LTE Evolution: Standardization & Deployment

The Long Run to 5G
INTRODUCTION

The 3GPP (3rd Generation Partnership Project) Release 15 has kicked off, officially triggering the new era of fifth generation of telecommunications: 5G. And while carriers prepare to launch 5G networks, legacy technologies are still deployed in the market. Among them, LTE (Long Term Evolution) has been playing a key role in the adoption of 4G (fourth generation) since it was commercially launched in early 2010. In a matter of a few years, LTE has been successfully deployed around the world driving the entire wireless ecosystem to connect over 1 in 4 mobile users worldwide, a trend that is continuing to grow tremendously [1].

Many Mobile Network Operators (MNO) have heavily invested in the LTE network rollouts across the world for the transition from the 2G/3G (second/third generation) to 4G. This deployment has been an instrumental step to enhance the Mobile Broadband (MBB) proposition and improved coverage, as well as for offering more attractively priced data tariffs, greater availability and affordability of higher speed devices. The generational shift that is gaining momentum on the wave of the continuous enhancements and new features that the standard introduces has made LTE the fastest developing mobile technology ever. Statistics reflect as of July 2017, 782 operators were invested in LTE across 200 countries with up to 601 LTE networks commercially deployed and launched in 192 countries [1].
In addition, the GSMA reported that at the end of 2016 more than 65% of the world’s population had a mobile subscription for a total of 4.8 billion unique mobile subscribers that, by 2020, will reach 5.7 billion people with a global penetration rate to up to 73%, almost three quarters of the world’s population, as shown by the graph in Figure 1 [2]. Looking specifically at LTE, the contribution of this technology to the mobile subscribers is massive. GSA reported that the number of global LTE subscribers at the end on 2016 were up to 1.92 billion [3] with the number of 4G connections alone that are forecasted to almost double by the end of the decade moving from 23% in 2016 to 41% in 2020 [1].

The era of the cellular telecommunication began with the first generation (1G) of mobile technology. It was based on AMPS, analog frequency-division multiplexed technology, which was brought to live at the beginning of 1980s. The 2G was GSM (Global System for Mobile) that utilized the Time Division Multiplexed (TDMA) modulation and it was introduced in the early 1990s. GSM completely replaced its predecessor in only few years and it is still generating business opportunities and revenues. In the years 2000s it was the time of the 3G, the new disruptive technology based on Wideband Code Division Multiple Access (WCDMA). It took dominance in the market due to its proposition designed and developed to enhance the wireless data traffic; however, it has never replaced 2G completely. At the beginning of 2010, the new 4G generation started with two competing systems, LTE and WiMax, both based on a the OFDMA (Orthogonal Frequency Division on Multiple Access) modulation scheme. WiMax had a short commercial life and it was completely wiped out by LTE that started to dominate the broadband market and spread out very rapidly across different verticals, from the MBB for data-hungry applications, to the Machine Type Communication (MTC) system for low-power and low-data volume devices. This evolution of devices and technologies along the decades is highlighted in Figure 2.
As stated previously, over the years and up to today, only 1G completely disappeared. All the following generations and related deployed technologies, GSM/GPRS/UMTS/HSPA/LTE, are still very much alive and kicking and generate business for different industry sectors covering different needs of data rate, cost, power consumption, data speed and volume, latency, etc.

With the advent of 5G, for which the 3GPP targets commercial launches of devices in 2020, there will be a progressive technology shift towards new frontiers. Whether 5G will be a real technology revolution, rather than a progressive evolution, is still early to predict. Either way, its impact on the entire telecommunication ecosystem will be surely dramatic and will have a global scale. The telecommunication system will be radically changed, with mobile network that have significant improvements both in higher data rates and lower latency and lower power systems to generate a variety of business cases across a wide range of vertical markets. This, in turn, will enable all the key players in the industry, from the Communication Service Providers (CSPs), MNOs, infra vendors, device manufactures and so on so forth, to offer new and enhanced services and solutions and, foremost, to address the worldwide increasing demand of the digital society to have a world in which everything is always connected.

All those weaknesses and gaps that are still present in the current wireless generations, both from the technological and economic perspective, will be addressed with performances improvement and new added functionalities in the 5G standards with focus in three major areas of development: Ultra-broadband connectivity, Mission Critical Services and Massive MTC (mMTC).

In this fast-moving scenario, LTE will definitely continue to be the dominant mainstream mobile technology where 5G will be sitting upon and it will last for a long lap of time, very likely longer than what expected based on previous experience. As showed in Figure 3, GSMA reported that all cellular technologies had a life cycle that is approximately 20 years long from the launch to peak penetration, where the technology shift is around 10 years. If this prediction is correct, LTE will have its peak penetration in 2030 [4].

