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Making the Best Use of Unlicensed Spectrum for 1000x

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Contents

1	Executive summary	4
2	Opportunistically using unlicensed spectrum for 1000x	5
2.1	Aggregating with the licensed anchor to bring the best out of unlicensed spectrum	6
3	LTE – Wi-Fi link aggregation for Carrier Wi-Fi	7
4	LTE Unlicensed for new small cells	9
4.1	LTE Unlicensed and Wi-Fi fair coexistance — going above and beyond minimum requirements	11
5	Strong industry support for LTE – Wi-Fi link aggregation & LTE Unlicensed	13
6	Conclusion	13

1 Executive summary

Trail-blazing innovations were at the heart of Qualcomm Technologies, Inc.'s 1000x vision when we introduced the concept some three years ago. In the eventful journey since, many of the innovations we cited, such as hyper-dense small cells, Licensed Shared Access, and others have evolved from mere concepts to viable commercial technologies. After rigorous prototyping, intensive testing, trials, and productization, they are now ready to enter the mainstream. Following the same trajectory, we are bringing new innovations that take one key component of the 1000x vision, more and better use of spectrum, even farther. These innovations enable operators to make the best use of unlicensed spectrum, through aggregation.

Although licensed spectrum is the foundation for mobile operators in addressing the 1000 data challenge, opportunistically utilizing the unlicensed spectrum is becoming increasingly important to respond to the growth of traffic in an economical manner. The best way for mobile operators to use the unlicensed spectrum is to aggregate it with an LTE anchor in the licensed spectrum. There are two general approaches: 1) LTE – Wi-Fi link aggregation, to leverage their Wi-Fi networks using both 2.4 GHz and 5 GHz bands; or 2) Even tighter, LTE operating in unlicensed 5GHz spectrum (LTE unlicensed), suitable for small cell deployments. Both of these options provide higher capacity and an enhanced user experience through a single unified network (versus separate LTE and Wi-Fi networks). The choice between the two aggregation options is dictated by the operator's existing assets and deployment plans, and we expect many operators to utilize both.

LTE - Wi-Fi link aggregation needs support from both device and network sides. On the device side, the aggregation happens deep at the modem-level. On the network side, it can either be between collocated or separate (but coordinated) Wi-Fi and LTE Wi-Fi access points (APs). LTE – Wi-Fi link aggregation is part of the larger LTE – Wi-Fi convergence that has already started happening, and is defined for 3GPP Rel 13. We demonstrated LTE – Wi-Fi link aggregation at MWC 2015, and are working with partners to bring pre-standard LTE – Wi-Fi link aggregation solutions to market as early as 2016.

LTE Unlicensed, in the form of LTE-U or LAA, offers the tightest possible aggregation. It can provide 2x or more capacity and better coverage than Wi-Fi. LTE Unlicensed is designed to fairly coexist with Wi-Fi, with features that go above and beyond minimum requirements, including regulatory, standards, and conformance testing. LTE Unlicensed provides multiple deployment options for operators. In countries such as the US, Korea and India, LTE-U can be deployed using existing Rel 10/11/12 with fair coexistence features as early as 2016. In Europe, and Japan, both of which have "Listen Before Talk" (LBT) regulatory requirements, standard changes are needed, which is being standardized in Rel. 13 and called Licensed Assisted Access (LAA).

The mobile industry has shown strong support for LTE-U and LAA, with trials and product announcements. Qualcomm Technologies, Inc. (QTI) is a founder member of LTE-U forum, a collaboration between industry players formed to harmonize specifications. QTI has announced LTE-U device and small cell solutions. And we demonstrated the performance of both LTE-U and LAA and how they will coexistence fairly with Wi-Fi, at MWC 2015.

LTE – Wi-Fi link aggregation and LTE Unlicensed solutions are tools for mobile operators in solving the 1000x challenge. Beyond mobile operators, Wi-Fi will continue to be the main option for private, and enterprise local areas access for years to come. QTI is committed to bringing path-breaking innovations to all aspects of the wireless ecosystem, be it licensed or unlicensed spectrum, LTE or Wi-Fi technologies, network operators or private users.

2 Opportunistically using unlicensed spectrum for 1000x

For operators addressing the 1000x challenge, licensed spectrum is the foundation. At the same time, opportunistically using the available unlicensed spectrum to augment the capacity is also extremely important. Many operators already have deployed their own Wi-Fi networks or are working with third party providers, or doing both. But the challenge is seamless interworking, as these Wi-Fi networks in many cases are not integrated with 3G/4G networks. This makes it difficult for devices to seamlessly discover and connect to them, without user intervention. Moreover, mobile operators have no control over the quality of the service. Both 3GPP and Wi-Fi communities (WFA et al.) have been working toward tighter LTE – Wi-Fi interworking. The resulting convergence, is shown here in Fig.1.

