Enforcement and Spectrum Sharing: A Case Study of the 1695-1710 MHz Band

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***Abstract*—Spectrum sharing is a new reality for spectrum users. Implementing sharing regimes on a non-opportunistic basis means that sharing agreements must be implemented. To have meaning, those agreements must be enforceable. We make this discussion more concrete by reasoning about enforcement in a particular spectrum band (1695-1710 MHz) that is currently being proposed for sharing between commercial services (LTE) and an incumbent spectrum user in the US. We examine three enforcement approaches, exclusion zones, protection zones and pure *ex post* and consider their implications in terms of cost elements, opportunity cost, and their adaptability.**

***Index Terms*—Technological innovation, Wireless communication, Cooperative spectrum sharing, Enforcement in DSA**

I. Introduction

SPECTRUM sharing has moved from being a radical notion to a principle policy focus in the past decade. This becomes evident as one compares the FCC's Spectrum Policy Task Force (SPTF) report from 2002 [1] with the President's Council of Advisors on Science and Technology (PCAST) Spectrum report [2]. The former report considers spectrum sharing as a possible option while the latter makes spectrum sharing a key strategy for spectrum access.

With the significant exception of license free wireless systems, commercial wireless services are based on exclusive use. As a consequence of the growth of wireless broadband demand and services of all types, there is an urgent need for on-going spectrum policy reform to make spectrum sharing a reality. In spectrum sharing, a *spectrum entrant* or *secondary user* is granted usage rights contingent upon the licensee's (or *primary user's* requirements or usage). With this policy change, it becomes necessary to consider how sharing might take place in practice. Generally speaking, spectrum can be shared in frequency, time and geographical dimension or any combination of those dimensions. Beyond the technical aspects of sharing that must be resolved lie questions about how usage rights are appropriately determined and enforced. Weiss et.al [3] summarized the law and economics framework of enforcement and applied it in general terms to dynamic access networks. However, this generic application does little to assist policymakers on specific problems.

To that end, this paper considers spectrum sharing in the 1695-1710 MHz band from the perspective of enforcement. This is a band that is on the US National Telecommunications and Information Agency (NTIA) "Fast Track" for reallocation from government to commercial. This band is currently being used by the National Oceanic and Atmospheric Administration (NOAA) for Meteorological Satellites (MetSat) for satellite downlinks. Since earth stations are stationary, it provides a good starting point for working out sharing, especially from an enforcement perspective.

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II. Case Description

One of the broad visions of the President Obama's Spectrum Initiative [4] is that the Federal government must ensure sound government performance and effective use of its spectrum, pushing for effective repurposing, sharing, and innovative uses of spectrum wherever possible.

The NTIA issued reports [5] [6] to evaluate different Federal and non-Federal spectrum bands for the near-term viability of accommodating wireless broadband systems. NTIA recommends that 1695-1710 MHz spectrum band could be made available within five years, if the Geostationary Operational Environmental Satellite-R satellite is redesigned and other costs NOAA and other Federal agencies will incur in connection with sharing this spectrum band.

A. Primary User

NOAA's MetSat system is the Primary User (PU) and consists of geostationary and polar satellites that relay their information to earth stations throughout the US. There are 18 earth station locations that are critical to NOAA operations that are to be protected in the NTIA spectrum sharing framework. The other earth stations are operated by other groups, and they will not be protected in the NTIA spectrum sharing framework. The use of satellites in a polar orbit means that the earth station antenna must track the satellite as it crosses the sky. Thus, at some points in time, the large dish antenna of the earth station would have a very low elevation (i.e., it would be nearly horizontal). In this position, the antenna's highest gain main lobe would be most vulnerable to co-channel interference from a secondary user.

B. Secondary User

The Secondary User (SU) is presumed to be an LTE handset system operator. The shared band would be used for uplinks from the handsets to the base stations and would be paired with the 2180-2200 MHz band for the downlink [7]. These uplinks operate at lower power than base stations, so are less likely to cause interference with the PU. This band is attractive to network operators because it is directly adjacent to the AWS-1 uplink band

III. The General Aspects of Enforcement

In [3], the authors describe enforcement in DSA systems in some detail. The sections below summarize some of the concepts and apply them in broad terms to the case described here.

