THE LTE STANDARD

Developed by a global community to support paired and unpaired spectrum deployments

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Signals Research Group conducted a comprehensive review of the 3GPP standardization process and the underlying specifications that define LTE. The analysis sought to identify and quantify the similarities and differences within the overarching LTE specification documents as they pertain to the implementation requirements for specific frequency bands, with a particular focus on paired (FDD) and unpaired (TDD) spectrum. This whitepaper provides the findings from that study, including the results from our review of nearly 83,000 3GPP submissions, which demonstrate that the overwhelming majority of submissions occurring during a six-year period apply to both LTE duplex schemes and that companies from all over the globe supported and contributed to the modest number of submissions which were more specific to LTE operating in paired or unpaired spectrum.

As the sole authors of this paper, we stand fully behind the analyses and opinions that are presented in this paper. In addition to providing consulting services on wireless-related topics, Signals Research Group is the publisher of the *Signals Ahead* research newsletter.

1.0 Executive Summary

Signals Research Group (SRG) conducted an exhaustive analysis of the 3GPP standardization process that led to the development of LTE, and we reviewed all of the primary specifications that define the LTE standard. There is a misconception among some of the industry followers that LTE systems configured to operate in unpaired (LTE TDD) or paired (LTE FDD) spectrum have different origins, different technical characteristics, and different prominent contributors in the 3GPP standardization process.

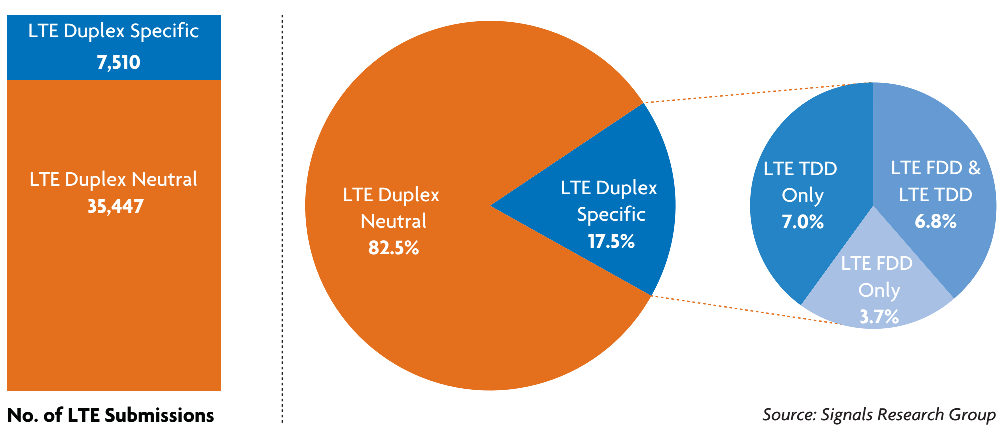
LTE is one standard developed by organizations from all over the world.

The objective of the whitepaper is to correct this misconception and establish that LTE is one standard developed by organizations from all over the world. It is truly a global standard, having been designed to operate in both paired and unpaired spectrum bands with a minimum amount of additional complexity. In this whitepaper we use LTE TDD to refer to the unpaired mode of LTE since this is the term used within the 3GPP standards body. However, TD-LTE is also commonly used instead of LTE TDD.

A further objective is to identify and quantify the similarities and differences between LTE as specified for use on paired spectrum, in which the downlink and uplink communications use different channels, and LTE as specified for use in unpaired spectrum, in which the downlink and uplink communications share a common radio channel and divide time. Based on this study, which included categorizing nearly 83,000 submissions that were submitted to the 3GPP over a six-year period (April 2005 through February 2011), we offer the following observations:

The overwhelming majority of 3GPP submissions for LTE are duplex scheme agnostic, meaning that they apply equally to both duplexing options. We identified 42,957 submissions out of 82,657 total that pertain to the development of the LTE standard. Of these submission documents, 82.5% of them do not distinguish in any way between the two duplex modes, meaning that only 17.5% of all LTE submissions contain duplex-specific language. Taking it one step further, we classified only 7.0% of the documents as pertaining to LTE TDD and 3.7% of the documents as relating specifically to LTE FDD. An additional 6.8% of the documents discuss both duplex schemes. We included all of these documents even though the language in the documents could merely state that the recommendation applies equally to both duplex schemes. A subjective review of these documents would have identified these occurrences and resulted in a lower percentage versus our all-inclusive approach which inevitably includes "false positives" in the results. Net-Net: The actual number of submissions that identify duplex-specific features and recommendations accounts for as few as 10.7% and no more than 17.5% of all submissions pertaining to LTE.

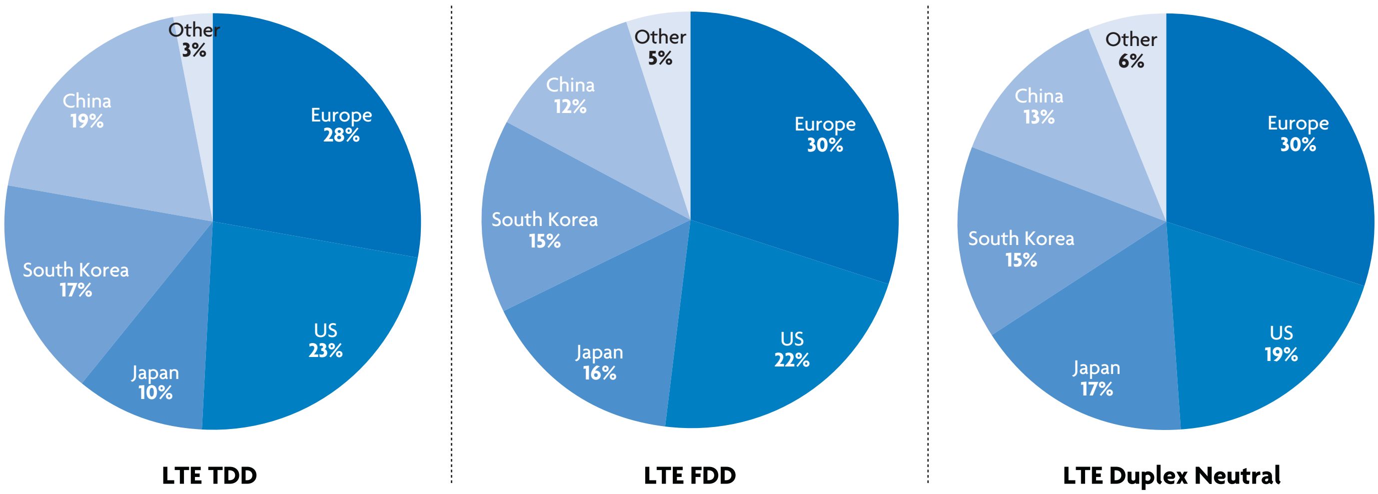
Distribution of 3GPP Submissions by Duplex Scheme



Source: Signals Research Group

We identified at least 104 companies that submitted contributions to the 3GPP standardization process during the timeframe of the review. Of these companies, 58 companies made contributions that specifically address LTE TDD and 52 companies made contributions that specifically address LTE FDD. Further, no single country or region can claim it had more influence during the standardization process.

Country/Regional Distribution of Submissions to the 3GPP RAN Working Groups



Source: Signals Research Group

Europe was the largest contributor with 28% of all LTE TDD submissions coming from the region. Other large contributors included the United States (23%), China (19%), South Korea (17%) and Japan (10%). Relative to the total number of contributions, each country's/region's contributions to LTE TDD was between 4.1% and 9.1% of its total LTE contributions and for LTE FDD the range was between 3.5% and 4.2%.

There is a very high degree of commonality in the technical specifications (TS) between the FDD and TDD modes of LTE. Based on our review of eight TS documents which define the majority of the LTE radio access network (RAN) as well as other pertinent specifications and publications, it is very apparent that the overwhelming majority of the specifications are duplex agnostic, meaning that they apply equally to both duplex schemes. While perhaps self-evident to most industry followers, LTE FDD and LTE TDD share a common core network with absolutely no distinction between the two duplexing modes of LTE.

LTE FDD and LTE TDD are virtually identical with the exception of a few technical characteristics that are specific to the Physical Layer.

LTE FDD and LTE TDD are virtually identical with the exception of a few technical characteristics that are specific to the Physical Layer. Examples where the two LTE modes are largely identical include the downlink physical layer channels, the use of resource blocks, the mapping of control channels to resource elements, the channel coding, the scrambling of each code word, the modulation types and how they work, and the basic implementations of MIMO. In the uplink, areas with large commonalities include the use of SC-FDMA, control channels (PUCCH), modulation schemes, channel coding, how resource elements are mapped in the frequency and time domain, and PRACH (Physical Random Access Channel), which defines the Physical Layer channel that carries attempts by the mobile device to access the system, including responses to paging messages and requests to transmit data. For both duplex schemes, the Medium Access Control (MAC) Layer is identical, with one minor distinction, the RLC (Radio Link Control) Layer is identical, and the Radio Resource Control (RRC) Layer is essentially identical, with some distinction regarding when a couple of messages can be sent.

Differences between the FDD and TDD modes primarily pertain to when an action or event is done and not to why or how something is executed.

There are some differences between the LTE FDD and LTE TDD modes that we identified, but these differences primarily pertain to when an action or event is done and not to why or how something is executed. The differences associated with when something is done stem from the discontinuous downlink/uplink transmissions that are an inherent part of any TDD duplex scheme. In a similar fashion there are also differences, or what are perhaps better classified as options/configurations, within each duplex scheme. These unique configurations allow LTE to be deployed in 34 different frequency bands – 23 LTE FDD and 11 LTE TDD – support six potential channel bandwidths, and seven possible downlink/uplink configurations for LTE TDD.

