. 4 or 8 Picos from each operator are randomly dropped in a cluster, with a minimum distance of 10 meters between Picos (equivalent to 1000 to 2000 small cells per square kilometer). 2/3 of users are randomly dropped within 70 meters radius from the cluster center, while the rest of users are randomly dropped throughout the Macro cell. Bursty traffic model is used based on Poisson arrival process, and heavy traffic load is chosen to load all the cells.

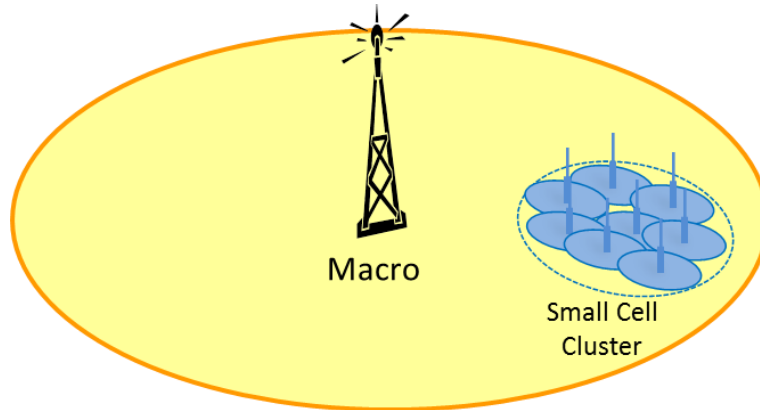


Figure 2-4 Clustered Picocell model with 8 Picos in a cluster)

LTE-U SDL is based on 3GPP Rel. 10/11, with the three coexistence mechanisms described in the previous subsection. Wi-Fi uses 802.11ac with the LDPC coding and channel selection. Both LTE-U and Wi-Fi support 2x2 MIMO with max rank 2 transmission. Short-term fading and realistic rate control for Wi-Fi and LTE are modeled. Additional simulation parameters were listed in Table 2-1.

Parameter	Wi-Fi	LTE-U
Frequency Band	5GHz	5GHz
Channel Bandwidth	40 MHz	40 MHz
Number of Channels	8	8
DL Antenna Configuration	2x2	2x2
AP/SC EIRP	27dBm	27dBm
Noise Figure	9 dB	9 dB
TXOP(Wi-Fi) / TTI(LTE) duration	3ms	1ms

Table 2-1 Simulation parameters for Wi-Fi and LTE-U

Figure 2-5 and Figure 2-6 show the median and 5-percentile DL rates across users with an unlicensed carrier (either Wi-Fi or LTE-U SDL), respectively, in the scenario of clustered 4 Picos per Macro per operator. The bursty traffic load is 750Mbps per Macro area. The baseline is when both operators use Wi-Fi in their Picos in addition to LTE-Adv HetNets. When operator B upgrades its Picos from Wi-Fi to LTE-U, its median and 5-percentile user rates increased to 3.1X and 2.1X of baseline, respectively. In this case, the Wi-Fi performance of operator B is not affected by the neighboring LTE-U, due to the coexistence safeguards. In fact, the Wi-Fi performance improves by about 10%, since the neighboring LTE-U Picos can finish transmission faster and incur less interference instead. Since the density of Wi-Fi AP and LTE-U small cell is moderately high, it is found that channel selection and opportunistic SDL are sufficient to meet the coexistence requirement without incurring CSAT. Lastly, when both



operators upgrade their Picos to LTE-U the median and 5-percentile DL user rates will be even higher.