A. Ex Ante and Ex Post

There are two principal loci at which usage rights may be enforced: *ex ante*: before a potentially harmful interference event has occurred; and (2) *Ex post*: after a potentially harmful interference event has occurred (though this does not mean that actual harm has been realized). Further, *ex ante* and *ex post* approaches work in tandem, not in isolation. Thus, a choice of an *ex ante* approach affects the *ex post* strategies.

The choice of how to design the enforcement mechanism directly and indirectly impacts the design and costs of usage rights enforcement. In particular, the costs of inducing good behavior (avoiding bad behavior) must be balanced against the social costs and benefits under different scenarios. So, the cost of strong *ex ante* rules is that they need to be enforceable and may pose the risk of overly restricting behaviors that may be welfare enhancing (e.g., innovation) as well as decreasing the value of the sharing opportunity for the entrant (i.e., the LTE operator(s)).

In the case of MetSat and LTE sharing, the question (more precisely) is what are the consequences of various *ex post* enforcement mechanisms are and how that affects the *ex ante* rules, which, in turn, potentially affects the value of the secondary sharing. The initially proposed mechanisms are very heavy on *ex ante* controls (e.g., a large exclusion zone) with no significant consideration of *ex post* mechanisms, i.e., the detection of events above -10 dB Interference-to-Noise-Ratio[1] that are clearly attributable to LTE and the adjudication of those events [6].

Ex post penalties serve (1) to promote cooperation between primary and secondary user and (2) to compensate for violations. In the case of MetSat, the PU is interested in preserving their ability to receive a weak signal, so it is difficult to conceive of a scenario in which a SU is harmed. Thus, in the analysis below, we assume that a SU can harm the PU, but not vice versa.

B. Precision of Enforcement

In general, we consider an enforcement approach to be more precise if it more specifically differentiates legitimate users and uses from illegitimate ones. The cost (including the complexity) of this depends on some attributes of the system itself. The maximum practical cost of enforcement is closely linked to the value of the resource: as the resource becomes more valuable, the more worthwhile it may be to invest in more precise enforcement technology.

For commercial LTE services (the SU in this scenario), the most precise enforcement mechanism would be able to control/identify particular handsets on a moment-by-moment basis based on factors such as the phone's location and the primary user's instantaneous usage. *Ex ante* enforcement would involve permission to transmit on the shared band and *ex post* enforcement would entail identifying the precise time and location of handsets whose signals exceeded the agreed-upon co-channel interference threshold. By contrast, the least precise enforcement mechanism would involve the creation of large exclusion zones as the *ex ante* mechanism, and a simple co-channel interference threshold detection system, perhaps with signal classifiers (to exclude non-LTE interference) but without any attempt at locating the interfering handset.

More precise approaches include: (1) *ex ante* approach would be to have a dynamic exclusion zone that was based on the current PU behavior and to identify the location and identity of the interfering radio *ex post*; or (2) rely exclusively on *ex post* enforcement where the penalties are established such that the secondary user privately develops "soft" exclusion zones based on interference history that maximize their total profit.

IV. Enforcement Approaches for 1695-1710MHz

A. Ex Ante approaches

Ex ante enforcement works by attempting to prevent interference. One such approach is use of exclusion zones. In this approach, the PUs and SUs would agree on a spatial database that defines these exclusion zones. In its initial submissions, NTIA proposed exclusion zones with a radius in the 72 – 121 km range (See Figure 1).

