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Co-existence Issues Between LTE Operating in Unlicensed Spectrum and Wi-Fi Networks

A Technical Paper prepared for the Society of Cable Telecommunications Engineers
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1. Overview

With the exponential growth in mobile data traffic taking place currently and projected into the future, mobile operators need cost effective ways to manage the load of their networks. Traditionally, this has been achieved by offloading mobile traffic onto Wi-Fi networks due to their low cost and ubiquitous deployment. Recently, LTE operating in the unlicensed spectrum (LTE-U) has drawn significant interest from mobile operators due to the availability of the unlicensed spectrum.

However, LTE was not designed to be able to share spectrum with other networks and therefore needs to be adapted to work with existing unlicensed radio technologies. Without these modifications, deployment of LTE networks in the unlicensed band poses significant challenges to the performance of current and future Wi-Fi networks.

We will examine how unmodified LTE would impact Wi-Fi networks in the same channels and present analysis on the potential performance degradation. We also show lab testing results which corroborate this analysis. Finally, we explore the requirements for solutions that would allow LTE-U and Wi-Fi to share the same channel and outline potential solutions that are under discussion.

2. Introduction

The exponential growth of mobile data traffic is driving mobile network operators (MNOs) to look into various cost effective solutions to meet the continuously increasing demand and offload traffic from the licensed spectrum. The low cost of Wi-Fi access points, the pervasiveness of Wi-Fi in mobile devices and the availability of unlicensed spectrum has made Wi-Fi the technology of choice for data offload. Nonetheless, the integration of Wi-Fi into the 3GPP core network remains complex despite the availability of four separate standardized methods dating back to 3GPP release 6 [1]. Despite the numerous options, none of them were found to be satisfactory by the MNOs and thus no wide deployments of the solutions are seen.

Most recently, the 3GPP is considering extending the use of LTE into the unlicensed spectrum as another means to enable traffic offload. The proposed architecture leverages an existing LTE capability known as Carrier Aggregation. Carrier Aggregation was developed to allow mobile operators to more easily combine licensed frequency bands in different parts of the radio spectrum into a single aggregated connection. The new enhancement being proposed also allows unlicensed spectrum bands to be aggregated in a similar manner and hence has been named LTE Unlicensed (LTE-U).

LTE-U offers MNOs a way to offload traffic onto the unlicensed spectrum with a technology that more seamlessly integrates into their existing LTE evolved packet core (EPC) architecture and eNodeBs. The eNodeBs require the addition of radios that operate in the desired unlicensed band(s). Furthermore, LTE-U may provide higher throughout and spectral efficiency than Wi-Fi, with estimates ranging from 2x to 5x improvement over Wi-Fi [2, 3].

Two modes have been proposed for LTE-U, distinguished by the supplementary and control channel configurations as shown in Figure 1 and Figure 2.

- License Assisted Access: In this mode, the unlicensed band is used as an auxiliary TDD channel capable of carrying data traffic in the downlink with the option to carry uplink data traffic in the unlicensed band as well or in the licensed band. The control channel remains in the licensed spectrum and therefore only mobile operators with licensed spectrum can use this mode.
- Standalone: In this mode, the data and the control channels of LTE-U operate in the unlicensed spectrum; thus there is no dependence on licensed spectrum availability to support LTE-U operations. This mode provides an option for operators that do not currently own spectrum to benefit from LTE-U capabilities.