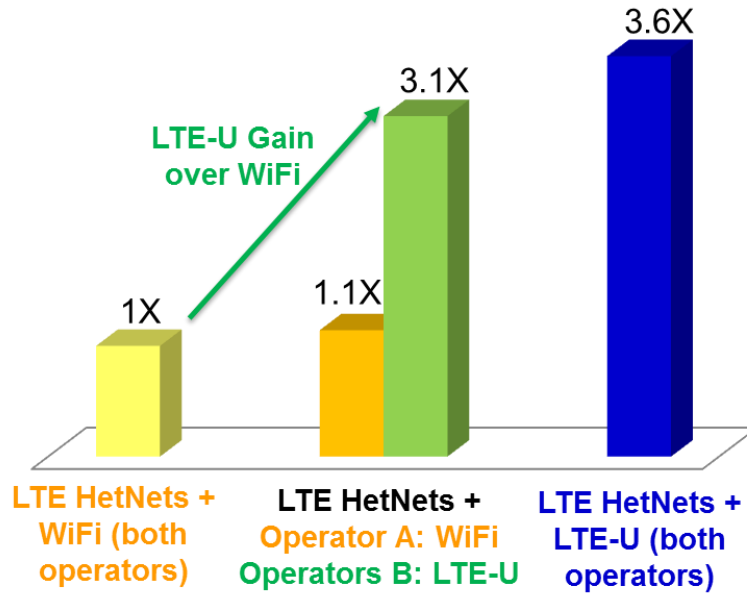


Figure 2-5 DL median user data rate gain, cluster scenario with 4 Picos per Macro cell per operator

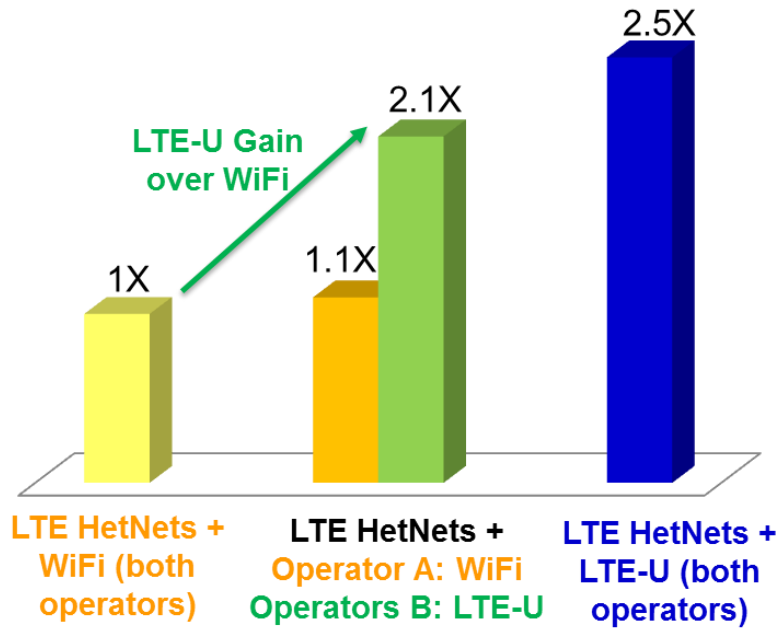


Figure 2-6 DL 5-percentile user data rate gain, cluster scenario with 4 Picos per Macro cell per operator

Figure 2-7 and Figure 2-8 show the DL performance of unlicensed carrier users in the scenario of



clustered 8 Picos per Macro per operator. The bursty traffic load is 1Gbps per Macro area. As the density of Wi-Fi AP and LTE-U small cell in this case is quite high, channel selection and opportunistic SDL mechanisms alone cannot guarantee harmonious coexistence with Wi-Fi. When operator B upgrades its Picos from Wi-Fi to LTE-U without CSAT, Wi-Fi users of operator A see a median rate gain to 1.4X. However, the 5-percentile Wi-Fi user rate drops to 0.35X since there is no CSAT protection for the Wi-Fi links sharing the same channel with nearby LTE-U. By introducing CSAT, the 5-percentile Wi-Fi user rate in the baseline is mostly maintained while the median Wi-Fi user rate is improved by about 46%. The median and 5-percentile user rates of operator B are improved by LTE-U to 2.4X and 1.4X, respectively – still significant gain with CSAT. It is clear that CSAT with other coexistence mechanisms can ensure the fair co-existence between LTE-U and Wi-Fi in highly dense deployment.