Figure 2 - Device Generations Along the Latest Decades
In the next chapters, this paper will dig into the LTE technology and its evolution from its earlier stages when it was defined in 3GPP Release 8. Then it will explore in more detail some of the key features that come with 3GPP Release 13 and Release 14. The importance of these two releases is massive not just because they deliver significant new functionalities that boost the customer experience and reduces network costs, but foremost because they are closing the 4G standards while paving the basis for the eve of 5G and in parallel, guiding the new technology evolution and deployment.

**LTE STANDARDIZATION**

LTE is a packet switch IP technology based on OFDMA digital modulation scheme to supports channels bandwidth up to 20MHz and antenna techniques with Multiple-Input-Multiple-Output (MIMO), such that multiple data streams are delivered and received on a given frequency time by multiple antennas. Figure 4 shows an example of 4x2 MIMO where 4 antennas are transmitting, on network side, and 2 are receiving, on User Equipment (UE).

**LTE**

LTE was first introduced in Release 8 of the 3PPP standards to increase spectral efficiency of the existing 3G technologies. It was commercially launched in early 2010 in Category 3 (Cat. 3) MBB devices able to reach the data speed up to 100Mbps in Downlink (DL) with 50Mbps in Uplink (UL). As LTE is a pure packet switch architecture, the provisioning of voice and other Circuit Switch (CS) domain services were initially diverted to reuse the existing CS infrastructures, either 3G UMTS (Universal Mobile Telecommunication System) or the 2G GSM, with a mechanism called Circuit Switch Fall-back (CSFB). In Release 9, voice started to be implemented over LTE (VoLTE) with dedicated voice bearer and Qualities of Services (QoS). Since then, VoLTE has been enhanced to implement new services and become a mandatory requirement for voice in many MNOs across the world.

Throughput was also increased to reach Cat. 4 of 150Mbps in DL using all the 20MHz channel bandwidth and 2x2 MIMO techniques.
LTE-Advanced

3GPP Release 8 and Release 9 put the basis of the LTE standards and its network architecture enabling a technology to be more efficient for the use of spectrum for higher data rates. However, with Cat. 4, LTE had already all consumed all the 20MHz bandwidth available for a channel. To address this limitation and to increase the data rate to support advanced services and applications, 3GPP Release 10 introduced LTE-Advanced to enhance data throughput and spectral efficiency with two major features. The first is Carrier Aggregation (CA) techniques, that allows to increase the overall channel bandwidth by aggregating two or more LTE carrier components, not necessarily contiguous, to transmit more Resource Blocks (the basis of data information) in an aggregated spectrum [5]. CA also enable MNOs with limited licensed bandwidth on single channel, less than the full 20MHz, to provide to users a more competitive data speed.

The second is by enabling a higher-order of MIMO for a bigger number of data streams transmitted from the network and received from the end-user device.

Release 10 and Release 11 also introduced additional features to improve the data throughput and coverage specifically at the cell edge. Interference management schemes and enhanced interference cancellation, such as enhanced Intercell Interference Coordination (eICIC) technology and Coordinated Multipoint Transmission (CoMP) scheme, improved the network performance for higher cell capacity.

In Release 11, 3GPP also added specific features to prevent and control possible overload of the Radio Access Network (RAN) due to the raising number of commercial MTC devices that LTE was generating in a market still dominated by most cost-effective legacy technologies, especially by GSM.

Release 12 defined, for the MTC ecosystem, a new LTE device category for lower data rate and low power consumption, Cat. 0, limiting the data speed to 1Mbps (with channel bandwidth that was further reduced to 1.4MHz in the following Release) with single antenna reception, support of half duplex and no MIMO. The new Cat. 0 enabled to increase network capacity, extend the device battery life by reducing the energy consumption both at the network and UE level, reduce the data traffic when and where really needed, and ultimately maximize the cost efficiency.

On the opposite front, for higher data-rate applications, three performances improvements were implemented for enhanced MBB (eMBB). CA was extended to aggregate up to five (5) carrier components to create a wider data pipe of 100MHz including channels using different LTE modulation schemes that are Time-Division (TDD) and Frequency-Division (FDD) multiplexing. MIMO was brought up to enable up to eight layers and enhanced beamforming. Higher modulation schemes for spectral efficiency improvements were increased from 64QAM (Quadrature Amplitude Modulation) to 256QAM in DL.
In addition, technologies already defined in earlier release were optimized to expand into new frontiers. Evolved MBMS (eMBMS), also called LTE Broadcast, was originally introduced in earlier Releases (from the 6 onwards) to enable a broadcast/multicast mechanism to deliver shared content across to multiple UEs. With LTE-Advanced, LTE Broadcast implemented a more efficient way to deliver mass media contents over the cellular networks by enabling more dynamic, scalable and cost effective applications and, as such, fulfill the request for watching long and live video streams on demand on mobile devices. As well, in the public safety and critical communications, eMBMS allowed more efficiency into the mission-critical push-to-talk calls (voice/data/text) service by transmitting audio data over a single IP multicast transmission to all group participants in a cell. On the same wave, Release 12 begun to address the stringent demand for lower latency in the end-to-end setup time and transport delay for the new use cases for situational awareness introducing the Device-to-Device (D2D) proximity services functionality.