A global contingent of operators and vendors harmonized LTE TDD on a single frame structure, even though it removed some commonality with earlier time-division-duplexing-based 3GPP 3G standards. During the early development stages of LTE, LTE TDD had two frame structure options, including one frame structure that was very similar to the frame structure used by TD-SCDMA (or LCR TDD, as it is referred to in the 3GPP specifications). Other than this distinction, LTE TDD had little, if anything, in common with earlier time-division-duplexing-based 3GPP 3G standards. Following the initial recommendations by China Mobile, Vodafone Group, and Verizon Wireless, the 3GPP RAN Working Group agreed to *"a single optimized TDD mode, based on Frame Structure 2, further optimizing performance and ensuring ease of implementation of FDD and TDD modes within the same E-UTRA equipment."*

Following this decision within 3GPP the LTE specifications no longer support a relationship that previously existed with LCR TDD. Further, this action was consistent with an earlier recommendation from Vodafone Group, T-Mobile International, TeliaSonera, and Telefonica that: *"Unnecessary fragmentation of technologies for paired and unpaired band operation shall be avoided. This shall be achieved with minimal complexity."* Operators recognized that the pitfalls associated with the large discontinuity between how the 3G (UMTS) specifications defined FDD and TDD modes resulted in the unsuccessful market adoption of a global 3G solution for their unpaired spectrum.

A recent IEEE paper[1] from engineers at Datang Telecom further reinforces this approach. The papers states, *"…during the process of developing LTE and LTE-Advanced specifications, the maximum commonality between TDD and FDD has been emphasized in the Third Generation Partnership Project (3GPP), and realized by achieving a good balance between the commonality of basic structures and optimization of individual characteristics."*

1 Technical Innovations Promoting Standard Evolution: From TD-SCDMA to TD-LTE and Beyond, Shanzhi Chen, Yingmin Wang, Weiguo Ma, and Jun Chen, State Laboratory of Wireless Mobile Communications, China Academy of Telecommunications Technology, IEEE Wireless Communications, February 2012

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2.0 Introduction

According to our latest count, LTE was deployed in approximately 20 different frequency bands around the world and using five of the six potential channel bandwidth options that are defined in the LTE specifications. Most of the deployments involved the use of paired spectrum with a dedicated radio channel for the downlink communications between the eNodeB (LTE base station) and the mobile device, and a dedicated radio channel for the uplink communications. According to the GSA (Global mobile Suppliers Association) there were also 21 deployments of LTE in unpaired spectrum, in which the downlink and uplink communications share a common radio channel and divide time.

Although there hasn't been a lot of distinction in the popular press about one operator using a 20 MHz radio channel and another operator using a 10 MHz radio channel, there has been more than idle curiosity paid to the existing or anticipated deployments of LTE TDD networks. The curiosity in LTE TDD is somewhat warranted because these deployments will reinforce the global adoption of LTE as the standard of choice and they will result in far greater utilization of certain spectrum resources that previously were sitting fallow. The spotlight that sometimes gets cast on LTE TDD has also created some confusion in the market since there is a belief that LTE TDD is somehow much different than LTE FDD and that LTE TDD had its genesis in earlier time-division-duplexing-based 3GPP 3G standards.

At the request of Ericsson and Qualcomm, Signals Research Group (SRG) conducted an exhaustive analysis of the 3GPP standardization process that led to the development of LTE, and we reviewed all of the primary specifications that define the LTE standard. As an organization, SRG has a long history and a specialized focus on technology-related matters, not to mention more than a passing interest in the work taking place within the 3GPP standards body. Therefore, we were well-suited for the actions and skill sets required for this study.

It is quite possible that a large number of operators will support a mix of LTE FDD and LTE TDD in their networks.

Over an extended period of time it is quite possible that a large number of operators around the globe will support a mix of LTE FDD and LTE TDD in their networks. For most of these operators, LTE TDD provides an additional capacity layer that will be used to offload mobile data traffic from their more widely-deployed LTE FDD networks. Regardless of the exact mix of LTE deployment configurations, including frequency, channel bandwidth and duplex scheme options, the findings from our study demonstrate that all of these configurations stem from a common set of LTE specifications.

This whitepaper documents the findings from our study of the decision-making process within 3GPP that led to the LTE standard, an analysis of approximately 84,000 3GPP submissions, and a review of the primary LTE specifications.

Chapter 3 contains a technical analysis of the LTE specifications. It includes insight into the original criteria that defined the LTE performance requirements, including support for paired and unpaired spectrum. Chapter 3 also discusses the dual emphasis within 3GPP on the need to support a wide range of deployment options with only a minimal number of differences in how each option is implemented. Finally, the chapter concludes with an analysis of the similarities and differences between the two duplexing options, as defined in the primary specifications that define the LTE standard.

Chapter 4 provides the results of our analysis of approximately 84,000 3GPP submissions. The chapter begins by providing the methodology that we used to analyze the documents and the highly-objective criteria that we used to classify each submission so that we could quantify the number of submissions that only pertained to a specific duplex scheme. Finally, Chapter 4 concludes by providing a series of figures and tables, along with our commentary, that reveal the vast majority of the submissions were duplex scheme agnostic and that a large contingent of operators and vendors from around the globe were responsible for endorsing and developing the common and duplex specific parts of LTE.

3.0 The LTE Specifications and the Commonality between Duplex Schemes

This chapter begins by providing a brief history lesson of the work and rationale within 3GPP that ultimately led to the current LTE standard. It is followed by our analysis of the current LTE Release 8 specifications, which identifies the similarities and differences in the implementation of LTE pertaining to the choice of frequency band and the use of paired or unpaired spectrum.

3.1 Following the Development of LTE Release 8

The first discussions regarding the development of a new radio interface to follow the planned enhancements of HSPA began back in November 2004 within the 3GPP organization. Since the beginning, a global contingent of operators and vendors recognized the need for a common set of specifications that would achieve the performance criteria and which would also provide enough flexibility to support the widely diverse spectrum and technology migration strategies of operators all over the world.

As noted in one of the very first submissions,[2] the E-UTRA (Evolved UMTS Terrestrial Radio Access) requirements included, but were not limited to the following:

- Significantly increased peak data rates
- Increased cell edge bit rates
- Significantly improved spectrum efficiency
- Radio Access Network latency below 10 ms
- Scalable bandwidth "1.25, 2.5, 5, 10, 15 and 20 MHz bandwidth are required"[3]
- Operation in paired and unpaired spectrum

The last two requirements are particularly important because they demonstrate the operators and vendors recognized from the start that in order for LTE to become a truly global standard, it would need to satisfy the requirements of all operators who would be migrating to the technology from a different starting point – different technologies, different frequencies and different amounts of paired and unpaired spectrum resources.

3.1.1 Support for Paired and Unpaired Spectrum

There was universal recognition from the start that LTE must operate in both paired and unpaired spectrum.

As with the need for scalable bandwidths, there was universal recognition from the start that LTE must operate in both paired and unpaired spectrum. In the very early days of the LTE standardization process most of the discussion within 3GPP focused on the choice of modulation and access schemes that would most effectively and efficiently achieve the requirements of the new standard, while introducing the least amount of complexity. Throughout this entire process there was very little distinction in the 3GPP submissions between the two duplex schemes that were previously included as part of the scope of the study item during the initial RAN Plenary Working Group meeting. Instead, the discussion focused on the best combination of modulation

2 RP-050155, "Agreed Text Proposals for the Requirement TR," 3GPP RAN Rapporteur, March 2005

3 1.25 MHz was later changed to 1.4 MHz to include guard bands and to help with emissions. The current specification defines 1.4, 3, 5, 10, 15, and 20 MHz allocations.

and access schemes for the downlink direction and for the uplink direction, irrespective of the duplex scheme.

Ultimately, the 3GPP RAN Working Group 1 selected OFDM/OFDMA for the downlink and OFDM/SC-FDMA for the uplink. The 3GPP felt SC-FDMA (Single Carrier – Frequency Division Multiple Access) would be more efficient in the uplink due to limitations in the mobile device and its ability to mitigate the high peak to average power ratios (PAPR) that are an inherent characteristic of OFDMA.

The initial flexibility and uncertainty pertaining to how each concept supported paired or unpaired spectrum did not go unnoticed by the operator community.

Just as there were multiple concept proposals (e.g., OFDMA, MC-WCDMA, MC-TD-SCDMA) for how to address the E-UTRA requirements, at the time there was also a fair amount of flexibility and uncertainty pertaining to how each proposed concept or technical feature supported paired or unpaired spectrum. This initial flexibility and uncertainty did not go unnoticed by the operator community. In its submission,[4] Vodafone Group, T-Mobile International, TeliaSonera and Telefonica stated the following:

> *"Unnecessary fragmentation of technologies for paired and unpaired band operation shall be avoided. This shall be achieved with minimal complexity.…*
>
> *"In case both TDD and FDD are used in E-UTRA the differences in the physical layer should be kept to the absolute minimum necessary, it should be investigated during the study item how this can be achieved."*

The operators concluded their submission with the following recommendation, that reads, in part,

> *"Our current assumption is that one single technology should be developed to support the deployment of E-UTRA in both paired and unpaired spectrum. In other words in the case both FDD and TDD would be required, the difference in the specifications should be the minimum necessary for the support of the different frequency arrangements."*

Operators expressed concerns that they didn't want the material differences that exist between the paired and unpaired implementations of UTRA to continue with E-UTRA.

The operators' concerns weren't without good justification. As the operators mentioned in their submission, there are large differences between the paired and unpaired implementations of UMTS. These material differences made it virtually impossible, or at least highly impractical, for them to use their unpaired spectrum that many of them licensed during the 3G spectrum auctions that took place toward the beginning of the last decade. The technical requirements for the TDD variant of UMTS were well-defined within 3GPP, but because of their dissimilarity with the more widely deployed FDD requirements, the UMTS TDD ecosystem never developed and to date most operators have not done much to use their unpaired 3G spectrum.

Given the limited spectrum resources and the realization that future spectrum allocations would consist of a greater mix of unpaired spectrum, operators recognized that it didn't make sense to develop "different technologies" for paired and unpaired spectrum. Worth pointing out, in our analysis of the 3GPP submissions and in our review of all of the RAN Working Group meeting notes, the dissimilarity in how paired and unpaired modes of UTRA and E-UTRA were treated is clearly evident. With UTRA (e.g., UMTS/HSPA+), the TDD modes were treated as separate agenda items within each RAN Working Group meeting and there were a large number of contributions that were specific to the TDD mode. We note that with UTRA there are actually two distinct and quite different TDD modes: LCR-TDD (Low Chip Rate – TDD) refers to

4 R1-050731, "Support of operation in paired and unpaired spectrum," Vodafone Group, T-Mobile International, TeliaSonera, Telefonica, RAN WG1 Meeting #42, September 2005

TD-SCDMA and operates in 1.6 MHz of unpaired spectrum. HCR-TDD (High Chip Rate – TDD) specifies the implementation that was originally targeting 5 MHz and 10 MHz unpaired spectrum. Moreover, there were separate technical specifications for TDD and FDD in UTRA.

