THE 600 MHz SPECTRUM AUCTION: AN ANALYSIS OF THE BAND PLAN FRAMEWORK AND RESPONSE TO CERTAIN PROPOSALS

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Abstract

This is our second paper in response to the Commission's NPRM. Our first paper analyzed the lead band plan framework set forth in the NPRM and provided a set of core principles that, when adhered to, would significantly enhance that framework. In this paper, we focus on certain specific band plan-related issues about which there have been debates and discussions among the commenters in this proceeding. We begin by explaining why the Commission should reject proposals to permit LTE-TDD (also known as TD-LTE) systems to operate in the 600 MHz bands. We show that, compared to LTE-FDD systems, LTE-TDD systems are much less widely deployed, are more complicated to deploy, lead to relatively smaller cells to attain the same target cell-edge throughput as LTE-FDD systems, and cannot fully exploit certain LTE-Advanced features. We further show that, in a 600 MHz deployment, LTE-TDD systems would result in harmonics that interfere with other mobile bands (*e.g.*, a PCS band), would produce fewer spectrum blocks for mobile licensed use, and would interfere with LTE-FDD systems operating in the 600 MHz band. We next address several guard band (including duplex gap) issues. First, we explain why the duplex gap should be no smaller than 10-12 MHz and no larger than 15 MHz. Second, we discuss why unlicensed operations in the duplex gap should be permitted only if they would not cause interference to licensed spectrum and only if they are required to accept all interference from licensed users. Third, we explain that the size of the guard bands needed to protect licensed mobile services from interference due to television stations using adjacent frequencies depends on several factors, and that the licensed uplink spectrum will require a guard band of at least 6 MHz, and the licensed downlink spectrum will require a guard band ranging from at least 6 MHz (when located adjacent to television stations operating at 50 kW or less) up to 10-14 MHz (when located adjacent to television stations operating at or near 1 MW).

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1. EXECUTIVE SUMMARY.

In our initial paper[3] we analyzed the lead band plan framework set forth in the Federal Communications Commission's ("FCC") NPRM,[4] and we provided a set of core principles that, if adhered to, could dramatically improve that framework. Several other commenters, including, for example, the National Association of Broadcasters, Qualcomm, T-Mobile, Intel, and Verizon, agreed with these core principles.[5] In this paper, we provide further analyses related to four specific band plan-related issues.

1. *No LTE-TDD in 600 MHz.* As we show below, the Commission should not permit the 600 MHz spectrum to be repurposed for mobile wireless use. First, in bands where multiple providers are expected to be providing service, such as in the 600 MHz band, the use of LTE-TDD would necessitate substantial coordination among all of the network operators using those bands to avoid harmful interference that would otherwise occur. Such coordination would significantly increase the costs of deploying services and introduce substantial uncertainties as to the extent to which the repurposed spectrum will be impaired by interference. Second, LTE-TDD networks typically require relatively smaller cells to achieve the same target cell-edge throughput as LTE-FDD networks in coverage-driven deployments. Furthermore, for a given cell size of a macro cell or micro cell, the cell-edge throughput would be smaller for LTE-TDD than LTE-FDD. Third, deployment of LTE-TDD spectrum in the 600 MHz bands would result in harmonics that, as we discussed in our initial paper, can cause significant interference to PCS and other frequency bands. Fourth, due to the need for more guard bands for LTE-TDD systems, various likely auction scenarios would end up allocating significantly less spectrum for mobile use if LTE-TDD is permitted. Fifth, incorporating LTE-TDD into the 600 MHz bands would limit provider's ability to fully exploit certain LTE-Advanced features that can significantly enhance network performance and user experience. Sixth, a mixed LTE-FDD and LTE-TDD approach would not only have all of the problems summarized above, but it would require additional guard bands between TDD spectrum and FDD spectrum to ensure satisfactory network performance, and it would result in significant co-channel interference when some base stations or eNodeBs use LTE-TDD while nearby eNodeBs use LTE-FDD in the same spectrum block.

2. The size of the duplex gap. The duplex gap is a guard band between the paired uplink and downlink frequencies in a FDD network that is needed to prevent interference between uplink

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[3] *See* Jeffrey Reed and Nishith Tripathi, *The 600 MHz Spectrum Auction: An Analysis Of The Band Plan Framework*, attached as Exhibit A to Comments of AT&T Inc., *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268 (Jan. 25, 2013) ("Reed-Tripathi Initial Paper").

[4] *See* Notice of Proposed Rulemaking, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, 27 FCC Rcd. 12357 (rel. Oct. 2, 2012) ("NPRM").

[5] *See, e.g.,* Letter From AT&T, Intel, National Association of Broadcasters, Qualcomm, T-Mobile, & Verizon Wireless to FCC, GN Docket No. 12-268 (filed Jan. 24, 2013).

and downlink signals. Google and Microsoft have suggested that the duplex gap should be as large as 28 MHz.[6] As we show below, based on fundamental wireless engineering principles and significant input from AT&T and AT&T's vendors (including chipset and device manufacturers), the duplex gap should be at least 10-12 MHz wide, but it should not exceed 15 MHz. A smaller duplex gap would raise significant interference concerns and reduce achievable throughput, and a larger duplex gap would raise significant practical implementation concerns and could reduce the amount of paired spectrum available for licensed mobile broadband use.

3. *Unlicensed Services In The Duplex Gap.* The FCC should permit unlicensed services to be operated in the duplex gap only if two conditions are met: (1) the unlicensed users must operate in a manner that fully protects licensed users from interference and (2) unlicensed users must accept any interference that may occur from licensed operations. These conditions are necessary to avoid subjecting spectrum located near the duplex gap to impairments that would decrease its value to providers and consumers by reducing capacity and quality. These conditions are also necessary to facilitate the FCC's goal of creating fungible paired spectrum blocks, by ensuring that spectrum near the guard bands is not subject to more interference than spectrum located farther from the guard bands. The precise restrictions that would have to be placed on unlicensed users in the duplex gap will depend significantly on the specifics of any contemplated unlicensed services. Among other things, the appropriate restrictions will depend on whether the services are uplink or downlink or both, power levels, band size, geographic locations, and filter performance. Accordingly, whether any particular unlicensed service should be permitted to operate in the duplex gap, and the limitations on that service needed to protect licensed users, must be assessed after it is clear what services are being considered for operation in the duplex gap.

4. *The size of the guard bands.* The size of the guard bands needed to protect licensed mobile services from interference due to television transmissions operating in adjacent frequencies is different for uplink and downlink mobile spectrum. It will also vary depending on the power level of the adjacent television stations. For these reasons, until there is a more established band plan framework, it is not possible to predict with certainty the precise size that will be needed for the guard bands to protect against interference. However, based on past testing in the 700 MHz frequencies, and analyses conducted by AT&T and its vendors, we can provide some general guidelines. In particular, based on the tentative analyses that have been conducted by device manufacturers and equipment vendors, the guard band between the downlink of the mobile spectrum and full powered (*i.e.*, 1 MW) television channels should be at

[6] *See* Comments of Google Inc. And Microsoft Corporation, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268, at 37 (Jan. 25, 2013) ("Google-Microsoft Comments").

least 10-14 MHz, and the guard band between the downlink of the mobile spectrum and lower powered television channels (*i.e.*, 50 kW and lower) should be at least 6 MHz.[7]

2. LTE-FDD Versus LTE-TDD Systems.

Long Term Evolution Frequency Division Duplex ("LTE-FDD") is by far the dominant LTE technology worldwide. 4G Americas reported in September 2012 that, of the 100 LTE deployments worldwide, only 9 are Time Division Duplex LTE ("LTE-TDD") systems.[8] In the U.S., all of the LTE networks that have been commercially deployed to date use FDD. The Commission has thus quite understandably focused its 600 MHz band plan on making additional spectrum available for LTE-FDD. It is our understanding, however, that Clearwire is planning to deploy an LTE-TDD system in the U.S. using Band 41 (2.5 GHz spectrum). Although Clearwire owns more than enough TDD Band 41 spectrum for such a deployment (more than 160 MHz in the top 100 markets),[9] Clearwire and its principal owner, Sprint, have asked the Commission to consider a band plan framework for 600 MHz spectrum that would allocate all or part of the spectrum for LTE-TDD. For the reasons set forth below, we believe that the Commission should not permit LTE-TDD use in the 600 MHz spectrum bands.

2.1 Significant And Costly Coordination Would Be Required For An LTE-TDD Band Plan In The U.S. 600 MHz Frequencies.

LTE-FDD systems allocate separate spectrum for uplink (*i.e.*, mobile device transmit and base station receive) and downlink (*i.e.*, base station transmit and mobile device receive). As a result, LTE-FDD band plans are designed to ensure that no two providers will be operating in a manner such that the base station (*i.e.*, "eNodeB") of one provider is transmitting in frequencies that are adjacent to the receive frequencies being used by another provider's eNodeB, thus avoiding adjacent channel interference ("ACI") between the two systems resulting from significantly different uplink and downlink power levels.

By contrast, in LTE-TDD systems, any spectrum within the licensed frequencies can, in general, be used for either transmitting or receiving signals at any given time. As a result, where two providers are operating LTE-TDD systems in the same geographic area using adjacent spectrum, there is significant potential for ACI between the two systems. That is, there is significant

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[7] In the scenarios where the uplink mobile spectrum is located next to the TV channel (*e.g.*, due to different markets clearing different amounts of spectrum), a minimum guard band of 6 MHz is recommended based on the experience with AT&T's 700 MHz Band 17 networks.

