LTE-UNLICENSED: AUGMENTING MOBILE DATA CAPACITY, BUT COEXISTENCE NEEDS CONSIDERATION

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Abstract

Cable Operators (MSOs) are exploring new service opportunities based on wireless voice and data. There have been several interesting options proposed from wholesale small cell backhaul for licensed mobile operators to retail mobile services such as Wi-Fi First MVNO to widely deployed Wi-Fi for broadband services or widely deployed LTE neighborhood small cells in homes similar to community Wi-Fi. An interesting opportunity with significant strategic implications is emerging based on a nascent LTE technology.

Key players in the mobile ecosystem have recently put forth a set of proposals to the 3GPP standards body to enable LTE in unlicensed spectrum bands to effectively aggregate licensed and unlicensed spectrum use under a single radio technology ("LTE-Unlicensed" or LTE-U). This report highlights three different modes of operation of LTE-U and its likely deployment scenario in small cells. The report suggests potential opportunities that LTE-U may afford to cable operators and highlights challenges that lie ahead, mainly the ability of LTE to equitably coexist with Wi-Fi and other technologies in unlicensed spectrum. Timing of likely implementation for standardized and pre-standard releases are explored, and technical differences between LTE and Wi-Fi are detailed to highlight the further development of LTE-U that is required to enable coexistence necessary for continued open innovation in unlicensed spectrum.

WHAT IS LTE-UNLICENSED (LTE-U)?

The massive growth in data traffic on both mobile and wireline networks and the proliferation of smartphones and other connected devices continue to put pressure on network operators to increase capacity. For mobile network operators, spectrum is a fundamental resource in this pursuit. However, the licensed spectrum, especially the valuable low-frequency bands with low propagation loss traits, is limited, and is rapidly being exhausted by a dense and growing subscriber base. With a significant amount of unlicensed spectrum globally available in the 5GHz band,[1] the mobile operators and vendors are looking to use unlicensed spectrum to augment the capacity of licensed frequency carriers. In a 3GPP Radio Access Network (RAN) plenary standards meeting in December 2013, the proponents, including Qualcomm, Ericsson, Verizon, China Mobile, Huawei, and others, formally proposed "LTE-Unlicensed" (LTE-U) to utilize unlicensed spectrum to carry data traffic for mobile services with the initial focus on the 5725-5850 MHz band for this use. [2]

As the name implies, the goal of LTE-U is to extend LTE to unlicensed spectrum. LTE-U proponents seek to leverage unlicensed spectrum as a complement to licensed spectrum to offload best-effort traffic through the carrier aggregation framework that has already been defined in

LTE Advanced. In this so-called "licensed-assisted" access, a primary cell carries critical control signaling, mobility, and user data that demand high quality of service on licensed spectrum while less-demanding, best-effort traffic is carried on a secondary cell on unlicensed spectrum (Figure 1)[3]. In this framework, the use of unlicensed spectrum is always accompanied by a primary carrier on licensed spectrum.

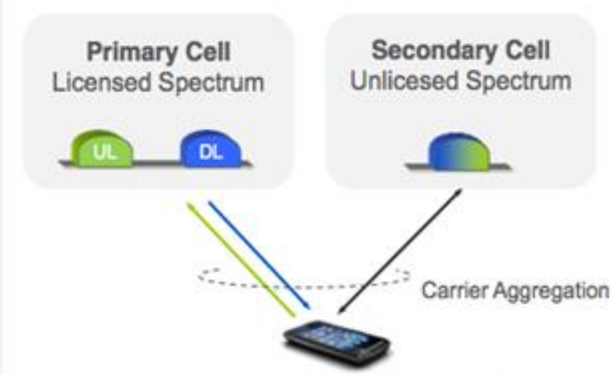

Figure 1 – "Licensed-Assisted" Access in LTE-U (Ericsson 3GPP contribution RP-140260)

There are two main deployment options for aggregating unlicensed spectrum to a licensed carrier to augment capacity, and a third option to run LTE on unlicensed spectrum standalone, without the primary cell on licensed spectrum. First, in the Supplemental Downlink (SDL) mode of operation, the unlicensed spectrum is utilized only for the downlink to augment capacity and increase data rates in a heavily trafficked downlink, which is typical in today's network use. Secondly, the Carrier Aggregation (CA) mode of operation allows use of unlicensed spectrum in both the downlink and uplink, just like typical LTE TDD systems. A key advantage of the CA mode is the flexibility of adjusting the amount of unlicensed spectrum resource that can be allocated for uplink or downlink.

In both the SDL and CA modes, unlicensed spectrum is used only for the data plane, and all the control plane traffic is handled through licensed spectrum in the licensed-assisted manner as depicted in Figure 1, to maintain operator control of both licensed and unlicensed spectrum resources. A primary focus of the LTE-U deployment scenario envisioned by the key proponents in 3GPP currently is the SDL mode as it affords simplicity of deployment and operation to mobile operators and less complexity on devices. A third option that has not been formally proposed in 3GPP is the Standalone (SA) mode, which offers the possibility of higher spectrum efficiency of LTE over unlicensed spectrum. In the SA mode, both control plane and data plane traffic are carried over unlicensed spectrum such that operators without licensed spectrum can potentially take advantage of high efficiency and seamless mobility handling in interference-limited scenarios that is a hallmark of LTE technology. In essence, LTE-U as currently envisioned in 3GPP, without an SA option, will tie use of the technology to wireless carriers with licensed spectrum, precluding use by those who do not have spectrum licenses.

