Radio Regulation Summit: Defining Inter-channel Operating Rules

A report on a Silicon Flatirons Summit on Information Policy, held 8/9 September 2009

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2 Executive Summary

On September 8 and 9, 2009 the Silicon Flatirons Center convened a closed-door meeting of legal, economic, technical and regulatory experts in Boulder to explore ways of defining rights and obligations regarding inter-channel operation that would facilitate investment in radio systems and the resolution of conflicts among rights holders.

Engineers and regulators have traditionally sought to maximize concurrent radio operation by minimizing overlaps in geography, frequency, and time. This event geographical and temporal overlaps to focus on frequency spillovers – often referred to as out-of-band or adjacent channel interference – because they are the technical basis for a number of highly publicized cases where traditional approaches for managing interference have not worked well.

The meeting used three US case studies to ground the discussion: 800 MHz rebanding, WCS/SDARS and AWS-3. Difficulties in the 800 MHz band were due to a conflict between public safety's right to interference protection and Nextel's right to operate in the same band using a geographically different network topology. In WCS/SDARS, both parties wanted new rights, using claims of interference as leverage. The AWS-3 conflict has aspects of both the preceding cases: a lack of clarity over the meaning of extant rights, and a political tussle over the creation of new rights.

There was consensus that increasing service diversity, flexible license rights, and the shift to mobile and ad hoc operation had brought the industry to an inflection point where past methods of governance were no longer adequate. Attendees felt that properly defined rules and rights could shift some of the coordination burden from regulators to the market.

The participants agreed that interference problems were rooted in boundary conflicts between different technical architectures and/or commercial interests, whether due to changes in the use of a band, unforeseen new operating requirements, or unexpected variances in the ability of receivers to reject interference. However, there was no agreement on whether the problems exemplified in the case studies were due to poorly defined rules or other some cause, e.g. poor governance or commercial self-interest.

The role of receiver performance in interference was a recurring theme. There was broad support for taking receivers into account more explicitly when drafting rules, for example by regulating resulting signal levels rather than in terms of the customary rules on individual transmitters. However, there was debate about implementation, particularly the difficulties of using models rather than measurement to determine interference.

Attendees agreed that scenarios, explicit or implicit, were unavoidable when crafting rules even though they inevitably encoded assumptions, some of which would turn out to be wrong. There was support for clustering similar services together to limit inter-channel interference conflicts.

While there was extensive discussion of the institutional frailties of the Federal Communications Commission (FCC), no consensus was reached about the causes or extent of the problem, or whether the FCC should be replaced by the courts as the venue for dispute resolution.

3 Introduction

Over the last two decades, radio regulators have become increasingly interested in delegating service and technology decisions to market participants, rather than making such determinations themselves. This approach depends on licensees having some certainty about the assets they are using. It is therefore increasingly important to define generic radio operating rights and to provide certainty about what they entail.

Of the many aspects of operating rights, the coordination of inter-channel interference (an umbrella term this report uses for out-of-band and adjacent channel interference) provides a convenient and timely way to evaluate the effectiveness of current mechanisms, and suggests ways to devise new ones.

Radio regulators have been slow to develop comprehensive, generic rules on inter-channel interference. To date, this issue has been dealt with on an ad hoc, band-by-band basis. This worked while technologies/services were relatively static, radios were largely stationary, and there was little rivalry between frequency-adjacent radio users with divergent technologies and business models. However, rapidly changing technology, mobile and ad hoc networking, flux in market participants, and a greater diversity of frequency-adjacent operations have rendered the ad hoc approach increasingly clumsy and costly.

The Silicon Flatirons Center convened a closed-door meeting of legal, economic, technical and regulatory experts to tackle this problem on September 8 and 9, 2009 in Boulder, CO. The meeting sought to develop a general approach to defining rights in inter-channel operation that would facilitate investment in radio systems and the resolution of conflicts among rights holders. In other words: how should property rights and obligations be defined *ex ante* to allow problems to be resolved by market participants without requiring *ex post* intervention by a regulator?

A list of attendees is given in Section 9. Participants were invited to speak as individuals, and to express views that may not be those of their organizations; the resulting discussion is therefore reported without identifying them.

A web page with links to resources prepared for the meeting is available on the Silicon Flatirons site: http://www.silicon-flatirons.org/events.php?id=761. It includes a reading list and links to the material presented at the meeting.

This meeting was part of Silicon Flatirons' multi-year *New Models of Governance* project, a dialogue between academia, public interest groups, business and policymakers that seeks to define the principles, organization and practices that should define the policy responses to today's dynamic technological environment. For more information, see http://www.silicon-flatirons.org/initiatives.php?id=governance.

3.1 Report Structure

This report consists of five main parts: this introduction (Section 3); a survey of the case studies and a summary of discussion arising from them (Section 4); an introduction to the invited presentations and a summary of discussion arising from them (Section 5); a review of themes that emerged in discussions more generally (Section 6); and a concluding section that characterizes areas of consensus, takes lessons from the case studies and identifies remaining questions (Section 7). There is summary of the result of an online poll of attendees in Section 7. The document closes with a list of attendees in Section 9 and a list of abbreviations in Section 10.

Readers seeking a bibliography are referred to the reading list provided on the web site for this meeting.[1]

In order to distinguish clearly between remarks made by participants, and commentary by the author, paragraphs reporting participants' comments use italic text, e.g. *thus*.

3.2 Context

Radio engineering and regulation has traditionally sought to maximize the amount and quality of concurrent radio operation. A key constraint is that, for practical reasons, radio operations overlap in all the major dimensions that characterize "spectrum": space (or geography), frequency, and time. These overlaps, or spillovers, are often non-linear; for example, terrain irregularities mean that radio energy does not decline smoothly with distance from a transmitter. Additional complexity arises from desensitization of receivers by strong unwanted signals, and non-linear mixing (aka intermodulation) in the receiver of transmissions at very different frequencies to create interference in the desired channel.

This event focused on frequency spillovers because they are the basis for a number of highly publicized—and seemingly interminable—cases where traditional approaches for managing interference between users of the radio spectrum have not worked well.

The traditional approach worked in part because command-and-control spectrum regulation dictated the particular use of technology and services. Matters were also simplified because the state of the art limited the number of technical factors that had to be considered. Today, however, new approaches like flexible-use licenses and unlicensed operation mean that operators have much greater scope in their choice of services and technology than before. In many cases, they can change waveform, coding, power, bandwidth etc. on the fly.

This meeting focused on licensed allocations. In theory, a well-defined property right enables the licensees at a frequency boundary to resolve interference conflicts through bargaining supported by adjudication. In practice, however, it is not always that simple: both because defining usable property rights is hard, and because high transaction costs can preclude negotiation in some situations.

The success of the emerging property rights model requires careful and empirically-based understanding of interference management. Regulators need to understand when and how to develop a generic standard for permissible interference that can accommodate many kinds of services and many possible implementation technologies. Because regulators cannot tailor the rights definitions to work perfectly in all possible situations, any regime will be necessarily incomplete and imperfect as it seeks a balance between precision and flexibility and tries to future-proof rights allocations.

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[1] http://www.silicon-flatirons.org/documents/misc/OOBSummit/OOB%20Summit%20Reading%20List.pdf

3.3 Case Studies

The meeting used examples from recent US experience to provide a context for conversation. The case studies, introduced and described in more detail in Section 3.5 below, are referred to in short-hand fashion as 800 MHz rebanding, WCS/SDARS and AWS-3. They were used to explore how rights and obligations have been defined in the past, what the associated deficiencies were (as evidenced by post-rights-distribution litigation and delay), and to the extent possible, current best practices.

The case studies vary along a number of dimensions. In AWS-3, the affected services on either side of the frequency boundary are competitive, creating tensions between the parties in terms of their incentive to negotiate. In 800 MHz, there were great differences in technology architecture, nature of service, and the number of parties on either side of the argument. In WCS/SDARS, there are few licensees on either side of the frequency boundary, reducing transaction costs and making (other things being equal) negotiations more practicable – at least in theory; however, both parties were seeking changes in use beyond their issued licenses, complicating the search for a resolution. In all three cases, the regulator was called on to resolve differences; the market failed to do so.