[8] Press Release, 4G Americas, 4G Americas Reports 100 Commercial LTE Networks in 49 Countries, http://www.marketwire.com/press-release/4g-americas-reports-100-commercial-lte-networks-in-49-countries-1699482.htm.

[9] Phil Goldstein, *Sprint's Hesse Looks Beyond Clearwire for Spectrum Purchases,* FierceWireless, Feb. 20, 2013, http://www.fiercewireless.com/story/sprints-hesse-looks-beyond-clearwire-spectrum-purchases/2013-02-20.

potential that the eNodeB of one LTE-TDD system will be transmitting in frequencies that are adjacent to the frequencies that a nearby eNodeB is using to receive signals at a given instant. In such circumstances, the signal from the transmitting LTE-TDD eNodeB will interfere with the other LTE-TDD eNodeB's ability to reliably receive the desired uplink signals, resulting in reduced throughput or lost connections.

Figure 1 illustrates the ACI between the eNodeBs of different TDD service providers operating in the same geographic area, where the operators have not synchronized timings and other LTE parameters.

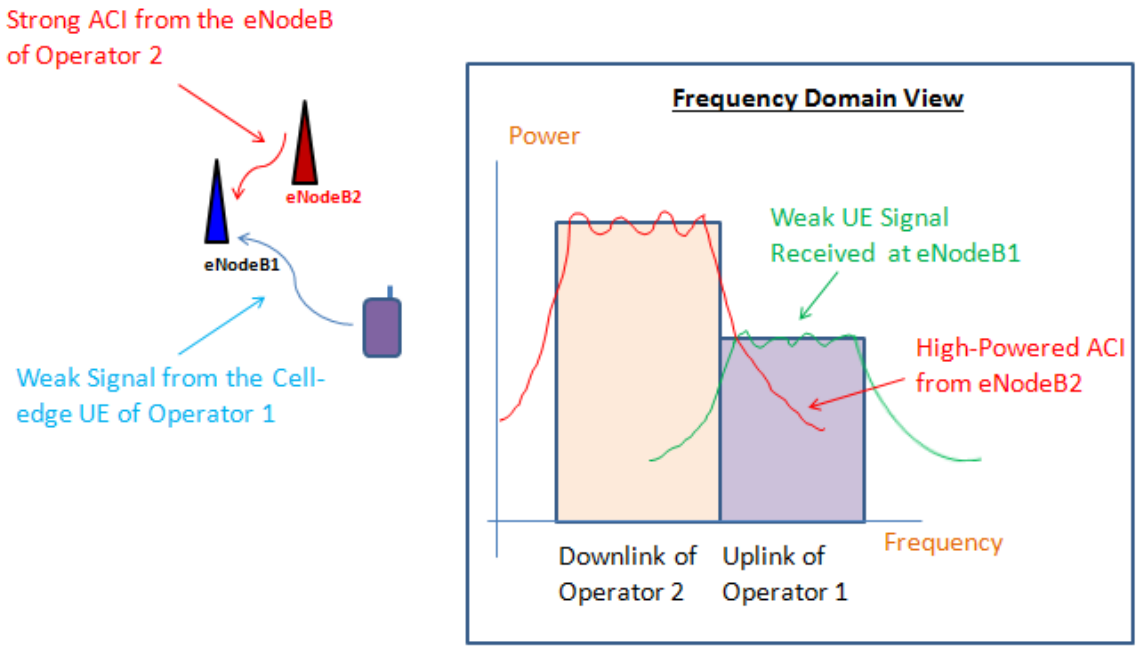

Figure 1. eNodeB-to-eNodeB Adjacent Channel Interference in LTE-TDD Systems

In Figure 1, the eNodeB1 of Operator 1 is trying to receive a weak signal from its customer's user equipment ("UE"). The eNodeB2 of another operator is located close to eNodeB1. Hence, the power level of the interfering signal is quite strong compared to the desired signal from the UE that the eNodeB1 is attempting to retrieve. At a given instant, Operator 1's uplink coincides with Operator 2's downlink, causing severe eNodeB-to-eNodeB ACI. As shown in the frequency domain view, the interfering signal could be quite high compared to the desired signal, especially when the UE is near the cell edge and the two eNodeBs are located close to each other.

This interference can be severe due to the wide disparity of the transmit power levels of the eNodeBs and the UEs. The maximum effective transmit power for an LTE UE is 23 dBm.[10] If

[10] LTE has defined Power Class 3 for traditional UEs. This power class corresponds to the maximum transmit power of 23 dBm. *See* 3GPP, TS 36.101, User Equipment (UE) Radio Transmission and Reception, Release 11, Version V11.2.0, September 2012.

there is another eNodeB nearby that is transmitting in frequencies that are adjacent to the frequency being used by the UE, significant ACI can occur because the eNodeB could easily be transmitting at effective power levels that exceed 45 dBm, far exceeding the 23 dBm of a UE. As a result, the interfering signal caused by the nearby transmitting eNodeB can easily overwhelm the signal of a UE at the receiving eNodeB, thus making it more difficult or impossible for such receiving eNodeB to retrieve the desired signal from the UE.

Figure 2 shows the ACI from one UE to another UE in case of different TDD service providers operating in the same geographic area, where the operators have not synchronized the timings and other parameters.

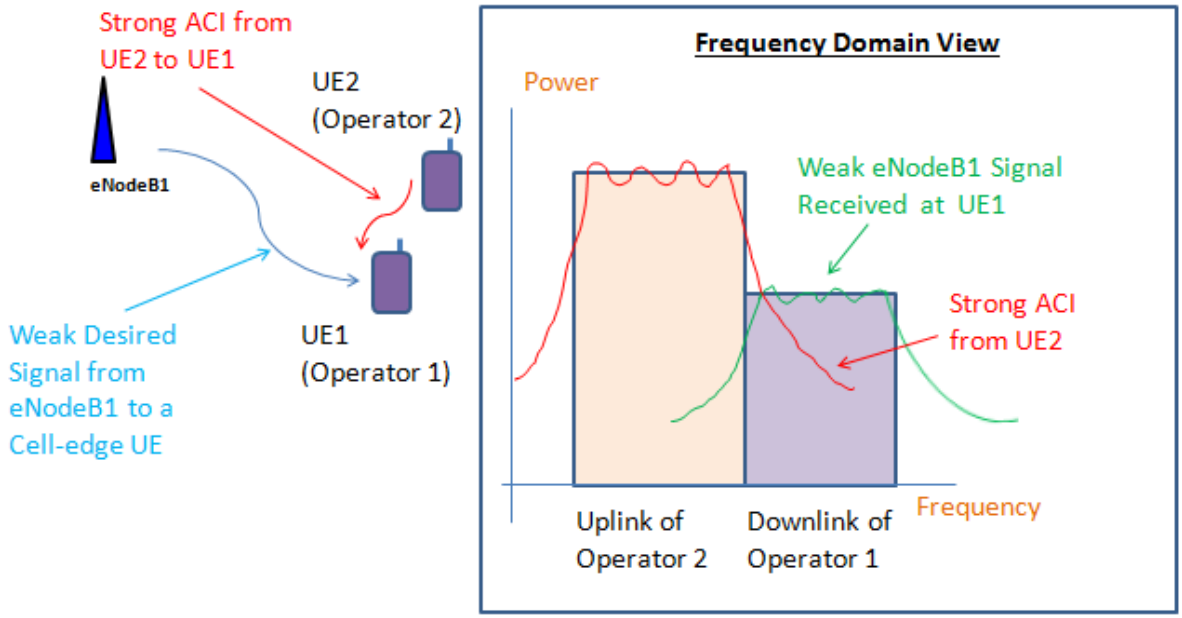

Figure 2. UE-to-UE Adjacent Channel Interference in LTE-TDD Systems

In Figure 2, the eNodeB1 of Operator 1 is sending the desired signal to its UE1. UE2 of another operator is located close to such UE1. Hence, the power level of the received interfering signal is quite strong compared to the received desired signal at UE1 that UE1 is attempting to retrieve. At a given instant, Operator 1's downlink coincides with Operator 2's uplink, causing severe UE-to-UE ACI. As shown in the frequency domain view for the received signals, the interfering signal could be quite strong compared to the desired signal, especially when the UEs are near the cell edge, because one UE's desired signal would be quite low and the interfering UE would be transmitting close to its maximum transmit power.

In areas where only one network operator is using an LTE-TDD system, that operator can design its network to avoid ACI among its own eNodeBs via a suitable timing configuration that is the same for all eNodeBs. However, where there are multiple operators using LTE-TDD systems in adjacent spectrum frequencies, each operator's LTE-TDD network would be subject to ACI from all other operators' LTE-TDD networks. As a result, a very significant level of coordination

among operators is necessary to avoid ACI. This difficulty is likely one reason why there are so few areas around the world where more than one LTE-TDD network is operating in a given frequency band.

It is our understanding that the U.S. 600 MHz spectrum is expected to be licensed to multiple network operators. Therefore, if the 600 MHz bands in the U.S. were allocated for LTE-TDD, significant coordination would be necessary among the 600 MHz spectrum licensees.

In such circumstances, there would essentially be two ways to mitigate the ACI among different LTE-TDD systems. The first approach would be to design an LTE-TDD band plan that places significant guard bands between the blocks of the LTE-TDD spectrum, thus minimizing the potential for ACI. But this approach is not practical because it would substantially reduce the overall amount of spectrum that could be put to use for mobile broadband services (a large part of the spectrum would have to be set aside as guard bands).[11]

The second approach would be for LTE-TDD operators to coordinate their networks in a manner that avoids ACI to and from other LTE-TDD networks using the adjacent spectrum. Before discussing how this coordination could be done, it is important to recognize, that this coordination must occur among all LTE-TDD providers using adjacent spectrum in a given area. If one LTE-TDD carrier does not participate in the coordination scheme, that carrier's system will interfere with (and be subject to interference from) the other LTE-TDD operators in the area.