**LTE-Advanced-Pro**

Release 13 and Release 14 define the standards that go under the framework of LTE-Advanced-Pro, a step forward to boost higher data speed for the Gigabit LTE class devices, and to optimize the MTC technologies.

CA raised up to 32 the number of aggregating component carriers. Despite there is no operator with such spectrum bandwidth available, this enhancement clearly indicated that the standards were ready to go beyond the LTE limits and to enter the new ecosystem that 5G will define. LTE-Advanced-Pro also introduced LAA (License Assisted Access) for an opportunistic use of unlicensed spectrum over 5GHz to complements the Operators’ demand for meeting the growing data traffic. LAA leveraged on previous releases and proprietary solutions, like LTE-U (LTE on Unlicensed spectrum), to aggregate free unlicensed spectrum to a LTE anchor component in licensed spectrum and increasing, in such way, bandwidth and capacity while maintaining the reliability. LAA however, can interfere with Wi-Fi technologies that use the same frequency band over 5GHz. To address this limitation, 3GPP acts mandates LAA to ensure fair coexistence between LTE and Wi-Fi implementing mechanism of Listen-Before-Talk (LBT) to reduce interferences and increase usability by checking that the channel is free before transmitting. As well, new techniques of LTE and Wi-Fi aggregation, LWA (LTE-WLAN Aggregation) and LWIP (LTE WLAN Radio Level Integration with IPsec Tunnel), were introduced using Wi-Fi as the opportunistic unlicensed spectrum technology and avoiding, any conflict in the 5GHz band, while increasing the bandwidth.

Another important improvement in Release 13 was the support for Massive MIMO (M-MIMO) with higher-order of antenna elements, from 8 up to 64 at the eNodeB, to support full-dimension of MIMO (FD-MIMO) leveraging on 3D beamforming for high capacity demand. M-MIMO systems are designed to become more efficient at higher frequencies.

Release 13 also introduced major advances for the MTC and public safety use cases. The two new technologies defined for this purpose are eMTC (enhanced MTC, otherwise referred to as LTE-M or Category M) and NB-IoT (NarrowBand-Internet of Things) that were designed for
optimizing coverage, device battery life and costs, as well as to handle the increased capacity for a massive number of connected devices.

Release 14 is just being frozen at beginning of June 2017 taking to an end the 4G standards. Here, 3GPP identifies groups of use cases and requirements for market segments and verticals in the telecommunications ecosystem that would need to support in the future. Those can be largely classified into the categories as shown in Figure 5 and listed below [6]:

1. Enhanced Mobile Broadband
2. Critical Communications
3. Massive Machine Type Communications
4. Network Operation
5. Enhancement of Vehicle-to-Everything

Release 14 introduced for mMTC new power classes, higher data rate to support VoLTE in eMTC devices, as well as some positioning enhancements. For Mission-Critical, including Vehicle-to-Anything (V2x) applications, new enhancements for video, data services and reduced latency. For eMBB, LTE aggregation of unlicensed spectrum was extended to the uplink channel with new aggregating modeling with both LTE components in bands above 5 GHz (eLAA) and WiFi (eLWA, eLWIP). As well, new unlicensed spectrum in the 3.5GHz frequency was identified to bridge the transition from 4G to 5G use cases. The new bands include B42 and B43, for Europe, Asia-Pacific and Canada, and CBRS for the US Market for shared commercial use of the 3.5 GHz band with the incumbent military radars and fixed satellite stations.

As far as the network is concerning, it has started to shift to a complete virtualized system integrating concepts of digitalization of the infrastructure and slicing network mechanisms for reconfiguring its layers according to the end-user application.
5G

From early June 2017 onwards, all will be around 5G. The first commercial launch is in the roadmap for 2020 but major stakeholders are already making huge investments and put a lot of pressure to accelerate its deployment. The Pre-Release 15 for the initial studies of 5G started in early Q4 2016 but there are already several Companies that are claiming to have solutions based on 5G technology. Early adopters are planning demonstrations and events ahead of what expected indicating that the industry is running faster than the standards. Few examples are the Winter Olympics in South Korea in 2018 and Olympics in Tokyo-Japan in 2020, where all the communications are expected to run over 5G.