3.4 Types of Interference

There are many ways to categorize interference. In his introductory remarks,[2] Dale Hatfield first distinguished between operations using the same frequency range but in adjacent geographical areas, and operations using adjacent frequencies in the same area. The meeting focused on the latter case, often known as out-of-band or adjacent channel interference.

Broadly speaking, such interference can be due either to energy from a frequency neighbor "spilling" into a victim's assigned frequencies, or to energy outside the victim's assigned frequencies that the its receiver cannot ignore. Interference occurs across frequency boundaries because the filters that delineate these boundaries are imperfect. Since the filter on a transmitter is not perfectly sharp, it spills energy on either side of its designated channel into that of a victim receiver in an adjacent channel. Since a receiver cannot filter out all energy outside its designated channel or band, it will pick up some inter-channel interference, even if the adjacent transmission had a perfect filter. Energy from outside a victim's operating frequencies may desensitize a receiver, hiding desired signals, or it may generate signals within the operating frequency range by non-linear mixing in the receiver (known as intermodulation interference).

[2] Dale Hatfield, "Introduction and Overview", available: http://www.silicon-flatirons.org/documents/misc/OOBSummit/SFC%20Interference%20Summit%20-%20September%2009w0.ppt

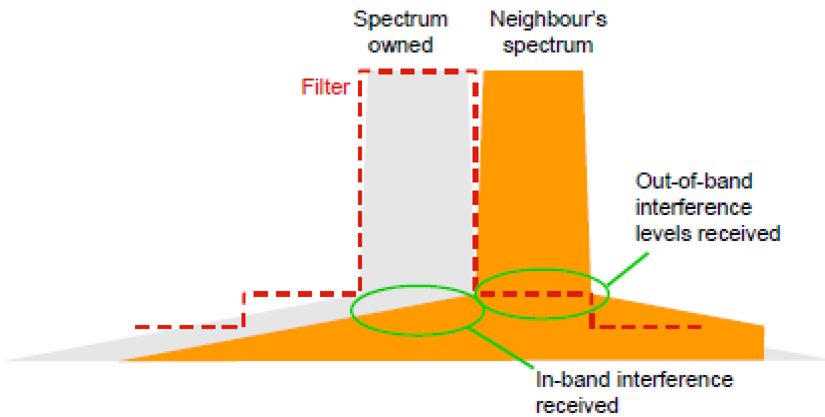

FIGURE 1: IN-BAND AND OUT-OF-BAND INTERFERENCE EFFECTS
(FROM WEBB 2009, REF. IN FOOTNOTE 4 BELOW)

One can further distinguish interference among similar operations using different channels in the same band, and between services in different bands.[3,4] There are typically two filters in a receiver, one for the desired band (a “front-end” or Radio Frequency [RF] filter), and a subsequent one for a particular channel within the band (an Intermediate Frequency [IF] filter); see Figure 2. The interference taxonomy used here is summarized in Table 1.

TABLE 1
A TAXONOMY OF INTERFERENCE TYPES

1) Co-channel: Interferer and victim use same frequencies, but in different geographical areas
2) Same area, different frequencies
   a) Adjacent channels: Interference between signals in the same band, but in adjacent channels (or in adjacent band, but right at the band edge)
      i) Energy in the victim’s channel due to transmitter sidebands
      ii) Energy in the adjacent channel that is accepted by the receiver due to imperfect IF filtering
   b) Front-end overload: strong unwanted signals causing distortion through de-sensitization or inter-modulation
      i) In-band: overload caused by in-band signals on nearby channels
      ii) Out-of-band: Unwanted signals in adjacent band

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[3] A band is assumed to consist of many channels.

[4] For other categorizations, see e.g. William Webb, “Licensing Spectrum: A discussion of the different approaches to setting spectrum licensing terms”, section 2, available: http://www.silicon-flatirons.org/documents/misc/OOBSummit/Licensing%20Spectrum%20v1.1.pdf; Michael Whittaker, “Space-Centric Management: A General Solution for Equitable Access to Radio Spectrum Space under Conditions of Flexible Use”, section 4, available: http://www.itu.int/osg/spu/STN/spectrum/workshop_proceedings/Background_Papers_Final/Michale%20Whittaker%20-%20space_centric_management_spu(mjw).pdf

In cases where either or both out-of-band or adjacent channel interference are being referred to, this document will use the umbrella term "inter-channel interference."

This document uses the convention that interference in the desired channel caused by, say, mixing between signals in two different channels is not classified as "co-channel"; rather, it is considered inter-channel since the interfering service operates on a different channel to the victim.

Overload is a function largely of the selectivity and linearity of the front end, whereas adjacent channel interference depends on the selectivity in the IF stage. Overload is often due to a transmitted signal that is so strong – either in the adjacent band, where the fraction that passes the victim's front-end filter overloads the receiver, or in the victim's band itself, where the sideband energy of the transmitted signal cannot be filtered out – that not even high performance receivers can reject it. Adjacent channel interference, on the other hand, is typically due to inadequate IF filtering in the receiver.

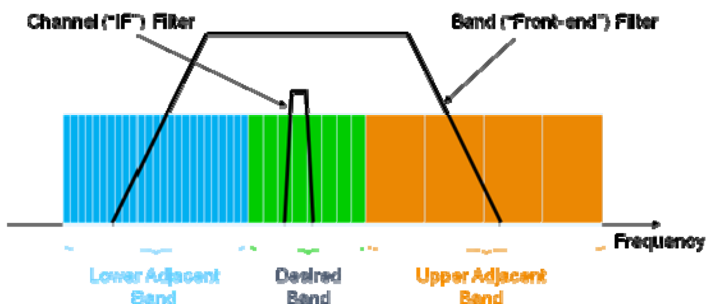

FIGURE 2
(FROM HATFIELD 2009, REF. IN FOOTNOTE 2 ABOVE)

The sharpness of the front-end RF filter, and the linearity and dynamic range of the RF low noise amplifier (LNA) determine how sensitive the receiver will be to overload. The quality of IF filtering affects channel selectivity, and can limit the effect of intermodulation interference. The linearity of the RF LNA influences the degree of intermodulation, and thus complements the degree to which IF filtering will limit intermodulation problems.

Hatfield pointed out that inter-channel interference is more apt to be problematical than co-channel cases for a variety of reasons. First, interference can occur at any location within the geographic service area, not just at the edges. Next, since system architectures and technologies in adjacent bands may be vastly different, the actual or perceived risk of interference may be asymmetrical. Providers in adjacent bands are more likely to have very different perspectives, incentives and even cultures; the 800 MHz case, for example, saw conflict between public safety operators and commercial entities. The number of players or stakeholders involved may also be much larger than in other interference cases. Finally, receiver performance plays an especially important and complex role in adjacent channel/adjacent band interference issues; see, for example, the discussion of filters in the next paragraph and in Section 6.2.1 below.

Adjacent channel interference is particularly acute in the "near-far" case, as in the 800 MHz example (Section 4.1 below). Imagine a police officer in a basement talking to a dispatcher via a distant, high power station on a mountaintop. The resulting signal in the basement is really weak. If there is a cell tower on the building across the street operating on a channel adjacent to the police communications, the signal from the cell tower leaking into the adjacent band may be strong enough to block the desired signal from the mountaintop.

3.5 Acknowledgements

The author and the Silicon Flatirons Center thanks all the attendees for the time, energy and insight they gave to this meeting; they are listed in Section 9. Ira Barron, Dale Hatfield, Kathleen Hamm, Therese Kerfoot, Paul Kolodzy, Mark McHenry, Preston Marshall, Bob Matheson, Greg Rosston, Ed Thomas and William Webb provided valuable feedback on a draft as well as additional insights. Matheson and Hatfield patiently tutored the author in the rudiments of radio interference. Kerfoot did sterling work preparing the reading list; she also created the meeting transcript on which this report is based.