Regulations typically limit unlicensed operations to a maximum transmit power of 1 watt or less[4]; therefore, LTE-U will be deployed as small cells in outdoor venues or indoor. While the LTE-U standard development progresses, it is likely that certain mobile operators are economically motivated to deploy pre-standard LTE-U small cells as early as end of 2015. These pre-standard solutions may leverage the LTE R10/R11/R12 carrier aggregation features and the 5GHz RF front end, (primarily from 802.11ac), which are already in place in vendor product plans. These underlying technologies will allow pre-standard LTE-U to ramp up to scale. To facilitate possible coexistence with Wi-Fi, the initial pre-standard[5] LTE-U small cells will likely be integrated with Wi-Fi in jurisdictions that do not require explicit Listen Before Talk (LBT) regulations, such as the United States, China, Korea, and a few other countries.

A key motivation for mobile operators in considering the use of LTE-U is that it helps to make more spectrum available under a single radio access technology. Today, some mobile operators have "carrier" Wi-Fi networks to offload traffic to ease the load on their primary mobile networks. By combining the use of both licensed and unlicensed spectrum under one (LTE) radio technology, the operators are looking to simplify the network management with a tighter integration under a single RAN and gain additional control over unlicensed spectrum resources. In essence, LTE-U enables tighter integration of both core LTE network infrastructure, and established management and security capabilities that it affords, along with a single radio technology over both licensed and unlicensed spectrum for better control of user experience.

Opportunities for Cable Operators with LTE-Unlicensed

LTE-U offers several interesting ways for cable operators without licensed spectrum holdings to partake in the mobile value chain. One possibility is the "LTE-U small cell as a service" (SCaaS) model in which a cable operator can build out LTE-U small cells in select locations and offer SCaaS as a neutral host to multiple mobile network operators on a wholesale basis. Another possibility is for cable operators to parlay owned LTE-U small cells along with Mobile Virtual Network Operator (MVNO) agreements to provide retail mobile services. A third model is to extend the "Cable WiFi" concept with LTE-U Standalone mode to take advantage of possible efficiency gains. In all cases, LTE's built-in attributes for high efficiency are leveraged in unlicensed spectrum use as described below.

LTE has been designed to offer high efficiency in interference-limited mobile scenarios. Several vendor studies on LTE-U performance relative to Wi-Fi show about 3-5x improvement of LTE over Wi-Fi in unlicensed spectrum.[6] Qualcomm claims that LTE-U provides better RF coverage and offload as compared to Wi-Fi, and that the same capacity can be provided with fewer nodes with LTE-U vs. Wi-Fi. For an "inside-out" deployment scenario wherein small cells, deployed indoors, provide indoor as well as outdoor coverage and capacity, Qualcomm states that Wi-Fi requires 5x more Access Points (AP's) to provide the same capacity as LTE-U.[7] Separately, in the Nokia research, for a given system bandwidth and transmission power, the average user throughput on LTE is reported to be about 4x higher than Wi-Fi in both "sparse" and "dense" scenarios.[8] As indicated in both the Qualcomm and Nokia studies, it is generally accepted that LTE provides a better link performance over Wi-Fi due to the centrally coordinated and managed nature of LTE, which consequently provides more reliable and predictable performance over Wi-Fi. By comparison, Wi-Fi supports collision avoidance features to operate in unlicensed spectrum, and as network load increases, the collision avoidance becomes more burdensome and reduces throughput, with link performance negatively impacted.[9]

These studies of efficiency rely on modeling of the respective air interfaces of LTE and Wi-Fi. However, unlicensed spectrum enables participation of many network operators, and the inherent sharing properties of Wi-Fi enable this coexistence. Today, Wi-Fi carries the majority of Internet traffic as a function of its coexistence properties, making its implementation extremely efficient given the comparative amount of spectrum available for use with Wi-Fi.[10] LTE, however, is not built for a contended RF environment, and the impact of concurrent LTE operations in unlicensed spectrum is as yet unclear. If LTE-U standards require an equitable Wi-Fi coexistence technology we expect some of its efficiencies to be reduced.

In the "LTE-U Small Cell as a Service (SCaaS)" model, cable operators can leverage their network assets for backhaul and pole attachment rights to offer operator-neutral LTE-U small cell as a service on a wholesale basis. Cable operators can potentially offer a complete facility-owned, offload solution to mobile operators, including the (unlicensed) spectrum, with no concerns about who owns what and which spectrum is being used. This opportunity may allow cable operators to offer coverage and capacity solutions to mobile operators without making a significant investment in the Enhanced Packet Core (EPC) infrastructure, which in this wholesale model would be furnished by mobile network operators. LTE-U can be a better technology than Wi-Fi (on a single operator basis) especially for dense deployment scenarios where higher overall capacity can be achieved with better efficiency gain promised by LTE and improved coverage with deployment of newer LTE techniques such as enhanced Inter-Cell Interference Coordination (eICIC) and Coordinated Multipoint (CoMP).