A lot of work has been done in previous 3GPP Releases to optimize and enable LTE for a smooth transition to 5G to cover use cases for three major verticals:

- eMBB (enhanced Mobile BroadBand)
- mMTC (massive Machine Type Communications)
- URLLC (Ultra-Reliable and Low Latency Communications)

And indeed, the majority of all these applications claimed to be 5G, will continue to run over evolved LTE infrastructures and devices that progressively will adhere to the new standards and requirements.

Release 15 and Release 16 will define the Phase One and Phase Two, respectively, for the normative on Next Generation architecture. Phase One, Release 15, will focus on the 5G New Radio (5G NR) requirements to address the more urgent subset of the commercial needs. The 5G NR design should be forward compatible in order to guarantee that additional features can be added transparently in later releases. In the 3GPP Technical Specifications Groups (TSG) #72, the 5G NR was defined to support two operational modes, Standalone and Non-Standalone that will have to coexists. The two operation modes enable the radio according to the following definition:

- Non-Standalone (NSA) 5G NR will utilize the existing LTE control plane as an anchor, therefore its existing radio and core network to manage all the mobility management functionalities as well as coverage, and where the new 5G carrier will be added on top.

- Standalone (SA) 5G NR will use instead the full control plane capability for 5G NR within the new 5G core network architecture under definition in the 3GPP standards [7].

Despite that the two operation modes in the original study should have had to coexist from the beginning, in March 2017 there was a common consensus in the 3GPP to pull ahead of 6 months (to March 2018) the completion for the NSA and prioritize it with respect to the SA solution. The workplan is illustrated in Figure 6 and it also highlights its focus on eMBB development.
This change from the original plans indicates that standards have strong intention to catch up and re-align with the industry that have announced eMBB applications based upon the NSA solutions and, in turn, allowing longer life to LTE to maximize investments for the other use cases. There will definitely be catalysts to accelerate the evolution to 5G beyond the eMBB and especially in the URLLC and Mission Critical use cases where the target for user plane latency should be down to 0.5ms for UL and 0.5ms for DL (and for eMBB would be 4ms for UL and 4ms for DL), as autonomous vehicle, vehicle-to-vehicle communications, use of drones or robotics, and remote surgery, just to name few, [7]. As well, in the longer period mMTC use cases will need to address challenges for continuous and ubiquitous coverage in urban areas with very high connection density of MTC devices, longer battery life beyond 15 years and lower device cost. Networks would evolve toward much more flexible and distributed elements where a very large number of Small Cells will be working in combination with macro sites and smaller base stations resulting in a system composed of heterogeneous network (HetNet). 5G will therefore be the technology that empowers the shift from the hardware-based architecture to software-based initiatives, such as Network Functions Virtualization (NFV) and Software Defined Networking (SDN) where the elements of the network are hosted in virtual environments to provide the higher degree of flexibility, adaptability and where Network Slicing protocols will directed the traffic to the best service functions according to the specific business case applied at any given time. Automated cloud networks and Mobile Edge Computing techniques (MEC) will further bring those innovations to the network that make possible to deliver both low-latency solutions for performance-critical applications and guarantee robustness at the edge of the radio access network, therefore closer to the end user, where the computing power will be transferred according to specific customers’ needs.

The spectrum available is also a hot topic of discussion between industry and regulators that will have to come to an agreement to facilitate the deployment of 5G use cases in the 3 classes of main opportunities that are in the frequencies of 700MHz for extended coverage, 3.5GHz (from 3.4 to 3.8Ghz) for capacity and cost, and 28GHz (form 26 to 28GHz), in the millimeter-wave, for ultra-capacity.
What Release 16 will include is not detailed yet. It will very likely go on the same path of Release 15 to include additional studies, use cases and requirements to enhance the 5G technology and generate massive business opportunity for new sources of revenue streams and an economic growth, that is still to be completely uncovered.

Figure 7 shows the 3GPP roadmap for the 5G specifying milestones and work deliverable dates of the TSGs.
KEY TECHNOLOGIES IN DEPTH

As seen in the previous chapter, LTE has evolved quite consistently along its standards adding, release after release, new features that complete and enhance the telecommunication ecosystem broadly and in so many business ramifications as no other technologies ever before. Starting from its initial definition and architectural basis, LTE has become a more and more complete solution with LTE-Advanced, first, and then with LTE-Advanced-Pro, before ending up in the 5G era.