To understand how operators in a multi-operator LTE-TDD environment must coordinate their systems, it is useful to begin by reviewing how LTE-TDD systems work in general. In TDD systems, transmissions are divided into time segments that are transmitted over a given frequency at specified times (measured in milliseconds). The receiver, by coordinating with the transmitter, knows which time segments contain the information it is attempting to receive, and the receiver is thus able to reconstitute the data that was transmitted to it. In Figure 3, below, we illustrate a simplified timing structure for an LTE-TDD system.

[11] *See also* Comments of Nokia Siemens Networks US LLC, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268, at 12 (Jan. 25, 2013) ("Nokia Siemens Comments").

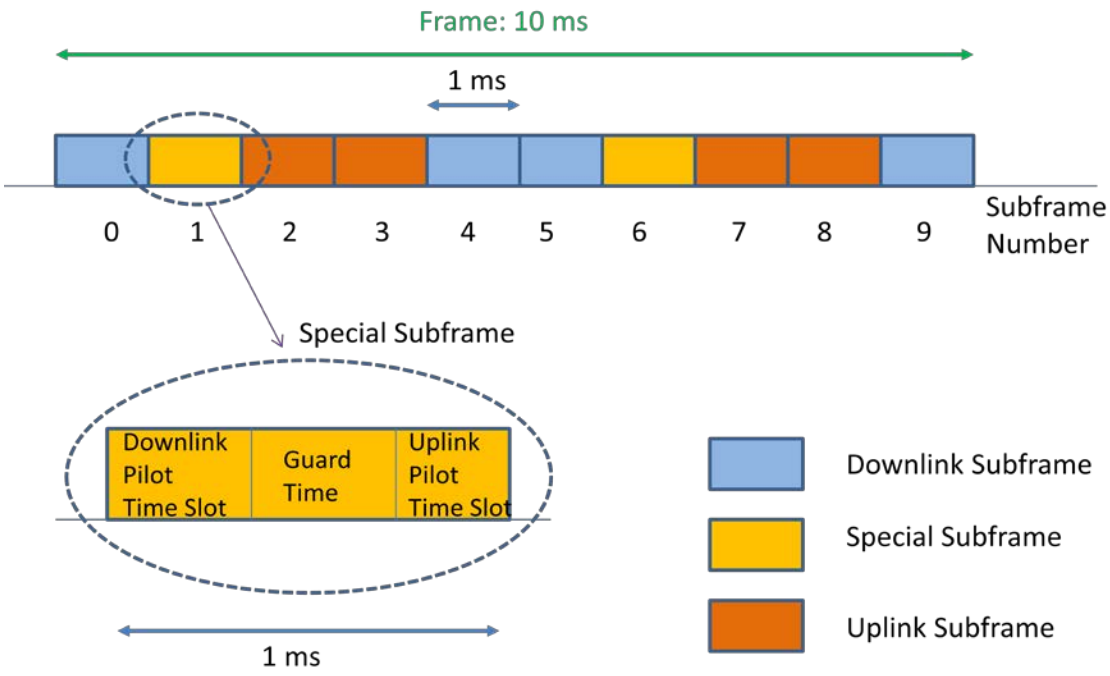

Figure 3. Example Timing Structure of an LTE-TDD System[12]

As Figure 3 illustrates, LTE-TDD systems use 10 millisecond (ms) time periods called "frames." Each frame is subdivided into ten 1 ms time periods called "subframes," and subframes are numbered from 0 to 9. A subframe could contain a downlink transmission, an uplink transmission, or a "special" transmission. A downlink subframe carries the downlink traffic and signaling messages from the eNodeB to the UE(s) and conveys both the downlink resource allocations and the uplink resource allocations. An uplink subframe carries the uplink traffic and uplink signaling messages from the UE(s) to the eNodeB.[13] A "special" subframe facilitates switching from downlink to uplink.[14]

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[12] The LTE standard allows several possible timing structures for TDD. Figure 3 shows one of the supported configurations (*i.e.*, the "subframe assignment 1"). The same principles apply to other configurations.

[13] The uplink subframe also allows the UE(s) that do not have a dedicated radio connection with an eNodeB to use a common random access channel to contact the eNodeB.

[14] As shown in Figure 3, the special subframe includes a downlink portion called the downlink pilot time slot, a guard time, and an uplink portion called the uplink pilot time slot. The downlink pilot time slot includes the primary synchronization signal to facilitate downlink synchronization by the UEs and allows the flexibility to carry downlink traffic and downlink signaling messages. The guard time enables an entity (*e.g.*, an eNodeB) to stop transmitting and to prepare to receive. The uplink pilot time slot may contain (i) reference signals that enable the eNodeB to estimate uplink channel conditions before the regular uplink

With this general understanding of LTE-TDD systems, it is easy to see how the ACI discussed above will occur. The subframes described above are transmitted in the frequencies used by the LTE-TDD network operator. Absent coordination, when two LTE-TDD network operators are using adjacent spectrum, one operator may allocate certain subframes to uplink, while the other system allocates the same subframes to downlink. In this situation, one carrier's eNodeB would be attempting to receive at the same time that the other carrier's eNodeB is attempting to transmit in an adjacent frequency, thus causing ACI.

To avoid this interference, the LTE-TDD operators must tightly coordinate their networks to ensure that they are always either all transmitting or all receiving at any given time.

This coordination is complex. To begin with, all of the LTE-TDD network operators must agree on a framework for determining the time to ensure that the timing of their 10 ms frames and 1 ms subframes are the same. A typical approach is for the operators to agree on the use of an accurate and common timing mechanism, such as a Global Positioning System ("GPS") and to agree when to start a given frame and subframe based on the GPS-based time.

Once the frame and subframe timings are agreed upon, the operators must ensure that they use the same settings for certain operational parameters. For example, the operators need to agree on which subframes to use as the downlink subframes and which subframes to use as the uplink subframes. In this regard, the operators must agree to use the same ratio of downlink subframes to uplink subframes so that the downlink (or uplink) subframes for all TDD operators occur at the same time. The TDD eNodeB advertizes the downlink/uplink ratios in a System Information Block 1 message via a parameter called "subframe assignment" or "sa." For example, in case of subframe assignment = 1, subframes 1 and 6 are special subframes, subframes 0, 4, 5, and 9 are downlink subframes, and subframes 2, 3, 7, and 8 are uplink subframes. Such a configuration corresponds to the downlink/uplink ratio of 6:4, where 6 is the effective number of downlink subframes (which is the sum of the number of regular downlink subframes and two special subframes) and 4 is the number of uplink subframes. Seven different downlink/uplink ratios or subframe assignments are supported in LTE-TDD.[15]

The need for all of this coordination to avoid ACI among LTE-TDD systems can significantly increase the cost and uncertainty associated with spectrum allocated for use in LTE-TDD systems as compared to spectrum allocated for use in LTE-FDD systems.

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transmissions start from the UE(s) or (ii) random access opportunities that are useful for small cells.

[15] Operators also have to agree upon common values for various special subframe parameters, including (1) the length of downlink pilot time slot; (2) the guard time; and (3) the length of the uplink pilot time slot. There are nine special subframe patterns that specify different durations for the downlink portion, the guard time, and the uplink portion. The TDD eNodeB advertizes the special subframe configuration in the System Information Block 1 message via a parameter called "special subframe pattern (ssp)."

There will likely be significant transaction costs associated with achieving the coordination that is necessary in LTE-TDD systems that are not required for LTE-FDD systems. As noted, if 600 MHz spectrum were allocated for use in LTE-TDD systems, each operator that uses 600 MHz spectrum will have to coordinate with all the other operators using 600 MHz spectrum to avoid ACI. Negotiating and attaining these agreements will require human resources, financial resources, and likely significant time. In addition, disputes may arise that may need to be resolved through actions by the FCC or in courts.

To further complicate matters, each provider may have to negotiate such coordination with different sets of other providers in each area. For example, "Provider A," may have to coordinate with "Provider B" and "Provider C" in New York, but with "Provider D" and "Provider E" in Chicago.

Furthermore, operators will have to frequently update their coordination arrangements to the extent they wish to alter the coordination parameters, including, for example, the downlink-to-uplink ratio.

The need to coordinate with multiple other providers and different sets of providers throughout the U.S. would also add significant uncertainty as to the actual amount of expected interference to any provider that purchases 600 MHz LTE-TDD spectrum. When assessing the value of 600 MHz spectrum allocated for LTE-TDD systems – and hence auction bids – potential bidders must account for the fact that they may not be able to reach coordination arrangements (or that it will take significant time and resources to reach coordination agreements) with other operators in at least some areas, thus significantly impairing the usefulness of the spectrum.

In addition, to reach coordination agreements with all other 600 MHz LTE-TDD operators in a given area, at least some operators will likely have to settle for sub-optimal coordination arrangements. As discussed above, any successful coordination arrangement must include agreement on the subframe downlink/uplink ratio, which effectively dictates the relative downlink/uplink capacity in a network. If one carrier desires substantially more downlink capacity in its network and another carrier desires significantly less downlink capacity (and correspondingly more uplink capacity), any coordination agreement will require one or both of the providers to agree to a sub-optimal uplink/downlink ratio for their network. Such a conflict of interest may arise due to the different traffic demands of different operators.