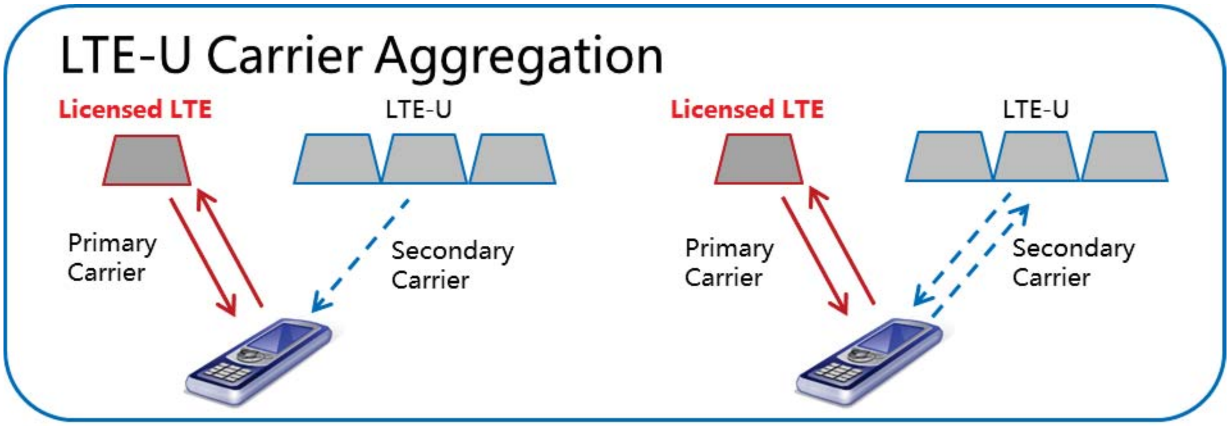

Figure 1 LTE-U License Assisted Access

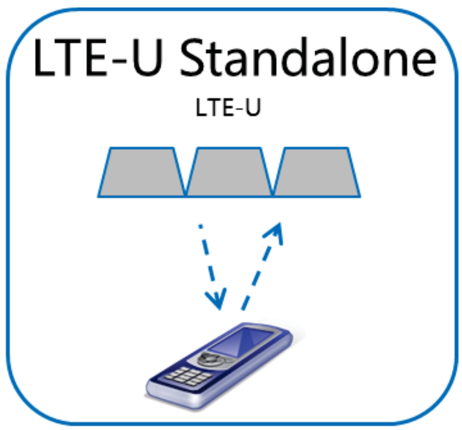

Figure 2 LTE-U Standalone

So far, industry focus has been on implementing LTE-U in the 5 GHz spectrum bands based on the belief that the UNII bands are far more open that the 2.4 GHZ ISM band. However, with the availability of smart phones and Wi-Fi APs supporting 802.11ac, the usage on the UNII bands is expected to grow rapidly in the next two years as users upgrade their smartphones. Table 1 shows the different rules for the UNII bands.

Table 1 UNII Spectrum Access Rules Across Jurisdictions

Region	5.15-5.25 GHz	5.25-5.35 GHz	5.47-5.725 GHz	5.725-5.825 GHz
US	1W	250mW + DFS	250mW + DFS	1W
EU	200mw + LBT + DFS + indoor only	250mw + LBT + DFS	250mW + LBT + DFS	n/a

In this paper, we consider the potential impact of LTE-U on Wi-Fi networks for the Licensed Assisted Access mode being proposed in the 3GPP covering:

1. A brief review of the lower layers of LTE and Wi-Fi protocols
2. An analysis of the LTE "quiet period"
3. Results of lab testing for several scenarios
4. An exploration of potential coexistence solutions including requirements

3. A Comparison of Wi-Fi and LTE Lower Layers

Although both Wi-Fi and LTE PHY layers are based on the OFDM technology, their transmissions are not orthogonal due to different subcarrier spacing and lack of synchronization.

Table 2 Mac Layer Comparisons

	LTE	*Wi-Fi*
Multiple access	Multiple users served simultaneously, occupying different frequencies in channel	Absent of MU-MIMO, only 1 user is served at a time, takes up entire channel spectrum
Channel usage	Frames are contiguous, so channels are approximately "always on"	Channel is occupied only when packets needs to be transmitted
Channel access	Centralized scheduling on DL and UL. LTE does not contend, it simply transmits	Distributed Coordination Function (DCF), contention-based[1]
Collision avoidance	None, channel access is centrally scheduled	CSMA/CA + RTS/CTS (In principle, "sense before transmit")
Co-existence	Has not had the need to be able to coexist with other technologies	Already coexists well with other technologies in unlicensed band, although with no common fairness mechanism

Table 2 shows that the LTE MAC may be more efficient at spectrum usage compared to Wi-Fi MAC, particularly when large number of users access the medium. This is primarily due to the centralized scheduling nature of the LTE protocol at the eNodeB. LTE will fill the airtime when the traffic load permits. The maximum sector capacity is independent of the number of UEs being served by the LTE eNodeB. On the other hand, as the number of users increases in the Wi-Fi network, the performance of CSMA/CA and channel utilization degrades due to the increased probability of collision [5].