Figure 8 summarizes the key features and technologies developed for LTE and that will hand over into 5G in the next coming years in three major areas of use cases: eMBB, mMTC and URLLC:

Since Release 8, MBB has been the key driver for major studies and investments around LTE. The innovations that have contributed to reach higher and higher data rate have evolved at the same pace aggregating more and more carriers for a wider channel bandwidth across the widespread frequency spectrum (licensed and unlicensed) used by LTE, combining information density in higher modulation schemes and optimizing antenna technologies. While the MTC segment is currently centralizing the attention of the industry with new investments and efforts for an easily scalable and affordable system, this chapter will look at the eMBB segment evaluating pro and cons of each advancement that has boosted LTE to reach the Gigabit class, and highlighting the key drivers for their commercialization and deployment. In particular, the technologies and use case proposed will cover LTE carrier aggregation in unlicensed spectrum, MIMO Antenna techniques and Higher QAM Modulation schemes.

LTE Carrier Aggregation in Unlicensed Spectrum

Carrier aggregation was introduced in Release 10 to fulfill the industry’s requirement to increase the data speed over a LTE channel limited to a bandwidth of 20MHz. One of the methods to achieve the target of 16bps was to increment the channel bandwidth over the limits in a contiguous spectrum by adding more carrier components for an enlarged the data pipe. LTE-Advanced defined up to 5 carriers for a 100MHz bandwidth in DL, as illustrated in Figure 9. The same aggregation process with up to 5 components is also applied for the UL channels.
In CA, the user is by default served by a Primary Serving Cell (PSC), the anchor cell, that handles the main connectivity process. To the Primary Carrier Component (PCC), the network aggregates a number of additional Secondary Carrier Components (SCC) from the Secondary Serving Cells (SSC), all of them having different coverage. Figure 10 below illustrates this process highlighting the different coverage of the serving cells around a single user and therefore the need of a PSC to handle the main control signaling.

CA also addresses the limitation of the high fragmented LTE spectrum spread out across the licensed and unlicensed frequencies above 5GHz and enables MNOs with less than 20MHz channel bandwidth to be more competitive in the market. In addition, it increases capacity for typical network loads, that are generally filled with traffic in burst mode, as for smartphone applications or web browsing and mail messaging, by around ~50% reducing over-the-air latency [8]. The aggregation process across the wide spectrum, makes indeed LTE-Advanced a very flexible and scalable technology that has been the key successful factor of its wide and rapid diffusion across the world.
LTE-Advanced-Pro has gone to the next step aggregating to the anchor cell in the licensed spectrum, carrier components in the unlicensed spectrum above 5GHz. Therefore, with as little as 20MHz of licensed spectrum it is possible for MNOs to benefit of the bandwidth-rich unlicensed frequencies availability supplementing their spectrum holdings without the costs of a new spectrum license.

This includes techniques as LAA in the LTE domain (LTE-U was earlier introduced as proprietary solution and worked out in Release 12 limited to the North American market), and LWA and LWIP where the SCC is taken from the Wi-Fi technologies. This aggregation mechanism is described in Figure 11. The anchor PSC shall always sit in the licensed spectrum to guarantee higher degree of robustness for critical information and QoS. The SSCs in unlicensed spectrum are used to improve the data speeds for a better user experience as well as to boost network capacity. The upper part of the figure concerns the LTE aggregation in unlicensed spectrum, therefore LAA/LTE-U, the lower part of the figure instead considers the aggregation with Wi-Fi, therefore LWA and LWIP.

However, LAA/eLAA with Wi-Fi overlap in the 5GHz spectrum causing mutual interference and channel degradation. To guarantee effective and fair coexistence between Wi-Fi and all LAA networks deployed by different operators, 3GPP introduced the new features of LBT, Discontinuous Transmission, Dynamic Frequency Selection, Carrier Selection and Transmit Power Control. Those techniques check that the channel is free before transmitting evaluating the Energy Detection (ED) threshold with a given detection accuracy for which a channel is considered free, the Maximum Channel Occupancy Time (MCOT) to transmit, and Minimum Idle time before transmitting data [9]. In this way, LAA can meet consistently with the standards that mandate to not impact the Wi-Fi services (data, video and voice services) more than an additional Wi-Fi network on the same carrier (metrics could include throughput, latency, jitter etc.).
The other limitation for the use of frequencies in unlicensed spectrum is that the short wavelength for high frequency makes very difficult for the signal to reach indoor locations. There are use cases however, where aggregating licensed and unlicensed spectrum properly can be useful to boost indoor connectivity too, such as the case of Customer Premises Equipment (CPE) or for indoor Small Cells. These applications will be presented in the two use cases that follow.

**Use Case: Fixed-LTE CPE**

Fixed-LTE devices embedding LTE modems in routers and gateways are seeing a growing demand and their shipments in expected to increase in the coming years [10]. Currently Fixed-LTE CPEs are challenging the Fixed-line connectivity, typically FTTH (optical fibre), in those locations where it is limited, or poor, or where investment costs to deploy becomes too expensive. In the future, it is expected that Fixed-LTE can become the mainstream of the connectivity being more and more reliable and providing comparable speed with FTTH systems [11].