For all of these reasons, it is our view that operators would place substantially lower value on 600 MHz spectrum if it were allocated for use in LTE-TDD systems than if it were allocated for use in LTE-FDD systems.

We disagree with the assertions made by Sprint and Clearwire that LTE-TDD systems would not necessarily raise costs and uncertainty compared to LTE-FDD systems. Sprint, for example, states that in some instances even LTE-FDD operators must coordinate with each other to avoid interference. But neither Sprint nor any other commenter that addresses LTE-TDD systems

suggests that the level of LTE-FDD coordination comes even close to the level of coordination that is needed for LTE-TDD systems.

More fundamentally, Sprint's observation that even LTE-FDD providers may sometimes engage in some coordination is irrelevant to the 600 MHz spectrum at issue here. The Commission can, and should, adopt a 600 MHz LTE-FDD band plan that avoids potential inter-provider interference, and thus avoids the need for any significant coordination among providers. And particularly to the extent that package bidding and block assignment processes provide horizontal frequency contiguity, the LTE-FDD band plans proposed by the FCC and other parties to this proceeding obviate the need for any significant coordination among the FDD operators. By contrast, any LTE-TDD band plan would necessarily require the significant coordination described above (unless the FCC chooses to set aside very large amounts of spectrum as guard bands between each operator's licensed spectrum, which would lead to much less amount of usable licensed spectrum).

Sprint and Clearwire assert that LTE-TDD systems are typically more flexible than LTE-FDD systems. Sprint and Clearwire suggest that LTE-TDD operators can easily adjust the relative times being used for uplink and downlink – and hence relative uplink and downlink capacity – to account for changes in how consumers use mobile services. They state that LTE-FDD, by contrast, is inflexible in this regard due to the fact that specific spectrum is allocated for uplink and downlink.

This is simply not accurate in a multiple LTE-TDD operator environment. First, for practical deployments, it is not correct that an operator can dynamically change the uplink/downlink ratio in a particular eNodeB (or even a cell), to match consumer traffic patterns at that eNodeB. As we explained above, within any operator's network, all eNodeBs must use the same uplink/downlink ratios. Thus the uplink/downlink ratio must essentially be changed on all eNodeBs in an area or none of them. Furthermore, it is not true that an LTE-TDD operator would be able to easily and unilaterally alter the uplink/downlink ratio even for all of its own eNodeBs. As discussed above, each operator in an area must use the same uplink/downlink ratio. We note that Sprint expressly recognizes in a footnote that "TDD operators must agree on asymmetry ratios and synchronize their transmissions in order to avoid adjacent-channel interference in the absence of guard bands," which it concedes is a "disadvantage of TDD."[16] Therefore, if an operator seeks to change that ratio for its network, it must obtain the agreement of all other operators in the area(s) where it wishes to make that change. And there will always be uncertainty as to whether the other operators would agree to make that change, especially if other operators are experiencing different traffic patterns.

Sprint and Clearwire also overlook the fact that LTE-FDD networks are becoming increasingly flexible in terms of the relative amount of uplink and downlink capacity. Although commercial

[16] Comments of Sprint Nextel Corporation, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268, at 20 n.40 (Jan. 25, 2013).

LTE-FDD deployments typically use symmetric downlink channel bandwidth and uplink channel bandwidth today, the 3GPP standards have supported asymmetric channel bandwidths for the downlink and the uplink from the first LTE release (*i.e.*, Release 8). Carrier aggregation in LTE-Advanced further facilitates higher degrees of asymmetry by allowing different numbers of carrier frequencies and different amounts of channel bandwidths for the downlink and the uplink. In fact, asymmetric carrier aggregation with more resources in the downlink and fewer resources in the uplink would be quite common in practical LTE-Advanced deployments. LTE characteristics (applicable to both FDD and TDD) such as adaptive modulation and coding, fast feedback about channel conditions, multiple antenna techniques, fast scheduling, and hybrid automatic repeat request (H-ARQ) provide additional flexibility to meet the QoS requirements of different users and different applications in the downlink and the uplink.

Finally, we note that a TDD band plan would require more coordination effort for the LTE-TDD operators with TV broadcasters to manage co-channel interference in adjacent markets than an FDD band plan. In TDD operations, one would have to define exclusion zones based on acceptable levels of interference to both base stations and mobile devices, and in a typical deployment, the worst case scenario (*i.e.*, the larger exclusion zone) will dictate the network design. In an FDD band plan, the operator would be concerned with *either* protecting base station receiver (for uplink) or mobile receiver (downlink) but not both at the same location. Combined with the fact that different markets will clear different amounts of spectrum, the network design in an LTE-TDD band plan would be significantly more challenging compared to an LTE-FDD band plan.

2.2 LTE-TDD Systems Have Smaller Cells or Lower Cell-edge Throughput.

Another significant disadvantage of LTE-TDD systems compared to LTE-FDD systems is that LTE-TDD systems typically require smaller cells to attain the same target cell edge throughput.[17]

To understand why this is so, it is useful first to review the difference in the number of physical resource blocks ("PRBs") needed by LTE-FDD and LTE-TDD systems to transmit the same amount of data in the same amount of time. In an LTE system, each 5 MHz block of spectrum has 25 PRBs that can be used to transmit or receive data. All else being equal, the amount of data that can be transmitted in any given time increases with the number of PRBs allocated to the transmission.

Now, consider an LTE-FDD system that can complete a data file transmission in 10 seconds using 5 PRBs. All else being equal, a LTE-TDD system could not complete the same data file transmission in the same time using only 5 PRBs. To see this, consider a LTE-TDD system that is designed with a 50:50 uplink/downlink ratio, which means that, unlike the continuously transmitting LTE-FDD system, it uses only half of its time transmitting and the other half of its

[17] *See* Harri Holma and Antti Toskala, *LTE for UMTS: Evolution to LTE-Advanced* (2d ed. 2011); Angel Ivanov, *TD-LTE and LTE-FDD- A Basic Comparison*, Ascom Document: NT11-1036 (Jan. 12, 2012).

time receiving. Using 5 PRBs, this LTE-TDD system would require twice the time to transmit the same data file compared to the LTE-FDD system. Therefore, to achieve the same performance as an LTE-FDD system, the LTE-TDD system must allocate more PRBs to the transmission. In this example, the LTE-TDD system might need to allocate 10 PRBs (*i.e.*, twice the number of PRBs used by the LTE-FDD system) to achieve the same average data transfer rate as the LTE-FDD system. Since an LTE-TDD system has twice as many PRBs as an equivalent LTE-FDD system, both systems appear to have similar average throughput when the LTE-TDD has 50% downlink and 50% uplink.

With this backdrop, however, it is easy to see why an LTE-TDD system requires smaller cells to achieve the same cell edge throughput as an LTE-FDD system, all else being equal. Consider the uplink cell-edge throughput first. The maximum available transmit power for a UE is 23 dBm. This power is spread equally over each of the PRBs being used in a transmission. As a result, the greater the number of PRBs used in a transmission, the lower the transmission power levels per PRB. In other words, the power spectral density (*i.e.*, power per Hz) is lower when more resource blocks are used. Hence, to achieve the same reliability of successful packet retrieval, the propagation path loss between the eNodeB and the UE needs to be smaller when more PRBs are used. Thus, all else being equal, a UE that is transmitting over a larger number of PRBs must be closer to the base station to achieve the same throughput and reliability as a UE that is transmitting using fewer PRBs (and that is at a larger distance from the eNodeB).

LTE-TDD systems are likewise disadvantaged for downlink. Consider the downlink throughput near the cell-edge. For a given maximum power level at the eNodeB, the power per PRB is smaller for an LTE-TDD system because the LTE-TDD system requires more PRBs than an LTE-FDD system to achieve the same data-rate. The supportable throughput per PRB is thus smaller for the LTE-TDD system compared to the LTE-FDD system in areas farther away from the eNodeB. Hence, after accounting for the uplink/downlink ratios, the LTE-FDD system will generally yield higher cell-edge throughput in the downlink than the LTE-TDD system.

2.3 Harmonics.

An allocation of 600 MHz spectrum for LTE-TDD could also result in harmonics that interfere with mobile services using PCS spectrum, as well as other wireless services spectrum. As we explained in our first paper, transmissions in the frequency range from 643-665 MHz would create third order harmonics that fall within the receive bands for PCS spectrum, and thus would interfere with PCS mobile services. We note that Qualcomm's analysis of harmonics generated by transmissions in these frequencies supports our conclusions.[18]

Allocating these frequencies from 643-665 MHz to LTE-TDD, as Sprint proposes, would result in exactly this type of harmful interference. As noted, LTE-TDD can transmit or receive in any of

[18] Comments of Qualcomm Incorporated, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268, at 6-7 (Jan. 25, 2013) ("Qualcomm Comments").

its allocated frequencies. Thus, when LTE-TDD systems transmit in the 643-665 MHz frequencies, it will result in harmonics that fall within the receive frequencies for the PCS spectrum. For this reason, Alcatel-Lucent states that "it is not recommended that TDD operate at 1/3 the PCS downlink band (643 to 665 MHz) . . ."[19] For these reasons, we proposed that the Commission's 600 MHz band plan framework avoid allocating these frequencies to the uplink.