4. The Coexistence Challenge

LTE-U poses significant coexistence challenges for Wi-Fi networks due to the inherent differences between channel usage and access procedures used by each technology. Wi-Fi is designed to coexist with other technologies through channel sensing and

[1] Although Point Coordination Function is also defined in Wi-Fi, it is not widely implemented, and therefore not discussed in this paper.

random backoff. On the other hand, LTE is designed with the assumption that one operator has exclusive control of a given spectrum; LTE traffic channels are designed to continuously transmit with minimum time gap even in the absence of data traffic. Consequently, Wi-Fi users will have little chance to sense a clear channel and deem it suitable for transmission.

Since LTE is an almost continuously transmitting protocol. In order for Wi-Fi users to transmit, they need to wait for a “quiet” period when LTE is not transmitting. Even when there is no data traffic present on the air interface, LTE periodically transmits a variety of control and Reference Signals. How long LTE remains truly “quiet” depends on the periodicity of these signals. We will examine the control signals next.

4.1. LTE “Quiet Period”

4.1.1. LTE FDD System

As shown in Figure 1, LTE-U can be achieved via several different access modes, depending on which link is carried in the unlicensed spectrum. One realization of LTE-U is to carry one or more DL carrier(s) of an LTE FDD network on the unlicensed spectrum. The periodicity of the DL control and Reference Signals will dictate whether and when Wi-Fi may be able to leverage these quiet periods and be able to transmit.

Figure 3 shows a pair of LTE DL Resource Blocks (RBs) with a Physical Downlink Control Channel (PDCCH) and Reference Signals[2]. The PDCCH carries UL and DL scheduling assignments, among other vital control information. The PDCCH occurs at the start of every subframe, or every 1 ms, taking between 1 and 3 OFDM symbols. The Reference Signals are present regardless of whether DL data transmissions are present, and are used for channel estimation for coherent detection. The Reference Signals are transmitted in every DL subframe at fixed locations, spanning the entire DL bandwidth.

LTE transmits other periodic signals such as primary and secondary synchronization signals on the DL. The periodicity of these signals are much longer than the Reference Signals.

The periodicity of the Reference Signals dominates the duration of the “quiet” periods on the LTE DL, with a maximum of 3 symbol periods, or approximately 215 μs.

[2] Only standard slot configuration is considered, i.e., normal cyclic prefix with 7 symbols per slot. No MIMO configuration is considered.