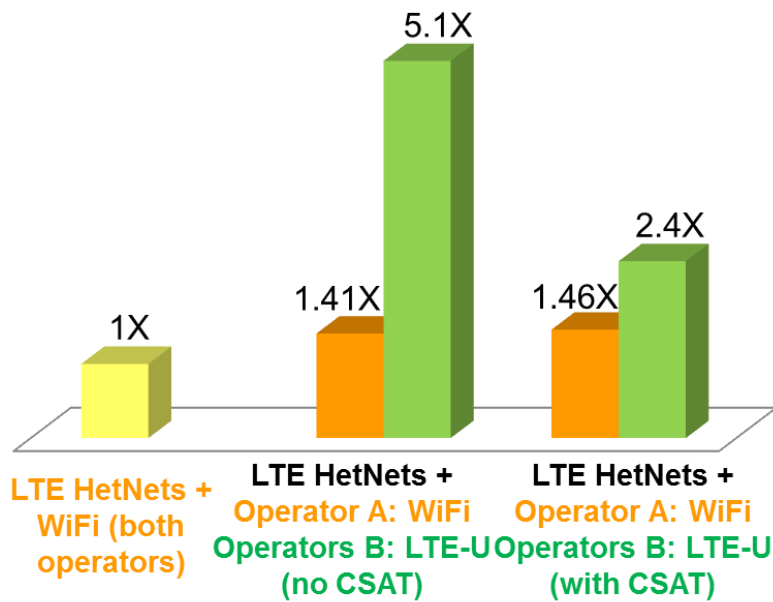


Figure 2-7 DL median user data rate gain, cluster scenario with 8 Picos per Macro cell per operator

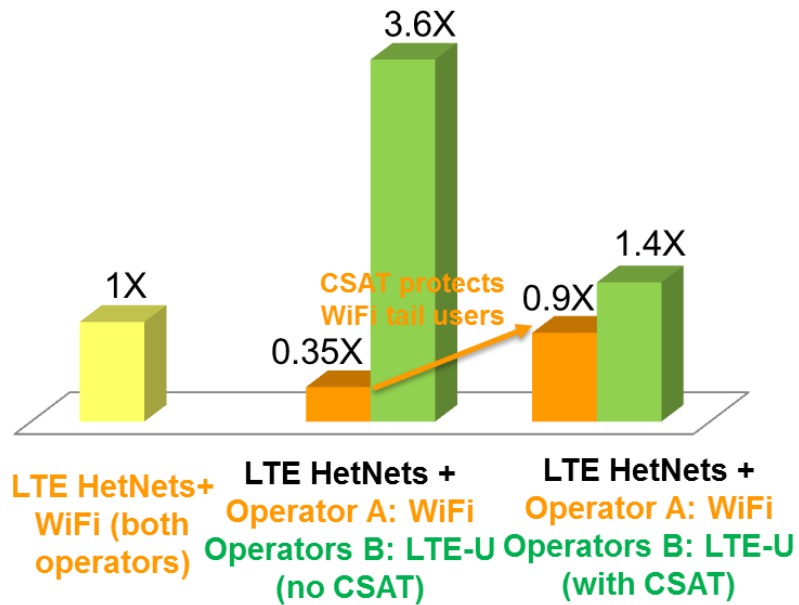


Figure 2-8 DL 5-percentile user data rate gain, cluster scenario with 8 Picos per Macro cell per operator

2.3 Lab Demo

LTE-U channel selection and CSAT have been implemented on prototype platform by Qualcomm for demonstration and tests. In the channel selection demo, the initial and periodic channel scanning has been implemented by the LTE-U small cell/AP, while 802.11k device-assisted measurements are also performed by Wi-Fi devices.

In the lab demo shown in Figure 2-9, the candidate channels for center LTE-U eNB and co-located Wi-Fi AP135 are channel 149, 157, and 165. Initially AP channel scanning finds a neighboring Wi-Fi AP1 on Channel 165, and the eNB select Channel 149 for LTE-U transmission. Later, neighboring Wi-Fi AP1 moves to Channel 149, and it is discovered by periodic channel scanning of eNB/AP. As a result, the eNB switch LTE-U to Channel 157. 802.11k STA-assisted scanning is able to discover the hidden node Wi-Fi AP2 on Channel 157, and the eNB eventually switch to Channel 165 as the clean channel for LTE-U SDL operation.