4 Case studies

4.1 800 MHz Rebanding

4.1.1 Introduction

Dale Hatfield introduced the 800 MHz case study, and also the WCS/SDARS and AWS-3 issues that will be covered below. Details can be found in his presentation and the reading list. [5,6]

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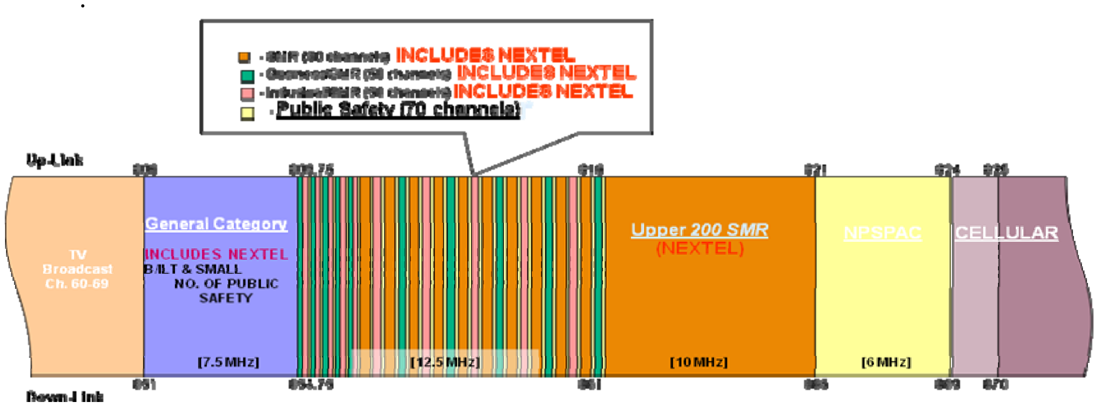

FIGURE 3: BAND PLAN FOR 800 MHZ
(FROM HATFIELD 2009, REF. IN FOOTNOTE 2 ABOVE)

The FCC allocated the 800 MHz band with well-designed wideband duplex structures, with corresponding uplink and downlink frequencies separated by 45 MHz.

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[5] Dale Hatfield, "Introduction and Overview", slides 16, 21-23. Available: http://www.silicon-flatirons.org/documents/misc/OOBSummit/SFC%20Interference%20Summit%20-%20September%2009w0.ppt

[6] http://www.silicon-flatirons.org/documents/misc/OOBSummit/OOB%20Summit%20Reading%20List.pdf

Several sets of users were placed into corresponding pairs of allocations within the uplink and downlink bands, including cellular phones and various types of LMR users. (Figure 3 illustrates the band plan.) No difficulties were reported by cell phone users; the problem occurred between the various LMR users. The allocation rules for the sub-bands shared by various commercial, government, and public safety LMR users assumed that a receiver could adequately reject unwanted signals from within the band. However, Nextel noticed that the formal rules for the band put no restrictions on exactly where transmitters could be located. It decided to convert the customary long-range LMR architecture (that used mountain-top, high tower-top, or building-top antenna sites) to a short-range cellular architecture providing much more capacity in crowded urban areas. To this end, Nextel deployed two new features: low antenna sites in the middle of cities and digital modulation which had broader sidebands.

Even though Nextel's transmitter power was below customary levels, the low antenna sites caused very high field strength signals at street level near their transmitter sites. This high signal level caused overloads in the front ends of receivers belonging to other users whenever these users were close to the Nextel transmitter sites. As a result, a public safety receiver tuned to a weak signal from a distant tower could be subject to interference from a relatively high power cellular base station signal in an adjacent channel. Because of the way that the various services were interleaved in the band, there was no practical way that RF filters in receivers could be built to remove the Nextel frequencies and still pass the desired frequencies. In addition, the Nextel digital modulations created sidebands that overlapped the adjacent channels belonging to other users.

In a Report and Order released on 6 August 2004, the Commission proposed reconfiguring the 800 MHz band to spectrally segregate public safety systems from ESMR ("Enhanced" Specialized Mobile Radio) and cellular telephone systems.

4.1.2 Discussion

The conflict in this band has many causes. Public safety and commercial operation were interleaved on alternating channels. Participants who had been involved in the band explained that this was done to solve the "combiner problem": co-located transmitters will interfere with each other if they are too close in frequency. At the inception of the band, the rule of thumb was 1 MHz separation; nowadays it is 250 kHz. Since different services were interleaved, no filter could separate them in the uplink and downlink bands, respectively. Public safety receivers therefore had a very limited capacity to reject adjacent channel interference once a significant in transmitter deployments led to a disparity in received adjacent channel power.

It was noted that technical solutions existed to ameliorate the problem: either Nextel or public safety could have taken steps to eliminate the problem and obviate rebanding. For example, public safety could have moved to a cellular architecture, or Nextel could have reduced the ground-level field strength near their transmit towers. However, neither side was willing to bear the cost.

Resolution by negotiation was made very difficult due to high transaction costs: the public safety sector is Balkanized into huge numbers of small players. The perspectives of the parties also differed substantially: one scenario entailed the protection of life and property. In response to an observation about how spectrum usage rights could have led to a negotiated *solution, a participant noted that public safety entities do not negotiate: they just go to Congress.*

A discussant observed that it would probably be most efficient if one could design a shared network upfront where public safety truly had priority; this would be more efficient than giving public safety its own band. However, the political economy of such a solution is daunting. One participant noted that emergency services tend to be more receptive to sharing bands with military, and another concurred that requirements are not going to be very different between civilian police and the military across many scenarios, including high demand ones like aerial video surveillance.

A participant reflected after the meeting[7] *the problem of the spill-over due to Nextel's wider digital sidebands should have been solved by enforcing reasonable emission masks, though the unexpectedly high signal levels may have allowed interference even with emission masks that worked with lower level signals. The major additional rule needed to ensure a benign out-of-band environment is a limit on the maximum field strength at street level or other locations where large numbers of other users will be found. With such a rule, Nextel would have been allowed to build sites wherever they wanted, but they would need to meet this limit, for example by using antennas with nulls at vertical angles near and below the horizon at low transmitter sites with high transmitter power.*

4.2 WCS/DARS

4.2.1 Introduction

There are a variety of interference claims by operators of Satellite Digital Audio Radio Systems (SDARS) and Wireless Communication Service (WCS): for example, WCS licensees worry about interference from terrestrial SDARS transmitters, and SDARS is concerned about interference from unlicensed devices and mobile WCS devices.[8]

WCS and SDARS are in adjacent frequency bands, bounded at the upper end by Aeronautical Telemetry (AT):

Figure 4: WCS/DARS Band Plan
(From Hatfield 2009, ref. in footnote 2 above)

The signal originally delivered to SDARS receivers was weak, coming from satellites. This resulted in gaps in coverage, particularly in urban areas, and lead SDARS operators to deploy ground-based signal repeaters. WCS receivers now had to contend, not with a very weak signal coming from outer space, but a very strong signal come from a repeater on the top of nearby buildings. Cheap receivers can reject a weak signal in an adjacent channel, but not a strong one. This is a near-far problem similar to the 800 MHz problem in the previous case study.

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[7] Personal communication, email November 10, 2009

[8] See the reading list for references

WCS was intended to provide digital radio services to fixed devices. However, WCS licensees wanted to enable mobile operation, creating a potential problem for SDARS. Rather than having to reject merely a weak adjacent channel signal from a distant building, an SDARS in-car receiver would now have to reject interference from an adjacent vehicle. WCS licensees also contended that the original out-of-band emission requirements were too tough and asked that they be changed. Such a modification, possibly further exacerbating the interference into SDARS also created concern among users of the aeronautical telemetry band that starts at 2360.

4.2.2 Discussion

A participant familiar with the case history noted that after setting aside an allocation for SDARS, the FCC decided to allocate left-over frequencies, resulting in the creation of WCS. However, protecting SDARS operation required such stringent out-of-band emission requirements that it emasculated this spectrum.[9] *In hindsight, he noted, the initial allocation specifically for SDARS was a bad idea; rather, it should have been a flexible allocation that covered both the SDARS band and the WCS band. It could then have been left to the licensee to decide whether to use it for terrestrial or satellite terrestrial service, as long as they internalized the cost of the interference. Instead, the Commission tried to shoehorn an emasculated low emissions service to function as a sort of wide guard band for a satellite service. Another attendee noted that the FCC decision on WCS was influenced by pressure from Senator McCain for a quick rule-making; the process was completed in less than six months.*

Conflict arose when both groups of licensees decided that they wanted to change their service architecture. SDARS operators installed a large number of ground repeaters using an experimental license.[10] *This created an unforeseen conflict of architecture similar to the 800 MHz case, although in case in adjacent bands rather than adjacent channels. On the other side, WCS providers wanted to use their license for mobile applications, which would have required a relaxation of the out-of-band emission requirement. Commission staff tried to get the parties to negotiate by threatening an Order; the parties went through the motions, but have not yet reached a resolution.*

A further complication in this case is that, unlike cellular where service providers often have a portfolio of infrastructure and license assets that allow them some flexibility, neither WCS nor SDARS had anywhere else to go: neither have an alternative network or frequency allocation to fall back on.