LAA and eLAA can help to boost the LTE connectivity even further adding free unlicensed spectrum to an anchor LTE that continues to guarantee security, reliability and QoS. However, as seen earlier, unlicensed frequencies above 5GHz will not penetrate in indoor location. Therefore, the CPE design shall be re-defined by placing the Antenna (or, to some extent, the entire device) in outdoor location and cabling the signal to the indoor Wi-Fi Access Point offering a perfect solution for offloading data to the end-user. The two systems in fact, unlicensed LTE and Wi-Fi, do not share the 5GHz band and therefore do not conflict each other while co-work completely independently serving different scopes. LAA becomes a real boost to the enhanced LTE connectivity in a much bigger data pipe with carriers in a spectrum that is free of charge.

Figure 12 shows as LTE carriers in the licensed and unlicensed spectrum are cabled to the CPE from an outdoor antenna. The aggregated LTE data pipe is then off-loaded through Wi-Fi access point. CPE can really benefit from this architecture and enhance the Fixed-LTE proposition to offer much higher data stream over the Gigabit class of devices becoming the first step into the 5G ecosystem and, at the same time, seriously challenge the Fixed-line technologies as the mean to bring indoor connectivity.
Use Case: Small Cells

LTE and Wi-Fi (generally WLAN) can also work together in combined mode while enabling link aggregation of the two technologies to increase throughput. This is another use case where instead of a conflict there is a boost for the end-user data speed that gets data from the combination of the two rather than either or the other in a coexistence environment using mitigation techniques as LBT.

LTE continues be the anchor cell in licensed spectrum and therefore used as reliable technology for control and mobility management to secure QoS. WLAN is opportunistic unlicensed component used to increase the data rate. There are two different available options for integrating LTE and WLAN according where the aggregation is actually executed, those are:

- LTE-WLAN Aggregation [LWA]
- LTE WLAN Radio Level Integration with IPsec Tunnel [LWIP]

In LWA the aggregation of LTE and WLAN happens at RAN level. The packets are sent independently using the two technologies over split and switched bearers and are then reassembled by the Packet Data Convergence Protocol (PDCP) layer in the user equipment making the aggregation transparent to the upper layers. LWA is controlled by E-UTRAN NodeB (eNodeB), based on User Equipment (UE) measurement reporting, and supports two deployment scenarios [12]:

- Collocated: when LTE Small Cell (or more generic eNodeB) and WLAN Access Points coexists
- Non-collocated: where the eNodeB and WLAN Access Point are connected via a new standardized interface, Xw, that supports control and data plane, this can be the case of MNO partners with a WLAN operator.

LWIP is the other method to aggregate LTE with WLAN. It has been specifically architected to be able to leverage and be transparent to the legacy WLAN infrastructure enabling faster time to market. In LWIP, an IPsec tunnel is used to transmit DL traffic from the LTE Small Cell eNodeB to the UE through the WLAN Access Point in a secure manner.

The key advantage of LWIP with respect to LWA, that requires an additional interface (Xw) for security and flow control capabilities, is its full backward compatibility with any legacy WLAN. In addition, LWIP also enhances the uplink performance through IP layer switching to aggregate LTE and WLAN uplinks channels. On the drawback side, both the eNodeB and the UE need to be upgraded to the new architecture: the UE must support the dual connectivity mechanism to combine the data streams with PDCP aggregation; the eNodeB may need to host the Security Gateway LPIW-SecGW that is a new component that completes the IPsec tunnel from the UE to the eNodeB across the WLAN Access Point.
LWA and LWIP aggregating technologies are illustrated in Figure 13. For LWA the orange part is the additional interface component that shall be supported in case of non-collocated LTE/WLAN access points.

These two technologies LWA and LWIP apply to the world of the smartphones in which the devices are able to receive both LTE and Wi-Fi signals and combine them together.

### Antenna Techniques, MIMO

3GPP introduced MIMO as basis technology of LTE to increase the overall bitrate and achieve better cell coverage through transmission of two (or more) different data streams on two (or more) different antennas. This technique is quite important because it allows to reach high performances simply by using the same resources in both frequency and time that are separated only by their different reference signals, and therefore without increasing the average transmit power or frequency bandwidth.

MIMO has been part of LTE from its very first origins in Release 8 to support multiple layers, or multiple transmitting antennas, for DL per UE. It can work in two different configurations, MU-MIMO (Multiple User MIMO) and Single User (SU-MIMO). In MU-MIMO the allocation of different spatial layers can serve different users in the same time-frequency resource in both DL and UL, where the UL is limited to a single layer per UE. In Single User (SU-MIMO), the multiple spatial layers are all allocated to a given UE and it can use beamforming techniques to improve the signal strength and achieve higher bitrates to a single client. Release 8 defined a configuration with up to 4 layers in transmission in DL that was extended to up to 8 layers in Release 10. SU-MIMO was enhanced in LTE advanced Release 10 to support up to 4 transmission-streams in UL.