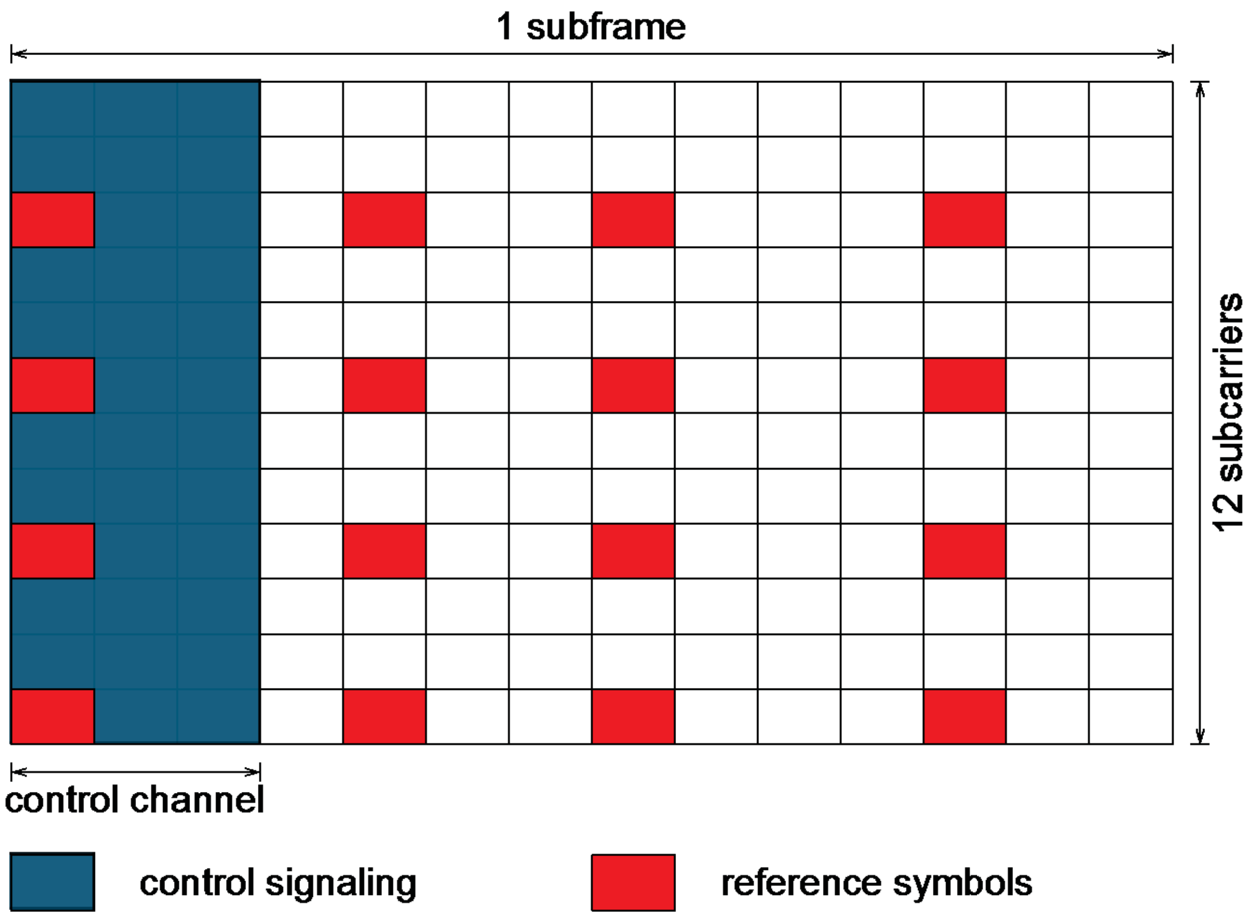

Figure 3 LTE DL control and reference signals

4.1.2. TD-LTE "Quiet Period"

Another realization of LTE-U, shown in Figure 1, is to carry both the UL and DL traffic of a TD-LTE network on the unlicensed spectrum. In TD-LTE, seven UL/DL configurations are defined to allow for the adaptation of different UL-DL traffic profiles by assigning more or less subframes within a frame for UL or DL data transmission.

To enable fair access to the channel in the unlicensed spectrum, LTE-U using a TD-LTE network may be designed to intentionally not schedule data transmission for X subframes during the period of every Y total subframes. For example, UL/DL configurations 0, 3, and 6 all show that a maximum of 3 UL subframes (or 3 ms) are scheduled together, and therefore can be intentionally muted by the eNodeB. This duty cycle approach to coexistence allows LTE-U to maintain the efficiencies it enjoys due to the scheduled nature of the LTE air interface while providing Wi-Fi APs opportunities to access the channel.

4.2. How does LTE Quiet Period Compare to Wi-Fi?

For LTE-U, the maximum quiet period is

- 3 symbols, or approximately 215 µs, on the DL of a LTE FDD network
- Up to 3 subframes, or 3 ms, on a TD-LTE network

Wi-Fi APs and devices need to back off for a random period of time prior to transmission. The back off can potentially occur outside the window of the LTE quiet period. When a transmission does occur, the burst length for a 1518 byte frame is approximately between 110 µs and 1.8 ms, depending on the modulation and coding used.

Unless the LTE-U traffic channels are designed differently than LTE traffic channels in licensed spectrum, LTE-U will apply continuous traffic to devices in a periodic fashion. LTE-U will present signficant challenges to Wi-Fi throughput and delay performances by maintaining control of a large share of the airtime.

4.3. Prior Work

The problem of Wi-Fi and LTE coexistence and the potential impact of one network over the other have recently been studied and simulation results have been presented in a handful of research and industry publications.