The failure to reach a resolution was not due to transaction cost problems: there were only a few parties in this case. A contributory factor may have been uncertainty about the contents of the Order that the Bureau had in its back pocket. There was discussion about whether the rules were clear enough to allow negotiation. One attendee observed that the

[9] "[A]ll emissions into the 2320-2345 MHz band from fixed WCS transmitters must be attenuated below the transmitter output power ("p") by at least 80 + 10 log (p) dB and all emissions from mobile WCS transmitters must be attenuated below p by at least 110 + 10 log (p) dB", "*Amendment of the Commission's Rules to Establish Part 27, the Wireless Communications Service ("WCS"),* Memorandum Opinion and Order, 12 FCC Rcd 3977, 3991 (1997) http://wireless.fcc.gov/auctions/14/releases/fc970112.pdf"

[10] The FCC staff reportedly felt that this action exceeded the terms of the license, but the Commission declined to act.

issue was never critical enough for either party to force them to go forward. WCS operators were not going to build a mobile network overnight; they were trying to improve the value of their spectrum. At the same time, SDARS were still operating with their questionably legal network of repeaters, and did not want to force the issue.

4.3 <u>AWS-3</u>

4.3.1 Introduction

The AWS-3 band adjoins the upper band of the (paired) AWS-1 allocation. The AWS-1 licensee is worried that operations in AWS-3 would cause interference they had not bargained for at the time they obtained their license.[11]

At the heart of the debate is the question of co-existence of FDD and TDD systems: between systems that separate transmissions from base stations and mobile units into different frequency bands (Frequency Division Duplex or FDD), and those where base stations and mobiles both transmit in the same band but at different times (Time Division Duplex or TDD).

Existing licensees in the AWS-1 band use FDD, and have mobile receivers operating adjacent to the AWS-3 band; within their band, AWS-1 mobile receivers only have to reject adjacent channel signals from distant base stations. However, TDD mobiles (as well as base stations) will transmit in the adjacent AWS-3 band. An AWS-3 mobile transmitter can be very close to an AWS-1 mobile receiver – two cell phones across a coffee shop table, for example – and the resulting adjacent channel signal into the AWS-1 receiver could be very strong, raising concerns of harmful interference.

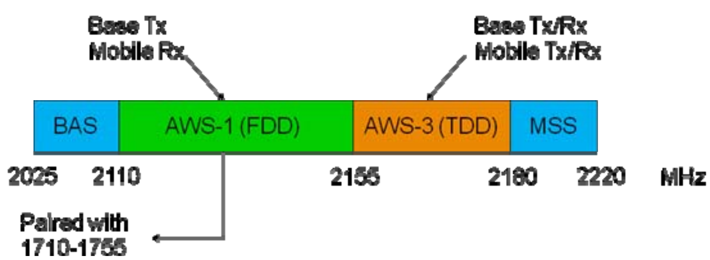

FIGURE 5: AWS BAND PLAN
(FROM HATFIELD 2009, REF. IN FOOTNOTE 2 ABOVE)

4.3.2 Discussion

Two participants agreed that one of the most difficult situations is where the rules are defined at different times. In perfect world one would settle all the rules before going to auction so that everyone knows what they are dealing with. In this case, though, AWS-1 had service rules while AWS-3 had been allocated without them.

An attendee noted that the FCC was attempting to force a political outcome in AWS-3 that had nothing to do with interference issues: the Commission precluded AWS-1 parties

[11] See Reading List for further background, e.g. FCC'S OFFICE OF ENGINEERING AND TECHNOLOGY, Advanced Wireless Service Interference Test Results and Analysis, Oct. 10, 2008, *available at* http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-08-2245A2.pdf

from avoiding the interference potential of TDD in AWS-3 by mandating a particular business model (the winning bidder should open up 25 percent of its network for free broadband access) as a condition of the license.

A discussant noted that all TDD / FDD cases suffer from base-to-base interference as well as the mobile-to-mobile case focused on here.

It was noted that there was also an interference case at the bottom end of the AWS-1 block where it adjoins Broadcast Auxiliary Service (BAS); see Figure 5. The FCC set rules without realizing how poor the performance of BAS receivers was; it was then found that there was harmful interference from AWS-1 into BAS under those rules. The AWS-1 licensee ended up spending two years working with BAS operators to develop filters to solve that interference problem. In this case, negotiations between the incumbent (BAS) and newcomer (AWS-1) were successful because the rules were clear and AWS-1 was obligated to become compliant.

Ofcom performed extensive modeling of FDD vs. TDD, and the ITU has published a study on the topic.[12] Spectrum Usage Rights (SURs) optimized for FDD would not preclude TDD, but would be so restrictive that no one could use the TDD approach unless they could negotiate some change in parameters with their neighbors. While the AWS-3 rules did not require TDD, the FCC knowingly created a band conducive only for TDD use.

5 Presentations

Four participants delivered prepared remarks to stimulate discussion.

5.1 Dale Hatfield

Dale Hatfield provided an introduction to the topic and case studies.[13] The material he presented and the subsequent discussion are reflected above, with the exception two other interference cases that were covered in the slides not discussed: "Mobile Satellite Service (MSS) Ancillary Terrestrial Component (ATC) Interference to GPS/GNSS" and "Military Radar Interference with 4.9 GHz Public Safety."

5.2 Greg Rosston

Greg Rosston framed his presentation by reference to Ronald Coase's seminal articles on the problem of social cost. The "Coase theorem" – which can be paraphrased by saying, "as long as you have an asset in a world with no transaction costs, the initial allocation of rights does not matter" – is often invoked but seldom fully appreciated. One might contend that tradable rights could have solved the 800 MHz problem; however, the "no transaction cost" assumption was violated in this case since there were thousands of public safety departments with whom Nextel would have had to negotiate. Since

[12] International Telecommunication Union (2003), Coexistence between IMT-2000 Time Division Duplex and Frequency Division Duplex terrestrial radio interface technologies around 2 600 MHz operating in adjacent bands and in the same geographical area

[13] Dale Hatfield, "Introduction and Overview", available: http://www.silicon-flatirons.org/documents/misc/OOBSummit/SFC%20Interference%20Summit%20-%20September%2009w0.ppt

transaction costs are not zero, the initial frequency allocation does matter in this case, as in others. A regulator seeks to facilitate transactions to allow the market to correct for the probably initially inefficient allocation. There are, no doubt, many problems with defining property rights, including uncertainties about boundary definitions arising from radio propagation, and interference that often varies substantially in time and space. However, administrative decisions face the same problems. One can improve the functioning of the market by finding ways to define rights so that parties have incentives to resolve problems through negotiation.

Attendees returned to these topics at various times, which is not reported here since it is reflected in the discussion noted throughout this report.

5.3 William Webb

William Webb outlined how the United Kingdom has tackled this problem since 2004 with Spectrum Usage Rights (SURs).[14] An important challenge was that changes in use, which are socially desirable because they can lead to more intensive operation as well as innovation, could result in additional interference. Ofcom wanted to reassure license holders that they would not be materially affected by a change in use by a neighbor. Much consultation produced SURs, not defined in terms of what one can transmit, but in terms of the interference that one is allowed to cause. These rights are defined in terms of three parameters: in-band interference, out-of-band interference, and geographical boundaries. All are measured in terms of power flux densities, i.e. power at a spatial point per unit area and frequency, using units like $W/(m^2 \cdot Hz)$. Webb encapsulated the value of SURs as simplifying negotiation by making it obvious what is being negotiating away.

5.3.1 Discussion

A number of participants expressed support for the overall approach of defining the permissible power levels for energy radiated in licensee and adjacent bands. Although SURs could be tailored to a specific use, the approach is explicitly service and technology neutral. No one objected to the approach of shifting from a transmitter-based to resulting signal-based approach, although one participant was very skeptical about the utility of models (see Section 6.4.5 below).