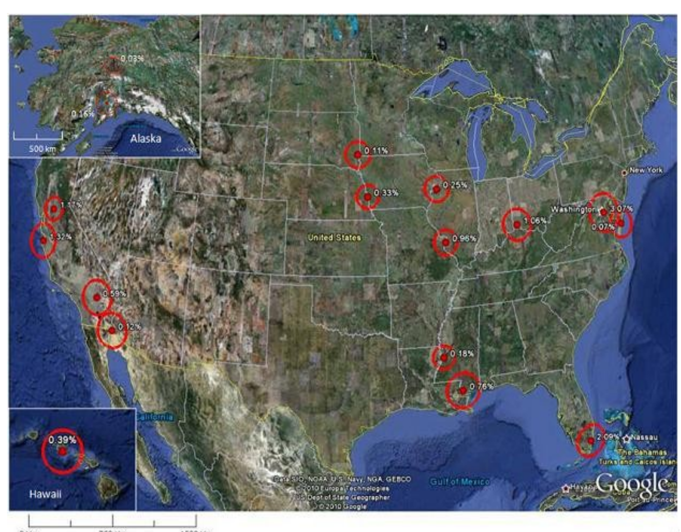

Figure 1 - Proposed Exclusion Zones

[1] Based on ITU-R Recommendation SA1026.

An “exclusion zone” means that no in-band emissions from SUs would be permitted in its interior. Handsets operating in the region would have to be handed off to a different uplink frequency to continue operating. Since the PU is a receive-only earth station, there should be no in band emissions at all in the exclusion zone.

The opportunity cost of these exclusion zones can be high. Spectrum prices can vary significantly [8] and different valuation approaches can produce different results [9]. Nonetheless, the exclusion zones in this band have been estimated to reduce auction revenue by approximately $1.1 billion [10].

Since the antenna orientation of the MetSat earth station is not fixed, the use of fixed exclusion zones represents a worst-case solution. In any particular reception episode, the exclusion zone is ovate, as shown in Figure 2. A circular exclusion zone is the union of all possible instantaneous exclusion zones.

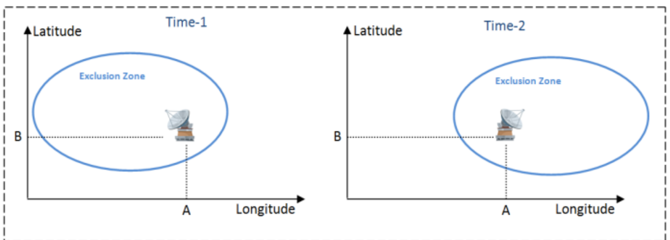

Figure 2 - Instantaneous exclusion zones

B. *Ex post approaches*

Exclusion zones do not provide a guarantee of co-channel interference avoidance. Since propagation is unpredictable, uplink signals could occasionally travel farther than expected. Furthermore, the exclusion zones do not explicitly account for tall features, like tall buildings and mountains that can cause longer than expected propagation distances. As a result, *ex post* mechanisms may be needed to provide data to PUs and SUs to further tune the system for future interference avoidance.

By definition, *ex post* mechanisms are invoked after an interference event attributable to the SU occurs. To be in a position to take *ex post* action, the PU must be able to detect very low signal energy (-10 dB INR) at their antenna site and determine that it is associated with SU activities.

To associate interference event with the SU(s) means that the PU has either some knowledge about the SU’s signal characteristics and/or an identification code that can easily be obtained by demodulating part or all of the SU’s signal. For example, in the case of MetSat, the SU will most likely be a carrier using LTE, which has a distinct electromagnetic signature. If multiple SUs exist, the LTE signal would have to be demodulated to identify the source of the interference. Demodulating very low level signals is very difficult, which could lead to higher adjudication costs if the source of an interfering signal attributed to a specific SU.

If SU interference is detected, the event is entered into an adjudication system, which establishes a procedure by which a determination of fault is made. If the adjudicator finds fault, then a remedy is ordered.

It is often the case that an *ex post* remedy involves a penalty or a fine that serves both to compensate the PU and deter the SU. To ensure cooperation, the SU should find it cheaper to avoid interfering with the PU than to pay the penalty. In particular, $d * P \geq B$, where d is the probability of detection and successful adjudication, P is the penalty paid and B is the benefit the SU obtains from transmitting in a way that causes interference. The uncertainties of RF propagation mean that interference events may be accidental. If the average payment is based on willful interference, the SU will (1) have an incentive to optimize their system to eliminate interference events and (2) be indifferent to intent (i.e., willful or accidental).