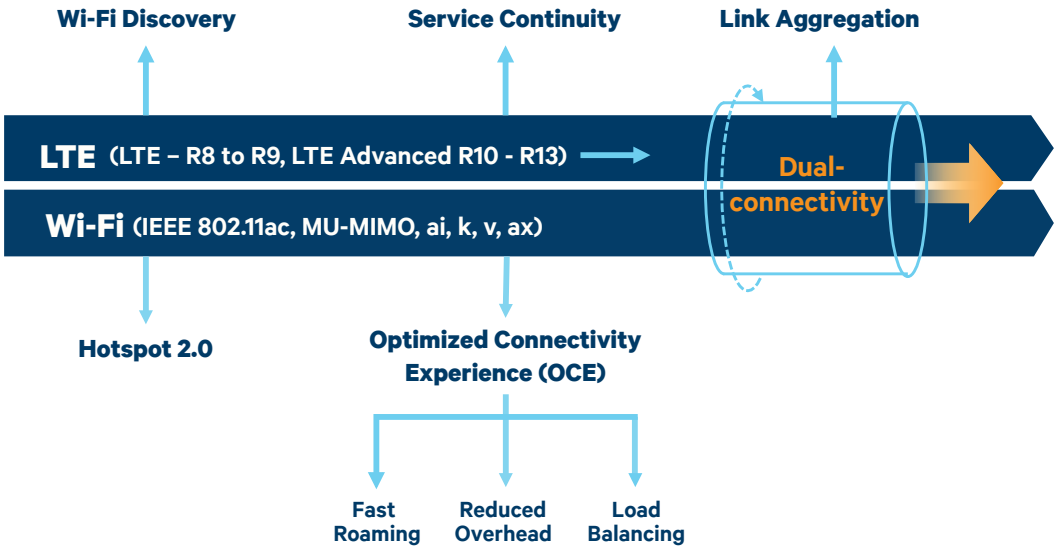

Fig. 1: 3GPP and Wi-Fi communities working toward tighter interworking of LTE and Wi-Fi

The elements of this "tighter' interworking range from seamless Wi-Fi discovery, to service continuity to link aggregation. For example, Hotspot 2.0, allows operators to extend SIM card-based authentication to Wi-Fi, and is deployed in commercial networks. Hotspot 2.0 coupled with discovery mechanisms defined in 3GPP, are making the process of discovering and connecting to Wi-Fi from LTE (and 3G) much more seamless. Following discovery was seamless service continuity of operator services from LTE to Wi-Fi networks, especially VoLTE and VoWi-Fi. Service continuity is being deployed in commercial networks.

Wi-Fi has evolved rapidly over the last decade, and continues to advance, offering successively higher data rates, capacity, and user experience. The latest version, 802.11ac realistically breaks the 1 Gbps barrier and its MU-MIMO feature delivers in increase in capacity. The next version, 802.11ax which is now in the works, will further increase performance. Most of these enhancements are benefiting private/enterprise and mobile operator deployments alike. The upcoming initiative called Optimized Connectivity Experience (based on 802.11ai, 11k and 11v) is especially focused on solving the challenges associated with dense deployments, which significantly benefit Wi-Fi networks deployed by mobile operators (often referred to as carrier Wi-Fi). Some of the features

being introduced are: 1) Faster roaming between different APs or networks, which enables seamless, real-time services; 2) Marked reduction in management overhead; and 3) Intelligent load balancing, wherein, the users are steered towards APs that can provide the best connectivity based on loading, rather than only focusing on signal strength.

Looking at LTE – Wi-Fi interworking, what takes the performance much farther is going beyond standard defined interworking techniques and moving towards LTE – Wi-Fi convergence. As shown in Fig. 2, convergence involves providing an optimized link selection, seamless services, interference mitigation, and link aggregation between the LTE (and 3G) and Wi-Fi links, and beyond.

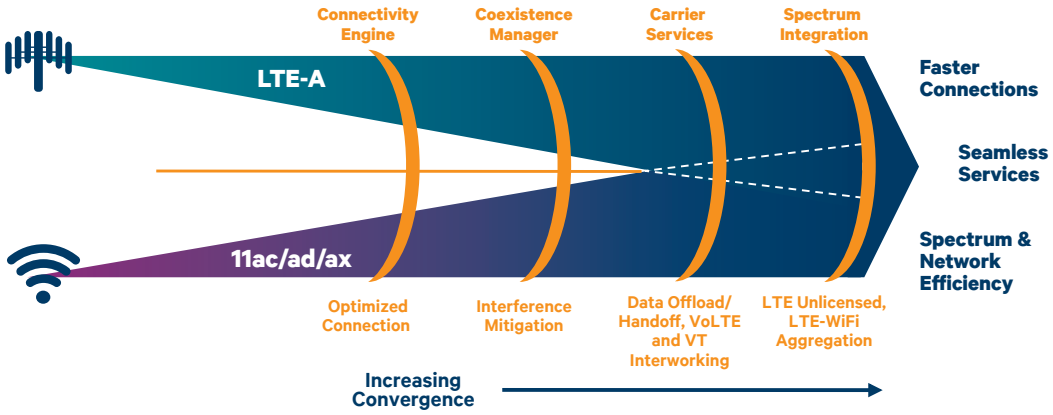

Fig. 2: LTE and Wi-Fi convergence

Convergence requires many enhancements in addition to the standard defined features, for example, the Connectivity Engine (CnE) from QTI in addition to supporting Hotspot 2.0, and discovery mechanisms defined in 3GPP, also incorporates proprietary algorithms to make the link selection much more intelligent. CnE also has all the key elements and smart algorithms needed to effectively deliver seamless service continuity, and so on.