During a discussion about the application of this approach to different problems, Webb noted that the licensing system could remain the same, but parameters could change. For example, one could issue a license with quite liberal out-of-band emission rights in one place, but with very strict out-of-band emission conditions if it is right next to say an emergency service band.

SURs do not resolve current problems, but they can facilitate the resolution of future problems. For example, assume that one licensee chose to use really cheap receivers, and then their neighbor changed their use and upset those receivers. As long as the new use conforms

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[14] See William Webb (2009), "Licensing Spectrum: A discussion of the different approaches to setting spectrum licensing terms" available at http://www.silicon-flatirons.org/documents/misc/OOBSummit/Licensing%20Spectrum%20v1.1.pdf; Ofcom (2008), "Spectrum Usage Rights: A Guide Describing SURs" available at http://www.ofcom.org.uk/radiocomms/isu/sursguide/sursguide.pdf

to the SUR, the party that bought cheaper receivers has no recourse; it took a gamble that failed, and will not be protected by the regulator.

In a discussion regarding receivers, Webb observed that licenses based on power flux density limits inherently set the limits of the receivers and the bands that they have to operate in. He argued that explicit receiver requirements are not necessary since an operator can derive the signal levels their receiver has to tolerate by examining the terms of neighboring licenses.

Attendees spent some time probing the Ofcom approach. In addition to the measurement/modeling issue mentioned above, the framework does not deal with temporal variation, packetization, or the coherence of interference. SURs do not work very well for point-to-point scenarios like microwave links, since the rules do not specify angle-of-arrival for interference. Webb noted that SURs are primarily meant for area coverage and that, for directional applications, Ofcom would license the entire band to one entity so that it could optimize use to its preferences. SURs also use a "test area" to account for high interference in one area and low interference in another area; the interference results depend on the test area size and other factors. A discussant observed that these complications demonstrate how hard it is to simplify the interference problem for efficient management.

In reflecting on the adoption of SURs, Webb noted that cellular operators might not see much benefit for them because change of use is very unlikely and the band is already intensively used. A traditional transmitter license is easier to comply with since it limits what one can transmit. SURs mainly benefit neighbors because they obtain some certainty as to the maximum interference they will receive; the neighbor is protected against the SUR holder making a substantial change and causing interference. If the neighbor is also a SUR license holder, then there is a symmetrical relationship where both parties benefit.

However, one discussant raised the prospect of radical technology changes that are not encompassed in the definition of SURs. For example, DARPA is exploring Multi-User Detection (MUD) techniques that multiply spectral use intensity 4-5 times, but at the same time raise the noise floor of neighboring operators significantly.[15] *A legacy SUR definition could block the deployment of such a system since both the new technology, and techniques receivers can use to mitigate the noise it creates, are unknown at the time of its creation.*

Responding to a question about changing the parameters of a SUR, Webb noted that bilateral changes agreed by neighbors would be public since it would entail reissuing the license. Changing the model used to determine whether harmful interference has occurred is problematic since it might require a licensee to reengineer their network. As a result, Ofcom will only upgrade to a new model if all the all license holders in the affected bands agree.

Webb contended that SURs could have prevented the problems noted in the case studies. In the 800 MHz case, it is likely that Nextel would probably have breached their putative SUR by deploying a much denser transmitter network. SURs could also have handled the SDARS case: If the license criterion is the amount of interference one is allowed to

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[15] See e.g. "DARPA Interference Multiple Access" http://www.darpa.mil/STO/strategic/dima.html; ,J Farkas et al, "Application of Multiuser Detection to the Common Data Link Waveform", http://202.194.20.8/proc/MILCOM08/Milcom08/pdfs/1115.pdf; S. Verdu, *Multiuser Detection*, Cambridge University Press, Cambridge, UK, 1998

produce in some statistical manner, then it is completely agnostic from the type of network that is producing it. However, at this early stage SURs have not yet been put to such tests.

5.4 Preston Marshall

Marshall described the results of four years of work at DARPA, working out the consequences of the assumption that, in the end, the densest use of military spectrum in ad hoc systems will be TDD, because TDD reacts best to asymmetric demands.[16]

The result is "infastructuralist" at its heart, rather than cellular. While the conclusions do not apply directly to current cellular operations, the key early insight is widely applicable: Do not seek interference avoidance, but rather understand how to manage and mitigate the effects of interference, and seek techniques that obviate all of this planning and knowledge that were being discussed in such depth at this meeting.

Marshall proposed a frequency allocation solution summarized as follows: "I want to guarantee you access to spectrum, but I will not necessarily guarantee you 100% one frequency range. Rather, I will guarantee you an aggregate of access to sufficient frequencies to meet a certain amount of service."

The core limiting capability for the military is not in-channel interference but out-of-band emissions (OOBE). This will be the case in all ad hoc scenarios, including emerging civilian ones. Marshall advocated treating OOBE as the shared responsibility of devices, rather than as a problem to be solved by the regulator. Applied to the 800 MHz case, this requires a change in mindset from managing transmitted energy to managing behavior. Rather than assigning one channel to one operator, the regulator would give ten operators a list of ten frequencies, distributed over their tuning range; if one (say) public safety operator is blocked by OOBE because it is desensitized by (say) Nextel, it has the responsibility to find a new channel and move there. If none of them are good, then the operator can come back and complain to the regulator; but if one of them is good, it is the operator's responsibility to find it and use it.

Marshall argues that not all interference responsibility should be placed on transmitters, nor can it be. Receiver standards are a first step. Further, a licensee should be given some responsibility for avoiding interference in its receivers, not just for preventing it through its transmissions. In the *status quo*, the whole burden is unfortunately placed on the transmitter; the receiving party can use as weak and inflexible a technology as they wish.

The core idea is that one cannot complain about interference if you did not try to mitigate its impact, analogously to the legal principle that even an injured party has a responsibility to minimize their damage. (Squatter's rights are too politically loaded to be addressed directly; it is politically impractical, though tempting, to deny protection if a licensee uses poor receivers.) Mitigation can occur in frequency (a licensee is given redundant candidate frequencies to choose between) and/or time (a system design has to be robust against occasional signal failures).

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[16] Preston Marshall (2009), "Quantifying Aspects of Cognitive Radio and Dynamic Spectrum Access Performance" available at http://www.silicon-flatirons.org/documents/misc/OOBSummit/09.09.09%20Marshall%20Silicon%20FlatIrons%20Presentation.ppt

5.4.1 Discussion

One attendee strongly supported Marshall's contention that interference should be measured at the service level (in terms of system data throughput) rather than at the link level (in terms of interfering signal levels). He further advocated that even in a band intended for a particular service (e.g. Advanced Wireless Service rules for cellular) there should be different parameter sets for different technologies like FDD and TDD; that is, interference rules should be sensitive to the implementation architecture. While he admitted one can go too far on this– some would argue against specifying standards – it is important to understand that no "service-based" regulation is technology neutral.

Several participants discussed the possibility that dynamic spectrum access (DSA) technology could significantly mitigate out-of-band problems since a DSA radio can select a new channel when an out-of-band problem occurs. It would, however, be necessary to have sufficient available frequencies so that there is a high probability that a channel without out-of-band limitations would be available to the DSA radio. There was a difference of opinion about whether there were enough channels available to facilitate this kind of channel hopping for cellular services.

An advocate of the approach noted that the Internet does not try to make links reliable; it focuses on network capacity, not link capacity. Rather than focusing on the physical layer to solve interference problems, one should attend to the network and application aspects of services.

In response to a question of who would be hurt by moving to such a regime and what the costs might be, Marshall indicated that frequency and spectrum mangers might be impacted because it represents a shift from managing frequency to managing operating behavior.

Participants explored a number of the difficulties created by applying these ideas. While the approach would work in a peer-to-peer situation with smart radios, it is difficult to make legacy services like broadcasting smart. It is difficult to write new rules for the "old bricks"; industry is still building equipment based on "walkie-talkie rules." In general, it will be difficult to get end devices to upgrade. One example is the long upgrade cycle in maritime radio equipment compared to cellular; in another example, the Land Mobile Radio industry (serving public safety and other organizational clients) proudly assured the FCC some time ago that they could upgrade from 25 kHz to 12.5 kHz to 6.25 kHz over the next 25 years.[17]

It was argued that the 800 MHz problem could have been solved by moving to a network where one guarantees not the link, but communications. Arguably, a mission critical application like police communications needs to have multiple ways of getting the job done.