With E-UTRA, there was very little individual attention paid and very few individual meeting agenda items identified that were specific to one of the two modes of LTE.

With E-UTRA, there was very little individual attention paid and very few individual meeting agenda items identified that were specific to one of the two modes of LTE. There were, however, individual submissions that may apply to a specific duplex scheme. Further, as required by the 3GPP Working Group, if a feature is not common to LTE FDD and LTE TDD then it must be clearly expressed and justification provided. This requirement simplified our review of the 3GPP specifications and it helps validate the conclusions that we reach. Our analysis of the 3GPP submissions in the next chapter focused on identifying those submissions/contributions which are specific to either the TDD mode or the FDD mode of LTE instead of applying to the overarching LTE standard, which encompasses both duplexing schemes.

At the RAN Plenary #37, which took place in September 2007, a crucial change to the LTE specification began to unfold, and this proposed change eventually resulted in the very high commonality between the FDD and TDD modes of LTE. Prior to the September RAN Plenary, 3GPP was working toward two different frame structures for the TDD implementation – namely Frame Structure 1 and Frame Structure 2. As discussed in a subsequent section the frame structure defines the basic physical layer of the air interface and how information (e.g., data and control channel information) are grouped together.

The rationale for the additional frame structure was that it was needed to support a smooth migration from LCR-TDD (TD-SCDMA) to LTE in unpaired spectrum. However, as three noteworthy contributors to the submission,[5] namely China Mobile, Vodafone Group, and Verizon Wireless, rightfully pointed out, *"the LTE specification should be simplified and the number of deployment options reduced in order to have a competitive LTE system."* The operators also cited three specific benefits associated with the proposed single TDD frame structure.

- Reduced LTE system and specification complexity, including reduced test complexity and the elimination of the potential need for a mobile device to support two unique TDD modes (e.g., for roaming);
- Speeding up the LTE specification process and allowing the specifications to become stable much faster; and
- Simplifying the product development discussions to "remove any confusion in product development as to the basic physical layer design that should be considered for LTE TDD mode.

This submission was followed by a second proposal,[6] submitted by a who's who of vendors and operators from around the globe to consolidate on,

> *"A single optimized TDD mode, based on Frame Structure 2, further optimizing performance and ensuring ease of implementation of FDD and TDD modes within the same E-UTRA equipment."*

5 RP-070750, "A proposal for simplifying LTE TDD," China Mobile, Vodafone Group, Verizon Wireless, RAN Plenary Meeting #37, September 2007

6 RP-070750, "Way forward for simplifying LTE TDD," China Mobile, Vodafone Group, Verizon Wireless, Alcatel-Lucent, CATT, Ericsson, Huawei, Nokia, Nokia Siemens Networks, Nortel, Qualcomm, RITT, ZTE, RAN Plenary Meeting #37, September 2007

Ultimately, at the RAN Working Group 1 Meeting #51 held in November, the proposed changes were reflected in a change request (CR) to the 36.211 (E-UTRA; Physical channels and modulation) specification, and support for LTE in unpaired 1.6 and 3.2 MHz channels was removed. In Section 3.2, we explain the differences between the two remaining frame structures that are used to support LTE in paired and unpaired spectrum. However, from an historical perspective, this decision, which was endorsed by operators and vendors from around the globe, helped solidify the commonality between the paired and unpaired modes of LTE. Further, this decision removed some of the commonality in the basic frame structure that previously existed between LCR-TDD (TD-SCDMA) and LTE TDD.

3.1.2 Support for Different Channel Bandwidths

The requirement for scalable bandwidths was intended to help operators more easily migrate from narrowband technologies to LTE.

The requirement for scalable bandwidths was intended to help operators more easily migrate from narrowband technologies (e.g., GSM and CDMA2000) to LTE while also recognizing that wider bandwidth deployments of LTE would be required to achieve the target peak data rates. Ultimately, operators licensed, or would license, spectrum where they would, at least initially, be limited to narrowband deployments of LTE while also having spectrum where wider LTE radio channels could be used.

Operators on a global basis have already deployed 1.4, 5, 10, 15, and 20 MHz LTE networks.

This situation is evident today since operators on a global basis have already deployed 1.4, 5, 10, 15, and 20 MHz LTE networks. The 1.4 and 5 MHz deployments occur in the United States and Japan where operators have limited spectrum in a particular frequency band or market, and/or where operators are transitioning from a legacy technology, such as CDMA2000, and they need to retain much of the spectrum to support their existing subscribers. The wider channel deployments of LTE – 10 MHz and greater – occur in Europe, Asia, and North America with the 20 MHz deployments predominantly occurring in the higher frequencies, such as 2600 MHz, where more spectrum is inherently available. Several operators currently support the simultaneous use of different LTE channel bandwidths in their networks, either separated by frequency band or by geography.

As we discuss in a subsequent section, regardless of the channel bandwidth, the basic tenants of LTE remain unchanged. There are naturally adjustments that must be made to accommodate the allocation and mix of data and control channels for the different bandwidths, just as there are different performance requirements for each channel bandwidth. These frequency- and bandwidth-specific parameters were intentionally included from the start to give the LTE standard the flexibility that it needed. Conversely, the differences in the parameters are very modest so that they can be easily incorporated into an infrastructure vendor's or device/chipset supplier's solution.

With the appropriate selection of filters and other circuitry, operators are able to leverage the same exact solution to support different channel bandwidths.

In fact, with the appropriate selection of filters and other circuitry, operators are able to leverage the same exact solution to support different channel bandwidths. Case in point, our personal LTE smartphone operates in a 2 x 10 MHz channel in most cities in the United States, including where we live. However, when we visited the Windy City (Chicago) last year it automatically reverted to 2 x 5 MHz since at the time our operator had less spectrum resources for its initial LTE deployment in that market. The same eNodeB configuration was also used in both markets although minor tweaks to the RF components were required to the Chicago-based infrastructure when it was enabled to radiate across 10 MHz of contiguous spectrum. Despite these important differences that existed in the two markets, the same LTE standard applied.

3.1.3 Support for Different Frequency Bands

As previously indicated, LTE was designed from the start to support a wide range of deployment options, including the choice of frequency band and channel bandwidth. Based on the previous actions of various regulatory agencies, some frequency bands naturally lend themselves to being classified as paired spectrum while other spectrum is better suited for being unpaired spectrum. In some countries, the choice of duplex scheme for a particular frequency band is regulated or predetermined before the spectrum is licensed, while in other countries the operator has some flexibility in the decision. However, the "choice" is somewhat predetermined based on how adjacent spectrum is being used and whether or not the spectrum can support paired channels.

As of Release 10, the LTE specifications support 34 frequency bands – 23 FDD and 11 TDD.

As of Release 10, the LTE specifications support 34 frequency bands – 23 FDD and 11 TDD bands (reference Table 1 on the following page). In total, the specifications classify frequency bands supporting 818 MHz of FDD spectrum (1,636 total when counting both the downlink and uplink frequencies) and 959 MHz of TDD spectrum. These numbers are somewhat misleading since there is partial overlapping between many bands, both within a given duplex scheme and also between duplex schemes. For example, the uplink channels that are defined as part of Band 4 are also defined as part of Band 3. Another good example to point out is Band 35, a TDD allocation involving spectrum at 1850 – 1910 MHz. In many markets Band 35 isn't available because the spectrum is also considered part of Band 2, meaning it is already supporting an FDD mode of 2G, 3G or LTE. As a final example, Band 38 and Band 41 overlap each other, with Band 38 (2570 – 2620 MHz) being a subset of Band 41 (2496 – 2690 MHz).

LTE TDD, by itself, has 329 possible deployment configurations.

Taking it to the next level, there are six potential channel bandwidth options although depending on the frequency band, not all channel bandwidths are supported. For example, it should be self-evident why Band 13, with only 10 MHz of paired spectrum, can't support 15 MHz and 20 MHz channels. Based on our review of TS 36.104, LTE Release 10 supports 134 possible frequency + channel bandwidth combinations (87 FDD and 47 TDD). If we include the seven possible downlink-uplink configurations of TDD (discussed in the next section), LTE TDD, by itself, has 329 possible deployment configurations.

The deployment configurations are reflected in the specifications because in many cases there are eNodeB or mobile device implications that impact the performance requirements. Examples of mobile device performance requirements that are impacted include the transmit power and tolerance, A-MPR (Additional Maximum Power Reduction), EVM (Error Vector Magnitude), and the spectrum emission mask, to name a few.

Although performance requirements are less impactful than implementation requirements, the point remains that the LTE standard is all-encompassing and that it was designed to support a wide array of deployment scenarios. These deployment scenarios naturally lend themselves to creating unique requirements pertaining to the selection of frequency band, duplex scheme and the channel bandwidth within the same set of specifications.

Table 1. LTE Operating Bands

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit $F_{UL\_low} - F_{UL\_high}$	Downlink (DL) operating band BS transmit UE receive $F_{DL\_low} - F_{DL\_high}$	Duplex Mode
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD
5	824 MHz – 849 MHz	869 MHz – 894MHz	FDD
6	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD
11	1427.9 MHz – 1447.9 MHz	1475.9 MHz – 1495.9 MHz	FDD
12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
15	Reserved	Reserved	FDD
16	Reserved	Reserved	FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	FDD
20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
21	1447.9 MHz – 1462.9 MHz	1495.9 MHz – 1510.9 MHz	FDD
22	3410 MHz – 3490 MHz	3510 MHz – 3590 MHz	FDD
23	2000 MHz – 2020 MHz	2180 MHz – 2200 MHz	FDD
24	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD
25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
...			
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
41	2496 MHz - 2690 MHz	2496 MHz - 2690 MHz	TDD
42	3400 MHz – 3600 MHz	3400 MHz – 3600 MHz	TDD
43	3600 MHz – 3800 MHz	3600 MHz – 3800 MHz	TDD

Note 1: Band 6 is not applicable
Note 2: Restricted to E-UTRA operation when carrier aggregation is configured. The downlink operating band is paired with the uplink operating band (external) of the carrier aggregation configuration that is supporting the configured Pcell.