In [4], a paper published by Nokia Research, a simulator-based system-level analysis has been performed to assess the performance of LTE and Wi-Fi networks coexisting in an office environment. Single-floor and multi-floor office environments with different assumptions on the density of Wi-Fi and LTE nodes have been considered in the simulation. Although the simulation model, the assumptions on Wi-Fi and LTE system parameters and deployment environment can be improved, the results presented in [4] validate our analysis presented in this paper: channel sharing between Wi-Fi and LTE networks is significantly unfair for the Wi-Fi network.

In [3], a whitepaper published by Qualcomm, LTE-U is described as a better neighbor to Wi-Fi than Wi-Fi to itself. It is also claimed that LTE-U provides operators substantial improvements in data throughput without any impact to Wi-Fi users when Qualcomm's proprietary coexistence mechanisms are applied. While these claims are derived from simulations, the simulation models used are not available publically.

In [2], Huawei provides the result of their simulation on spectrum efficiency comparison between Wi-Fi and LTE in a sparse deployment scenario. It states that the simulation includes coexistence updates to LTE-U to accommodate Wi-Fi, but does not provide sufficient detail on the effectiveness of the coexistence features. The trends of interference based on traffic load appear credible, if LTE-U to LTE-U coordination is achieved or interference avoidance is deployed.

5. Lab test Results

We have a created a test bed at Cablelabs to allow us to obtain actual results of the impact of LTE on Wi-Fi. Our test bed has be set up with the following conditions

- Simple conducted network
  - 1 – Wi-Fi AP
  - 1 – Wi-Fi Client
  - 1 – LTE eNodeB (freq. down converted)
  - The testing was conducted inside a shielded enclosure to prevent external Wi-Fi networks from impacted the testing
- LTE
  - eNodeB signal was frequency shifted to ISM Ch. 1 (2.412 GHz)
  - Equal power at the Wi-Fi AP and client
  - Control and reference traffic only, no data traffic
- Wi-Fi throughput test signal power: -60 dBm (good average signal level)
  - ISM Ch. 1 (2.412 GHz)
  - DL/UL loss was symmetrical
  - Single 20 MHz channel
  - 1 spatial stream, long guard interval (max MCS 4) or 39 Mbps
- 100 Mbps UDP traffic offered load
  - Reported throughput figures are averaged over 1 minute
- Spec CCA threshold for non Wi-Fi signals
  - 802.11-2012 "The receiver shall hold the 20 MHz primary channel CCA signal busy for any signal at or above –62 dBm in the 20 MHz primary channel.

We simulated increasing proximity of the interfering LTE eNodeB to the Wi-Fi devices by increasing the eNodeB power level on the conducted network as shown in Figure 4 and recorded the impact on the throughput of the Wi-Fi AP to client connection.

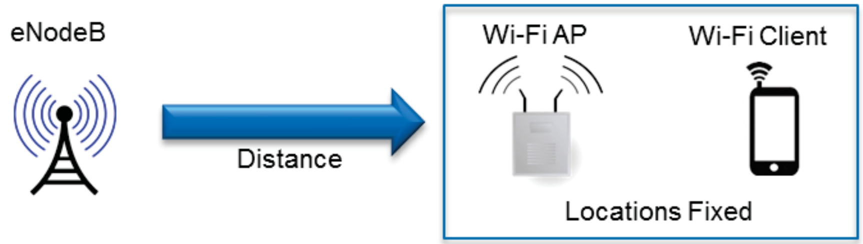

Figure 4 Proximity of eNodeB to Wi-Fi devices

5.1. Test Case: Interference vs. Throughput

As can be seen in Figure 5, as the LTE eNodeB is moved closer to the Wi-Fi devices, the Wi-Fi throughput degrades to effectively 0 Mb/s as the signal level approaches the Wi-Fi CCA threshold for non Wi-Fi signals.