C. *Data collection in ex post enforcement*

Ex post mechanisms require the ability to detect co-channel interference and potentially adjacent channel signals. It is further helpful if the source of the interference can be localized. Finally, for long term credibility, the detection mechanism must be free from incentives to over- or under-report events. While a variety of institutional arrangements may be possible, it is likely than an independent sensor network (similar to what was proposed in [7]) would emerge as an SU might distrust a PU-operated sensing system (and vice versa) because the PU would have an incentive to maximize penalty payments from the SU.

To help localize the source of the interference, at least two sensors near the PU antenna would have to be in a position to detect the interfering signal. Since the orientation of the MetSat antenna is variable, the sensors must ring the earth station site. Eight sensors located every 45° on a circle around the earth station, each with >90° beam width antennas should provide sufficient coverage (assuming their sensitivity can be high enough with that beam width). The sensor network would have the responsibility of classifying and reporting interference events.

D. *Locus of adjudication in ex post enforcement*

The locus of adjudication is a critical question. The adjudicator (1) must be trusted by the PU and SU and (2) have jurisdiction to adjudicate interference events. The parties could designate an arbitrator to make a determination of both the legitimacy of a supposed interference event and its consequence; however it is easy to imagine that some interference allegations might be appealed. In the case of the 1695-1710 MHz band, the civil courts would likely refer the matter to the FCC for resolution, but the FCC has no jurisdiction over federal frequency bands and the NTIA has no mechanism for dealing with civil disputes. The recent PCAST report on spectrum [2] briefly addresses this issue, but more work remains to be done; it is not the purpose of this paper to resolve this question, simply to point out that it requires clarity in resolution.

V. Alternative Scenarios

A. *Dynamic Exclusion Zones*

While a static exclusion zone is relatively straight-forward to enforce, it has high opportunity costs, as noted above. For example, in the Washington DC metro area, it is easy to imagine an exclusion zone that covers Wilmington DE and Baltimore MD during a hypothetical reception episode, but not Washington DC, Richmond VA or Norfolk VA.

Since the orbits of the satellites are predictable, the exclusion zone becomes spatio-temporal (instead of only spatial). A dynamic exclusion zone could function as effectively as the static exclusion zone proposed by NTIA at a lower opportunity cost. To be implemented, the dynamic exclusion zone could either be implemented in the database or it could be computed in the handset. The design decision to rely on signalling or local computation would be based on a joint optimization of handset power and signalling overhead.

Even with exclusion zones, co-channel interference is possible. If exclusion zones are sized to avoid interference, then there may not be a strong basis for *ex post* action, except to determine if the interfering station was located within the exclusion zone during the interference episode. Unless the PU builds a sensor network that broadly covers the exclusion zone, then it will be difficult to offer concrete evidence of SU transmission within the exclusion zone.

B. Protection Zones

In its final report, CSMAC proposed to eliminate exclusion zones entirely in favor of *protection zones* [9]. This would allow SU operation as long as the aggregate received co-channel interference at the PU antenna is below a yet to be determined threshold[2]. CSMAC claims that these protection zones are smaller than exclusion zones (14 – 95 km *vs* 72 – 121 km, depending on the location in question). For the Suitland MD site, the protection zone still encompasses the Washington DC metro area. According to the CSMAC report, the protection zones are smaller because they are based on more realistic propagation models rather than the worst case ones underlying the exclusion zones.

This approach essentially reorganizes the locus of enforcement from *ex ante* toward *ex post*, since protected zones would definitely require spectrum sensing and an adjudication procedure. Because transmission could be permitted in the protection zone, its opportunity cost would likely be substantially lower than that of the exclusion zone ($1.1 billion according to [10]).

C. Ex Post Only

Taken further, the parties could rely exclusively on *ex post* enforcement. In such a scenario, the penalties for interference would be set so that the SU would have an incentive to discover profit maximizing protected zones. That is, if the cost of interference is sufficiently high, the SU would find it advantageous to modify their behavior in a way that balances the consequence of interference with the consequence of not transmitting in a region. Such a system would require regular calibration of the interference penalties so that the PU's operational SINR can be attained.

[2] The CSMAC Working Group 1 Final Report [9] uses a new Interference Power Spectral Density (IPSD) measure as the essential threshold.