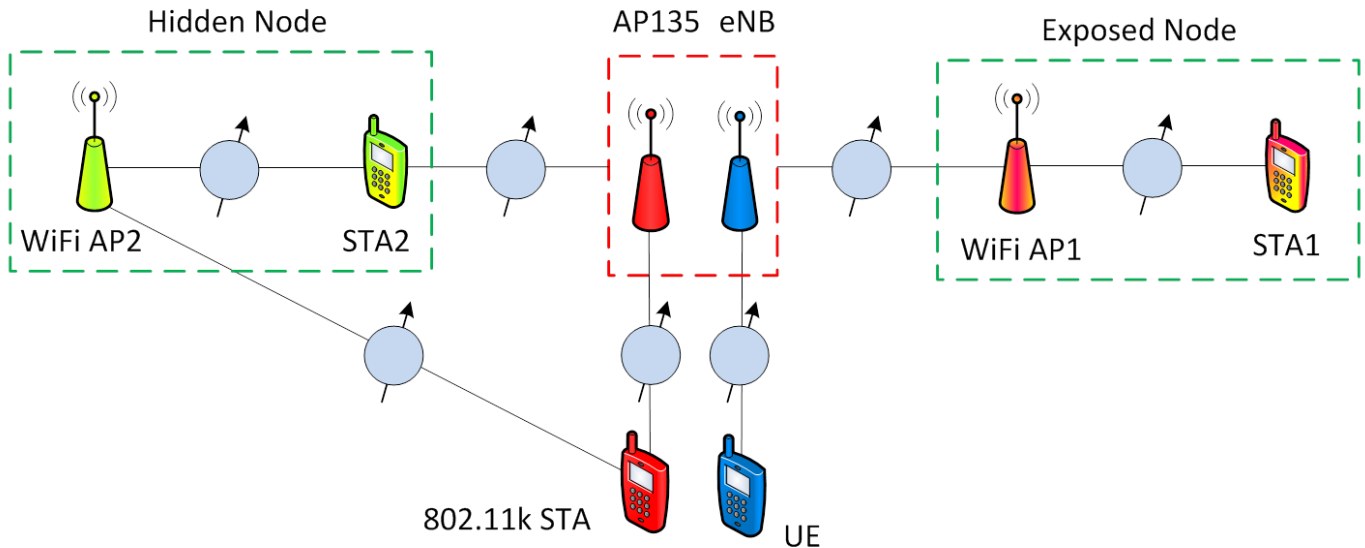


Figure 2-9 Channel Selection Lab Demo

Figure 2-10 shows the setup of CSAT lab demo. The eNB/AP prototype supports LTE aggregating a 10MHz licensed carrier with a 10MHz unlicensed SDL, while the neighboring Wi-Fi supports a 40MHz link (20+20). The LTE-U SDL is in the same channel as the neighboring Wi-Fi AP's secondary channel, with controllable attenuation between the two transmission links. The LTE DL rate and neighboring Wi-Fi throughputs are shown in Figure 2-11. In the baseline, there is no interference between the two links due to large attenuation between the two system and both enjoy high throughput rates: 73Mbps on LTE and 77Mbps on Wi-Fi. However, when the two links are close to each other, the interference effect is shown in the CSAT disabled period. The LTE throughput is 70Mbps while the Wi-Fi throughput is 24Mbps, which shows that co-channel sharing without CSAT impacts Wi-Fi more than LTE-U. When the CSAT is enabled, the channel sharing becomes more fair and Wi-Fi throughput is increased to 49Mbps – similar to the LTE throughput of 50Mbps.