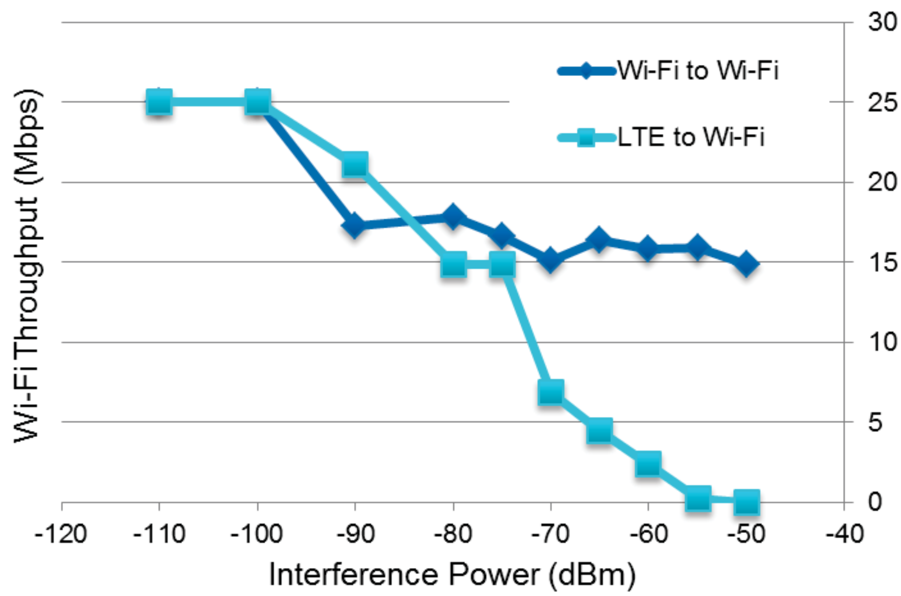

Figure 5 LTE Interference Power vs. Wi-Fi Throughput

For comparison, we repeated the test replacing the eNodeB with a second Wi-Fi AP operating on the same channel and recorded the impact on the measured connection again. As can be seen, the Wi-Fi throughput is impacted but levels off as the Wi-Fi CSMA/CA mechanisms arbitrate the channel access.

5.2. Test Case: LTE Duty Cycle

We modified the test bed to allow us to turn the eNodeB signal on and off at specific intervals to emulate a duty cycle coexistence mechanism. We varied the duty cycle on / off period and the percentage of time that LTE was on during the duty cycle period

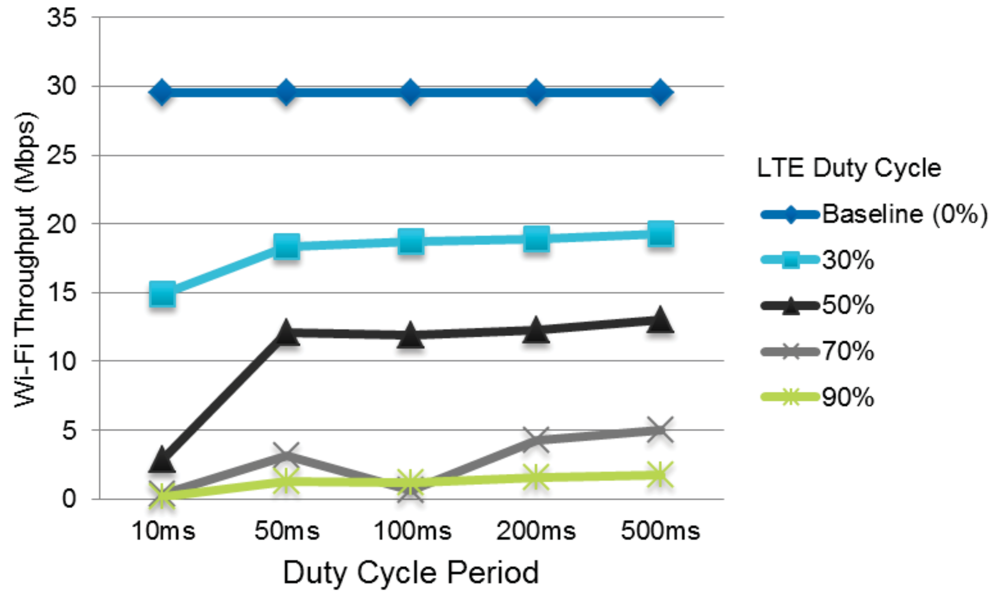

Figure 6 Wi-Fi Throughput vs. LTE Duty Cycle

As shown in Figure 6, above 50 ms, the impact of LTE on Wi-Fi is independent of the duty cycle period. With a 10 ms duty cycle and increasing presence of the LTE signal, the Wi-Fi CSMA/CA mechanism is negatively impacted.