Another interesting opportunity for cable operators is to leverage owned LTE-U small cells along with MVNO arrangements to offer retail wireless service. By leveraging owned small cells for offload, and the MVNO licensed spectrum control channel with lower traffic, cable operators have the potential to offer mobile services at lower cost as offload traffic can be delivered at lower cost than the wholesale rate at which cable operators would "rent" mobile capacity from mobile operators. With a bulk of MVNO service cost tied to network expenses, the MVNO business case can yield higher operating profitability as LTE-U small cells are deployed to where subscribers dwell and consume most of their traffic. A CableLabs' internal analysis of "Wi-Fi first" business model has shown that the service operating margin, excluding handset sales and costs, can be increased more than 13% for incremental 10% offload to Wi-Fi.

In the "Cable LTE-U SA" model, cable operators without licensed spectrum can potentially leverage LTE-U SA mode as an alternative way to offer end-to-end services to their home subscribers. Whether the "better" performance through LTE as delineated above can be achieved in the LTE-U SA mode is unclear as the key concept of "anchoring" on licensed spectrum, for crucial control signaling to ensure quality of service, is obviously not possible in this particular method. In addition, the coexistence properties of LTE-U are unknown, and multiple operators using the same unlicensed band may significantly diminish the efficiency benefits noted above. Assuming that LTE-U SA can somehow achieve a similar performance gain as LTE-U SDL, or even moderately better than today's Wi-Fi network for a given network load, then it may be advantageous for a cable operator to deploy LTE-U instead of Wi-Fi (assuming that cost differential of deploying Wi-Fi vs. LTE-U small cells are "reasonable") for utilization of unlicensed spectrum as LTE-U could conceptually provide more reliable and predictable wireless services.

Wi-Fi Coexistence Challenges and Risks

LTE-U in the context of the existing Wi-Fi ecosystem is not without challenges. The expected ramp of 802.11ac in the targeted 5GHz band for LTE-U could raise challenges and risks if the LTE-U does not take proper measures to equitably coexist with Wi-Fi in a "fair" manner. In general, the lack of coordination and management of mutual interference is the main challenge in the coexistence of different wireless technologies in unlicensed spectrum. Although most technologies are designed to handle interference management between systems of the same kind, it becomes especially challenging in heterogeneous systems with different time slots, scheduling modes, for example, time division multiple access (TDMA) vs. carrier sense multiple access (CSMA), and other media access control mechanisms. As the possibility of two dominant wireless access technologies, LTE and Wi-Fi, sharing common unlicensed spectrum bands becomes more likely with the active push for LTE-U by the mobile ecosystem, it is imperative for the respective standards organizations, 3GPP (for LTE) and IEEE (for Wi-Fi) to carefully study the LTE-U/Wi-Fi coexistence problem and define standard mechanisms to fairly utilize unlicensed spectrum without detriment to performance and user experience of the respective services. These coexistence strategies should consider both the existing base of access points and user devices as well as the future base of (especially 802.11ac) devices to come. (As depicted in the "green" region in Figure 2, a bulk of 802.11ac chipsets and subsequent Wi-Fi use of 5GHz is still to come.) Without a mutually agreed upon standard for coexistence that defines a trusted "arbitration" of fairness, LTE and Wi-Fi ecosystems risk the "tragedy of the commons," whereby each ecosystem may try to rationally allocate the unlicensed spectrum for its use, but may deplete efficient use of that spectrum for all by not coordinating effectively across technologies.

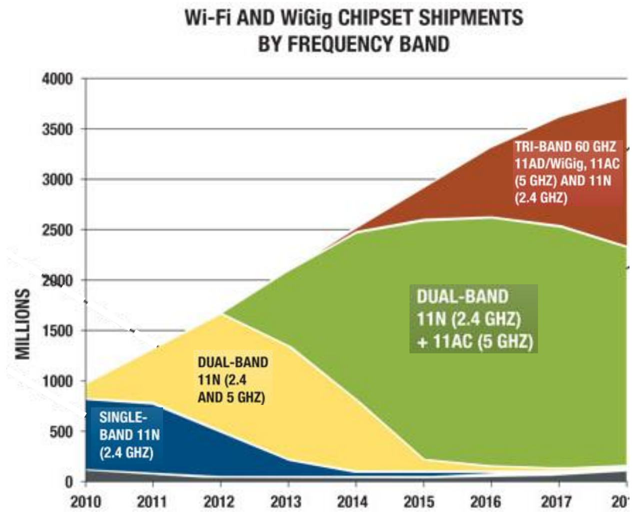

Figure 2 – Wi-Fi/WiGig Global Chipset Shipment Forecast (source: ABI Research, 2013)

Wi-Fi is designed to be asynchronous and decentralized in nature as it is intended for unlicensed spectrum use where multiple radio technologies can potentially contend for the spectrum resource. Wi-Fi uses channel access known as Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). In this contention-based channel access protocol, the Wi-Fi node (AP or device) first "listens" to a channel before transmitting. Only when a channel is deemed "empty" (i.e., observed interference level is below a certain threshold) is the node allowed to transmit. If the channel is deemed "occupied," then the node defers transmissions for a random time period ("backoff") to avoid collision. For this reason, Wi-Fi is generally not efficient in highly dense environments with lots of devices competing for the common unlicensed spectrum resource.