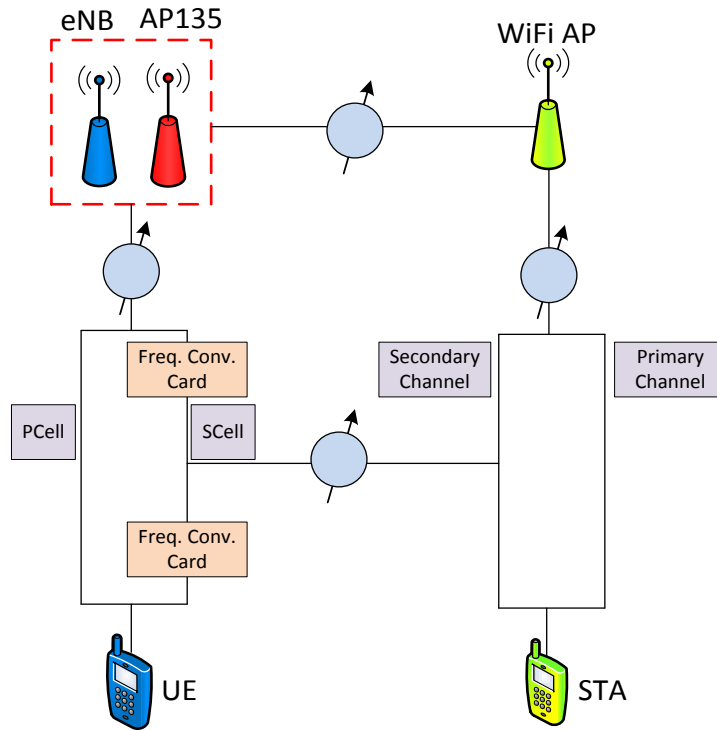


Figure 2-10 CSAT Lab Test Setup

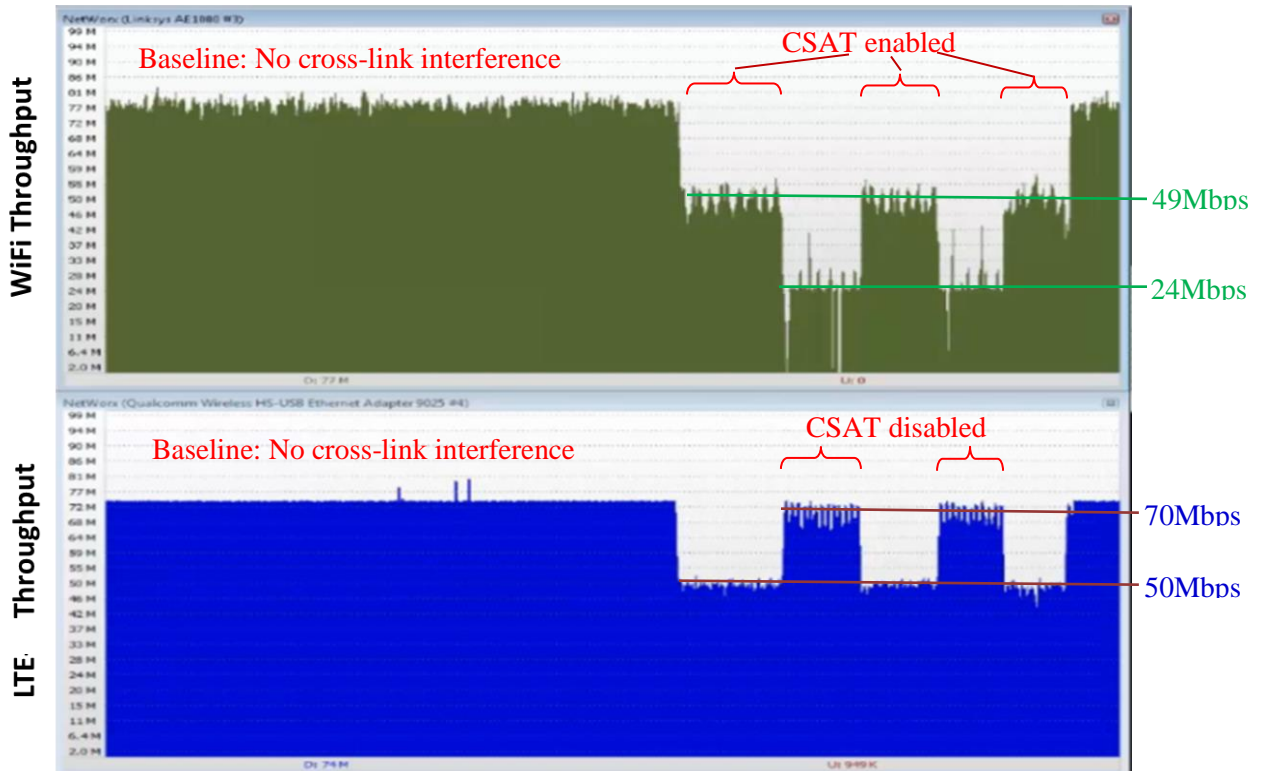


Figure 2-11 CSAT Lab Demo

3. LTE-U Coexistence Considerations for Markets with LBT Requirements

3.1 LBT Requirements

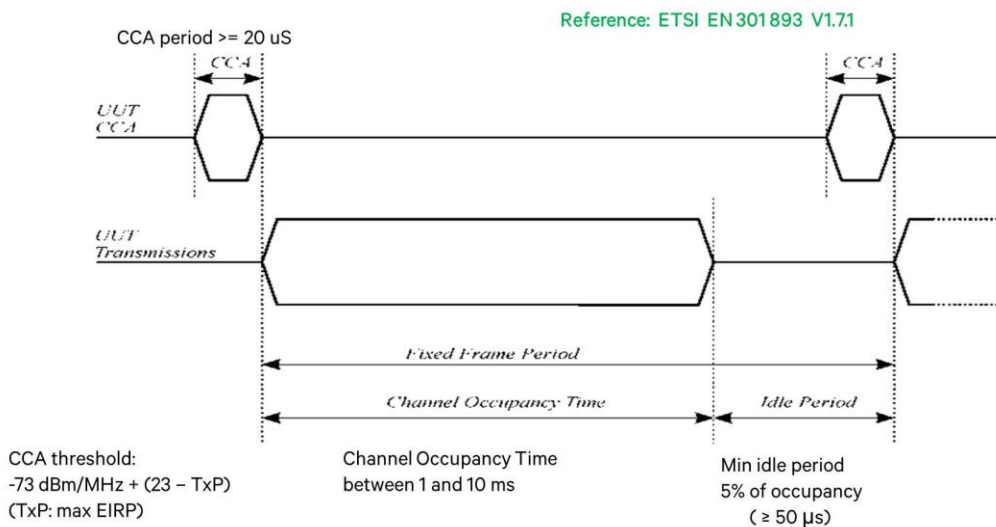


Figure 3-1 ETSI LBT specification for Frame Based Equipment

In many markets such as Europe, Japan and India, there exist regulations for unlicensed spectrum that require equipment to periodically check for presence of other occupants in the channel (listen) before transmitting (talk) in millisecond scale. Hence this is often referred to as Listen Before Talk (LBT). Figure 3-1 shows the requirements defined by ETSI for LBT for frame based equipment. The listening time is also called Clear Channel Assessment (CCA) period. When a device or AP wants to transmit, it has to detect the energy level at a designated time for duration equal to CCA period. If the energy level in the channel is below the CCA threshold, then the equipment can transmit for duration equal to Channel Occupancy Time. After that, if the equipment wishes to continue its transmission, it has to repeat the CCA process.

3.2 LTE design modifications for LBT

There are a number of modifications required before LTE transmissions can meet regulatory requirements in LBT regions. These modifications are needed to enable a mobile to detect and acquire network from several possible PLMNs broadcast in unlicensed band, assess channel availability (CCA), reserve the channel for transmission and finally