Source: TS 36.104, "E-UTRA User Equipment radio transmission and reception," (Release 10, December 2012)

3.2 Similarities and Differences in the LTE Standard for the Two Duplexing Schemes

The summary of this section is as follows. In general, there are a vast number of commonalities between the two duplex schemes which fall under a common set of LTE specifications. Virtually all of the differences that do exist pertain to "when" something is done versus "what," "how," and "why" something is done. The differences in the timing of events with TDD stem almost entirely from the discontinuous downlink/uplink transmissions that occur with the TDD duplex scheme. With FDD, virtually every downlink and uplink subframe is available to carry a particular payload (e.g., data or control channel information). In a similar fashion, within each duplex scheme the LTE specifications support another layer of options/configurations for how and when something is done in order to provide as much flexibility as possible to support various network deployment scenarios, including expanded cell site coverage areas and variable channel bandwidths, to name a few.

In addition to reviewing the historical documentation that lead to the Release 8 LTE specifications and analyzing the tens of thousands of 3GPP submissions for FDD- or TDD-specific contributions, we also reviewed the actual LTE Release 8 specifications to identify technical features, parameter settings, and/or performance requirements which are unique to a particular duplex scheme.

We identified only a relatively minor number of instances where duplex-specific features exist in the specifications.

Consistent with our analysis of the 3GPP submissions, which serve as the basis for the LTE specifications, we identified only a relatively minor number of instances where duplex-specific features exist in the specifications. In a similar fashion, we also identified instances where features, parameter settings, and/or performance requirements differ within the same duplex scheme according to the targeted frequency band and channel bandwidth assignment. These findings suggest that there is a tremendous amount of commonality between the paired and unpaired modes of LTE. Further, the differences that we identified in the specifications due to the choice of duplex scheme, frequency band, and channel bandwidth, help make LTE the universal success that it is today with the same basic specifications, infrastructure, and device/chipset supporting the multitude of deployment scenarios that operators from around the world face.

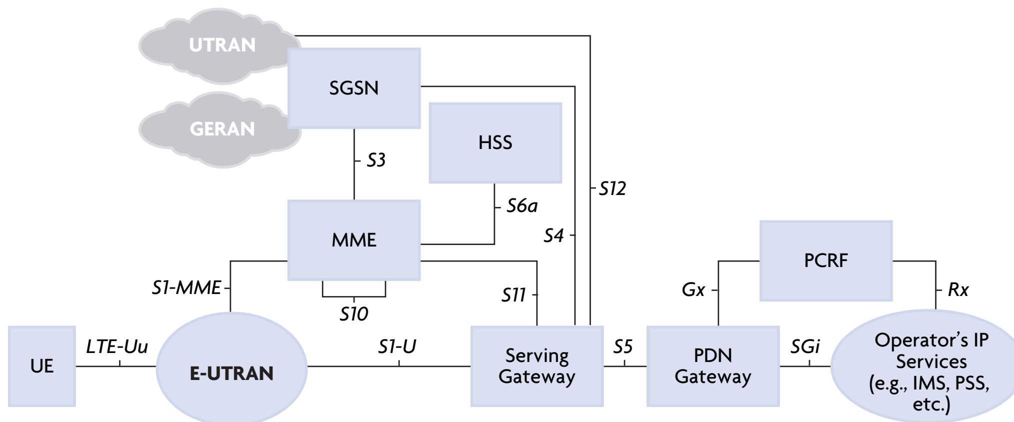
From a RAN air-interface perspective, we reviewed the following LTE specifications. Collectively, these specifications represent the bulk of the specifications that pertain directly to the E-UTRA.

- TS 36.201 – E-UTRA LTE physical layer; General description
- TS 36.211 – E-UTRA Physical channels and modulation
- TS 36.212 – Multiplexing and channel coding
- TS 36.213 – Physical layer procedures
- TS 36.214 – E-UTRA Physical layer; Measurements
- TS 36.321 – E-UTRA Median Access Control (MAC) protocol specification
- TS 36.322 – E-UTRA Radio Link Control (RLC) protocol specification
- TS 36.331 – E-UTRA Radio Resource Control (RRC) protocol specification

The EPC network is completely agnostic to the choice of duplex scheme in the E-UTRAN.

We also reviewed TS 23.401 (GPRS enhancements for E-UTRAN access), which defines the Evolved Packet System, or the evolution of the core network architecture that is closely linked to the new LTE air interface in the radio access network. This review went relatively quickly since we knew in advance that the Evolved Packet Core (EPC) network should be agnostic to the choice of duplex schemes in the air interface. We did not find any references in the document to duplex scheme, frequency, channel bandwidth, etc., and this finding is reflected in Figure 1, which shows a common E-UTRAN that connects to the EPC over the S1-MME and S1-U interfaces. We also note that in the November 2007 Change Request (CR) which reduced the TDD frame structure to a single option the CR clearly indicated that the proposed changes would not impact any core network specifications.

Figure 1. Architecture for 3GPP Accesses



Source: recreated from TS 23.401

The basic difference between the two duplex schemes from a specification perspective is the frame structure.

As previously noted, the basic difference between the two duplex schemes from a specification perspective is the frame structure. The frame structure defines how information, including data traffic and control channel information, is grouped together into digestible chunks. Specific information is grouped into a bucket or subframe of a specified length that is a function of time (e.g., 1 ms). The length of the subframe is critical because it defines the timescale along which the processing tasks are defined. A change in the timescale causes a redesign in the process pipelining and timeline.

The subframe length is important in another way. The base station allocates (schedules) data resources for transmission or reception on a subframe basis. Therefore, the subframe length influences packet lengths, processing timings, and protocol timings, all of which can have a significant impact on the processing chain. Having different subframe lengths between FDD and TDD would be a difference that would be without merit and it would only add to the complexity – something that the operators did not want.

In a *Wall Street Journal* article from last year,[7] commentary from a senior executive at Huawei reinforces the commonality between the two modes. Quoting the article, "*In China, both China Telecom and China Unicom have said that they prefer to adopt the FDD-LTE protocol, which is the world's more popular fourth-generation network standard. Market leader China Mobile, however, is betting on a less frequently used standard called TD-LTE. Still…the carriers' choice between the two standards doesn't make a big difference to Huawei, given that much of the technology used in the two standards are similar and Huawei's chipsets support both.*"

7 "Huawei Expects Growth Despite US Setback," Juro Osawa, The Wall Street Journal, April 3, 2013

As an analogy, there are numerous and largely incompatible analog and digital television systems around the world. The analog systems are comprised of NTSC, PAL and SECAM, and the digital systems include ATSC, DMB-T/H, DVB and ISDB. Among other attributes, one of the areas in which they can differ is the frame rate and the color encoding system. This was a situation that the 3GPP was trying to avoid when it developed the LTE standard.

The length of the subframe is identical with the two duplex schemes.

When the 3GPP consolidated on a single TDD frame structure that had the same subframe length as the FDD frame structure (1 ms), they removed from the specifications the TDD frame structure with a length of 0.675 ms that was originally introduced to accommodate LCR TDD (TD-SCDMA). With this important change it became possible to support both duplex schemes with a common baseband architecture (in terms of our analogy, there was no longer any need to sell and support expensive TVs that supported multiple standards). This was not possible between LTE (either the FDD or the TDD mode) and LCR TDD (TD-SCDMA).

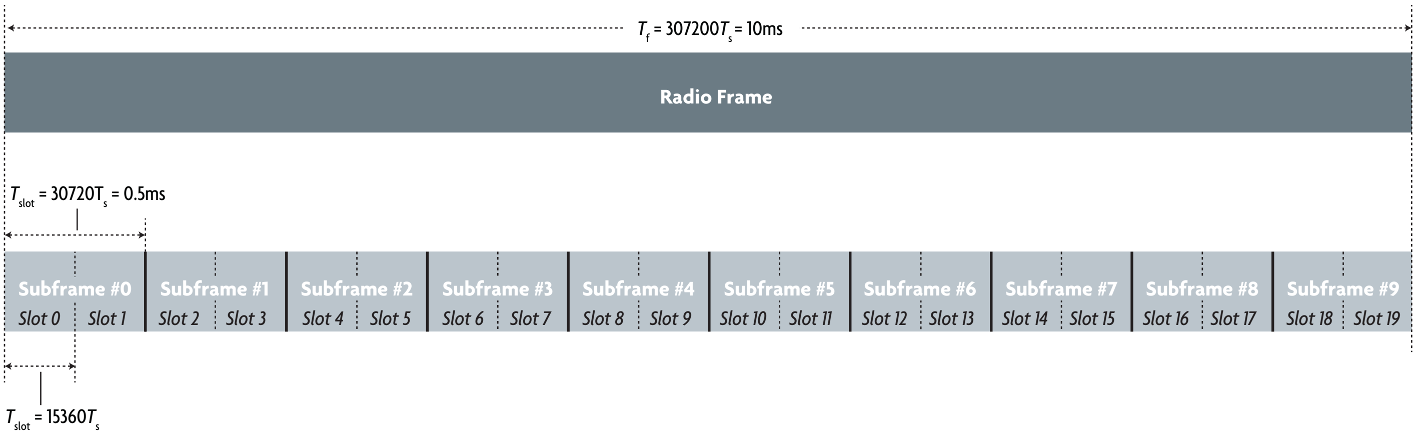
There are, however, still some differences between the FDD and TDD frame structures that are worth mentioning. FDD uses Frame Structure Type 1 and TDD uses Frame Structure Type 2 – a modified version from the original Frame Structure Type 2. Although there are still huge similarities between the FDD and TDD modes of LTE, LTE TDD must treat certain things differently since unlike FDD, the uplink and downlink transmissions of data and control channel information share the same radio channel. The uplink/downlink transmissions don't collide with each other because they are separated in time – at any given instance the mobile device is either receiving data (downlink) or it is sending data (uplink). Conversely, with FDD the mobile device can send and receive data at the same time since the two parallel flows are separated by frequencies. With FDD, a dedicated radio channel is used for the downlink and a dedicated radio channel is used for the uplink. These characteristics are not specific to LTE and simply state the definitions of the two well-known duplexing schemes.