There was debate over the consequences of this approach for technology neutrality. One discussant contended that defining behavior implicitly defines classes of technology. One can only define behavior based on your knowledge of existing technology, which will lead to conflicts over unforeseen future operations. Marshall agreed that defining behavior locks in technology, but argued that defining the responsibilities of behavior leaves one's options open.

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[17] For the current state of play, see e.g. http://urgentcomm.com/policy_and_law/news/narrowbanding-mandate-webinar-20091028/

6 Themes

6.1 Benefits Sought

Various desirable consequences of better inter-channel rules were proposed, including enabling new technologies, allowing more efficient spectrum use, reducing the social cost of delayed conflict resolution, and avoiding the chilling effect of uncertainty on investment. The regulatory issues that typically take longest to resolve at the FCC entail interference: someone is seeking a new license and incumbents fear interference, or someone who has an existing license claims interference from an incompatible use.

One discussant observed that less interference should not be the goal of regulation. Rather, the goal should be to determine the most efficient use of spectrum and then construct flexible means to reach that goal. Minimizing interference is not the same as maximizing efficiency.

While there seemed to be agreement that rules can and should only be changed incrementally, some attendees expressed an interest in considering the long-term challenges and identifying the solutions towards which one could strive.

It was noted that one should distinguish between questions of definition and certainty of rights, and venue and mechanisms for negotiation between the parties. This meeting focused on the former, rather than the latter.

6.2 Source of problems

There are many successful negotiations to resolve interference problems among parties, and many of them do not come to light. Two participants observed that successful resolutions typically occur where the parties have the same interests, and that adjacent channel problems often arise where the parties do not have similar interests. This is most visible where adjacent bands have different rules.

The participants explored in some detail the various sources of the difficulties revealed by the case studies. The group agreed that it was worth separating technical and institutional causes; the following sub-sections address these topics in turn.

6.2.1 Technical factors

The coexistence of different technical architectures is a common source of inter-channel interference problems. Disparity in transmit power was one theme: high power public safety towers versus many lower-power Nextel base stations, and satellite versus ground repeater SDARS transmitters. If everyone were using similarly architected systems, conflicts would not have arisen in these cases. Both 800 MHz and WCS/SDARS are classic high site/low site interference cases. Rules that prohibited having high site/low site services in adjacent channels may have prevented the problem, but the FCC did not use them.

Unforeseen new requirements emerged as another theme. The high power SDARS ground transmitters were not foreseen in the rules, nor were the plans of WCS operators to go mobile. Further, the manufacturers of public safety equipment did not anticipate the way in which the 800 MHz band might be used by Nextel when they designed their receivers.

Generalizing, a discussant pointed out that while co-channel property rights are easy to manage, inter-channel rights are more tricky because radio system designs make a huge number of assumptions about the interference that will be generated by neighbors; when these assumptions fail to hold, difficulties ensue. Inter-channel interference issues also tend to emerge over time, as services are deployed, often with characteristics different from those that were envisaged at the outset.

One participant noted that one of the biggest sources of difficulty with inter-channel interference is technical complexity. The resulting interference level depends on so many parameters that it is difficult to get consensus among the parties when making calculations and predictions. Since there are no standards or accepted case history, huge resources are spent on technical analysis with each new proceeding. The biggest benefit of the Ofcom SUR approach is perhaps that it adopts a standard analysis methodology as part of the rules. The FCC broadcast TV rules have a similar interference analysis approach;[18] *interference complaints have been rare, though the price paid is the existence of many vacant channels, also known as "white space".*

An attendee noted that it is always good to be reminded that interference occurs in the receiver, and that the FCC does not regulate receiver characteristics directly. In spite of Moore's Law trends elsewhere, there was general agreement among the participants that the quality of receiver front ends was declining. It is expensive to build a receiver with a narrow, linear, tunable front end that can reject out-of-band interference. The device price-performance curve changed dramatically once manufacturers figured out how to make RF front ends using standard silicon rather than exotic materials. A better filter could be had by doubling the part cost from 50c to $1, but this is deemed unacceptable for very cheap devices made in large manufacturing runs with severe cost pressures. The result is that fully integrated – and thus very cheap – devices with significantly poorer performance than previous generations are now becoming much more prevalent.

This trend is particularly noticeable in the digital TV industry where the TV set vendor is decoupled from the television service provider. Even in the cellular industry, where there is a coupling between the service provider and the manufacturers of the phones, service provider engineers have complained that handset manufacturers would hand over equipment and expect them to live with it.[19]

Declining receiver performance, as well as the move toward mobile and personal receivers operating on batteries – highly linear amplifiers that can prevent out-of-band problems are inefficient and hence require more primary (battery) power – underlines the importance of inter-channel rights. However, while some of the analog aspects of receivers are not improving, there are also improvements. For example, most digital systems incorporate substantial error correction, which is especially good at eliminating low-duty-

[18] FCC, "Longley-Rice Methodology for Evaluating TV Coverage and Interference," *OET Bulletin* No. 69,

February 06, 2004. Available: http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet69/oet69.pdf

[19] Some providers are now beginning to change the dynamic of this negotiation by taking a bit more control over the development of the handset.

cycle impulsive interference. Other systems have incorporated OFDM modulations that can ignore narrowband interference and frequency-selective fading.

In a comment following the event, a participant observed that both out-of-band and adjacent channel issues revolve around receiver selectivity: out-of-band in the front end, adjacent channel in the IF or demodulator. Although there are significant engineering issues, they share common policy issues. First, allocating non-conflicting frequencies is not an effective means to reduce the interference. Further, interference is often a function of the receiver characteristics, not the licensed transmitter. A licensing process limited to transmitter properties therefore does not address all the causes of interference. Turning to mobile or incrementally deployed systems, he observed that interference here depends strongly on particular situations; thus, neither spectrum users nor the regulator can be confident of non-interference in advance of deployment and operation. The risk and resolution is deferred until after significant investment has been made. Next, the emphasis on low cost and low energy consumption will cause receiver sensitivity and mobility to become more challenging considerations, since the technology options that meet consumer needs tend to be poorer in their response to both out-of-band and adjacent channel energy. Finally, the shift from symmetric voice and SMS services to asymmetric Internet services will also likely exacerbate the situation as a FDD up/down link band design becomes less attractive for data services.

6.2.2 Institutional factors

The discussion of institutional considerations focused on the FCC; while raised in the context of inter-channel interference, most of the criticism was applicable generally.[20]

The topic of "spectrum squatters" came up a number of times. Operation beyond the terms of a license creates facts on the ground that may amount to a quasi-property right. The situation is exacerbated when (as is typical) spillover regulations apply only to individual transmitters, not the aggregate output from multiple sources. For example, exceeding the terms of their experimental license allowed SDARS operators to create squatter's rights when their action was not contested by the FCC. Further, the use of cheap receivers with poor out-of-band interference rejection creates a de facto *right limiting the ability of adjacent licensees, or even incumbents, to change their use of a band. This is particularly difficult when the general public is involved, as in the classic "garage door opener" case,*[21] *or when receivers and transmitters are deployed by different parties. It is politically potent when a constituent can say, "I bought this receiver in good faith and now I am being interfered with – the new entrant should solve the problem."*

A couple of attendees agreed that the FCC has demonstrated a pattern of inaction, leading to the creation of such rights de facto *rights. Fear halts deployment; for example, the US Department of Defense (DoD) has been reluctant to adopt a regulatory framework giving*

[20] For a broader discussion of the FCC's institutional shortcomings, see the record of the Silicon Flatirons/Public Knowledge conference on "Reforming the Federal Communications Commission", National Press Club, Washington, D.C., January 5, 2009. Available: http://www.silicon-flatirons.org/events.php?id=560 and http://fcc-reform.org/

[21] See e.g. http://www.freerepublic.com/focus/f-news/1295530/posts for a US example, and http://www.emcuk.co.uk/awareness/Pages/InterferenceExamples/RadioSusceptibility.htm#Tetra for a UK case

other parties access while retaining ownership and priority because it was afraid of squatter's rights emerging. Likewise, commercial operators have resisted secondary use of their channels by the military, even in limited geographies (e.g. desert ranges), because the mere existence of the equipment for such operation creates the possibility that it may be used elsewhere, thus establishing a presumption of access.