2.1 Aggregating with a licensed anchor to get most out of unlicensed spectrum

In a wireless link, the signaling and control information is very crucial to not only maintain the robustness of the link but also to make sure the resource allocation is managed properly. It becomes even more critical in a dense deployment, where there is a lot of interference and all the nodes in the network are competing with each other for resources. In such cases, managing the resources and making sure that they are allocated in an orderly way is a basic need. Also, the resource allocation and the other signaling/control information has to be reliably communicated between the APs and devices—a task best handled by a robust link on licensed spectrum. This is one of the reasons, among many, why getting best performance out of unlicensed spectrum requires its aggregation with an LTE anchor in the licensed spectrum.

There are two options to achieve this aggregation, as shown in Fig. 3: LTE – Wi-Fi link aggregation and LTE Unlicensed (LTE-U or LAA).

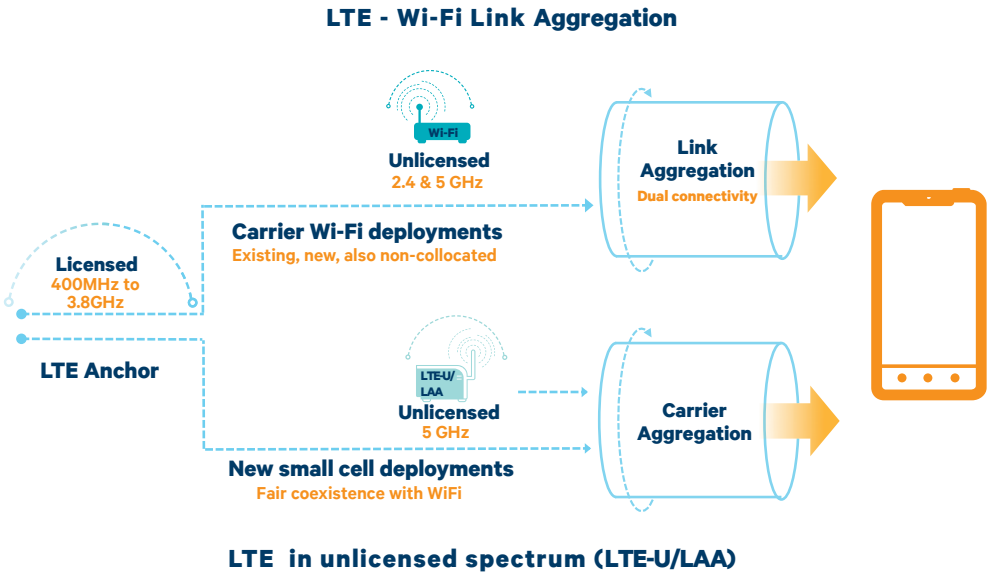

Fig. 3: Two options for aggregation: licensed and unlicensed spectrum. Many operators will use both

LTE – Wi-Fi link aggregation is for leveraging carrier Wi-Fi networks and uses both 2.4 GHZ and 5 GHz unlicensed bands. In this option, the LTE base station (eNodeB) will control the amount of traffic scheduled over Wi-Fi, and thereby ensuring proper load balancing between the LTE and Wi-Fi links.

LTE Unlicensed (LTE-U/LAA) is for new small cell deployments and uses 5 GHz unlicensed band. For both LTE-U and LAA, all the signaling and control is sent through the reliable, licensed anchor (the LTE network) and the unlicensed link is used only for data. This is one of the reasons why LTE Unlicensed can perform better than Wi-Fi alone.

Both options use a single, unified core network that provides cost efficiency and simplicity of management to operators, while offering seamless service continuity and a better broadband experience to users. The choice between the two aggregation options depends on the operators' current assets and future networks plans. We expect many operators to deploy both options.

3 LTE – Wi-Fi link aggregation for Carrier Wi-Fi

Simply put, LTE – Wi-Fi link aggregation combines a link from Wi-Fi with the anchor from LTE on licensed spectrum. As shown in Fig. 4 LTE and Wi-Fi APs don't even have to be collocated for aggregation.