The differences between the two duplex schemes really pertain to when the data and information are sent and not the actual data and information itself.

In general, the type of data and control channel information that is transmitted and how the data and information are processed and interpreted by the FDD and TDD modes of LTE are the same. There are also nuances within the TDD frame structure that are required to support different downlink/uplink ratios as we discuss later in this whitepaper.

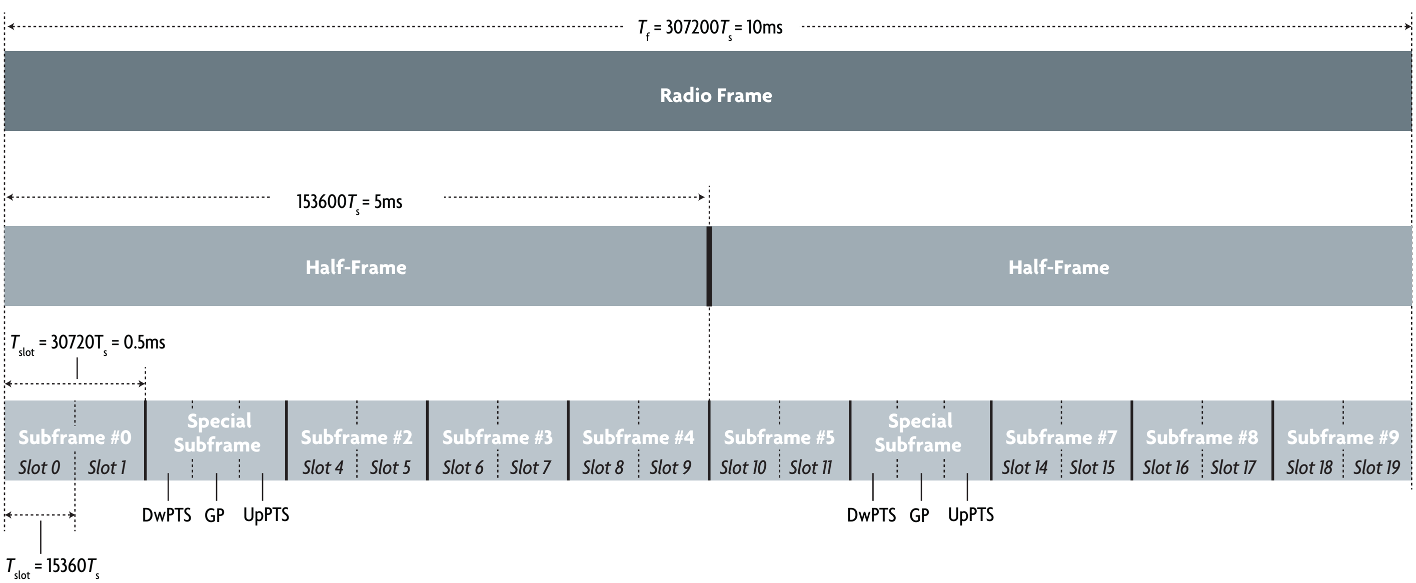
Figure 2 (FDD) and Figure 3 (TDD) show the two frame structures that are currently defined in the LTE specifications. Both frame structures use a 10 ms frame structure that is subdivided into ten subframes (1 ms each) with each subframe further divided into two slots (0.5 ms each). Frame Structure Type 2 introduces what is called a special subframe. DwPTS (Downlink Pilot Time Slot) and UpPTS (Uplink Pilot Time Slot) provide control channel information and GP (Guard Period) is the "quiet time" that is inserted between downlink and uplink transmissions to ensure that the two transmissions do not occur at the same time. The LTE specifications support some flexibility in the length of each of these parameters.

Figure 2. Frame Structure Type 1 (FDD)



Source: recreated from TS 36.211

Figure 3. Frame Structure Type 2 (TDD)



Source: recreated from TS 36.211

The LTE specifications allow operators with unpaired spectrum to change how subframes are allocated between the downlink and the uplink ito support asymmetric traffic patterns.

Even within Frame Structure Type 2 (TDD), there are numerous options, or configurations, built into the specifications that allow an operator to commit more network resources (e.g., subframes) to the downlink or to the uplink direction. This feature gives the operator some flexibility, if coordinated between cells and carriers, in dealing with asymmetric mobile data traffic that typically favors the downlink. By assigning more subframes to the downlink the operator can handle more downlink data traffic with the tradeoff being fewer resources available to support the uplink.

The 7 potential configurations for Frame Structure Type 2 are defined within the same set of specifications, just as the same specifications define two duplexing schemes.

In total, there are 7 potential configurations for Frame Structure Type 2. The configurations range from as many as 8 downlink subframes and 1 uplink subframe, plus 1 special subframe, to only 2 downlink subframes and 6 uplink subframes with two special subframes. Since the subframes carry the data and critical control channel information that allow communications to occur, the specifications must define in detail how to deal with each configuration. These configurations are defined within the same set of specifications that we reviewed, and clearly there are not separately published specifications for each configuration. In a similar vein, FDD and TDD fall under the same set of specifications, but they have some differences which must be clarified when appropriate.

The uplink physical channel structure, the use of SC-FDMA, control channels (PUCCH), modulation schemes, and how resource elements are mapped are nearly identical for the two duplexing options.

TS 36.211 defines the specifications for the physical channels and the modulation schemes. Although the specification clearly identifies the distinction between the two frame structures, there is otherwise very little delineation between the two duplexing options. The uplink physical channel structure, the use of SC-FDMA, control channels (PUCCH), modulation schemes, and how resource elements are mapped in the frequency and time domains are nearly identical for the two duplexing options. There is a difference in how the physical resources are assigned since with LTE TDD certain sub-frames are allocated to the downlink/uplink or used to support the special sub-frame. In other words, with LTE FDD the uplink resources are continuous in time so data/control channel information can be assigned in every single subframe. With LTE TDD the uplink data/control channel information can only be assigned to a subframe that is intended for an uplink transmission.

Another difference that we observed in the uplink pertains to the sounding reference signal (SRS) which is used to support frequency selective scheduling in the uplink and general time tracking and power control by the eNodeB. Once again, the primary difference pertains to when SRS can be transmitted in the uplink. With LTE TDD it is only transmitted during uplink subframes or in the special subframe (UpPTS) while with LTE FDD, mobile devices can transmit it in every subframe. We also observed multiple tables which provided SRS configuration settings based on the channel bandwidth and regardless of duplex scheme.

A common set of LTE specifications support two different duplex schemes, just as they also support a wide range of options and configurations within a given duplex scheme.

PRACH (Physical Random Access Channel) defines the physical layer that carries attempts by the mobile device to access the system, including responses to paging messages and requests to transmit data. The underlying mechanisms for how this works are nearly identical between LTE FDD and LTE TDD. They differ with respect to when PRACH occurs and with TDD there is a new preamble format that is introduced. Worth noting, the specification defines an additional 3 preamble formats for FDD or TDD which are available to support a range of network deployments, for example cell sites with very large coverage areas. Further, the vast flexibility in the LTE specifications is exemplified in the number of underlying configurations for each preamble format. In essence these numerous configurations (64 for Frame Structure Type 1 and 58 for Frame Structure Type 2) define where the RACH is allowed in the time and frequency domains. The key point is that much in the same way a common set of LTE specifications supports two different duplex schemes, the specifications also support a wide range of options and configurations within a given duplex scheme.

In the downlink, virtually everything is common between the two duplex schemes beyond the two frame structures that we previously mentioned.

In the downlink, virtually everything is common between the two duplex schemes beyond the two frame structures that we previously mentioned. Commonalities include all of the physical layer channels (with a couple of nuances that we discuss in a bit), the resource blocks, which map certain physical channels to resource elements, the channel coding, the mapping of control channels to resource elements, the scrambling of each code word, the modulation types and how they work, and the implementation of MIMO.

Hybrid Automatic Repeat reQuest (HARQ) is a mechanism used in both LTE TDD and LTE FDD to address corrupted data that the mobile device or eNodeB cannot decode. In essence, with HARQ the data is retransmitted, perhaps with some additional error correction bits, until it is received successfully. The mobile device/eNodeB sends Acknowledgement messages (ACKs) confirming the data was received successfully and Non-Acknowledgement messages (NACKs) indicating that the data needs to be retransmitted. In both modes of LTE, the eNodeB uses the Physical HARQ Indicator Channel (PHICH) to ACK/NACK uplink transmissions sent by the mobile device and the mobile device uses the Physical Uplink Control Channel (PUCCH) to ACK/NACK downlink transmissions that it received from the eNodeB.

PHICH and PUCCH are identical in LTE FDD and LTE TDD with one caveat.

PHICH and PUCCH are identical in LTE FDD and LTE TDD with one caveat. With LTE TDD, the shared channel structure between the downlink and the uplink means that not every single sub-frame is available to support PHICH/PUCCH. Further, if the downlink/uplink configuration favors the downlink as is typically the case with TDD-based systems, there would be a "long time" between receiving a data packet and the transmitting of the corresponding ACK/NACK. In order to address this inefficiency, LTE TDD supports ACK/NACK bundling in which multiple data transmissions can be ACK'd or NACK'd in a single sub-frame. This feature is called ACK/NACK bundling. Worth noting, the Carrier Aggregation feature of LTE-Advanced supports a similar concept with a single uplink ACK/NACK for data packets received on multiple downlink radio carriers.

LTE uses primary and secondary synchronization signals (PSS and SSS) that provide the mobile device with synchronization information that is unique to each physical cell/sector. This information allows the mobile device to synch the start and stop points of each subframe and to subsequently make the necessary adjustments when it moves to a new cell/sector. Without sounding like a broken record, the underlying tenants of PSS and SSS are identical between the two duplex schemes, but their locations within the frame structure are different – a necessity given the various LTE TDD configurations.

Our analysis of the MAC and RLC Layer specifications did not reveal any meaningful differences between the two modes of LTE.