transmit for a duration set by regulation (1 to 10 msec). There are other modifications to meet the channel occupancy requirements on the uplink and H-ARQ ACK/NACK transmissions in an unlicensed band. There are many possible frame structures that can support these changes when operating in SDL or CA modes in unlicensed band. As an example of such



design, the modifications shown in Figure 3-2 are made to LTE PHY and MAC to meet the LBT, uplink channel occupancy and other requirements needed to operate LTE in an unlicensed band.

Discovery signals	<ul style="list-style-type: none">• Needed to discover and acquire access• Multiple PLMNs
LBT using Clear Channel Assessment (CCA)	<ul style="list-style-type: none">• Needed to meet regional requirements (Europe, Japan)
Beacon signals	<ul style="list-style-type: none">• To reserve the channel for transmission following LBT
Modified DL & UL waveform	<ul style="list-style-type: none">• Modified to enable LBT• UL modified to meet channel occupancy definition
Modified HARQ protocol	<ul style="list-style-type: none">• Asynchronous HARQ design considering no guaranteed access to channel

Figure 3-2 example modifications made to LTE PHY and MAC to operate in unlicensed band in LBT regions.

LTE PHY and MAC changes for LTE-U will be discussed in upcoming 3GPP meetings. Therefore, it is possible that the required modifications are defined in LTE Release 13 and beyond, providing a standard LBT mechanism for LTE to coexist with WiFi and other access technologies within the unlicensed bands.