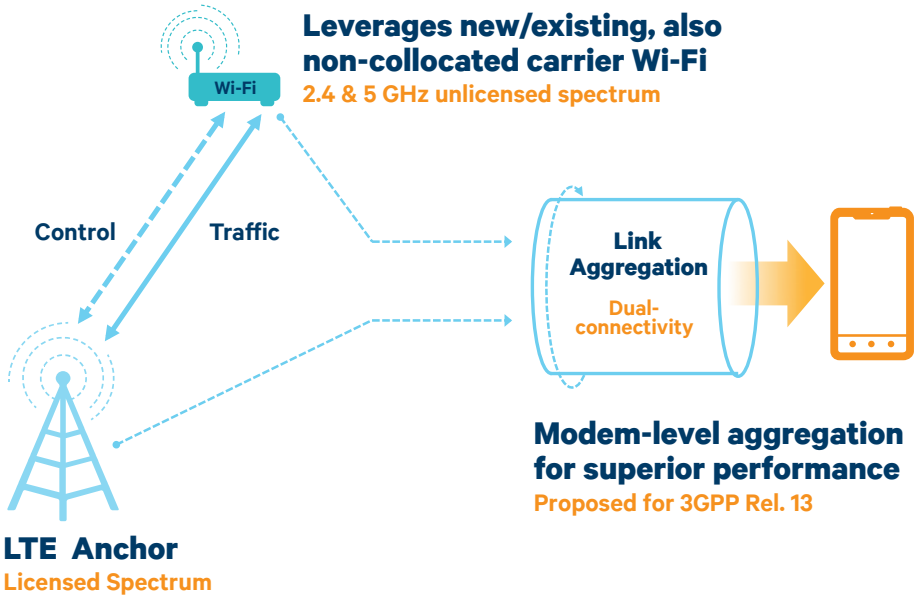

Fig. 4: LTE – Wi-Fi link aggregation for carrier Wi-Fi networks

Users will be simultaneously connected to both the links, enjoying higher data rates, and seamless mobility, as compared to separate (stand-alone) LTE and Wi-Fi networks. As mentioned before, many operators have already deployed their own Wi-Fi networks, and LTE – Wi-Fi link aggregation provides an excellent solution to better integrate them with the LTE network, and improve the overall performance. From the network perspective, Wi-Fi APs will be connected to the LTE network, just like any small cell would, and fully utilize LTE's core network, encryption, control, authentication, and other systems. The result is that LTE base station manage resource allocation of Wi-Fi AP. More importantly, since LTE and Wi-Fi APs don't have to be collocated, even LTE macros could be utilized. This means, once devices that support these features are deployed, the benefits of LTE – Wi-Fi aggregation will be available in short order, since only minimal changes will need to be made to the LTE and Wi-Fi infrastructure (depending on the vendors).

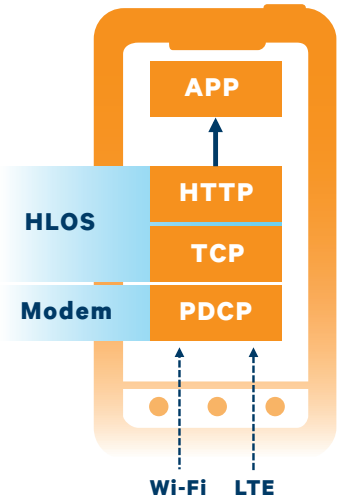

Fig. 5: Modem-level LTE – Wi-Fi link aggregation

Both 2.4 GHz and 5 GHz bands are supported and aggregation happens at the device, deep at the radio link level (PDCP layer) in the modem, as shown in Fig. 5

This is important because modem-level aggregation provides better load balancing (compared to other options) as LTE network is always aware of the loading and signal conditions of both the links and can balance traffic on the links accordingly. Additionally, it can quickly adapt to the fast changing link conditions, as compared to other options such as combining at the HTTP layer, in the high level operating system (HLOS), which are slow to adapt.

From the users' perspective, they are connected to both the networks, whenever available, and their data is intelligently distributed between the two links to provide the best performance. The aggregation of Wi-Fi link is seamless without any manual intervention, and is done whenever available and needed.

LTE – Wi-Fi link aggregation is proposed for 3GPP Rel 13, which is expected to be finalized in early 2016. We are working with partners to bring pre-standard LTE – Wi-Fi link aggregation solutions to market as early as 2016.

QTI has conducted a live demonstration of LTE – Wi-Fi link aggregation between a non-collocated LTE and Wi-Fi APs at MWC 2015, utilizing its over-the-air test network in San Diego. The demo also highlighted the seamless mobility between LTE – Wi-Fi aggregation and LTE only regions, as well as the performance of aggregation with less-than-ideal backhaul, which some Wi-Fi deployment might have1.

So, in essence, LTE – Wi-Fi link aggregation is an excellent choice for mobile operators to leverage their Wi-Fi networks, even when non-collocated, while utilizing both 2.4 GHz and 5 GHz bands to provide enhanced user experience, and better performance using a unified network.

4 LTE Unlicensed for new small cells

LTE Unlicensed extends the benefits of LTE Advanced to unlicensed 5 GHz spectrum and comes in three flavors; LTE-U and LAA aggregates unlicensed spectrum with a licensed spectrum anchor. The latest addition, MuLTEfire™ operates solely in unlicensed spectrum and broaden the LTE ecosystem to new deployment opportunities. MuLTEfire is not the focus here, but will also benefit mobile operators as an offload solution. LTE-U and LAA uses already commercial carrier aggregation feature to combine LTE on both licensed and unlicensed spectrums. LTE Unlicensed is ideal for new small cell deployments targeting 5 GHz unlicensed spectrum, which has up to 500 MHz[2] of bandwidth available in many regions of the world. LTE-U and LAArepresents the highest level of aggregation possible between the two spectrum types, as the same technology, same core network, and even the same small cells are used, as shown in Fig. 6.