However, throughput is only one of the key performance indicators of a data connection. Delay, delay variation, and loss should also be considered. Delay is a particularly important measurement. Low latency plays a bigger role than bandwidth in the perception of "speed" in interactive applications like web browsing or gaming. For webpage load times, connections >6 Mb/s show diminishing returns and delay (round trip time) becomes the dominant factor. Real-time applications have known latency thresholds where performance degrades and/or the applications fail to function. For example, VoIP requires one-way access network latency of <100 ms (or <300ms round trip). With some gaming applications, delay of >80ms reduces win probability and degrades the ability of the player to respond to action in the game. Ideally one way delay for gaming should be <20ms. The wireless connection is only one part of the total one way delay. This issue applies equally to LTE-U and Wi-Fi.

Figure 7 shows the impact of the duty cycle on delay in this test. As would be expected, delay grows linearly as the duty cycle is increased. Therefore any coexistence solution incorporating a duty cycle should consider the impact of delay in order to not "break" services that are possible today.

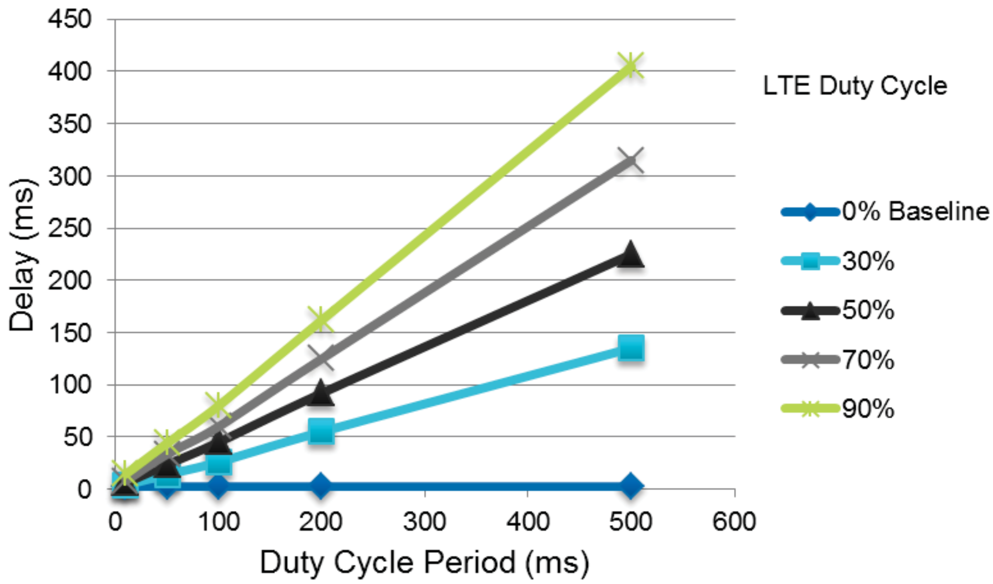

Figure 7 Wi-Fi Delay at the 95th Percentile vs. LTE Duty Cycle

6. Coexistence Solutions

While there is no regulatory requirement for coexistence in the unlicensed bands in a number of major regions such as North America and China, there is a requirement in other regions such as Europe. Wi-Fi has been developed to support the European Listen Before Talk (LBT) requirement universally, to the benefit of users everywhere.

Therefore, coexistence is a fundamental requirement for technologies within unlicensed bands to be successful. It is essential for all networks and all users to gain the most value from an unlicensed band. While regulators may not mandate coexistence everywhere, they are supportive and could decide to implement regulations if they felt that the market was not operating effectively. It is far better that the industry finds acceptable solutions. Coexistence needs to operate effectively among LTE-U and other technology networks. Therefore, coexistence needs to be mandatory in any standards developed and the standards need to be non-regional specific, a global standard.

Since 3GPP develops the standards for LTE, the focus of developing coexistence requirements is being discussed in that group. The IEEE is working on high efficiency WLANs in the 802.11ax task group and coexistence in the 802.19 working group. The rest of this section explores the requirements for coexistence and some of the concepts being explored.