Unlike Wi-Fi, resource allocation in LTE is much more efficient. LTE is synchronous and centralized in nature as it is designed for licensed spectrum where exclusive use of spectrum is guaranteed. LTE uses the Orthogonal Frequency Division Multiple Access (OFDMA) channel access technique that allows simultaneous transmissions with optimized allocation of frequency and time. LTE does not typically perform carrier-sensing detection (as exclusive use of licensed spectrum is assumed in the technology) and schedules channels optimally based on control and management signaling. With its scheduled nature and without carrier-sensing detection, LTE tends to be more "aggressive" in allocation of spectrum resource, while Wi-Fi tends to be more "polite" in its usage of spectrum resource.

In the absence of standardized LTE/Wi-Fi coexistence, LTE-U, as a simple re-band of LTE without any coexistence mechanisms, will crowd out Wi-Fi. A recent Nokia research paper[8] highlights this risk clearly. In the research, the team evaluated system level performance of coexistence of LTE and Wi-Fi systems based on simulations of "sparse" and "dense" environments.[11] The simulation results show that LTE performance is nearly unchanged in the presence of Wi-Fi use of the same band (less than 4% in most cases) while Wi-Fi performance degrades drastically in the presence of LTE (~70% in "sparse" deployment and over 90% in "dense" deployment). The primary cause is that Wi-Fi usage is often blocked by LTE co-channel interference, making Wi-Fi stay in "listen" mode most of the time, which directly impacts user throughput. With certain coexistence mechanisms, such as "smart" channel selection based on Wi-Fi and LTE channel measurements for example, it is plausible that the Wi-Fi performance degradation as observed in the Nokia simulations can be reduced. However, it really depends on how "aggressive" or "friendly" LTE-U will be in various coexistence scenarios, and those details have not been fully defined or reviewed by the wider body of ecosystem participants. Therefore, an early launch of pre-standard products in 2015 may expose coexistence concerns in deployed networks.

Unlicensed Spectrum Policy and Impact on Deployment Timing

Unlicensed spectrum policy, as determined years ago, generally did not anticipate the growth of wireless broadband or how integral Wi-Fi would become to the broadband ecosystem. As a result, in the U.S., China, Korea, and elsewhere, regulations governing the use of unlicensed spectrum primarily set governing power limits to protect adjacent band and co-band primary users, without specific requirements that facilitate coexistence among unlicensed users.

In this environment, coexistence in unlicensed spectrum has come about through the cooperation of all relevant stakeholders toward common goals. Therefore, there is no discernible legal barrier to entry of LTE-U in the U.S. and other jurisdictions with similar regulatory frameworks, and the features that will determine coexistence (both among LTE-U operators and between LTE-U and Wi-Fi) are unknown.

However, in Europe, Japan, and India, the regulatory framework is different, and specific coexistence protocols are mandated in unlicensed spectrum. These protocols, known as "listen before talk", generally replicate the CSMA/CA operation of Wi-Fi, thus enshrining Wi-Fi "politeness" in rule. In these jurisdictions, additional features will be required of LTE-U to ensure compliance and to achieve a true global scale.

Divergent regulatory requirements are likely to impact the rollout of LTE-U. In areas without mandated coexistence, LTE-U, in theory, can be implemented "as is", meaning with unspecified or proprietary and configurable coexistence features. In areas with specific coexistence parameters enshrined in rule, additional development and standardization will be required of LTE-U, which is likely to push out the timeline for initial implementation for such jurisdictions.

In subsequent sections of this paper, we explore the challenges posed by LTE-U to equitable coexistence in unlicensed spectrum, as well as the anticipated timeline and impact of the standards process.

LTE-U Timeline for Specifications and Products

LTE-U specification development remains in the planning phase within 3GPP. The timeline illustrated below is CableLabs' estimated projection of the LTE-U timeline based on recent 3GPP activity and conversations with key stakeholders.

Figure 3 – LTE-U Timeline for Specifications and Products

A workshop dedicated to LTE-U is being held at 3GPP-ETSI headquarters in June of this year. The purpose of the workshop is to form a consensus among 3GPP companies for the scope of LTE-U technical studies and specification work. The consensus will provide the basis for study item and potentially specification work item approval at the RAN plenary in September 2014. At least fourteen companies are advocating a brief study so that specification development can commence at the beginning of 2015 and be completed by the end of 2015. A more conservative estimate targets specifications to be completed in early 2016. Interest in LTE-U is sufficiently high that significant contributions for the anticipated study item are already being submitted into 3GPP in advance of study item approval. With standards being completed in 2016, it is reasonable to expect compliant products in 2017. But it is important to note that pre-standards products can be introduced well in advance of this date, since regulations in U.S., China and other regions do not prevent proprietary solutions within unlicensed spectrum.

The technical scope of the LTE-U standards will likely be determined at the RAN September meeting when the study items and potential specification work items are scheduled for approval. The emerging consensus among key stakeholders in 3GPP suggests that LTE-U will be specified for the 5GHz unlicensed band. Control signaling will remain in licensed spectrum, and the unlicensed spectrum will be used for traffic channels. Effort will be placed upon non-interference among LTE-U systems and enough coexistence features with Wi-Fi to satisfy global regulations of the 5GHz band. The "Listen Before Talk" requirements in Europe are one example of these regulatory requirements, and it is reasonable to expect that standards will enable implementation in a majority of global jurisdictions. However, pre-standard coexistence features are unknown and will likely be proprietary. In jurisdictions such as the U.S. that are likely to see pre-standard deployments, it is not clear that 3GPP coexistence features will be subsequently adopted, and divergent proprietary approaches may persist for some time.