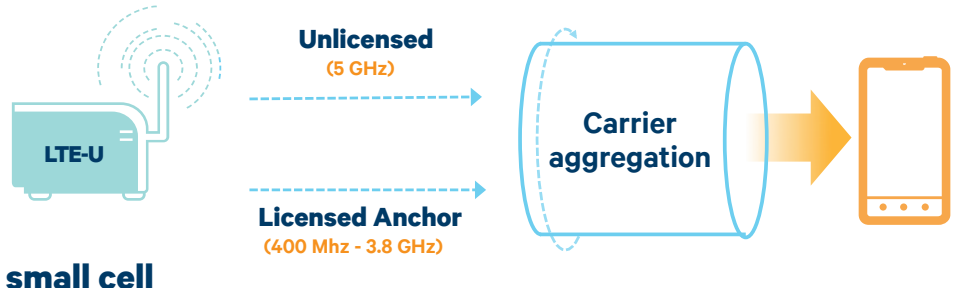

Fig. 6: LTE Unlicensed for new small cells

LTE-U and LAA can be deployed in either Supplemental Down Link (SDL) configuration, where unlicensed spectrum is used only for the downlink, or in a TDD configuration[3], in which, unlicensed spectrum is used for both uplink and downlink. Because of its simplicity, initial deployments will utilize SDL. LTE-U is defined as SDL and the initial release of LAA in Release 13 supports SDL, with evolution in Release 14 that is expected to define additional aggregation combinations.

All LTE Unlicensed solutions use the same LTE technology that has been designed for mobility from day one. LTE supports

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[1] In the demo, non-ideal backhaul was simulated though increase in latency of up to 4 msecs
[2] Initial deployments may use a subset of the available spectrum, such as US UNII 1 and 3 bands

coordinated, synchronized scheduling of resources (instead of the contention-based approach used in Wi-Fi), and has an efficient radio link with features such as scaling to lower date rates, handling larger delay spreads, Hybrid ARQ (HARQ), among many others. Because of these features, along with the use of a robust and highly-reliable, licensed anchor for all signaling and control functions, LTE-U and LAA can provide 2x or more capacity under similar conditions in dense deployments. See Fig. 7.

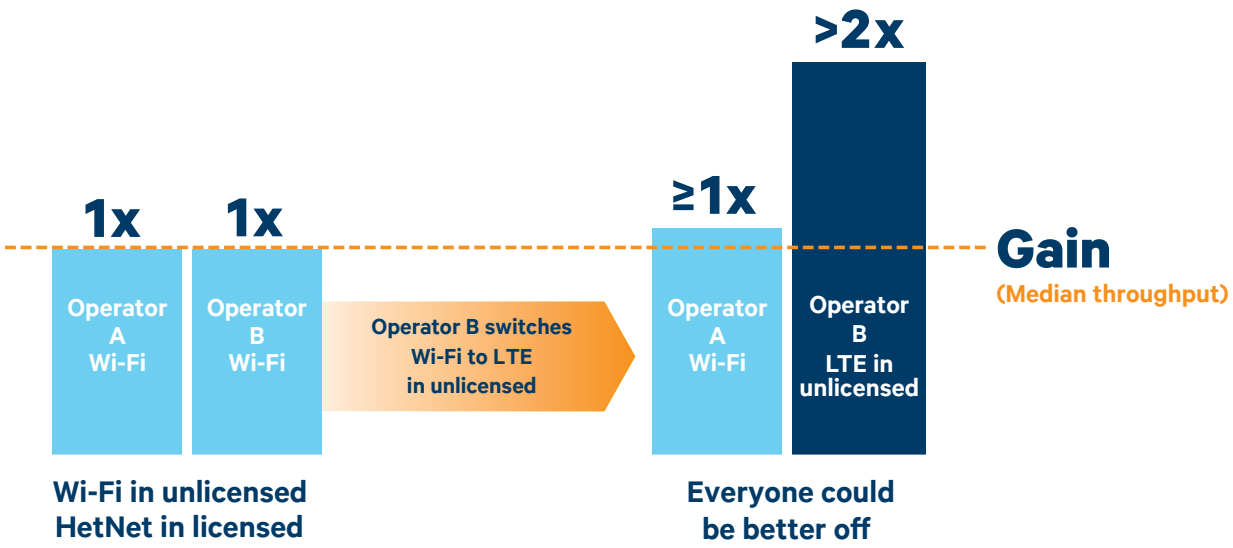

Fig. 7: LTE-U/LAA >2x better performance than Wi-Fi

A part of the higher capacity of LTE Unlicensed can also be traded off to provide better coverage as well. So, operators benefit from the higher capacity, better coverage and efficiencies of a common unified network. From the users' perspective, they enjoy enhanced, seamless user experience while using both the spectrum types, along with a "fatter" data pipe providing improved data rates (compared to LTE in licensed bands only).

Interestingly, LTE Unlicensed can also improve the performance of Wi-Fi in its vicinity, as shown in Fig.6. This is because, LTE being a coordinated system, all the devices collectively behave like a single device (from contention for resources perspective), effectively reducing overall interference. Thus LTE Unlicensed in many cases can be a better neighbor to Wi-Fi than Wi-Fi itself.

Right from conceptual state of LTE Unlicensed, we have paid a special attention to its fair coexistence with Wi-Fi— to be a good neighbor. The design incorporates many features that go above and beyond minimum requirements to ensure this fair coexistence.