Although the exact impact of this interference cannot be fully quantified without real-world testing across a multitude of devices, it is a significant risk. This harmonic interference can be problematic for a dual receiver or dual-transceiver UE supporting simultaneous operations on the 600 MHz band and the PCS band. For example, when a TDD UE is transmitting on a 600 MHz band, it may also be listening to a PCS band for a legacy network to receive an incoming page message from a 3G 1xRTT system or to make measurements of a 3G PCS system for an impending handover to the PCS band. Reception of the PCS band signal would be adversely affected by the 600 MHz transmission, leading to possibly missed page messages and delayed handover (increasing the likelihood of a call drop). Similarly, when a 600 MHz LTE-TDD UE is in close proximity to a PCS band UE, the harmonic transmission from the 600 MHz UE may cause significant interference to the PCS band UE. Alcatel Lucent has pointed out that a similar interference situation has been observed in the field, where a 700 MHz UE has caused harmonic interference to an AWS band UE.[20]

2.4 Less Overall Spectrum.

Allocating the 600 MHz spectrum in the U.S. to LTE-TDD would result in less overall spectrum being allocated for mobile broadband services. As Alcatel-Lucent points out, two significant guard bands of at least 10 MHz each on both sides of the TDD band (*e.g.*, a TV channel or Channel 37 on one side and the 700 MHz uplink on the other side) would be needed to protect the TDD systems and the systems adjacent to the TDD systems. These guard bands alone thus eliminate 20 MHz of spectrum from licensed mobile use. In addition, as noted, Alcatel-Lucent recommends not using spectrum in the 643-665 MHz range for uplink to avoid creating harmonics that interfere with PCS and other services.

Thus, for example, in areas where the auction clears all of the spectrum above Channel 37 for mobile broadband services, there would be 84 MHz of available spectrum. As we demonstrated in our prior paper, with appropriate guard bands, an FDD-system could efficiently allocate at least 70 MHz of this spectrum for mobile use. By contrast, as Alcatel-Lucent points out, an LTE-TDD system could allocate at most 64 MHz for mobile broadband use, due to the need for guard bands to protect Channel 37 and 700 MHz FDD systems.[21] Moreover,

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[19] Comments of Alcatel-Lucent, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268, at 11 (Jan. 25, 2013) ("Alcatel-Lucent Comments"); *See also,* Nokia Siemens Comments, at 13.

[20] *See* Alcatel-Lucent Comments, at 13-14.

[21] *See id.* at 11.

if the Commission were to also avoid allocating frequencies from 643-665 MHz to LTE-TDD, that would further reduce the amount of usable licensed mobile spectrum under a LTE-TDD allocation to 42 MHz – far less than the 70 MHz that would be available under the LTE-FDD plan presented in our initial paper.[22]

2.5 Other Considerations: Implications for Upcoming Enhancements for LTE Networks and Ecosystems.

As the FCC has correctly pointed out in the NPRM, LTE is the expected technology of choice for the 600 MHz deployments. While LTE-Advanced allows carrier or spectrum aggregation of multiple channels across different frequency bands to significantly increase peak and average throughput, such aggregation is feasible (i) within FDD bands or (ii) within TDD bands but not for a hybrid TDD-FDD situation. In other words, the LTE-FDD networks will not be able to exploit the carrier aggregation capability offered by LTE-Advanced to combine the 600 MHz TDD band with an existing FDD band such as the PCS band or the AWS band, significantly limiting user and network throughput relative to networks that can take advantage of these technology advances and hence reducing the value of the band to bidders since they could not do carrier aggregation with that 600 MHz TDD band.

Heterogeneous Networks (HetNets) represent another area where LTE-Advanced can improve network performance and the user experience. HetNets combine the benefits of large macrocells and small cells and enable high cell-edge throughput via more frequent reuse of precious radio resources in small cells. Features such as enhanced inter cell interference coordination (eICIC)[23] and further enhanced ICIC (FeICIC)[24] facilitate deployment of HetNets. The deployment of small cells[25] would be much more challenging for TDD due to the need for strict timing requirements across all the cells. FDD can circumvent such deployment challenges by using one frequency channel for all macrocells and a separate frequency channel for all of the small cells (that do not need timing coordination).

Channel reciprocity is frequently cited as an advantage of TDD systems compared to FDD systems, where the eNodeB can simply observe the uplink to reliably predict the downlink

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[22] *See* Reed-Tripathi Initial Paper, at 29.

[23] eICIC facilitates coordination between the macrocells and small cells via time domain scheduling of resources to minimize interference between the macrocells and small cells when the same radio channel (*e.g.*, in time domain) is used in microcells and small cells. Another way to minimize interference between the macrocells and small cells is to use different radio channels (*i.e.*, one channel for a macrocell and a different channel for a small cell).

[24] FeICIC involves interference cancellation at the UE receiver based on the knowledge of the time-frequency location of the cell-specific reference signals.

[25] Smalls cells could be femtocells in homes or somewhat larger cells such as pico cells and micro cells that could cover one or more buildings. *See* Small Cell Forum, http://www.smallcellforum.org/.

channel conditions. Such channel reciprocity is possible in TDD systems because the same spectrum is used for the uplink and the downlink. FDD systems require feedback from the UE on the downlink channel conditions, while TDD systems could theoretically avoid the need for such feedback. However, with the use of multiple antenna techniques such as spatial multiplexing in the current and emerging LTE deployments, TDD systems no longer hold any significant channel reciprocity advantage compared to FDD systems, because the number of antennas at the eNodeB and the UE are different. For example, for (2x2) downlink MIMO to work properly, the UE needs to estimate downlink channel conditions on a total of four propagation paths. The UE in current deployments, however, transmits from only one antenna and the eNodeB receives signals on two antennas, leading to reliable estimation of channel conditions on only 2 propagation paths. Since the channel conditions on 2 uplink propagation paths are not adequate to estimate downlink channel conditions on four propagation paths, the claimed channel reciprocity advantage of TDD systems compared to FDD systems is essentially non-existent in modern deployments.[26] The asymmetry in the number of antennas at the eNodeB and the UE is expected to persist in future deployments as well, because LTE-Advanced also defines more transmit antennas at the eNodeB and fewer transmit antennas at the UE. Finally, limited space in the UE (compared to the eNodeB) would very likely result in more antennas at the eNodeB and fewer antennas at the UE.

2.6 Additional Interference & Coordination Challenges In A Mixed TDD/LTE-FDD Environment.

Clearwire states that 600 MHz spectrum should be allocated with maximum flexibility so that providers can choose whether to use it for LTE-FDD or LTE-TDD. We respectfully disagree with this approach. We recommend that the FCC limit the use of 600 MHz spectrum to LTE-FDD services because, in addition to the interference and coordination challenges associated with LTE-TDD deployments (discussed above), a mixed TDD and FDD environment would create additional significant interference concerns.[27]

First, a mixed TDD and FDD environment would create significant potential for co-channel interference. We explained co-channel interference in our initial paper. In short, co-channel interference occurs where the interfering wireless system is transmitting in the same frequencies in which the victim wireless system is attempting to receive. Because the interfering signal is using the same frequencies as the receiver and thus is inside the passband of the receive filter, the receiver is unable to filter (and thus attenuate) the interfering signal. In

[26] Even in the case of uplink switched time diversity, the random nature of fading would not make TDD much more efficient than FDD. Furthermore, although supported in the standard, typical UEs are not capable of switching the antenna to transmit a signal.

[27] *See, e.g.,* Nokia Siemens Comments, at 11 ("Interleaving of FDD and TDD blocks in a random manner is not recommended as it will require guard bands at each FDD/TDD frequency border").

these circumstances, the throughput for the receiver can be significantly impaired, and the receiver may even lose its radio connection.

In a mixed LTE-TDD/LTE-FDD environment, LTE-TDD and LTE-FDD networks could be deployed using the exact same frequencies in adjacent geographic areas. Because the LTE-TDD network can transmit at any given time in any given frequency, the LTE-TDD network will inevitably end up transmitting in the same frequencies that the LTE-FDD network in the adjoining geographic area uses to receive transmissions. In these circumstances, the LTE-FDD base station will not be able to filter the strong co-channel LTE-TDD signal, and will thus experience significant interference that can substantially reduce throughput and result in lost connections. It is also possible for the LTE-FDD system to cause interference to the LTE-TDD system.

This co-channel FDD-TDD interference is not a hypothetical concern. This is a problem that AT&T faces today in Kansas City. AT&T owns lower 700 MHz B and C block licenses in much of Kansas City. However, two other providers own 700 MHz C block licenses in certain parts of Kansas City. These other providers have deployed a WiMAX-TDD network. As a result, the TDD-WiMAX base stations used by these providers are transmitting in the lower 700 MHz C block spectrum in areas immediately adjacent to where AT&T is operating an LTE-FDD network using lower 700 MHz spectrum. As a result of the AT&T system's close geographic proximity to the TDD-WiMAX system, several AT&T base stations experienced crippling interference when attempting to use the lower 700 MHz C block for LTE-FDD. AT&T has thus been forced to operate only with 700 MHz B block spectrum in large portions of Kansas City, resulting in substantially lower capacity and throughput than would be achievable if AT&T's 700 MHz C block spectrum were not impaired by the nearby 700 MHz WiMAX-TDD transmissions. AT&T's experience in Kansas City provides an example of what would likely occur throughout the country if the FCC were to allow mixed FDD and TDD use in 600 MHz spectrum.