Our analysis of the MAC, RLC and RRC Layer specifications, TS 36.321, TS 36.322 and TS 36.331, did not reveal any meaningful differences between the two modes of LTE. The TS 36.322 specification does not contain any language or descriptions which mention anything that is duplex specific. TS 36.321 mentions the aforementioned nuance with PRACH and it includes a table which provides a slightly different timing mechanism associated with implementing Semi Persistent Scheduling (SPS). There are also unique settings for each of the six downlink/uplink configurations of LTE TDD, once again demonstrating the need for flexibility due to all of the LTE deployment options that exist. SPS is an optional scheduling mechanism that makes it more efficient to schedule lots of users and lots of small data packets, such as would be the case with VoLTE. To the best of our knowledge, SPS is not commercially deployed today although it will become more common place with VoLTE.

Finally, TS 36.331 is for all practical purposes identical between the two duplex modes. It does indicate, for example, that System Information (SI) messages cannot be sent by the network during an uplink TDD subframe. Further, the specification indicates how the network and mobile devices communicate their capabilities and features with each other. In the case of LTE TDD, this communication includes whether or not the mobile device supports LTE TDD and the downlink/uplink configuration of the network. Similar types of information are communicated with LTE FDD in the same format/structure, but LTE TDD does introduce a couple of new parameter settings which otherwise wouldn't exist.

4.0 The LTE Specifications and the Commonality between Duplex Schemes

In addition to analyzing numerous 3GPP specifications to identify similarities and differences that may exist between the two primary duplexing options associated with the LTE standard, we separately reviewed approximately 84,000 submissions made to the 3GPP RAN Working Groups (WG 1 through WG 3) over a six-year period spanning from April 2005 through February 2011. This highly-objective review process sought to identify those submissions which were specific to only one of the duplexing schemes as well as those submissions which applied equally to LTE FDD and LTE TDD (i.e., the submissions that were duplex scheme agnostic). Further, we tracked the organizations responsible for making the submissions to determine if there was a single company or only a small subset of 3GPP participating organizations that were largely responsible for endorsing and developing LTE TDD.

Only 3.7% of all LTE submissions deal specifically with the FDD mode and only 7% deal with the TDD mode of LTE.

As discussed in the last chapter, a global list of operators and vendors required LTE support for unpaired spectrum in the initial set of requirements. Further, a who's who list of operators and vendors from around the world supported the move to a single LTE TDD frame structure, thereby removing the similarities that previously existed between LTE TDD and previous time-division-duplexing-based 3GPP 3G standards. In this chapter we demonstrate that out of all of the submissions made during the LTE standardization process, only 3.7% deal specifically with the FDD mode and only 7% deal specifically with the TDD duplex scheme. Further, our analysis reveals that companies primarily responsible for developing the over-arching LTE specifications played an equally important role with the TDD specific requirements of LTE.

4.1 Our Methodology

We focused our study on the three RAN Working Groups that were primarily responsible for developing the LTE standard. RAN WG 1 is responsible for the Physical Layer specifications. RAN WG 2 is responsible for the radio interface architecture and protocols, as well as radio resource management. RAN WG 3 is responsible for the E-UTRAN architecture, including several of its protocols. We excluded the other two RAN Working Groups because they deal more with performance parameters (WG 4) and mobile device conformance testing (WG 5). We also excluded all of the non-RAN Working Groups because they had no involvement in developing the air interface associated with the LTE standard. As discussed elsewhere in this report, the core network (EPC) is fully independent of the air interface and its choice of duplex schemes.

The period of our study was April 2005 through February 2011. This period reflects the time during which 3GPP was developing the LTE standard – Release 8 through Release 10. The 3GPP RAN Working Group meetings that we included in our study are provided in Table 2.

Table 2. Scope of Study

RAN Working Group	First Meeting	Last Meeting	# of Submissions
Working Group 1	TSGR1 #40bis	TSGR1 #64	27,446
Working Group 2	TSGR2 #48	TSGR2 #73	38,372
Working Group 3	TSGR3 #48	TSGR3 #71	16,640
Other (LTE specific, etc.)			1,284

Source: Signals Research Group

The information we used for our analysis is readily available from the 3GPP website.

The first step in the process was to build a database of all submissions during this period as well as the final report associated with each meeting. This information is readily available from the 3GPP website. However, the format and structure of the final report, as well as the location of the submissions and the all-important consolidated list of submissions, varies by working group. The variation also exists within each working group, based on the individual, or Rapporteur, chairing the meeting. We used the consolidated list of submissions to ensure that we had all of the submissions. Further, the consolidated list provides information regarding the status of the submission (e.g., if it was approved or withdrawn, etc.) and the company or companies responsible for the submission.

Once we had developed the consolidated database of all submissions and taken efforts to ensure that we were not missing any documents, we began the actual review process. Given the magnitude of the effort and our desire to produce highly objective results, we used an automated review process, combined with a list of objective criteria, to categorize each submission. As discussed in a bit, the objective criteria focused on a list of key words and phrases that are normally associated with LTE, including key words that could signify a duplex-specific implementation of LTE.

We used Excel VBA to develop a proprietary means of automatically reviewing each document. The program leveraged Microsoft APIs for Word, Excel and PowerPoint. Since many of the submissions were in Adobe PDF format, we had to convert those PDF documents to a text document to analyze their contents. In essence, the program searched each document for the key words, kept track of which key words appeared in the document and how many times the key words appeared, documented the source of the submission, and the status of the submission. We also avoided double-counting a submission by tracking whether or not the document was revised, and ultimately only counting the final revision. In a similar fashion, we tracked incoming and outgoing Liaison Submissions (LS) between working groups, but we only counted outgoing LS documents since an incoming LS would eventually appear as an outgoing LS in another Working Group.

Using our criteria, we categorized all 3GPP submissions according to their association with the LTE standard and their status.

Using our criteria, including a list of keywords, we categorized all 3GPP submissions according to their association with the LTE standard and their status. Table 3 provides a high-level illustration of how we categorized each submission. Our category counting methodology in Table 3 was done in a sequential process in order to ensure that each document was correctly categorized and that we did not include submissions which should not be included in the analysis. For example, if a document was categorized as being Administrative or Withdrawn (first two rows) then it would not appear in our final count, even if the document pertained to LTE. In a similar fashion, if an LTE document was an Incoming LS then it would be categorized as such, then no longer considered for the future categories (e.g., Outgoing LS) in order to avoid double-counting. Note the "TRUE" logic statement next to a category meant we counted the submission in the corresponding category but then removed the submission from the database so that it could no longer be counted in the remaining categories.

The results of our study tend to overestimate the number of submissions which were specific to a particular duplex scheme.

It is important to note that with this methodology a submission could fall into multiple categories. For example, a submission could be categorized as an LTE submission, an LTE TDD submission, and an LTE TDD Approved submission. A number of LTE submissions were classified as LTE FDD and LTE TDD, but as we discuss in a bit, and demonstrate in the next section, many of these submissions were really duplex scheme agnostic. For this reason, the results of our study tend to overestimate the number of submissions which were specific to a particular duplex scheme.

If a submission contained the word "FDD" or "TDD" in its title then we automatically categorized the submission accordingly. For remaining documents, we used the key words in Table 4 when we scanned the document to classify them as being LTE, LTE FDD-TDD, LTE FDD, and LTE TDD. The LTE FDD-TDD category captures those submissions which were counted as being LTE FDD and LTE TDD. Our belief, based on the submissions that we manually reviewed, is that many of these submissions that fell into this category just happened to include language (e.g., key words) that pertained to FDD and to TDD. For example, if a document states, *"This proposed feature applies to TDD and FDD"* then it would be treated as a duplex-specific submission. In reality, this type of language implies the exact opposite – the choice of duplex scheme didn't matter. We came across numerous documents that fell into this category that were really duplex-scheme agnostic, and it appears to us that the document was just trying to make it crystal clear that the submission applies equally to FDD and TDD.

We believe that classifying documents based on a single key word is overly generous based on the submissions that we manually reviewed.

As previously mentioned, we also kept track of the number of times key words appeared in the document in order to weight the significance of the submission belonging in a category. For example, if a submission contained 4 key words then there is a higher probability that it belongs in a particular category than a submission with only 1 key word. Ultimately, the results that we show in the next section include submissions with a single hit as well as submissions where we observed multiple hits. We believe that classifying documents based on a single key word is overly generous based on the submissions that we manually reviewed. However, by using 1 key word as the litmus test for a submission being classified as duplex-scheme specific, we still demonstrate that the overwhelming majority of submissions pertained equally to both duplex schemes (i.e. they were duplex scheme agnostic).

R1-110650 is an example of a document that we counted as being duplex specific (LTE TDD) when a manual review of the document would probably result in the document being classified as duplex agnostic. In summary the document discusses simulation assumptions for modeling CoMP (Coordinated Multipoint), which is an LTE-Advanced feature. We flagged the document as being LTE TDD because of a sentence that states, *"Scenario 3 is even more challenging to model for TDD, which faces particularly challenging interference conditions with the Rel-10 eICIC multiple cell-id approach."* In this case the reference to TDD deals specifically with potential performance differences between the two modes that could impact the simulation assumptions. There isn't anything in this sentence or throughout the entire document that distinguishes technical differences between the two modes.

Table 3 provides the list of key words that we used to identify LTE submissions, as well as those submissions that might be specific to a specific duplex scheme.

Table 3. Category Counting Methodology

Category	Long Name	Include
ADM	Admin	FALSE
WDN	Withdrawn	FALSE
LTE	Long Term Evolution	TRUE
ADM	Admin	FALSE
REJ	Rejected	FALSE
REV	Revised	FALSE
ILS	Incoming LS	FALSE
FDD	Frequency Division Duplex	TRUE
TDD	Time Division Duplex	TRUE
OLS	Outgoing LS	FALSE
NTD	Not Treated/Noted	FALSE

Source: Signals Research Group

Our category counting methodology in Table 3 was done in a sequential process in order to ensure that each document was correctly categorized and that we did not include submissions which should not be included in the analysis. For example, if a document was categorized as being Administrative or Withdrawn (first two rows) then it would not appear in our final count, even if the document pertained to LTE. In a similar fashion, if an LTE document was an Incoming LS then it would be categorized as such, then no longer considered for the future categories (e.g., Outgoing LS) in order to avoid double-counting. Note the "TRUE" logic statement next to a category meant we counted the submission in the corresponding category but then removed the submission from the database so that it could no longer be counted in the remaining categories.