MU-MIMO and SU-MIMO techniques are illustrated in Figure 14 for 4 layers, therefore respectively 4 transmission stream to 4 different users for MU-MIMO, left, and 4 layers to a single user for SU-MIMO, right.
In LTE-Advanced-Pro, 3GPP has started to leverage on the usage of more antenna arrays to increase the link spectral efficiency of the LTE system with Massive-MIMO (M-MIMO) that allowed up to theoretical 64 antenna ports at eNodeB. The higher-order MIMO system, over 8 layers, allows Full Dimension-MIMO (FD-MIMO) that will become extremely relevant in higher frequencies, over 3.5GHz, in the future. As illustrated in Figure 15, FD-MIMO enables a multi-user beam forming system in both horizontal and vertical direction generating a 3 Dimensional (3D) spatial link for progressive capacity enhancement in hotspot area.

In addition, Release 13 has also introduced enhancements on MU-MIMO by using the relevant reference signals and Channel State Indication (CSI) reporting mechanism as an indicator to evaluate the channel quality [13].
In Release 15 the target is to achieve even higher-order for Massive MIMO antenna system to support up to 256 antenna elements and new features like hybrid beamforming to combine analog beamformers in the Radio Frequency domain with digital beamforming, and distributed MIMO across different antenna ports from different mobile stations to a single user.

**Higher-Order Modulations Schemes**

To improve spectrum efficiency, Release 12 increased the modulation scheme in DL to a higher order, from the previous 64QAM to 256QAM, an advance in signal modulation that encodes 8 bits in a single symbol. This bit expansion provides 33% increase in bandwidth efficiency allowing to transmit around 100Mbps in a 20MHz channel instead of the 75Mbps available with 64QAM modulation, that encodes 6 bits in each symbol. The lower modulation of 16QAM, encodes 4 bits in each symbol. These encoding schemes are shown in Figure 16 that also reports efficiency improvements moving towards the higher modulation. Uplink channels are limited to 64QAM.

![Figure 16 - Modulation Schemes and Channel Efficiency Progression](image)

256QAM was a very important step forward to the 1Gigabit class devices that could be achieved when aggregating 5 carriers of 20MHz channels bandwidth in a 2x2 MIMO configuration that, in actual fact, allows to carry 200Mbps per each carrier.

There are advantages and disadvantage in higher modulation schemes. The faster data rate and higher levels of spectral efficiency comes, in fact, at the expense of channel fidelity requirements. Higher modulation schemes require, in fact, a robust channel with high SNR (Signal to Noise Ratio) and high sensitivity with respect to impairments (as signal interference and phase noise) to contain bit error rates and avoid retransmission that will slower the data throughput [14]. That makes that higher order should be used in good signal condition to boost data throughput, while lower order are the preferable solutions in high noise conditions or low lever signal, for example at the cell edge, to sustains a more reliable link with fewer data errors and retransmission.
TELIT PORTFOLIO

As seen in earlier chapters, LTE now and 5G tomorrow offer a wide range of business opportunities in three major areas of development, enhanced Mobile Broadband, Ultra Reliable Mission Critical applications and Massive MTC.

Telit has been developing for years its proposition along the MTC industry gaining a leadership position in the Machine-to-Machine (M2M) communications and Internet-of-Things (IoT) ecosystem. In a time where the technological evolution is increasing in scale and complexity as never before, Telit is expanding its portfolio to offer multiple connectivity options empowering both the NB-IoT and lower LTE Categories for MTC technologies, as Cat. 1 and Cat. M, and therefore to enable new applications and use cases for low data-rates, ultra-low power, reduced complexity and cost, that are gaining momentum on the wave of the 5G era.

Figure 17 shows the evolutionary roadmap that Telit is undertaking towards the technologies for mMTC use cases. Telit has been pioneering LTE for M2M applications and is working now in the leading-edge solutions to maintain its competitive advantage in know-how and quality products.

As well, Telit is also targeting the eMBB segment looking at solutions based on the latest standard technologies. Hereby, in the past few years Telit has established closed relationships with the most advanced chipset makers to introduce in its portfolio high speed modems on different form factors for different market verticals, as for M.2, miniPCIe and, more recently, LGA. Telit is now present in the market with solutions for Mobile Computing and the Routers and Gateways covering laptop and tablets as well as Fixed-LTE CPEs for residential and industrial routers, as reported in Figure 18.
While the market for Mobile Computing is getting to a stable and steady number of shipment of devices, though consistent and around 4 million unit in 2020, the CPE market is instead expected to growth reaching around 25 million units in 2025, almost doubling the figures for 2017 [10]. The two trends are shown in Figure 19 where it is appreciated the stable shipment for the Mobile Computing, the left graph, and the continuous incremental growth for the Fixed-LTE CPEs on the right.