In summary, it is reasonable to expect that LTE-U standard products capable of operating in the globally ubiquitous 5GHz band and meeting international regulatory requirements will be available in 2017. It is also reasonable to expect that the vendors will offer pre-standard products well in advance of 2017 that may not reflect the coexistence features mandated in many jurisdictions.

Wi-Fi MAC and PHY Primer

This section takes a closer look at the Wi-Fi Medium Access Control (MAC) and physical (PHY) layers in order to provide a reference for the discussion of LTE-U and Wi-Fi coexistence described in subsequent sections. Wi-Fi frequency use, channel structure and medium access mechanisms are described.

Wi-Fi leverages Orthogonal Frequency Division Multiplexing (OFDM). The same frequency channels are used for uplink and downlink traffic. Channel bandwidths include 20MHz, 40MHz for 802.11n. 802.11ac adds 80MHz and the potential for 160MHz channel bandwidths. Sixty-four subcarriers are spaced every 312.5 kHz within each 20MHz channel. Fixed location pilots are placed in every modulated symbol. Modulation rates are up to 64 QAM for 802.11n and 256QAM for 802.11ac.

Devices discover and associate with APs using MAC layer signaling and procedures. The Wi-Fi AP can identify itself and its capabilities by broadcasting MAC layer beacons, or it can respond to network discovery queries from clients. Beacons on APs can be disabled such that the AP remains hidden until responding to a client discovery request.

Wi-Fi is designed such that multiple Wi-Fi networks can coexist in the same unlicensed frequency band through the use of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) procedures as explained below. These procedures also allow for Wi-Fi's coexistence with other technologies such as Bluetooth and Zigbee. Since Bluetooth and Zigbee implement their own versions of coexistence procedures, all three technologies operate together within unlicensed spectrum.

Wi-Fi devices and APs attempt to transmit by first sensing if traffic is already on the medium from another Wi-Fi source, or non-Wi-Fi source. The channel must be free of energy for at least 34 microseconds (μs) before transmission is allowed. If the medium is free, the Wi-Fi device or AP applies traffic to the medium. Burst durations on Wi-Fi can range from ~13 μs to 65 milliseconds (ms). For example, a single 1518 Byte Ethernet frame may be transmitted within ~110 μs to 1.8 ms depending upon the modulation rate used for the transmission. The procedure to sense before applying traffic is also commonly known as "Listen Before Talk."

If Wi-Fi devices and APs sense traffic or interference on the medium, they will back off for a specified period of time, and then sense the channel again to determine if a transmission is possible. This is depicted in Figure 4 below. Device B senses that the medium is busy. Device B backs off a random period of time and then senses the channel again. The figure below illustrates the case where it is determined that the channel is free after the initial back off, so that Device B applies traffic to the channel. Had Device B determined that the channel is still busy, it would have backed off for a longer period of time before attempting to apply traffic again. All Wi-Fi devices use these procedures when they attempt to apply traffic to the channel. Collisions are possible when two devices correctly sense the medium is free, and then apply traffic at the same time. Wi-Fi devices will back off a random period of time before sensing the channel again whenever a collision is detected.

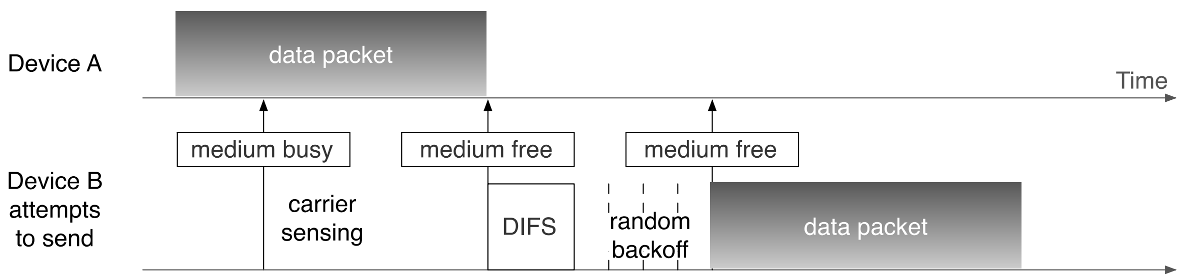

Figure 4 – Procedures to Apply Traffic to a Wi-Fi Channel

While the CSMA/CA procedures allow multiple Wi-Fi devices and network to coexist, they also introduce inefficiency as more devices attempt to use the channel and create collisions or back off for increasing periods of time. As more devices attempt to use the medium, the total aggregate traffic delivered by an AP decreases and service eventually becomes seriously degraded.

<u>LTE MAC and PHY Primer</u>

This section takes a closer look at the LTE MAC and PHY layer in order to provide a reference for the discussion of LTE-U and Wi-Fi coexistence described in subsequent sections. LTE frequency use, channel structure and medium access mechanisms are described.