We treated each submission equally even though an individual submission may have more or less impact on the LTE specification.

Finally, we used the "Source" field to identify the company or companies responsible for making the submission. In the event that multiple companies submitted the document we would give each company partial credit. For example, if a single company was responsible for a submission then it would receive a credit of 1 submission in the count tally. If two companies were responsible for a submission then each company would receive a credit of 0.5 for the submission. In many cases a single company may have been the primary contributor with other companies merely signing on as a means of demonstrating their endorsement for the submission. Since it would be impossible to identify these situations, not to mention the primary contributor, and in order to be fully objective, we gave each company partial credit for the submission. For purposes of our counting methodology, we also treated each submission equally even though an individual submission may have more or less impact on the LTE specification.

Table 4. Key Word Criteria

LTE	FDD	TDD	FDD-TDD	UTRA	UTRA FDD	UTRA TDD
LTE	FDD	TDD	FDD?TDD	WCDMA	UTRA?FDD	UTRA?TDD
EUTRA	Frequency?Division Duplex	Time?Division Duplex	TDD?FDD	UTRA	UTRA??FDD	UTRA??TDD
E?UTRA	Paired?Spectrum	Unpaired?Spectrum	FDD??TDD	HSPA	UTRA???FDD	UTRA???TDD
UE?EUTRA	Paired?Band	Unpaired?Band	TDD??FDD	HSDPA		
SC?FDMA	Frequency?Duplex	Time?Duplex	FDD???TDD	HSUPA		
Evolved?UTRA	Full?Duplex	TD?LTE	TDD???FDD	E?DCH		
Evolved?UTRA and UTRAN	Frame?Structure 1	TD?SCDMA	FDD????TDD	E?PUCH		
Evolved?RAN	Frame?Structure Type 1	Frame?Structure 2	TDD????FDD	HS?SCCH		
Long?Term Evolution		Frame?Structure Type 2	FDD?????TDD	HS?DSCH		
Single?Carrier FDMA		DwPTS	TDD?????FDD			
E?MBMS		Downlink Pilot Time Slot	Paired and Unpaired			
EMBMS		UpPTS	Unpaired and Paired			
Evolved Node B		Uplink Pilot Time Slot	Frame?Structure Type 1 & 2			
eNode B		ACK/NACK Bundling	Frame?Structure Type 1 & 2			
eNodeB		ACK/NACK Multiplexing	Frame?Structure 1 & 2			
eNB		ACK/NAK Bundling	Frame?Structure Type 1 & 2			
Intra?LTE		ACK/NAK Multiplexing	FDD?Frequency Division Duplex			
TD?LTE		DAI	TDD?Time Division Duplex			
		Downlink Assignment Index	antennas*FDD*antennas*TDD			
		Asymmetric DL/UL Scheduling				

Source: Signals Research Group

4.2 Results and Analysis

We analyzed nearly 83,000 3GPP submissions – 82,967 submissions to be exact, which companies submitted to RAN WG1, WG2 or WG3 over a six-year period. The period that we reviewed started with the first 3GPP meeting where LTE was discussed and concluded with the meetings that took place in February 2011. During this time the 3GPP developed the LTE Release 8 through Release 10 specifications. Based on our analysis of these submissions, 42,957 documents apply to LTE. The remainder of the documents applies to other 3GPP RAN activities, such as the development and evolution of UTRA (e.g., HSPA+).

The findings from our analysis of the 82,967 3GPP submissions are consistent with our review of the published specifications.

The findings from our analysis of these documents are consistent with our review of the published specifications – namely that the majority of the technical features that comprise the LTE air interface are duplex neutral, meaning that they apply equally to both duplex schemes. To be specific, 82.5% of the documents do not distinguish in any way between the two modes of LTE, meaning that only 17.5% of the LTE submissions that we analyzed have some sort of duplex-specific language contained somewhere within the submission. Breaking the results down further, we classified 3.7% of the submissions as being LTE FDD specific and 7.0% of the submissions as being LTE TDD specific. We determined that the remaining 6.8% of the submissions contain duplex specific language that applies to both LTE FDD and LTE TDD.

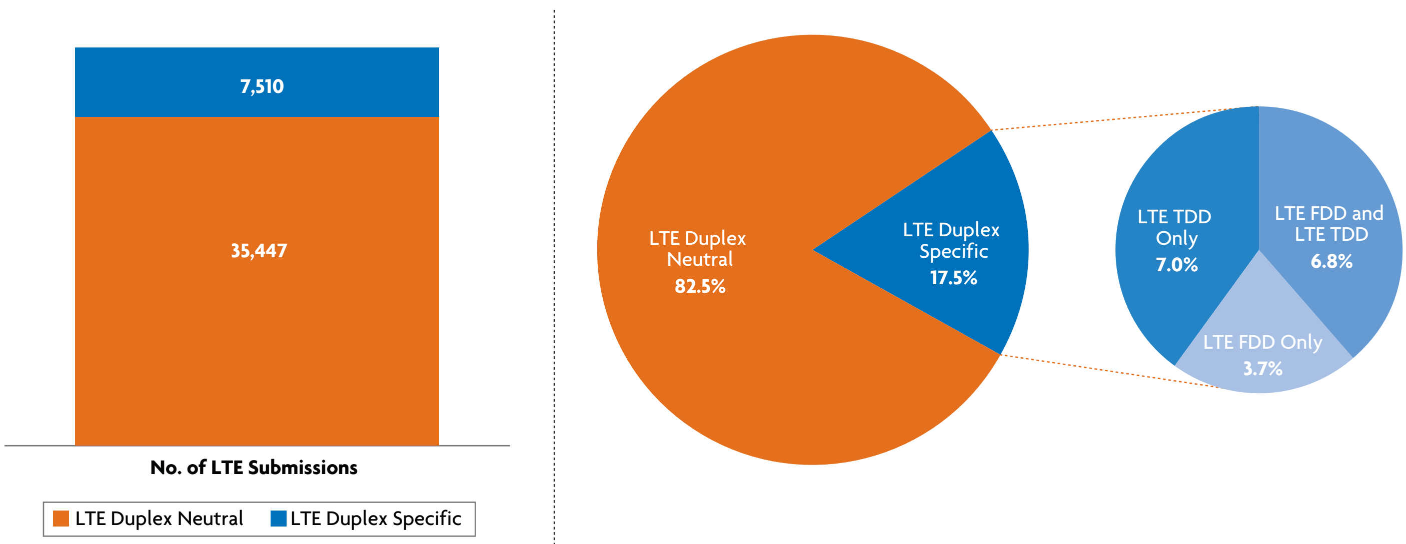
As previously mentioned, our approach was all-inclusive so the mere mention of either duplex scheme or the inclusion of a key word would cause the document to be flagged. This situation would occur even if the key word(s) was only briefly mentioned in the document with the document itself not pertaining to a duplex-specific feature. We did exclude key words that only appear in the abbreviations/acronyms section of the document. A subjective review of the duplex-specific submissions that we identified would likely result in the actual number dropping to a lower percentage. However, to keep the study entirely objective, we are including all submissions even if the end result is that we overstate the results.

Figure 4 provides the results from our study. Of the 82,657 documents that we reviewed, 42,957 documents are specific to LTE. Of these documents, only 7,510 documents contain duplex-specific language. We believe that our approach provides a very accurate upper and lower boundary. In all probability the LTE TDD submissions (7.0% of all LTE submissions) include a discussion or recommendation that is specific to LTE TDD. By our definition, if we classified a document as being specific to LTE FDD then it most likely discusses something that is unique between the two duplex modes so it would be appropriate to include these submissions as well – only 3.7% of all LTE submissions. This calculation brings the total number of duplex-specific submissions to 10.7% of all LTE submissions.

3GPP submissions which address duplex-specific features account for between 10.8% and 17.5% of all submissions that pertain to LTE.

Each submission that falls into the LTE FDD and LTE TDD category could contain duplex-specific recommendations or it could merely state the recommendation applies equally to LTE FDD and LTE TDD, so we believe that some but not all of these documents should actually be categorized as a duplex-specific submission. Net-Net: no more than 17.5% of all LTE submissions address duplex-specific features, including those that only apply to LTE FDD and those that only apply to LTE TDD. At the other extreme, the percentage of documents that contain valid duplex-specific information could be as low as 10.7%.

Figure 4. Distribution of 3GPP Submissions by Duplex Scheme



Source: Signals Research Group

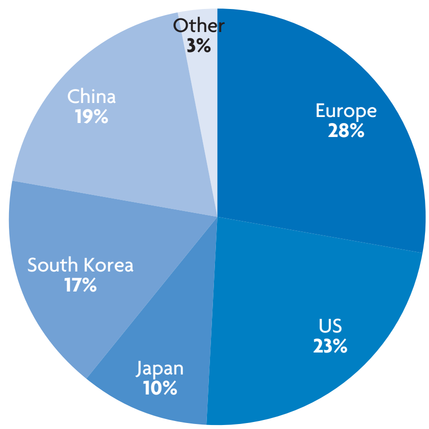
58 companies from all over the world made contributions that specifically address LTE TDD and 52 companies made contributions that specifically address LTE FDD.

We identified at least 104 companies that submitted contributions to the 3GPP standardization process during the timeframe of the review. Of these companies, 58 companies made contributions that specifically address LTE TDD and 52 companies made contributions that specifically address LTE FDD. Further, these companies were located all over the world with no single region contributing disproportionately more than another region.

It is worth pointing out that not all contributions are accepted into the final specifications. In fact, it is generally the case that very few submissions find their way into the published specifications. Therefore, the percentage values that we provide in this chapter do not necessarily represent approved submissions that can be traced to a specific published LTE specification or specifications. However, the point remains that many companies from all over the world actively contributed to both the development of LTE TDD and LTE FDD.