Our discussion in this section so far has focused on co-channel interference. But a mixed FDD and TDD 600 MHz band plan would also likely result in significant adjacent channel interference where FDD and TDD systems are operating in the same geographic area. If an FDD operator wins a block in the FDD portion of the mixed band, and a TDD operator wins the TDD portion of the mixed band in the same geographic area, there would be significant ACI between the FDD and TDD systems. Indeed, a 10 MHz guard band is recommended by Alcatel-Lucent between the TDD systems and the FDD systems to minimize interference. The overall amount of licensed spectrum would be much smaller when we account for such additional guard bands.[28]

3. Duplex Gap Size.

In LTE-FDD systems, it is important to have a guard band between the uplink and the downlink frequencies. The guard band between uplink and downlink frequencies in an FDD system is typically referred to as the "duplex gap."

[28] *See also, e.g., id.*

A sufficiently sized duplex gap in an LTE-FDD system is necessary to avoid different types of interference within the system. For example, transmissions from the transmit portion of the UE can cause severe ACI to the receive portion of the UE as shown in Figure 4. The duplexer's filters cannot provide adequate attenuation if the duplex gap is too small.

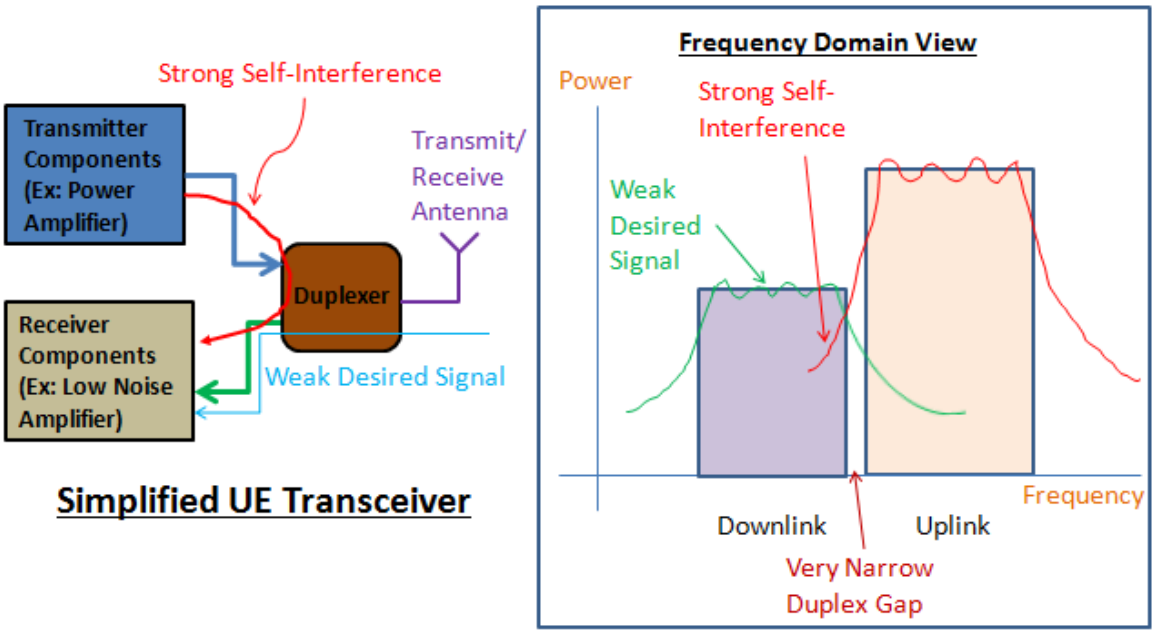

Figure 4. Self-Interference Inside a UE Transceiver due to Insufficient Duplex Gap

Another type of interference is eNodeB-to-eNodeB interference that the duplexer can mitigate. For example, if the duplex gap is too small, the downlink transmissions from an eNodeB could cause adjacent channel interference to nearby eNodeBs, adversely affecting the ability of these nearby eNodeBs to receive desired uplink transmissions from UEs. This type of interference is shown in Figure 5.

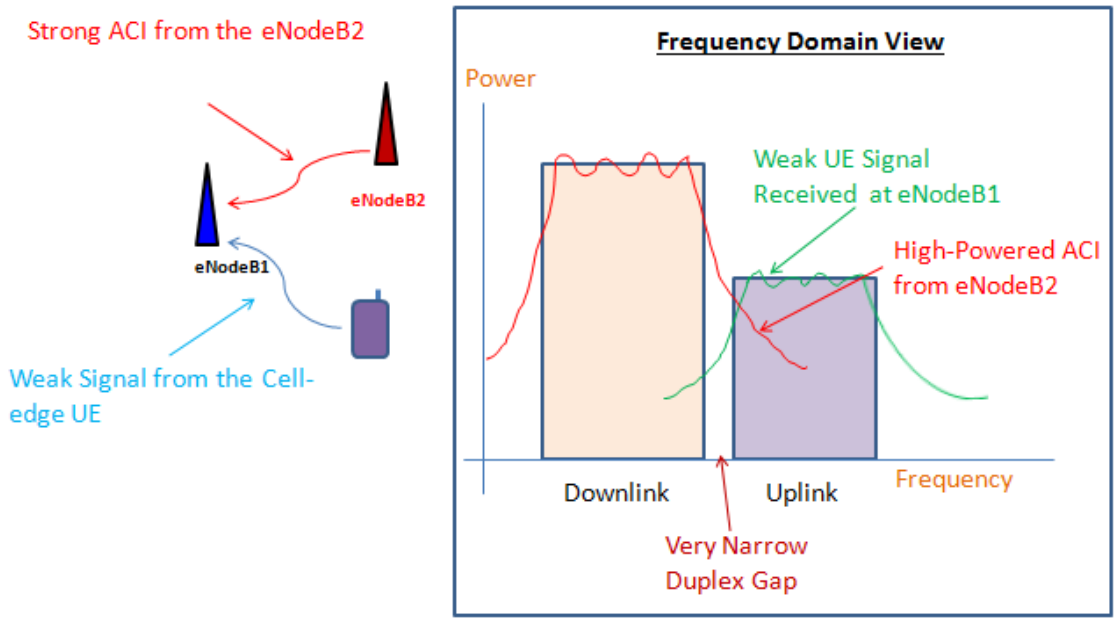

Figure 5. eNodeB-to-eNodeB Interference When Duplex Gap Is Too Small

As shown in Figure 5, eNodeB-to-eNodeB interference can be severe due to the wide disparity of the transmit power levels of the eNodeBs and the UEs. As noted, the maximum effective transmit power for an LTE UE is 23 dBm. If there is an eNodeB nearby that is transmitting in frequencies that are adjacent to the frequency being used by an eNodeB to receive the uplink signals from its UE, significant ACI can occur because the eNodeB could easily be transmitting at power levels that exceed 45 dBm, far exceeding the 23 dBm transmit power of a UE. As a result, the interfering signal caused by the nearby transmitting eNodeB could easily overwhelm the signal of a UE, thus making it quite difficult for the receiving eNodeB to retrieve the desired signal from the UE.

In addition to eNodeB-to-eNodeB interference, there can also be UE-to-UE interference. That is, the uplink transmissions from one UE would cause adjacent channel interference to nearby UEs, which impairs the ability of such UEs to receive desired downlink transmissions from their eNodeBs. This type of interference is shown in Figure 6.

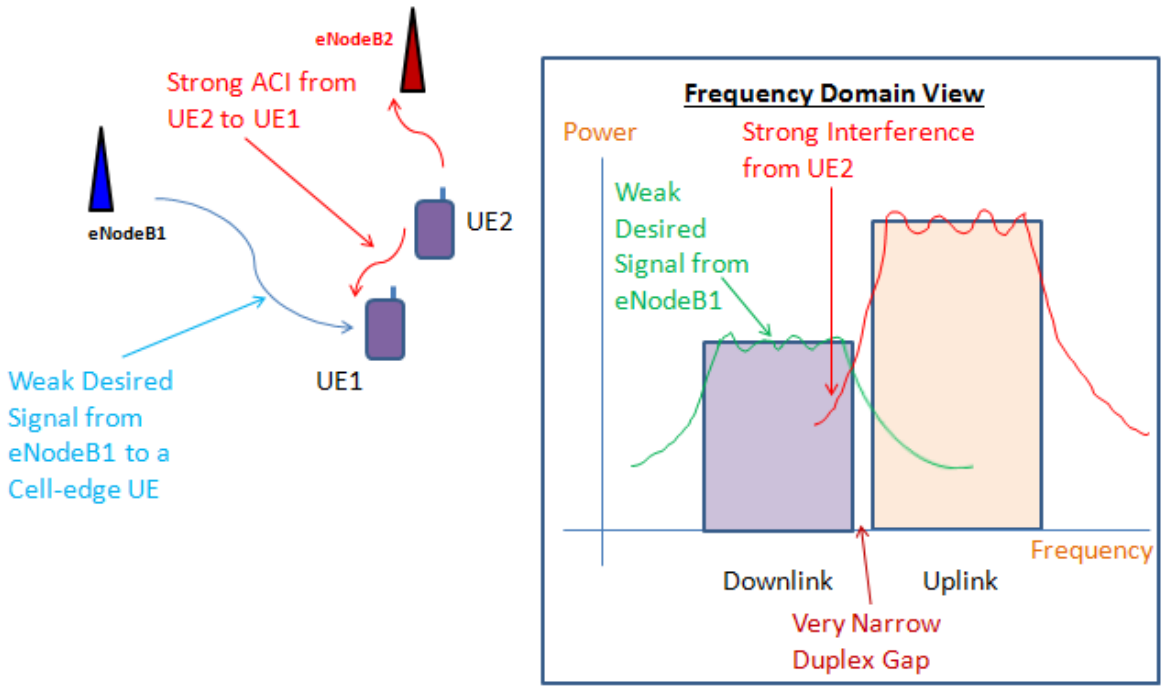

Figure 6. UE-to-UE Interference When Duplex Gap Is Too Small

The NPRM sought comment on the proper size of the duplex gap. At the time we filed our initial paper, the available analyses indicated that a duplex gap size for 600 MHz spectrum should be in the range of 10 MHz to 14 MHz. Upon further investigation by AT&T and its vendors, as well as the analyses of various other commenters in this proceeding, this range has been narrowed to 10-12 MHz. In addition, as we explain below, the maximum duplex gap should be no greater than about 15 MHz, because a larger duplex gap would either significantly reduce the available amount of paired spectrum, or force device manufactures to make design decisions that would result in larger or lower quality devices.