LTE-U, a version of LTE Unlicensed defined by the LTE-U forum, can be commercially deployed in many countries such as the US, Korea, and India using existing 3GPP Rel 10/11/12, along with fair coexistence features. For Europe, Japan and beyond that have specific channel occupancy requirements, called "Listen Before Talk" (LBT), changes to the LTE waveform will be required, and hence a new standard will be needed. The new waveform and other changes are part of a work item for Rel 13, called Licensed Assisted Access (LAA)

The next section explains the concept of fair coexistence in detail.

Assumptions: Two operators. 48 Pico+108 Femto cells per operator. 300 users per operator with 70% indoor. 3GPP Bursty model. 12x40MHz @ 5GHz for unlicensed spectrum; LTE 10 MHz channel at 2 GHz; 2x2 MIMO, Rank 1 transmission, eICIC enabled; LTE-U – LAA R13, 2x2 MIMO (no MU-MIMO).; Wi-Fi - 802.11ac 2x2 MIMO (no MU-MIMO), LDPC codes and 256QAM).

4.1 LTE-U/LAA and Wi-Fi fair coexistence – going above and beyond minimum requirements

The need for fair coexistence with Wi-Fi is at the core of the LTE Unlicensed system design, and has been a major consideration from day one. To that end, enabling features are weaved in at multiple levels, which go above and beyond the minimum regulatory requirements. As illustrated in Fig. 8, coexistence features range from customary regulatory compliance to transmission levels and power levels, to features meticulously designed for early deployments in the US, Korea, and India using Rel 10/11/12-based LTE-U, to adherence to specific LBT channel occupancy requirements in regions such as Europe and Japan with Rel 13, Licensed-Assisted Access (LAA), and finally conformance testing before commercialization, which is expected to be more rigorous than testing performed for today's Wi-Fi systems.

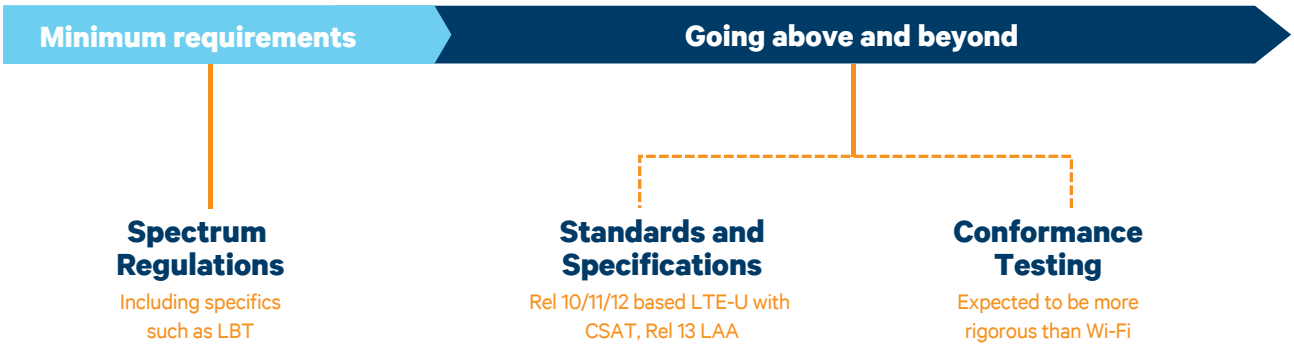

Fig. 8: LTE Unlicensed and Wi-Fi fair coexistence, going above and beyond minimum requirements

Both LTE-U and LAA uses unlicensed spectrum only when the data boost is needed, or else it will only rely on the licensed spectrum. When using unlicensed spectrum, it dynamically selects a channel that is not occupied by Wi-Fi (or other LTE Unlicensed users). With up to 500 MHz of available spectrum in the 5GHz band, there is a good possibility that it can get a free channel. If it can't, it has to share the channel with Wi-Fi (aka co-channel), and that's when the fair coexistence mechanisms kick-in. Depending on the geography, fair coexistence works in two ways. In countries such as the US, Korea, and India, where LTE-U can be deployed using Rel 10/11/12, coexistence will be achieved through an approach we call CSAT (Carrier Sensitive Adaptive Transmission). In regions such as Europe and Japan, the coexistence will be based on Rel-13 LAA, which inherently supports LBT channel occupancy regulatory requirements.

The basic idea of co-channel coexistence is time sharing based on channel sensing. The time scale can be a bit longer in CSAT and very short with LAA. Fig. 9 illustrates the working of CSAT with an example.