Figure 5 shows the distribution of LTE TDD submissions to 3GPP based on the originating source of the submission. This analysis demonstrates that five countries/regions were most responsible for influencing LTE TDD during the standardization process. Europe was the largest contributor with 28%, followed by the United States (23%), China (19%), South Korea (17%) and Japan (10%).

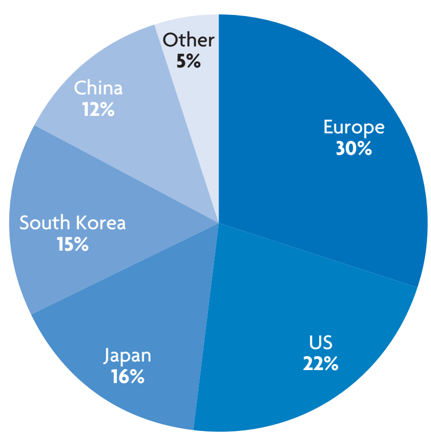
Figure 5. Country/Regional Distribution of LTE TDD Submissions to the 3GPP RAN Working Groups



Source: Signals Research Group

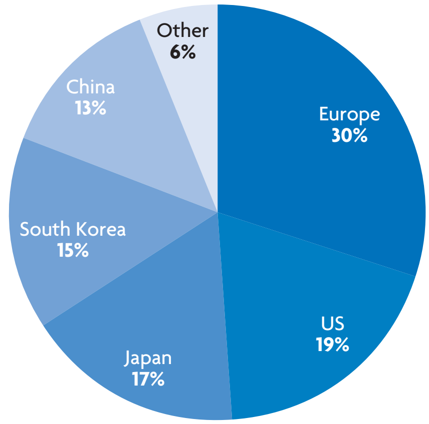
For comparison purposes, Figure 6 provides the distribution of contributions on a country/regional basis for the LTE submissions which were specific to LTE FDD and Figure 7 provides the distribution of contributions for the LTE submissions that are duplex agnostic. In general, the relative contributions are similar with China having slightly less influence on LTE FDD and LTE duplex agnostic and Japan having more influence.

Figure 6. Country/Regional Distribution of LTE FDD Submissions to the 3GPP RAN Working Groups



Source: Signals Research Group

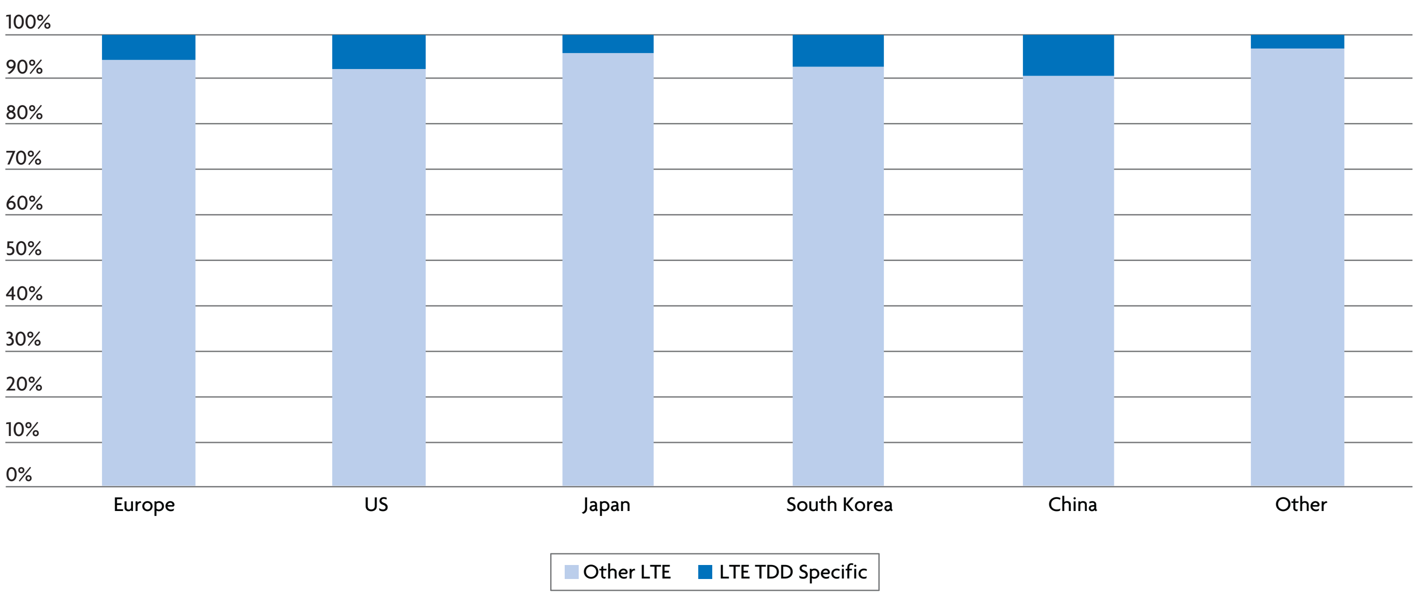
Figure 7. Country/Regional Distribution of Duplex Agnostic LTE Submissions to the 3GPP RAN Working Groups



Source: Signals Research Group

Figure 8 shows the percentage of LTE TDD specific submissions relative to the total number of LTE submissions from each region of the world. The percentages range from 4.1% to 9.1% (excluding "Other"), suggesting that each country/region applied approximately the same amount of priority to the development of LTE TDD as it did to the overall development and standardization of LTE.

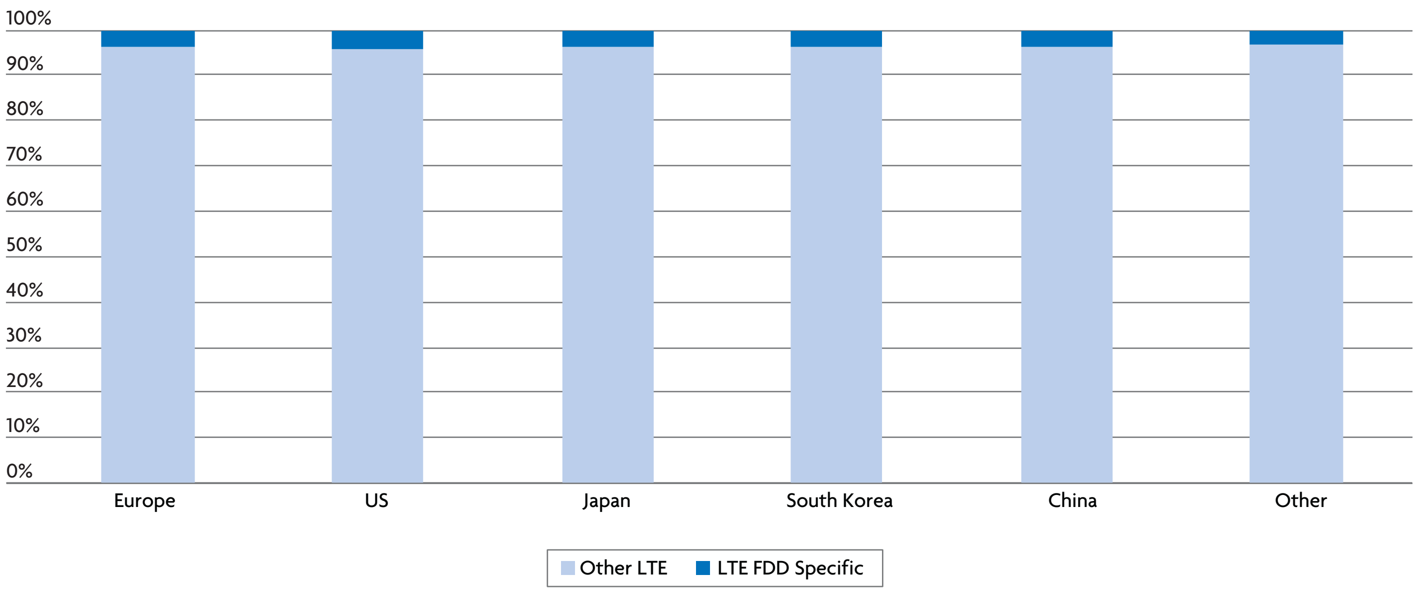
Figure 8. LTE TDD Submissions as a Percentage of Total Submissions – country/regional results



Source: Signals Research Group

Finally, Figure 9 shows the comparable results for LTE FDD specific submissions. The range, excluding "Other" was 3.5% to 4.2%. The percentages are naturally lower because there were not as many submissions that were specific to LTE FDD as compared with LTE TDD.

Figure 9. LTE FDD Submissions as a Percentage of Total Submissions – country/regional results



Source: Signals Research Group

5.0 Conclusions

The 3GPP developed the LTE standard to be as flexible as possible in order to support the plethora of deployment options that exist all over the world. According to September 2013 figures from the GSA (Global mobile Suppliers Association)[8] there are 213 commercial LTE networks, including 21 LTE TDD networks with 10 of these networks deployed by operators who also operate a LTE FDD network. We believe that LTE is deployed in approximately 20 different frequency bands, including 5 of the 6 channel bandwidth options.

Although the majority of LTE deployments are currently LTE FDD, it is likely that the contribution from LTE TDD will increase over time. This scenario is especially true given that many operators will use LTE TDD to provide an additional capacity layer within their more ubiquitous LTE FDD network. Another important reason for the anticipated uptake of LTE TDD is the availability of unpaired spectrum in many regions of the world.

It is evident from our research that all operators will be supporting a single standard, albeit a standard with enough flexibility to support a wide range of deployment scenarios.

Regardless of the exact mix of LTE FDD and LTE TDD, it is evident from our research that all operators will be supporting a single standard, albeit a standard with enough flexibility to support a wide range of deployment scenarios. The commonality between duplex modes is evident in the specifications that we reviewed with almost all technical features in the Physical Layer common to both duplex schemes. The differences really pertain to when something is done versus how or why it is done. Both duplex modes use an identical RLC Layer, nearly identical MAC and RRC Layers, and a common core network.

These commonalities exist because of the efforts of the 3GPP and its member companies, who wanted to avoid technology fragmentation and to make better use of unpaired spectrum resources. As such, a global contingent of companies from all over the world contributed to the duplex-specific aspects of LTE.

8 GSM/3G Market/Technology Update, GSA, September 5, 3013, rev1

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