LTE can be operated as either a Frequency Division Duplex (FDD) or Time Division Duplex (TDD) air interface. As with Wi-Fi, OFDM is applied on the downlink. Single-Carrier Frequency-Division Multiple Access (SC-FDMA), a very similar technique to OFDM, is applied to the uplink. Channel bandwidths of 1.4 MHz, 3 MHz, 5 MHz, 15 MHz and 20 MHz are standardized. Subcarriers are spaced every 15kHz and pilot locations vary from symbol to symbol. Traffic is scheduled in 10ms frames. Modulation rates are up to 64 QAM. Because the physical layers between LTE and Wi-Fi are different, they cannot coexist in the same spectrum at the same time without interference.

LTE is currently designed for use in exclusive licensed spectrum, meaning only one LTE network can exist in a given frequency band. LTE is not designed to coexist with other networks. The LTE network periodically broadcasts training and network identification information. Devices need to scan all exclusive license bands in the area in order to select the correct network. Once the proper network is identified, the mobile device will authenticate and attach using LTE access control channels. LTE control channel signals from the network are periodically transmitted. For example, primary and secondary synchronization signals are sent every 5 ms among other signaling, which results in very minimal "quiet time" in the channel.

When an application requests services or a data session, the network schedules a dedicated traffic channel for the device. Traffic is periodically transmitted in the scheduled traffic channel until all data is delivered. The transfer of traffic is carried within one or more Resource Blocks (RBs). As shown in Figure 5 below, mobile devices or User Equipment (UEs) are allocated subcarriers in time. A total traffic transferred to a mobile device may take several RBs. In periods of heavy traffic, the LTE network constantly places RBs on the channel in an organized schedule.

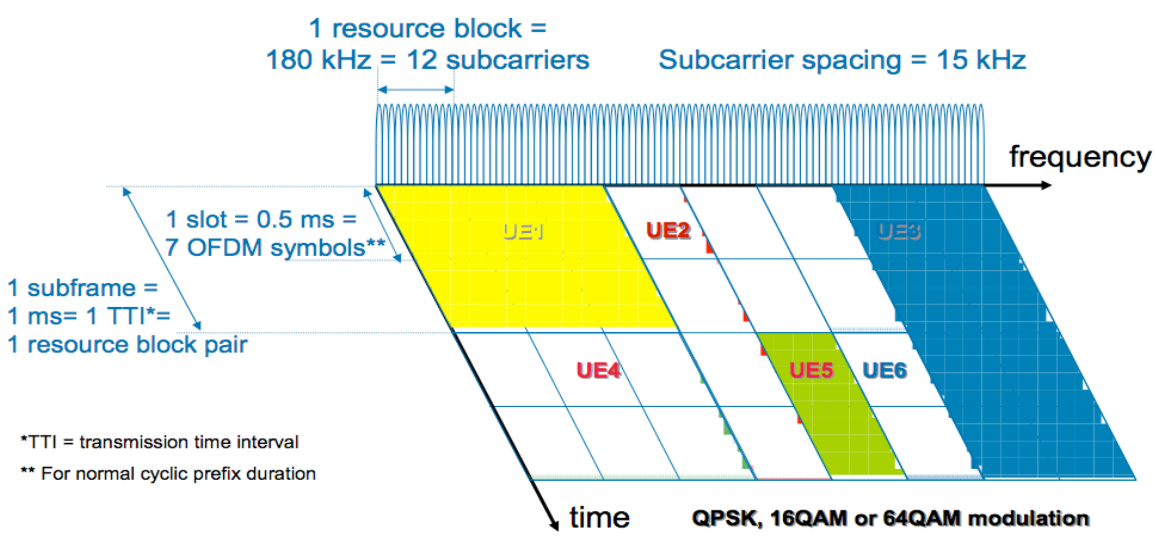

Figure 5 – LTE Resource Block for Traffic Transmission

As seen in Figure 6, the LTE network schedules periodic transmission of resource blocks that support multiple mobile devices with dedicated traffic channels. This centralized scheduling of the air interface eliminates the possibility of traffic collisions among mobile devices. Since only one LTE operates in a single frequency band, there is no possibility of collisions among LTE network providers.

As noted above, the LTE system supports both FDD and TDD operations. TDD operation requires that the frequency channel is divided between uplink and downlink transmissions. 10 ms frames are divided between uplink and downlink 1-ms subframes. The number of subframes assigned to the uplink and downlink is configured by the network operator. Guard time periods are placed between uplink and downlink transmissions. There are no network transmissions during the guard time.

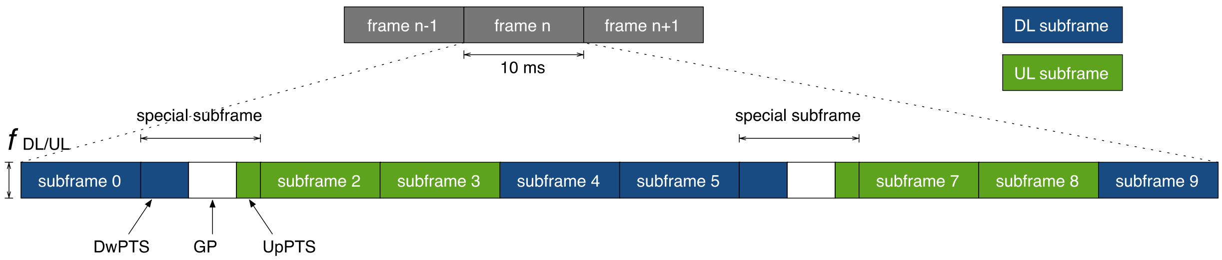

Figure 6 – LTE-TDD Transmission

In summary, the LTE air interface is centrally scheduled by the LTE network, which has exclusive use of the licensed spectrum. This avoids collisions among LTE devices and LTE networks. It also means that more of the total LTE cell data traffic capacity is still available for use as the number of devices in the cell increases. The centrally scheduled nature of the LTE air interface helps make it a more efficient method to transmit data compared to Wi-Fi.