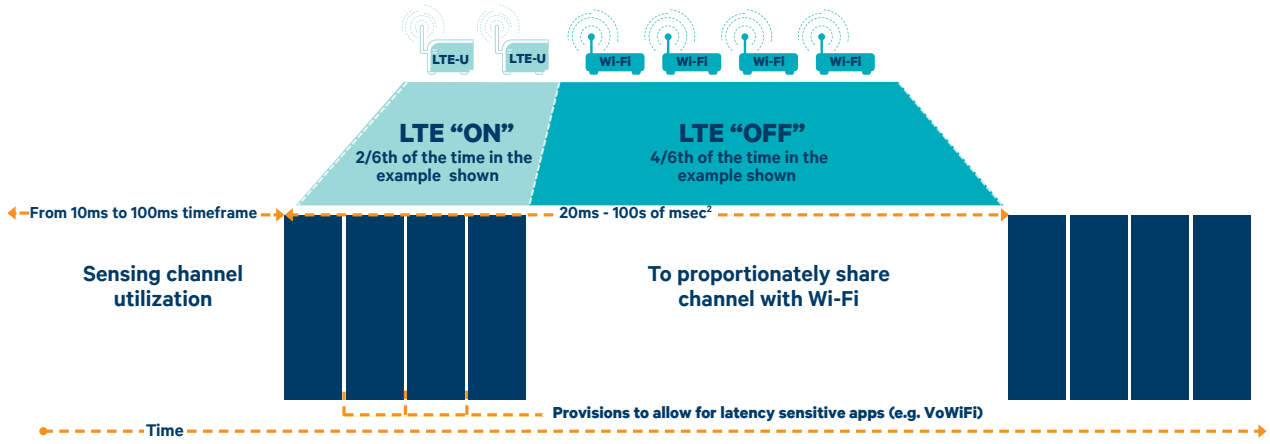

Fig. 9: Illustration of LTE-U/Wi-Fi fair coexistence based on CSAT

When LTE-U is off, it senses channel utilization by estimating the number of Wi-Fi APs, and turns itself OFF to give proportionate time to Wi-Fi. In the example shown, LTE-U senses the channel and understands that there are four active Wi-Fi APs in the vicinity. And of course it knows there are two LTE-U APs. So, it keeps LTE-U ON for 2/6th of the time, and LTE-U OFF for 4/6th of the time, allowing Wi-Fi APs to use the channel as they would normally do. The time scale for CSAT is configurable and can be as short as 20milliseconds to as long as 100s of milliseconds. Additionally, LTE-U also turns OFF for several times for a very short duration, during its designated ON time, to allow for latency sensitive applications such as VoIP over Wi-Fi to send and receive their packets.

QTI is a founding member of a consortium of industry leaders called the LTE-U Forum (**www.lteuforum.org**). The LTE-U Forum has published minimum performance and coexistence specifications for operating LTE-U base stations and consumer devices on unlicensed frequencies in the 5 GHz band. CSAT is fully complaint with the LTE-U Forum specifications.

In Rel 13, LAA, although the sharing concept is similar, there are subtle differences because of specific requirements of LBT (as defined in ETSI EN 301 893 V1.7.1). LAA senses the channel every 20 microseconds, and if free, occupies it for the next 1 - 10 milliseconds, the time can be set for dynamic utilization similar to CSAT, as illustrated in Fig. 10. If the channel is busy, it waits for a specific amount of time, based on a randomized counter (per LBT regulations), and then senses the channel again — and so on. In this manner, both LTE and Wi-Fi share the channel "fairly."

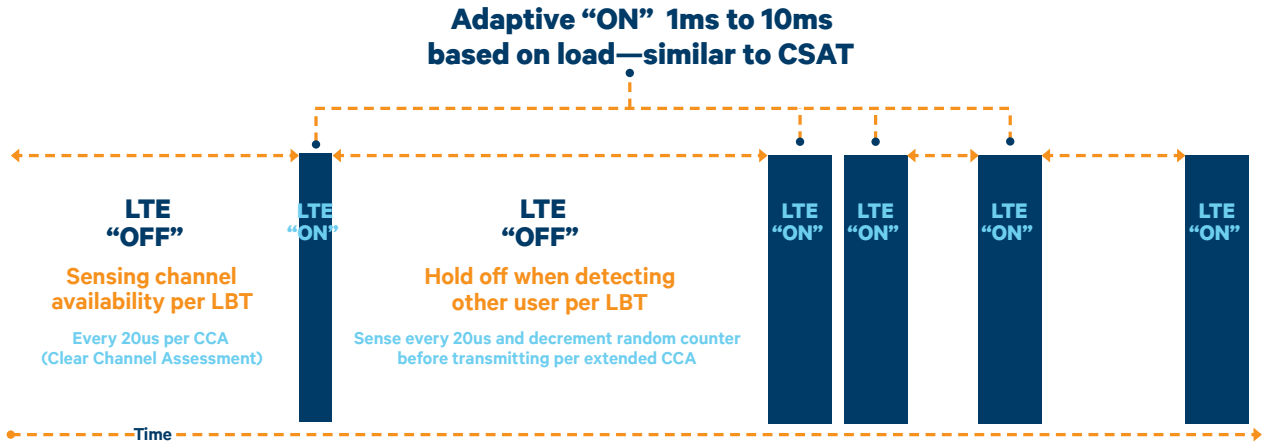

Fig. 10: Illustration of Rel 13, LAA based fair sharing supporting LBT

QTI has extensively tested both LTE-U with CSAT and Rel 13 LAA in the lab as well as in the over-the-air test network, to ensure that they work as intended in fairly sharing the unlicensed spectrum between LTE Unlicensed and Wi-Fi. Both were also demonstrated to the public at Mobile World Congress 2015 and CES 2015 (LTE-U with CSAT only).