VI. Implementation Considerations

Each of the approaches to spectrum sharing outlined above has different implications.

A. Exclusion Zones

Exclusion zones, whether static or dynamic, would rely largely on a database. This database would be an operational mechanism by which each exclusion zone would be defined. It is likely that the PU would maintain a reference database that would be copied by the SUs and incorporated into their operational LTE networks.

Database costs are challenging to estimate in the absence of expected query rates and response time requirements. In [13], the authors examine cloud-based database services. The advantage of this costing approach is that operating costs are explicitly included. A DSA-oriented estimate was performed as well [14], but it was missing the transaction rate and response time requirements as well. Further, it omitted operating costs. For our purposes, we make a estimate that initial capital costs for the database would be $200,000. The complexity of the database for a dynamic exclusion zone would be higher, but the transaction rate or response time should be similar[3].

Ex post enforcement in this approach could be used to (1) tune the contours of the exclusion zones to optimize operations and/or (2) detect violations of the exclusion zone by SUs. The costs of the objectives are quite different. In (1), a sensor network could be used to localize the strength and direction of SU associated interference events. So, the feedback from sensor network could be used to optimize the size and shape of the exclusion zone. This would require sensing near the PU's earth stations and implies ongoing discussions between the PU and SU(s). The adaption of the exclusion zone would be a relatively slow process and would depend on the level of cooperation (and trust) between PUs and SUs. Bilateral adaption of the exclusion zone means that the PUs would have to risk interference by allowing SU operations within the contours of the existing exclusion zone(s) and measuring interference. If none occurs over some time period, the exclusion zone can be shrunk. If interference occurs, the SU must agree to immediately cease operations and the exclusion zone is maintained. Similarly, exclusion zones would be expanded in locations where interference is measured. If the incentives to PUs and SUs can be made to align with the overall system goals, then this can work; if the incentives favor local optimization at the expense of system goals, then cooperation can be expected to be limited in the long term.

If we do not assume cooperation between SUs and PUs, then scenario (2) applies. In this case, the sensor network would have to be more comprehensive since the PU would seek to demonstrate SU operation within the exclusion zone. This cannot be done definitively from the PU earth station, so a network of sensors would have to be constructed.

[3] The database approach to managing spectrum sharing is being used by the TV White Space devices. We do not have space in this paper to discuss database designs and architectures for DSA applications.

The sensing node cost is dominated by the cost of the towers if they are needed. Backhaul costs can be significant if the needed data rate cannot be accommodated with low bit rate commercial wireless services. Without the towers, narrowband sensors of the kind needed here would be $500-$1000 [14]. Since these should not interfere with the PU's reception, towers need not be high; it is possible that sensors mounted on the earth station building would be sufficient. In that case external installation with directional antennas would add another $2000 in capital costs. Operating costs would consist largely of regular maintenance and backhaul costs.

In scenario (1), eight sensors may be sufficient to provide the information needed to optimize the contour of the exclusion zone (through the database) to minimize interference events. Thus, an estimate of capital costs for data collection in support of *ex post* optimization would be $24,000. Operation and maintenance costs would likely meet or exceed this figure over the life of the sensor.

In scenario (2), the costs become higher, as signal detection and localization capability for the entire exclusion zone must be provided. The number of sensors would clearly be higher, though it may be sufficient to place sensor stations every *r* km around the circumference (where *r* is the radius of the exclusion zone), so 7 additional sensor stations would be needed, at an additional cost of $7000 plus tower costs (which are much more difficult to assess). Operating costs would also be significantly higher, as on-site maintenance would require traveling to all sites.

B. Protection Zones

In the case of protection zones, sensing at the PU's earth station is sufficient, as the metric of interest is the IPSD. The sensors must be configured to measure this value and attribute it appropriately to the SU(s). This may require somewhat more post processing to estimate low level IPSD values (-10 dB INR) but may not result in significantly more costly sensors.

The existence of this *zone* also implies a database that defines its boundary. Thus, this approach would have to use a database similar to the exclusion zone approach. Operationally, the SUs would have to estimate the signal energy they are generating within the protection zone so as not to exceed the IPSD threshold. Feedback from sensors around the PU's earth station would be critical to optimizing this.