Minimum Duplex Gap Size Of 10-12 MHz. The minimum size of the duplex gap is driven by simple wireless engineering requirements needed to avoid interference between the uplink and the downlink in an LTE-FDD system. According to basic engineering principles, real world considerations, and analyses by AT&T and its vendors, the duplex gap in the 600 MHz bands should be no smaller than about 10-12 MHz.

There is a well-established engineering principle that the duplex gap should be greater than at least 1% to 1.5% of the center frequency in which the service is operating. For example, the IWPC, the international wireless consortium that includes the major filter manufacturers, has shown that a duplex gap below 1% can make it extremely challenging to design adequate filtering, and that even a duplex gap of 1.5% of the center frequency is generally "hard" to

accommodate.[29] The analysis presented by the IWPC shows that attempts to accommodate a smaller duplex gap would lead to unacceptable insertion loss that would significantly degrade performance.[30] These facts have been confirmed by Alcatel-Lucent and multiple terminal filter manufacturers.[31] This limitation has also been confirmed to AT&T and ourselves by various vendors. Based on these figures, an LTE-FDD band centered at about 650 MHz requires a duplex gap of at least between 6.5 MHz (1%) and 9.75 MHz (1.5%).

To accommodate real world production and environmental factors, however, the duplex gap needs to be even larger. For example, as explained by IWPC, there are significant variations in manufacturing processes for the acoustic filters that are widely used in mobile wireless devices, which can lead to about 0.15% variation in the filter response.[32] The manufacturing variation leads to 3 MHz bandwidth change at 2 GHz and 1 MHz bandwidth change at 650 MHz.[33] Variations also occur due the fact that different manufactures produce filters with different performance characteristics.[34]

Another factor causing variation in the filter response is variations in temperature.[35] The performance of a filter can vary substantially in hot weather compared to cold weather (or as the components in the device heat up and cool).[36] The change in the frequency response of a filter is referred to as temperature motion of the filter, which is defined by its temperature coefficient or "Tempco."[37] Tempco is specified in parts per million per degree C (*i.e.,* ppm/C). For a typical acoustic filter, Tempco is -30 ppm/C, and according to IWPC calculations, the frequency of a filter can shift by 6.9 MHz at 2 GHz center carrier frequency.[38] Calculations

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[29] *See* Presentation by the International Wireless Industry Consortium Mobile RF Filter Group, submitted in the FCC's GN Docket No. 12-268 on November 27, 2013 ("IWPC Presentation"). The IWPC is an organization of more than 140 Wireless and RF product manufacturers and suppliers including, for example, Avago Technologies, MuRata, TDK-EPC, and TriQuint Semiconductor, that together represent the majority market share of RF filtering solutions for mobile devices. *Id.* at 2.

[30] IWPC Presentation, at 10-11, 15.

[31] Alcatel-Lucent Comments, at 21-22 ("As detailed in the IWPC submission in this proceeding and confirmed by Alcatel-Lucent's discussions with terminal filter manufacturers, it is currently difficult to make terminal filters with duplex gaps narrower than about 1.5%.").

[32] *See* IWPC Presentation, at 12.

[33] *See id*.

[34] *See id*.

[35] *See id.* at 13.

[36] *See id*.

[37] *See id.*

[38] *See id*.

based on this methodology show that the frequency could shift by 2.2 MHz at the center carrier frequency of 650 MHz.[39]

Taken together, the variations in the filter response could lead to about (1 MHz due to manufacturing variations + 2.2 MHz due to temperature variations = 3.2 MHz) change in the frequency at 650 MHz. Using the 1% rule, the duplex gap needs to be (6.5 + 3.2= 9.7 or about 10 MHz). The use of 1.5% rule leads to (9.75 + 3.2 = 12.95 or 13 MHz).

There appears to be strong consensus within the industry that the minimum duplex gap that the filter can be designed for and that will protect against harmful self-interference in real-world deployments must be at least 10-12 MHz.[40]

Maximum Duplex Gap Size. If the goal of the auction is to maximize the amount of paired spectrum, the duplex gap should be no larger than the minimum needed to avoid interference (as described above, this minimum size is about 10-12 MHz). A simple example illustrates this point. Consider a device that can support a bandwidth of about 65 MHz (the bandwidth is the sum of the frequencies used for the uplink, downlink, and duplex gap). If that device has a duplex gap of 15 MHz, it will have 50 MHz left over for paired spectrum, resulting in five pairs of 5 MHz FDD spectrum blocks. A larger duplex gap would reduce the amount of spectrum available for FDD pairs. Thus, a duplex gap no larger than 15 MHz would maximize the available paired spectrum.

For these reasons, the proposal set forth by Google and Microsoft to include a guard band containing a 28 MHz duplex gap is not at all consistent with a band plan seeking to maximize paired spectrum and the efficient use of spectrum. In the example above, using 28 MHz of that spectrum for the duplex gap would leave only 37 MHz of spectrum for paired LTE-FDD blocks. As a result, the use of a 28 MHz guard band would reduce the amount of available paired spectrum to 30 MHz (3 paired blocks of 5 MHz) compared to 50 MHz (5 paired blocks of 5 MHz) if a 12 MHz duplex gap were used.[41]

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[39] According to IWPC, the frequency shift is given by (Tempco*(T2-T1)* f), where Tempco is the temperature coefficient, T2 is the upper limit on the temperature in degrees C, T1 is the lower limit on the temperature in degrees C, and f is the center carrier frequency. IWPC's calculations use Tempco= -30 ppm/C, T2= 85°C, and T1=-30°C. At 650 MHz, the frequency shift is -30((85-(-30)*650/1000000)= -2.2 MHz.

[40] Alcatel-Lucent Comments, at 21-22 (10 MHz to 12 MHz); Nokia Siemens Comments at 9 (at least 10 MHz); Qualcomm Comments, at ii (10 MHz to 14 MHz, with 11 MHz to 12 MHz ideal); Comments of Research in Motion Corporation, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268, at 12-13 (Jan. 25, 2013) ("RIM Comments") (greater than 2% of 600 MHz frequency, or about 12 MHz to 13 MHz).

[41] We note that the Spectrum Act provides that "guard bands shall be no larger than is technically reasonable to prevent harmful interference between licensed services outside the

Prof. Borth, in a paper attached to the Google-Microsoft Comments, recommends a duplex gap greater than 20 MHz to help achieve a low-cost and high-performing receiver.[42] We agree with Prof. Borth that the duplex gap should be large enough to facilitate a low-cost and simpler filter design and to sufficiently manage insertion loss. However, based on the information that we and AT&T have received from the filter manufacturers, a duplex gap of about 10 to 12 MHz is adequate for the current state-of-the-art filter design to achieve the filter performance goals that Prof. Borth and the FCC have outlined. The duplex gap of 10 to 12 MHz does not cause any appreciable increase in the filter complexity or cost compared to a much larger duplex gap. In contrast, as explained earlier, a 28 MHz duplex gap would cause much larger drop in the effective antenna gain at the UE if antennas were forced to operate in a larger overall bandwidth (covering the downlink band, the duplex gap, and the uplink band).

We respectfully disagree with Prof. Borth's assertion that intermodulation (IM) interference concerns alone justify a larger duplex gap.[43] Effective and efficient methods to counteract intermodulation interference include (i) avoiding the TV channels in the duplex gap, (ii) using an adequate guard band between the licensed spectrum and the TV spectrum, and (iii) placing relatively low-powered TV stations adjacent to the licensed mobile broadband spectrum. The proposed AT&T band plan makes effective use of these methods. Using a large duplex gap to solve the intermodulation interference is neither effective nor efficient, because the bandwidths of the IM products are quite wide. Rather, methods that prevent the occurrence of IM interference in the first place and that lead to significantly weaker power levels of the generated IM products are most effective.

It is also important to recognize that with currently available antenna technology, a maximum duplex gap no greater than 15 MHz should be used to achieve a band that can support 2 x 25 MHz of paired spectrum in 600 MHz spectrum. To understand why this is so, it is necessary to examine the engineering limits of antenna design for modern small form factor mobile devices.

The total bandwidth that a device can cover while operating at a specified efficiency level is governed by the volume of the antenna in the mobile device. All else being equal, an antenna with a larger volume can support more bandwidth than a smaller antenna. Given the small form factors of modern mobile devices and the myriad components that must be included in those multi-band devices (*e.g.*, chipset, power supply, camera, memory, GPS receiver, and so on), there are significant limitations on the size and number of antennas that can be placed in a

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guard bands." Middle Class Tax Relief and Job Creation Act of 2012, Pub. L. No. 112-96, Tit. VI, § 6407(b), 126 Stat. 156, 227-228 (Feb. 22, 2012) (codified at 47 U.S.C. § 1454(b)).

[42] *See* Declaration of David Borth, at ¶¶ 4-5 (Jan. 25, 2013) ("Borth Decl."), attached to Google-Microsoft Comments.