On the other hand, a participant commented the FCC's reaction to the recent 380 MHz garage door opener problem was especially courageous and positive for the long term, since it defended the DoD's full rights to frequencies that had been used on a Part 15 non-licensed basis by millions of garage door openers.[22] *Had the FCC not defended DoD's rights, it would have been a serious blow for any future frequency sharing.*

A number of participants noted the importance of achieving closure in a predictable timeframe. In some cases, delay cannot be blamed on the regulator but is due to the private motives of the parties. One or both may be best served by delay, as seemed to be the case in WCS/DARS. In cases where it is more costly for one party to wait than another, the one with time on its hands will wait and delay the decision. Delay and uncertainty can also be ascribed to the frequent practice of licensees that obtain a set of rules with the clear intent of immediately going back to obtain a change. Finally, some conflict resolutions require testing, which adds to the time required.

The FCC controls the shot clock, however, and can move quickly if it chooses to: it had six months to complete a local competition order in the Telecom Act of 96, and did so, though it took a heavy toll on personnel resources. However, one participant noted that the FCCs credibility is not very good in the marketplace: on Capitol Hill, among licensees, or would-be licensees. The FCC can move quickly, but often elects not to; acceleration in one area invariably results in a slow-down in other areas unless total resources are increased.

The Commission also places a low priority on enforcement. For example, it could have disallowed the SDARS industry's operation of ground-based repeaters beyond the terms of their experimental license but did not. The purpose of the experimental license was to establish out whether SDARS/WCS co-existence was possible, and its extension could be seen as an unpunished corruption of the rules.

There was no unanimity about the degree and consequence of political intervention in the FCC. One participant believed that the FCC could not be blamed, because it is subordinate to an institutionally corrupt Congress. Another contended that the FCC does not normally act under specific political pressure.

At times, problems arise because staff and Commissioners are working with intentionally incomplete or incorrect information. Parties know they get away with this: no one checks the accuracy of claims, as is done by the Justice Department and the SEC, and no one goes back to see that petitioners took the actions they promised.

There seemed to be agreement on the importance of a consistent framework of rules with a firm backstop that was quick and reliable. However, there was debate about whether a change in venue would help. One participant believed that enforcement of the rules by a judge

[22] See e.g. the FCC Public Notice DA 05-424 dated February 15, 2005 (http://fjallfoss.fcc.gov/edocs_public/attachmatch/DA-05-424A1.pdf), and the

GAO report "Potential Spectrum Interference Associated with Military Land Mobile Radios," December 1, 2005 (http://www.gao.gov/new.items/d06172r.pdf) *that is not subject to political influence would lead to better, faster decisions. Another participant disagreed, contending that the FCC was the best venue due to its technical expertise.*

One discussant noted that uncertainty about the security of property rights may have contributed to the lack of success of secondary markets. For example, a lessor may fear that success by a lessee might prompt the FCC to force a lease to continue if its termination could arguably lead to a lessee being driven out of business.

Political insecurity at the FCC about "unused spectrum" may create reluctance to allocate guard bands even where they might be useful. For example, MSS operators in 2000-2020 MHz feel comfortable with the 5 MHz guard band at 2020-2025 MHz and would like it to remain; if AWS-1 licensees in the A block were to ask for a 5 MHz guard band below 2110 MHz, it would lead to 10 MHz of "wasteland", which might be politically unattractive.

A number of attendees spoke to the importance of taking a strategic and holistic view toward spectrum planning, including doing annual in-depth studies. The European Commission periodically takes a broader look at the entire wireless scenario, considering all bands collectively. One participant observed that current rule-making is based on cases that are ten years old, and it does not take into account what has really changed in the operating environment. The world is very different now; for example, femtocells did not exist a decade ago. There is a need for a vision of where spectrum regulation needs to be thirty or fifty years from now.

Various participants underlined the importance of case studies. One of them added that the FCC should be doing after-action reviews to better understand what happened and learn from any mistakes; it would also be beneficial for each Commissioner to have an engineering advisor.

6.3 <u>The impact of changing technology</u>

The attendees mentioned a number of tech-driven changes that have, or will soon, contribute to regulatory challenges.

One participant argued that the shift from static to mobile receivers and, more generally, the rise of ad hoc networks that blur the distinction between base stations and clients undoes the principles on which radio regulation has been built. This had mortal consequences in the Iraq War when the operational concept changed from hub-and-spoke to peer-to-peer: interference management techniques that worked in a command-and-control scenario failed when communication occurred directly between soldiers 100 feet apart. The new framework for regulation should assume that everything becomes mobile, and everything becomes ad hoc*; femtocells will be everywhere.*

Large numbers of mobile devices mean that it will probably be impossible to guarantee that there will not be interference. For example, everybody switching on their cell phones in a plane as soon as it has landed creates a sudden, very high density of radio operation. Coping with such interference scenarios will require radios to become smarter and more flexible.

Mobility intersects with the use of scenarios (Section 6.4.1 below) to define operating rights. For example, imagine that rights are defined to avoid interference on the assumption that there will rarely be more than eight users within three meters of each other. If the reality *turns out to be ten people rather than eight, widespread harmful but legal interference will result. In such a case, the best thing to hope for would be a negotiation to change the limits.*

Another important factor is the emergence of a large number of wireless data networks with operators that have license assets across many bands. Some players now have many more ways of making a connection than previously, due to this aggregation of bandwidth.

There did not seem to be consensus on whether rights definitions have to change with technology, and more importantly, no proposals were made for ways to make such changes. Assuming static technology creates a dilemma: it provides certainty, but the inevitable changes will require renegotiation or redefinition of operating parameters.

6.4 Elements of Solutions

6.4.1 Scenarios

The challenge of making rules for mobile-to-mobile and other emerging deployments led to a discussion of the importance of scenarios in guiding rule making. There was agreement that rules (and associated rights) inevitably depend on assumptions about operating scenarios. The regulator has to make judgments about whether or not to worry about a particular interference scenario, even if no scenarios are mentioned in the resulting rules.

For example, Spectrum Usage Rights (SURs) as currently formulated are defined primarily for broad-area coverage scenarios, not point-to-point communications; the regulator decided that the latter situation would rarely occur or could be dealt with later. More specifically, in creating SURs for the L-band, Ofcom decided to split the band and offer two SUR parameter sets, one appropriate for high power, high tower uses, and the other half more appropriate for low power, low tower.[23] It did not require anyone to choose a particular one, but it did set the license terms for each, making it restrictive to operate anything other than was intended.

No one contested the propositions that one is captive to assumptions and that mistaken suppositions can have negative consequences. Any rules, including ones on device behavior (e.g. the approach advocated by Preston Marshall, see Section 5.4 above) will be based on one's knowledge of existing technology. In hindsight, rules made today will suffer from infirmities no less severe than the ones we diagnosed in the case studies. The danger of trying to manage inter-channel interference with rules is that one is defining it with today's technology in mind; rather, one should not just look at these cases, but imagine the future and how things could change under different circumstances. However, one participant noted that nothing had been said about what those general principles were: how should one relate the frequency bands to each other?

Thinking about regulation as an ecosystem resonated with many participants.

[23] They are separated not by a guard band as such, but by a band for low power with very restricted usage rights.

6.4.2 Clustering

The clustering or zoning of similar operations follows naturally from a scenario approach. For example, there might be value in putting low power, low antenna sites in one frequency range, and high power, high antennas in another.

As one participant pointed out, completely flexible uses are impractical unless used over wide frequency ranges or very large geographical areas where there are few edge effects. This underscores the importance of inter-channel rights since they are foundational to allowing one to define protection rights for potentially incompatible uses. Clusters of technologies allow one to make simplifying assumptions and provide a fair amount of flexibility, while still shaping the kinds of technology one might see in that band. These assumptions might include frequency versus time division duplexing (FDD vs. TDD); whether a band is for base station or mobile station use; and the quality of filtering, either explicitly in receiver specifications or implicitly in SURs.