The larger unknown is the cost of *ex post* enforcement. The *CSMAC Final Report* [12] does not address adjudication or the consequences of exceeding the IPSD threshold. If an adjudication procedure exists, then the interference events must be documented and attention paid to issues such as provenance and chain-of-custody, which requires back-end information system expenses. It may also require ongoing attention of an individual to act as a liaison between the adjudicator and/or the secondary user.

C. Ex Post Only

The logical extension of the protection zone concept is to not define a zone at all, but simply to define an IPSD threshold that cannot be exceeded. Penalties for exceeding this must be defined in advance and must be periodically re-calibrated to be in balance with the incentives SUs face to exceed the threshold.

This approach would not require a database, but would require the establishment and operation of a sensor network as well as the adjudication-oriented information system. If adjudication can be automated, this approach could perhaps be made more efficient.

D. Adjudication Costs

Both the protection zone and *ex post* only approach require an adjudication mechanism as discussed above. Approaches to adjudication can be highly variable, from binding arbitration through formal legal proceedings, so the cost structure and time to final resolution can be highly variable.

Regardless of the approach, adjudication requires paying for an adjudicator. Further, information management systems to support adjudication are required for the PU, the SU and the adjudicator to appropriately deal with evidence and open proceedings. Finally each entity will require ongoing professional staffing.

These costs can be reduced if some or all of the adjudication procedures can be automated. This would be desirable if interference events are frequent, but may not meet "due process" standards.

VII. Conclusions

DSA seems destined to be a feature of the wireless communication landscape for the foreseeable future. Thus, it is critical that we develop an approach to understanding, implementing and enforcing a set of rights and obligations that make sense for primary as well as (potential) secondary users. Spectrum sharing arrangements that do not explicitly define obligations and their enforcement are essentially non-binding [3] and thus provide no protection for incumbents or the secondary users. The emergent nature of DSA systems suggests that enforcement approaches should allow for learning from direct experience as well as the experiences of other DSA systems.

In this paper, we have examined a particular case of spectrum sharing (the 1695-1710 MHz band) and have examined the enforcement of the proposed sharing giving consideration to the nature of the incumbent and the secondary user. We have considered three approaches that occupy different points on the continuum from *ex ante* to *ex post*. Each of these has different implications on system costs for the primary and secondary users as well as different opportunity costs.

The approach that outlines obligations most clearly is the "exclusion zone" approach. This approach is also the most costly, since it requires a database and, in the worst case, an extensive sensor network and an as-yet poorly defined adjudication system. This approach also has the highest opportunity cost and provides the fewest opportunities for adaptive learning.

The approach proposed by the CSMAC [12] in its final report uses “protection zones”. This approach defines a maximum IPSD that can be present at the PU’s earth station, and permits some operations in the (smaller) protection zones as long as the IPSD is not exceeded. This also requires the development of an *ex post* adjudication procedure. This approach would also require a database, though it may be sufficient to have sensors near the earth station and not throughout the protection zone, so it is likely that the costs would be lower. The opportunity cost for this approach would clearly be smaller than the exclusion zone approach since the protection zones are smaller and some operations within them are permitted. Without a detailed analysis, one could assume that the opportunity cost scales linearly with the ratio of the populations affected by the two types of zones. Since some operations are permitted inside the protection zone, this approach is more amenable to learning and adaption.

The final approach proposed in this paper would rely exclusively on *ex post* enforcement. Thus, a database would not be needed, and a sensor network surrounding the earth station would be sufficient. A robust and efficient adjudication system with predictable outcomes and penalties would be important in this approach, however, since it is likely that more interference events would occur. This approach would result in a highly flexible and adaptive system and one that could yield *ex ante* rules that are aimed at reducing adjudication costs in the future.

Spectrum sharing will be a feature of many future wireless systems. Thus, developing effective methods to protect the rights of incumbents and entrants is important. Given the newness of this approach and the rapid technological change in the wireless industry, it is equally important that this approach be adaptive.

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