[43] Borth Decl. ¶ 15.

mobile device, and hence the bandwidth they can cover. As Qualcomm states, "[i]t is fair to say that there is no spare space in today's smartphones."[44]

There are two types of antennas that could theoretically be used in devices to support 600 MHz spectrum: (1) a passive antenna and (2) a "tunable" antenna.

A passive antenna is designed to cover a particular frequency range with a specified level of efficiency. Stand-alone passive antennas are used primarily for receiving and transmitting only specific frequency ranges. A single passive antenna that covers higher frequencies at the target efficiency is relatively small and a single passive antenna covering lower frequencies at the same target efficiency is relatively large.

For these reasons, the use of passive antennas to cover lower frequencies can be much more challenging than for higher frequencies. Antennas for higher frequencies can be quite small, and it is therefore easier to fit multiple high frequency antennas in a device. Moreover, the smaller size of higher frequency antennas allows for relatively small passive antennas that cover multiple frequency bands, creating greater space saving efficiencies in device design.

By contrast, the passive antennas needed for the lower frequency bands, such as 700 MHz or 600 MHz must be much larger to meet given efficiency standards. Even a 600 MHz antenna must be substantially larger than a 700 MHz antenna to meet the same efficiency standards. Qualcomm explains that "an antenna that is designed exclusively to support 600 MHz operations could require approximately 60% more volume than current 700 MHz antennas, which would substantially challenge current smartphone form factors," and given that there is already little or no space available in mobile devices, we share Qualcomm's "concern[] that if the Commission's band plan requires use of a separate antenna system for 600 MHz, smartphones would have to become much larger in order to perform acceptably."[45]

This problem would only be amplified if 600 MHz passive antennas were required to cover more than about 65 MHz. The 700 MHz passive antennas are designed to cover about 10% of their center frequency. And Qualcomm has found that to achieve the same level of efficiency in the 600 MHz range, this antenna would have to be 60% larger. To achieve not only the same efficiency but *also* greater than a 10% frequency range, the antenna would have be larger still. There are thus enormous practical impediments to adding 600 MHz antennas to small form factor devices that can cover a bandwidth greater than about 65 MHz.

A "tunable" antenna system is another option. The operating center frequency of a tunable antenna is set by adjusting its resonant frequency. As such, a single tunable antenna can be used in a device to handle multiple low frequency ranges with one frequency range being active at a time. For example, if we tune a 700 MHz antenna to operate at 600 MHz, the device will

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[44] Qualcomm Comments, at 13.

[45] *Id*.

be active on 600 MHz but not on 700 MHz. Sharing of the antenna system between the 600 MHz band and the 700 MHz is highly desirable because it saves space.

But here too, there are limits as to the frequency range that a tunable antenna can cover. As a rule of thumb, a tunable mobile device antenna can typically cover a frequency range of about 10% of the center frequency with good efficiency.[46] AT&T's vendors have confirmed that this would apply to tunable antennas for 600 MHz devices. Qualcomm has also explained that a reasonably sized and efficient antenna in the 600 MHz bands could cover only about 62 MHz.[47] With a 10% constraint, an antenna operating in a frequency range centered at 650 MHz could support a bandwidth 65 MHz. Consequently, a 600 MHz band that includes 2 x 25 MHz of paired spectrum can accommodate a maximum duplex gap of 15 MHz to ensure that the total frequency range being covered by the antenna does not exceed the maximum 65 MHz that can be efficiently covered by the antenna.

4. Unlicensed Operations in the Duplex Gap.

The NPRM asks whether unlicensed users should be permitted to operate in the duplex gap. In our view, unlicensed operations in the duplex gap should be permitted only if two criteria are satisfied: (1) the unlicensed users operate in a manner that fully protects licensed users from interference, and (2) the unlicensed must accept any interference that may occur from licensed operations.

These protections are critically important for a successful band plan and auction. Most fundamentally, failure to protect the licensed paired spectrum from interference generated by unlicensed deployments in the duplex gap (or a mandate that required paired spectrum licensees to somehow protect unlicensed users in the duplex gap) would impair the licensed spectrum in a manner that would decrease its value to providers and consumers by reducing capacity and quality.

Moreover, failure to protect licensed spectrum from interference from operations in the duplex gap would undermine the FCC's goal of creating a band plan with fungible paired spectrum blocks. Interference caused by operations in the duplex gap would have a greater impact on spectrum nearer to the duplex gap, thus making spectrum blocks closer to the duplex gap less desirable than spectrum blocks farther away from the duplex gap. Similarly, any requirement that licensees of paired spectrum provide some sort of protection to unlicensed users in the duplex gap would inevitably have a greater impact on licensees of spectrum blocks closer to the duplex gap than on paired spectrum in frequencies that are farther from the duplex gap.

The Commission can easily ensure that the second criterion is satisfied – *i.e.*, that unlicensed users are not entitled to any protections from interference from licensed users, and thus must accept any interference that may occur from licensed operations.

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[46] Jeffrey H. Reed, *Software Defined Radio: A Modern Approach to Radio Design*, (1st ed. 2002).

[47] Qualcomm Comments, at 15.

The challenge is designing rules that ensure that the first criterion is satisfied – *i.e.*, that the unlicensed users operate in a manner that fully protects licensed users from excessive interference. The difficulty is that the limitations needed to protect licensed users depend significantly on the specifics of the unlicensed service at issue. The amount of protection that an unlicensed system can provide to the licensed system depends on the filters, power levels, locations, and numerous other factors for the service being operated. The protection also depends on the types of services – *e.g.*, downlink only, uplink only, or both downlink and uplink. It can depend on the nature of the services and the physical layer characteristics of the unlicensed device such as power and modulation. For example, some unlicensed uses may be expected to operate in closer physical proximity to licensed mobile equipment and may therefore require greater restrictions to protect licensed mobile services.

For these reasons, we do not at this stage in these proceedings suggest a specific approach to ensuring that any unlicensed devices in the duplex gap do not interfere with licensed operations. We note, however, that very significant restrictions on unlicensed devices may be necessary to prevent such interference, given that the spectrum in the duplex gap is, by definition, immediately adjacent to both the uplink and downlink frequencies for licensed mobile services.

5. Guard Band Sizes.

The size of the guard band needed to protect mobile spectrum that is adjacent to television from interference will vary for uplink and downlink mobile spectrum, and will vary depending on the power level of the television stations. It can also vary based on the type of potential interference that may occur. For example, where the main concern is both adjacent channel interference and intermodulation interference, the guard band may need to be larger than if adjacent channel interference were the only concern. For these reasons, until there is a more established band plan, it is not possible to predict with certainty the precise size that will be needed for the guard bands to protect against harmful interference. However, based on past testing in the 700 MHz frequencies, and analyses conducted by AT&T and its vendors, we can provide some general guidelines.

Mobile Uplink Adjacent To Television Station. Based on experience where mobile uplink frequencies are adjacent to full powered television stations, a 6 MHz guard band is generally sufficient to protect against adjacent channel interference and potential intermodulation interference. This conclusion is based on the fact that AT&T is currently operating in 700 MHz Band 17 which has 6 MHz of separation from television channel 51, which are authorized to operate at power levels up to 1 MW. We understand from AT&T that this effective 6 MHz guard band has been sufficient to protect against harmful interference and has been verified by testing labs.

Mobile Downlink Adjacent To Television Station. There is no real world data that can be relied upon to determine the appropriate guard band where mobile downlink spectrum is located adjacent to a television broadcast station. The closest scenario of which we are aware is the

proximity of AT&T's 700 MHz Band 17 downlink spectrum, which is about 12 MHz away from the D-Block, and 6 MHz away from the E-Block (where Dish is expecting to deploy a television broadcast service at power levels up to 50 kW).

According to analyses by AT&T and Qualcomm, a 6 MHz guard band should be sufficient to protect against interference from 50 kW broadcasts.[48] It follows that a 6 MHz guard band should be sufficient in the 600 MHz bands to protect mobile downlink frequencies from adjacent television stations that are operating at or below 50 kW.

Although we are unaware of any testing as to the size of the guard bands needed to in the 600 MHz frequencies to protect mobile services from full powered (1 MW) broadcasts, we note that analyses of filter performance and other factors by Alcatel-Lucent, Nokia Siemens, and RIM indicate that these guard bands will likely need to be at least 10-12 MHz.[49]

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[48] *See, e.g.,* Jeffrey H. Reed and Nishith D. Tripathi, *Analysis of the V-COMM Report Estimating the Impact of Channel 51 and E Block Interference on Band 12 and Band 17 User Equipment Receivers*, at 6-7, 10-11, and 19-21 (Oct. 3, 2012), attached to Letter from David L. Lawson (AT&T) to Marlene H. Dortch (FCC), WT Docket No. 12-69 (Oct. 3, 2012) (presenting testing conducted by PCTest and 7Layers); Jeffrey H. Reed and Nishith D. Tripathi, *Supplemental Analysis: Impact of Channel 51 and E block Interference on Band 12 and Band 17 User Equipment Receivers*, at 9-13 (July 16, 2012), attached to Reply Comments of AT&T Services Inc., WT Docket No. 12-69 (July 16, 2012) (describing the testing conducted by PCTest and 7Layers); Comments of Qualcomm Incorporated, *Promoting Interoperability in the 700 MHz Commercial Spectrum*, WT Docket No. 12-69, at 6-29 (June 1, 2012).

[49] *See* Alcatel-Lucent Comments, at 23; Nokia Siemens Comments, at 15-19; RIM Comments, at 11.