3.3 Simulation Results

System simulations were run to evaluate the performance of LTE in unlicensed spectrum with LBT. Two operators were considered in each scenario. The baseline scenario is where each operator has its own LTE Advanced network with HetNet FeICIC/IC with one licensed FDD carrier of 2x10 MHz at 2.1 GHz. The macro cell sites for both operators are collocated. In addition, each operator deploys its own Picocells which are either placed uniformly (16-Pico case) or deployed in a hotspot region (Clustered 8-Pico). Each Pico has a Primary Component Carrier (PCC) operating in the same licensed channel as the Macrocell, along with either WiFi or a Secondary Component carrier (SCC) operating the unlicensed band. For the Clustered 8-pico case, there is a hotspot of 70m radius in which two-thirds of users are dropped within. The other one-third of users is dropped uniformly in the remaining area in the macro cell. Both operators deploy their 8 Picocells in the same cluster of 50m radius within that hotspot. For the 16-pico case, the Picocells are uniformly deployed in a macro coverage area, and the operators' Picocells are not co-sited. 3GPP traffic model 1 is used in the simulations. More simulation assumptions can be found in Table 3-1.

The median and cell-edge (defined here as the bottom 5-percentile) throughput changes are observed as the operators utilize the unlicensed 5 GHz spectrum for Wi-Fi or LTE-U (using the same Picocells as above).



	Value
Licensed Carrier (PCC) frequency	2x10 MHz FDD in 2.1 GHz
Unlicensed Carrier (SCC) (LTE-U, Wi-Fi) frequency	12x40 MHz SDL in 5 GHz
Inter-macro site distance	500 m
Unlicensed Channel Selection	Yes for WiFi and LTE-U
Inter-Operation Synchronization	Asynchronous
Wi-Fi interface	802.11ac
Wi-Fi/LTE-U MIMO	Both ranks 1 & 2 considered. No MU-MIMO
Wi-Fi/LTE-U rate prediction	Imperfect
LTE-Wi-Fi aggregation	Bearer selection

Table 3-1 Simulation assumptions

Figure 3-3 shows the median throughput gains when different technologies are being used in unlicensed spectrum in the case of 16 Picocells uniformly dropped in each cell for each operator. Taking HetNet licensed band + Wi-Fi as baseline, there can be 180% increase in user throughput when operator A deploys LTE-U instead of Wi-Fi. In this case, the deployment of LTE-U by operator A did not cause any reduction in median throughput of operator B, an indication that LTE-U co-exists fairly with WiFi. When both operators migrate to LTE-U, they would achieve a median throughput of 2.7x of baseline.



DL Median User Throughput Gain

(LTE-U SDL, 3GPP model, Scenario 1: 16 Picos per Macro cell per operator)