Leveraging on the widely deployed LTE Network, Fixed-LTE CPEs are currently shipped in areas where the wired line is too expensive to deploy like developing countries and rural areas. However, in the years to come and with the increasing robustness of the cellular solution, as well as the much higher data speed that eMBB will reach with 5G, CSPs will become more and more agnostic about the medium used to stream data. Very likely MNOs will offer new data plans that have competitive advantages even in urban areas respect FTTH system still far more expensive both in term of cost and time to deploy and maintain [11].

Figure 18 - eMBB Solutions for the Routers and Gateway and Mobile Computing Market Segments.
In this scenario, Telit will augment its portfolio with new products that constantly aligns with the latest technologies that the market requests, not just to reach data speed in the Gigabit class of LTE devices but foremost to pave the basis for the 5G products to serve a wide variety of use cases. The new products will implement some of the key LTE features like MIMO 4x4 on multiple CA that is gaining momentum among MNOs, LAA/eLAA to take advantage of both the 5GHz unlicensed spectrum and new spectrum opportunities in the 3.5GHz band (e.g. B42, B43 and CBRS), eMBMS to enhance the modem proposition towards new market segments targeting video streaming, VoLTE for voice based devices, and more to come.

CONCLUSIONS

Since its early definition in 2008 in Release 8, LTE has evolved towards two main directions. One toward the eMBB for higher data rate throughout, and the other to the integration with the new evolving paradigm of the IoT defining devices for lower power consumption, reduced complexity and cheaper BOM costs.

This continuous evolution not only has enabled incremental performance enhancements, but also it has allowed to go behind the traditional cellular ecosystem generating a variety of new applications in different verticals both for high data speed devices, such as entertainment, video streaming context augmented and virtual reality etc., and for the mMTC segment, like road traffic control, public transport monitoring, public safety, smart cities, robotics, health, metering and so on.

Even if Release 14 closes the LTE standards, the limit for its evolution are far to be frozen and will continue to enhance with features and improvements that will be smoothly assimilated and embedded into the new 5G ecosystem. The 3GPP target set for 5G commercial products to be in 2020 may not represent a real disruption in the market rather than just a smooth transition of technologies that will start to be more and more integrated into a single huge ecosystem. LTE will still have long live and will still provide answers to a very large number of use cases that the market can think of, and that have a real commercial scope. The GSMA has recently disclosed that 85% of the new use cases can still be covered by LTE while for only 15% of them 5G is really needed. LTE will Therefore continue to develop towards new frontiers.

MNOs are progressively upgrading their existing networks by adopting multiple-carrier LTE-Advanced and LTE-Advanced-Pro technologies that allow considerable progress in increasing the data speeds. These advancements will create opportunities to monetize the investment on LTE with new earlier adopted services in the context of 5G, long before 5G becomes a commercial reality. In turn, 5G technologies, such as Network Slicing, Automated Networks, Large Scale Array (LSA) Antennas, will generate flexible, programmable (NFV and SDN), cloud-native and MEC networks that are optimally configured and distributed enabling agility and cost efficiency. This high degree of optimization and efficiency can be capitalized in a myriad of use cases for new verticals and commercial applications for 5G use cases from eMBB to mMTC and URLLC. While previous generation of mobile networks were based on the idea where the technology comes first and use cases come afterwards, for 5G it happens the opposite. Starting from the use cases the market players should now build the technologies to address them. This is a revolutionary technological concept that gives an open check to the industry that can continue to enable loads of new use cases, many of them that are yet to be defined. Which, in turn, means that new technologies, yet unknown, would be developed to address those specific
business needs, in a vicious circle. The real 5G disruption comes as a customer centric concept where it is possible to create new business opportunities leveraging on legacy technologies and add new value for the customer and the global economy.

Overall, the message for the telecommunication industry is clear. The priority is to build up all the infrastructures and frameworks for what we need for the present and for what is expected for use in the future. This is 5G, a massive business opportunity for new sources of revenue stream and an economic growth that is still to be completely uncovered, and where the major stakeholders in the telecommunication ecosystem should stay aligned with the latest technology if they want to benefit from the economy of scale. In this context, Telit is leveraging on its strong background, know-how and experience in the M2M market to take leadership position both in the IoT and in the eMBB markets with a compelling portfolio that is already introducing the leading-edge technologies and latest standards.

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