Wi-Fi / LTE-U Coexistence Challenges

Wi-Fi and LTE-U data transmissions will interfere with each other if transmitted simultaneously. As explained in the Wi-Fi and LTE primers sections above, Wi-Fi includes coexistence procedures designed to allow multiple Wi-Fi systems to coexist, whereas LTE is designed with the assumption that one operator has exclusive control of a given spectrum. LTE traffic channels are designed to very efficiently continuously transmit when delivering traffic such that Wi-Fi will have little chance to sense the channel unoccupied and suitable for transmission. LTE also transmits periodic control and synchronization signaling even when no traffic is delivered to devices. So unless the LTE-U traffic channels are redesigned differently than LTE traffic channels in licensed spectrum, LTE-U will apply continuous traffic to devices in a periodic fashion. This raises the possibility that LTE-U may essentially control the unlicensed spectrum at the expense of Wi-Fi devices and other technologies in times of congestion. A research paper from Nokia indicates that LTE-U interference may degrade Wi-Fi performance over 90% during heavy traffic times.[12] Therefore, the LTE-U MAC layer will need to be designed to coexist with Wi-Fi if Wi-Fi is to be afforded a useful portion of the unlicensed spectrum. But how best to design coexistence into LTE-U without substantially degrading the data throughput efficiency of LTE-U remains an open question.

Ideally, coexistence requirements and solutions should provide a level playing field for each network and technology while accounting for local regulatory requirements. Air time fairness and data throughput efficiency are important considerations. The U.S. and China do not mandate specific coexistence requirements for 5 GHz unlicensed spectrum. Europe, however, does mandate the coexistence requirements as summarized below:

For Frame Based Equipment:

- Clear Channel Assessment time: equal to or greater than 20 µs
- Channel Occupancy Time: between 1 ms and 10 ms
- Minimum Idle Period: greater than 5% of the Channel Occupancy Time

For Load Based Equipment

- Clear Channel Assessment time: equal to or greater than 20 µs
- Time back off: N*Channel Occupancy Time, where N~[1,q]. q=4 or 32
- Channel Occupancy Time: less than (13/32)/q ms

Coexistence mechanisms should ideally provide each network an equal opportunity for airtime fairness. Specifically, each network needs to be able to utilize equivalent portions of spectrum over time as traffic conditions meet or exceed the data throughput capacity of the air interface. For example, if 10 networks attempt to utilize 100 MHz of unlicensed spectrum in UNII-3 band in the U.S., each network should be afforded an average of 10 MHz of spectrum over the time of the high traffic period. This does not necessarily provide each device in the network the same average data rate, which is dependent upon a number of factors. Air time fairness shares equivalent megahertz portions of spectrum equally among participants.

Coexistence mechanisms should also strive for data rate efficiency. But a range of coexistence techniques to help ensure air time fairness may present costs to data rate efficiency. For example, excessive clear channel assessment times, long back off periods, and short time periods where a device can apply traffic before being forced to yield the channel can all decrease the data rate efficiency delivered to devices. MAC layer signaling designed to communicate or negotiate air frequency use will increase the overhead of system. While the European regulations described above may bound some of these characteristics, in other areas of the world, such as the U.S. and China, the etiquette is unclear.

The legacy coexistence mechanisms in Wi-Fi have been accepted as sufficient in the wireless industry and are currently in use by billions of Wi-Fi devices across the globe. LTE-U is the new entrant technology targeted for the unlicensed band where Wi-Fi and other technologies currently successfully coexist. LTE-U needs to be designed in light of existing Wi-Fi systems in order to support coexistence.

One design direction for LTE-U would follow the Wi-Fi model for coexistence. LTE-U would first listen to a channel to ensure it is idle before applying traffic. Traffic would be applied for a specific maximum length of time. LTE-U would then release the channel for a specific back off period before starting the process again. Parameter values for these LTE-U procedures could be specified in order to ensure air time fairness with Wi-Fi. While this may provide an equitable solution for all technologies and networks in the band, it may come at a price for LTE-U. Proponents for LTE-U claim it can achieve up to 5x the data throughput efficiency compared to Wi-Fi if it is designed as a simple re-band of LTE with minimal coexistence techniques. But a significant portion of the LTE-U efficiency is due to the centralized and continuously scheduled nature of its air interface. If LTE-U is subject to the inefficiencies of the Wi-Fi's "listen before talk" procedures, it would lose much of the benefit of its scheduled air interface. The efficiencies of LTE-U could approach those of Wi-Fi if Wi-Fi like coexistence procedures are applied to LTE-U. While coexistence parameters may cause LTE-U to lose some efficiency relative to its theoretical maximum, means of coexistence are necessary not only to prevent interference with Wi-Fi, but also interference between multiple LTE-U operators using the same frequency band.