For more technical details, please refer to this: **LTE-U/Wi-Fi fair coexistence whitepaper.**

5 Strong industry support for LTE – Wi-Fi link aggregation & LTE-U

LTE – Wi-Fi link aggregation has strong industry support. It is planned for Rel 13, supported by many industry players. We are working with operators and infrastructure vendors to bring interoperable solutions to market ahead of an approved standard, while supporting standards activities in 3GPP. One operator officially announced its demonstration of LTE – Wi-Fi link aggregation at MWC 2015. We demonstrated LTE – Wi-Fi link aggregation at MWC 2015, using our prototype set-up, as well as with a leading infrastructure vendor.

LTE Unlicensed has witnessed tremendous support from the various quarters of the mobile industry. Some operators have announced plans to trial the technology in 2015. Some infrastructure vendors have announced product plans and release dates. Many industry players conducted LTE Unlicensed demonstrations at MWC 2015 and QTI has partnered with most of them. QTI also announced the industry's first LTE-U solutions: FSM99xx SoC for small cells and RF Transceiver WTR3950 for devices, both are expected to be available in the second half of 2015 for commercial deployments in 2016. The FSM99xx solution supports LTE-U (Rel 10) with CSAT coexistence features, and is designed for enterprise and metro small cells. The WTR3950 pairs with the WTR3925, supporting 3x20 MHz carrier aggregation, including 5 GHz band. A new industry consortium, the LTE-U Forum, of which QTI is a founding member, has been formed to bring different stakeholders together and harmonize specifications. The LTE-U Forum published minimum performance and coexistence specifications in March 2015. Licensed Assisted Access (LAA) with LBT got formally approved as a work item in Rel 13 in June 2015. Extensive Industry collaboration across the Wi-Fi and mobile industries are helping to further refine coexistence specifications and test cases, to ensure that LTE Unlicensed is a good neighbor to Wi-Fi.

6 Conclusion

As operators march toward addressing the 1000x data challenge, they are looking at all available avenues to leverage more spectrum. Licensed spectrum remains the main foundation, while leveraging available unlicensed spectrum is also extremely important. Realizing this, many are already investing in Wi-Fi networks to opportunistically offload data. But interworking between LTE and Wi-Fi is a major challenge in terms of providing seamless user experience and giving mobile operators the ability to fully manage their Wi-Fi networks. Both the 3GPP and Wi-Fi communities (IEEE, WFA et. al.) are working toward a "tighter" interworking of LTE and Wi-Fi technologies. QTI is working on solutions to enable an LTE – Wi-Fi convergence, which takes their performance even higher.

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Going forward, operators have two aggregation choices to best utilize unlicensed spectrum: LTE – Wi-Fi link aggregation, and LTE-U/LAA. Both will aggregate the unlicensed spectrum with an LTE anchor in the licensed spectrum and provide better performance and enhanced user experience using a unified network.

LTE – Wi-Fi link aggregation is a major step toward the convergence of these two technologies, and it is useful for mobile operators that either already have, or are planning to deploy Wi-Fi in the future. It utilizes both 2.4 GHz and 5 GHz bands. And importantly, LTE and Wi-Fi APs don't have to be collocated. On the other-hand LTE-U and LAA takes convergence to a different level, by offering and aggregating LTE on both licensed and unlicensed spectrums, specifically the 5 GHz unlicensed band. This solution is ideal for small cells. Since LTE-U and LAA uses the same technology, same network, and the same small cells, it represents the tightest possible convergence between the two spectrums, and hence offers better performance. The decision between the two options depends on the operators' existing assets and future network plans. We expect many operators to deploy both, as these solutions address different needs.

LTE Unlicensed has been designed specifically to fairly coexist with Wi-Fi, with many features and provisions that go above and beyond minimum requirements. This involves complying with regulatory requirements, adopting coexistence features such as CSAT for deploying with LTE-U (based on Rel 10/11/12) in the USA, Korea, and India, as well as adhering to Rel 13, LAA standard, in countries that have specific LBT requirements (i.e., Europe and Japan), and finally, compliance testing before commercialization, which is expected to be more rigorous than testing for today's Wi-Fi systems. And the third member of the LTE unlicensed family, MuLTEfire, promises to further broaden the deployment opportunities for LTE, especially for harder-to reach indoor locations. MuLTEfire operating solely in unlicensed will also benefit mobile operators through offload partnerships or through own deployments, for example in locations where LTE licensed spectrum is unavailable.

There is strong industry support for both LTE – Wi-Fi link aggregation and for LTE Unlicensed. LTE – Wi-Fi link aggregation is proposed to Rel 13, supported by many industry players. QTI demonstrated LTE – Wi-Fi link aggregation at MWC 2015. Looking at LTE Unlicensed, many operators and infrastructure vendors, as well as QTI, have announced trial plans, products and more. We demonstrated both LTE-U and LTE at MWC 2015 and CES 2015, highlighting its superior performance and its ability to fairly coexistence with neighboring Wi-Fi networks. A new industry consortium the LTE-U Forum, of which QTI is a founding member, has been formed to bring different stakeholders together and harmonize specifications. We are committed to making the best use of unlicensed spectrum in helping mobile operators address the 1000x data challenge.