Uniform Scenario

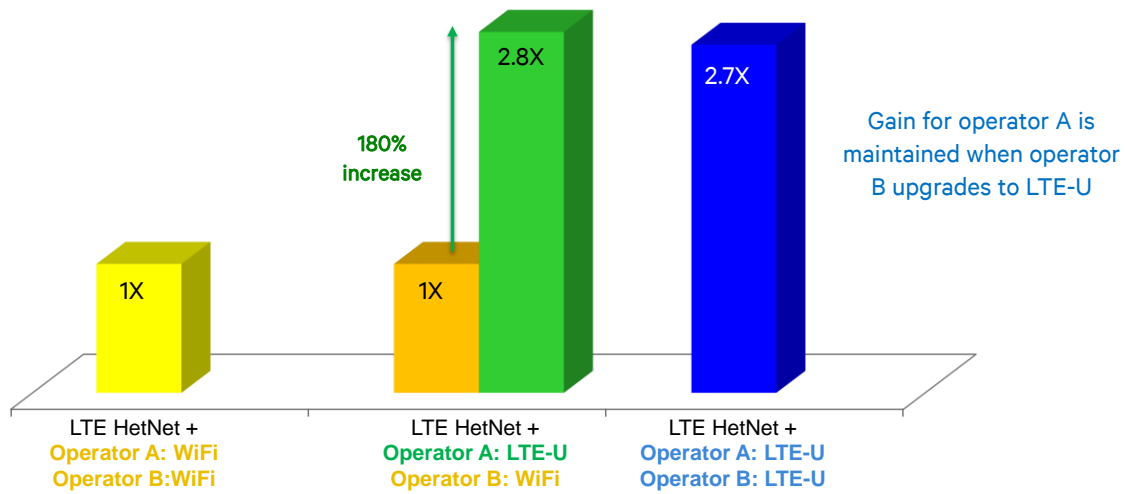


Figure 3-3 Downlink median user throughput gain for 16 Picocells per Macrocell per operator scenario

Simulations for the clustered 8-picocell scenario also show benefits from upgrading to LTE-U without affecting Wi-Fi. In Figure 3-4, when operator A upgrades from Wi-Fi to LTE-U, there is a boost of its median user throughput by 300% while operator B's median throughput stays roughly the same. When operators A and B deploy LTE-U, they both achieve a median user throughput of 3.7x of the baseline.



DL Median User Throughput Gain

(LTE-U SDL, 3GPP model, Scenario 3: 8 Picos per Macro cell per operator)

Cluster Scenario

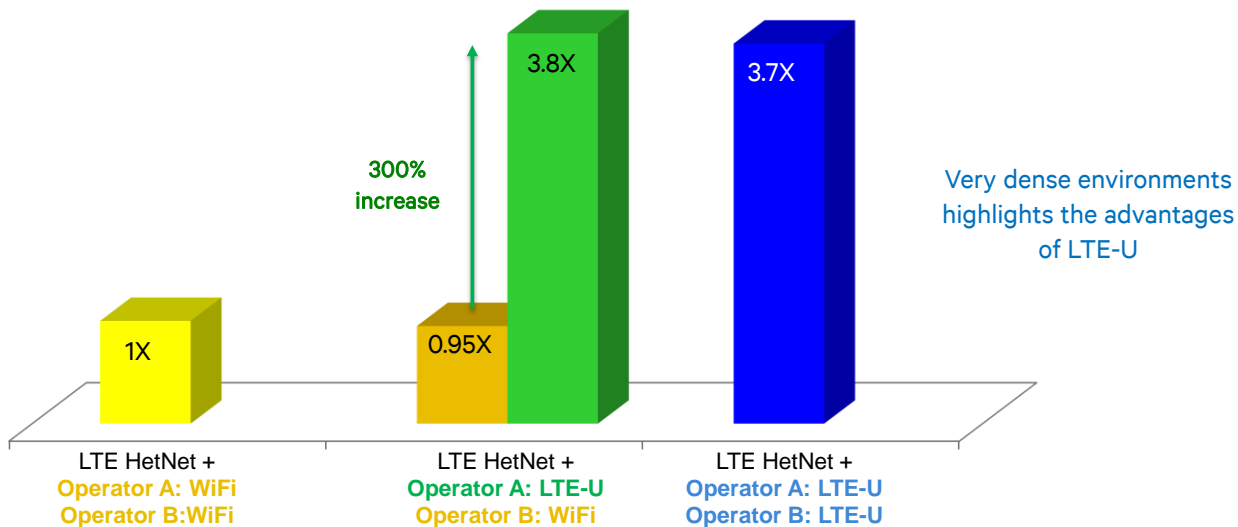


Figure 3-4 Downlink median user throughput gain for 8 clustered Picocells per macro per operator scenario

4. Conclusion

In this paper, two different co-existence mechanisms for operating LTE in unlicensed bands in regions with and without LBT requirement are described. In both cases, it was shown by simulations that significant throughput gain can be achieved by aggregating LTE across licensed spectrum and unlicensed spectrum. Such gains do not come at the expense of degraded Wi-Fi performance. Both technologies can fairly share the unlicensed spectrum.

The co-existence features for regions without LBT requirements are compatible with existing LTE standards and can leverage the large LTE Rel.10/11 ecosystem¹. In markets with LBT requirements, the LTE air interface standard will need to be modified to support the co-existence features and the proposal has been introduced in 3GPP as a component of the Release 13 LTE standard.

¹ Support for new RF band (5 GHz) of LTE is needed at both UE and eNB.