An alternative design direction may be for LTE-U to release the channel temporarily using currently designed scheduling mechanisms. Specifically, TDD LTE-U could be designed to intentionally not transit data for X frames during the period of every Y total frames. 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. This design direction would also afford other technologies to transmit for a portion of the LTE-U data transmit duty cycle in order to help ensure that LTE-U does not consume the entire spectrum as shown in the Nokia paper referenced above. But it should be noted that this approach leaves LTE-U firmly in control of the unlicensed spectrum. What kind of duty cycle should be specified to ensure air time fairness? Should this LTE-U duty cycle be designed to give up the channel 50% of the time when other systems are attempting to use the interface? Should the duty cycle be adaptive to take into account how many other Wi-Fi systems are in the area? How should the duty cycle be enforced to ensure air time fairness? And by whom?

In summary, air time fairness for all technologies and networks may come at a cost to the projected data throughput efficiencies of LTE-U. Therefore, a consensus of cross industry stakeholders is needed to ensure LTE-U is properly designed. A combined effort between 3GPP and organizations responsible for Wi-Fi, such as the Institute of Electrical and Electronics Engineers (IEEE) and Wi-Fi Alliance (WFA), may be needed to reach a standardized conclusion to these coexistence design tradeoffs. Coexistence solutions that are vendor proprietary or defined by a single set of stakeholders may come at the expense of air time fairness, and may persist in the marketplace even after standards are developed.

STEPS TOWARD LTE-U'S FULL POTENTIAL

LTE-U may provide higher data throughput to users in the increasingly crowded unlicensed frequency bands. However, the features that make LTE an efficient technology also make it a challenge to equitably coexistence with other technologies that use unlicensed spectrum, such as Wi-Fi. The U.S., China, and Korea do not mandate specific coexistence mechanisms, which both paves the way for expeditious implementation of LTE-U and raises additional questions about the impact to unlicensed users. Additional development is required to ensure that LTE-U is implemented equitably within unlicensed bands, and that it is available for all to use, regardless of licensed spectrum holdings. Doing so will not only preserve open innovation in unlicensed spectrum, but it will also increase the scope and scale efficiencies of LTE-U.

ENDNOTES

[1] About 500 MHz of unlicensed spectrum is available globally in the 5GHz band.

[2] With the recent FCC rule change in the 5150-5250 MHz band to allow outdoor use with a higher regulated power limit, the scope of unlicensed spectrum utilization can readily be extended to this UNII-1 band, effectively doubling the most useful spectrum for outdoor small cell deployments to 200 MHz in the U.S. Another 355 MHz is available in the 5GHz band for unlicensed use, with additional limits on transmit power and interference avoidance. And LTE-U may be implemented in other unlicensed bands, such as 2.4 GHz.

[3] 'Study on Licensed-Assisted Access using LTE: Motivation', Ericsson, Qualcomm, Huawei, 3GPP contribution RP-140260, March 2014. See http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_63/Docs/

[4] In the U.S., maximum regulated power is 1 watt in 5725-5850 MHz ("UNII-3") and, following recent FCC action, also in the 5150-5250 MHz ("UNII-1") bands. For more information on this recent FCC action to expand unlicensed use in the UNII-1 band, see: "FCC Votes to Expand Wireless Spectrum: A Win for Wi-Fi", Rob Alderfer, CableLabs, March 31, 2014, available at: http://www.cablelabs.com/fcc-votes-to-expand-wireless-spectrum-a-win-for-wi-fi/.

[5] LTE-U will likely be part of Release 13 study/work item based on latest 3GPP standards activity.

[6] Most of the Wi-Fi vs. LTE-U performance comparisons that we have looked at are based on licensed LTE coordination and control, low-level coexistence features and do not account for 802.11ac. It is unlikely that LTE-U with listen-before-talk or other coexistence features would perform as well.

[7] "Extending LTE Advanced to unlicensed spectrum" white paper published January 17, 2014. See http://www.qualcomm.com/media/documents/white-paper-extending-lte-advanced-unlicensed-spectrum

[8] Andre Cavalcante et. al., Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands, IEEE Vehicular Technology, Spring 2013.

[9] The link performance in LTE system also gets impacted as network load increases, but its impact is less severe as resource allocation is tightly managed through central coordination in LTE, unlike the "ad hoc" nature of Wi-Fi networks.

[10] According to the Cisco's 2013 Visual Networking Index, Wi-Fi carried 49% of all Internet Protocol traffic globally in 2012, compared to 48% for the fixed network and 3% for mobile. Accounting for the amount of spectrum dedicated to mobile versus Wi-Fi, Wi-Fi is therefore approximately 30 times more efficient than mobile.

[11] The Nokia paper showed Wi-Fi performance may be degraded over 90% under certain traffic load environments. In the Nokia simulation, the "sparse" environment consisted of 4 Wi-Fi AP's

and 4 LTE AP's and the "dense" environment consisted of 10 Wi-Fi AP's and 10 LTE AP's. In both scenarios, up to 25 Wi-Fi and LTE user devices each communicated with respective AP's. Both scenarios show substantial impact to Wi-Fi.

[12] Andre Cavalcante et. al., Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands, IEEE Vehicular Technology, Spring 2013.