6.1. Access to spectrum Requirements

- LTE-U and Wi-Fi networks must receive equal access to the unlicensed band:
    - In time

    - In spectrum width (channels widths may need to be reduced when many networks are operating in the same band
- When demand exceeds capacity, each network must be able to access an equal share
- When a particular network's user plane traffic demand is less than the spectral capacity of an equal share, that network must allow other networks to access the unused capacity
- This will require LTE-U to adapt other LTE-U networks and to the presence of Wi-Fi while Wi-Fi uses its current mechanisms
- A single solution must meet all regional regulatory requirements
    - Listen Before Talk can be considered as a potential approach
- Must support multiple LTE-U networks and multiple Wi-Fi networks in the same band

6.2. Coexistence with Existing Services Requirements

- Any services which are currently possible in Wi-Fi or LTE networks must be supported by mandatory coexistence requirements
    - Services may have specific KPI requirements such as browsing, VoIP, gaming, streaming video with multiple streams, video anywhere, video conferencing, etc.
- E.g., coexistence requirements need to ensure that LTE-U does not render Wi-Fi Alliance (WFA) Wi-Fi Voice Certified products unusable
- Client must support simultaneous LTE-U and Wi-Fi operations in the same band
    - Client's Wi-Fi radio must be capable of using any channel within the 5 GHz band when LTE-U is not utilized

6.3. Coexistence Concepts

The industry is actively looking for coexistence mechanisms that can be implemented in the standards being developed. Some of the concepts being explored include:

- LTE modifications
    - Look for unoccupied channels
        - Centralized geolocation database
        - Energy sensing of the channels
    - Listen Before Talk (LBT, potential 3GPP study Item)
    - Mute subframes (potential 3GPP study Item)
    - Include Wi-Fi preamble/header info in LTE transmissions
    - Duty Cycle

- Wi-Fi modifications
    - Making Wi-Fi more "aggressive"
    - OFDMA Wi-Fi (Under consideration for 802.11ax)

7. Summary

LTE-U is a new use of LTE in unlicensed spectrum. Since Wi-Fi is currently the dominant unlicensed access technology, it will be very important to ensure that LTE-U and Wi-Fi can coexist and share access to the unlicensed spectrum. Analysis has shown and lab testing has confirmed that the existing LTE implementations will dominate and prevent Wi-Fi from using any channel where LTE is present.

Even if LTE-U is successfully implemented, Wi-Fi will be with us for a long time to come. While Bluetooth and Zigbee are also popular technologies, they operate in the 2.4 GHz ISM band. If LTE-U is expanded beyond the 5 GHz UNII bands then it will be necessary to look at the impact on those technologies as well.

LTE-U has many desirable capabilities that Wi-Fi does not currently support. It remains to be validated but LTE-U may deliver better spectral efficiency than Wi-Fi currently provides in environments with multiple users. The IEEE 802.11ax project is exploring options to improve Wi-Fi and possibly leverage some of the LTE capabilities.

If LTE-U proves to be next evolution of wireless access networks, developing LTE-U Standalone will allow LTE-U to be deployed as an alternative to Wi-Fi for consumers or network operators who do not have licensed spectrum.

8. Bibliography

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9. Abbreviations & Acronyms

3GPP	Third Generation Partnership Project
AP	Wi-Fi Access Point
CCA	Wi-Fi Clear Channel Assessment
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CTS	Clear to Send
DCF	Distributed Coordination Function
DFS	Dynamic Frequency Selection
DL	Downlink
eNodeB	LTE Base Station
FDD	Frequency Division Duplexed
ISM	Industrial, Scientific And Medical (ISM) Radio Bands
LBT	Listen Before Talk
LTE	3GPP Long Term Evolution
LTE-U	LTE Unlicensed
MAC	Media Access Layer
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi User Multiple Input Multiple Output
OFDM	Orthogonal Frequency-Division Multiplexing
PDCCH	LTE Physical Downlink Control Channel
RB	LTE Resource Block
RTS	Request to Send
TDD	Time Division Duplexed
TD-LTE	LTE TDD
UE	User Equipment
UL	Uplink
UNII	Unlicensed National Information Infrastructure Radio Bands
WFA	Wi-Fi Alliance