There was some debate about whether zoning would work for radio operations, rooted in whether the real estate metaphor was applicable to wireless: one would need many "zoning codes" for radio, more – and this was the crux of the disagreement – than exist in land.

Some participants debated how the SURs approach might apply to the AWS-3 case. Ofcom's approach has been to make a prediction as to the most likely use in a band, and then to set the SUR terms accordingly. It was argued that this is not moving away from a liberalized, technology agnostic approach, but simply recognizing that it is better to set the rights based on the immediate use; the alternative would be to force everyone to negotiate before they can make any sense out of the rights and move any further. It makes sense to have all the FDD services grouped in one band and the TDD ones in another. This approach does not dictate a particular technology but makes it easier to deploy technology immediately after band award.

One example is the proposal by the European Commission that digital dividend spectrum be clustered to support three distinct service types: next generation broadcast, mobile service, and fixed wireless broadband access. Each cluster could be associated with a different SUR. Alternatively, clusters could be based around the range of interference protections, rather than specific services. This raised the question of whether parameters should be changed if the band is underutilized (see also Section 6.4.46.4.4 below on Operating Rights).

6.4.3 Receiver standards

Receiver performance requirements were discussed at various points. One participant observed that the regulator leaves licensees out to dry politically if it gives them transmission rights but does not intend to enforce receiver standards on potential victims. Another noted that when rules are transmitter-centric, licensees do not know what to be worried about; for example, a transmitter does not know what the delivered noise floor to a neighbor has to be in order to defend against charges of interference.

However, an attendee noted that defining the permissible co-channel and non-cochannel power levels effectively addresses all of the receiver quality issues that were raised without requiring direct control over receiver quality. This should provide future-proofing *against changing scenarios, since whatever happens to the receiver is irrelevant because the rules are simply specify signal strength that exists on the ground.*

While the Commission made it clear that it was not establishing receiver standards in the 800 MHz case, it tip-toed up to the line by making claims of interference protection conditional on receiver performance.[24] *At one time the FCC considered labeling receivers at the retail level as silver, gold or platinum quality; the idea was that a customer in an area with minimal interference could buy a silver receiver, and someone experiencing issues would buy a platinum-labeled device. This idea was not pursued due to objections from manufacturers, who always strongly oppose any kind of standards on the receivers, and uncertainty about whether the Commission had the authority to take such action.*

One participant noted a negative externality: the worse a receiver's performance, the cheaper it is to make. He proposed addressing this with a tax: if you have a poorly performing receiver, you pay more for the right to use it.

Another discussant observed that ratcheting receiver standards should be built into rule-making, requiring more interference tolerance as time goes on.

6.4.4 Operating Rights

A goal of the meeting was to explore whether new approaches to rights definition could obviate some of the interference conflicts that are brought to regulators.

6.4.4.1 Defining rights

An attendee framed the general problem as follows:[25] *FCC band allocation rules overtly contain detailed rules for each respective band, but the out-of-band environment for this band, call it X, is controlled entirely by allocations and licenses which are outside of Band X and not included anywhere within the rules for Band X.*[26] *Therefore, there are only vague, inferred connections between significant features of the Band X out-of-band environment and the allocation rules for all of the other existing allocated bands and licenses. For example, the connection between Band X receivers and Band Y high power transmitters is not included as part of the Band X rules or the Band Y rules. Further, even if the regulatory links were known, there are no formal property rights that describe how a licensee in Band X can be protected from any changes in the out-of-band environment. Therefore, each new case needs to essentially start from scratch and build the case (if it exists) for protecting existing licenses at the expense of future users. Since there are very few cases where there is an explicit link that associates the out-of-band environment of Band X with specific characteristics of neighboring bands or licenses, there is no obvious way to predict that changing some*

[24] The 800 MHz R&O FCC 04-168 released 6 Aug 2004, specifies for example in para 109 that "Voice units intended for mobile use: 75 dB intermodulation rejection ratio; 75 dB adjacent channel rejection ratio; -116 dBm reference sensitivity." In para 115, it explains that every 1 dB reduction in C/(I+N) performance over a compliant radio would increase the threshold at which they could claim interference. Available: http://www.800ta.org/content/fccguidance/FCC_04-168_08.06.04.pdf

[25] Feedback on the draft, personal communication, November 10, 2009

[26] In the 800 MHz case, strictly speaking, concerns adjacent channel rather than adjacent band interference, since unwanted energy was generated by operations on adjacent channels in the same band as the victim

allocation characteristic in a neighboring band would significantly affect the out-of-band environment in Band X – and presumably should therefore not be changed without concurrence from Band X users.

A number of attendees expressed support for the SUR approach outlined by William Webb. (The most notable point of contention was whether models or measurement should be used as the criterion for compliance; see Section 6.4.4.4 below.) There was a preference for rules that were focus on resulting signal levels rather than transmit power, since defining transmitter performance is insufficient for predicting interference. These rules are not receiver standards, inasmuch as they address performance characteristics only indirectly by describing interfering signal levels that have to be tolerated; the technologies used and performance parameters of receivers are not mandated.

The Ofcom approach specifies maximum power flux density levels (the resulting radiation at any point in, say, $W/(m^2 \cdot MHz)$) for the result of a rights-holder's transmissions at all frequencies and locations, thus covering both co- and adjacent channel cases. Another approach would specify this maximum, as well as a floor on the interference that the licensee had to accept.[27] *Ofcom does not define receiver parameters, since aggregating the maximum allowed signal strength generated by all neighbors gives a licensee knowledge of expected interference both in-band and out-of-band. On the other hand, in a mixed regime where not all licensees use SURs, the licensee has no certainty about its right to receiver protection without explicit maximum interfering signal levels.*

There was discussion about whether the interference rules should be driven more by the technology needs of particular services, e.g. TDD v. FDD, or a particular type of service, e.g. data or voice. It was accepted that defining behavior locks in some service/technology choices (cf. the discussion on Scenarios in Section 6.4.1 above). For example, SURs optimized for cellular deployment would not address air-to-ground scenarios such as unmanned aerial vehicles. However, there is an advantage simply to putting fairly rigorous limits on the kinds of signal fields that are delivered to ground level users, even if all scenarios are not addressed.

A discussant noted that it was important to distinguish between the options facing a service provider and the choices to be made by the regulator. One operator might have more options than another, perhaps by virtue of the breadth of their license portfolio or maturity of network infrastructure. The speaker did not think that the rights granted by spectrum management authority should take such diversity of options into account, even though operators with multiple bands had more ability to work around point interference than ones that did not.

One attendee noted that radiating any signal created a liability on another party since that signal can cause interference. As a thought experiment, he proposed that when someone gets a license to operate a system and starts radiating signals, payment should not flow to the government, but rather to everyone who might get interference from that signal. For every watt radiated, victim licensees get some share of the license fee because they are going to have to put up with that interference at some time as a function of geographic and frequency proximity.

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[27] This does not constitute receiver standards as such, inasmuch as it specifies the conditions a receiver must be able to tolerate, without dictating the performance of the receiver.

6.4.4.2 Rights vs. obligations

Some participants argued that obligations or responsibilities needed to be specified to complement rights. Current rules confer rights to operate but do not exact a corresponding obligation to accept a given amount of interference. This leads to conflicts when interference is experienced, since the licensee being interfered with claims "harmful interference" while the interferer argues that they are operating within the established rules.

It is problematic, one attendee noted, when a licensee obtains rights without attendant obligations and the neighboring band is vacant. When a neighbor appears, arguments start about obligations to accept interference. This creates problems for incumbents who obtain rights at auction, invest in building a system assuming a certain level of interference, and then argue that the operation of a new licensee amounts to a change in the rules. A solution would be to define both rights and obligations at auction, either implicitly or explicitly.

6.4.4.3 License terms and change conditions

While there was rough consensus that the regulator should define initial rights and responsibilities and then let the market operate in a decentralized way, a number of concerns were raised. To one participant, changes in technology seemed to require a way to update those rights and responsibilities as things change, but there is no obvious way to do that.

There was no agreement about limiting license terms. One participant proposed, for example, that the FCC includes in the conditions of a twenty year license that it would consider the renewal of this license, or varying its terms, after (say) twelve years. At one point the FCC considered adopting a service rule that required accepting progressively more interference over the period of the license, but it did not pursue this option.

Other participants argued that slowly changing rights over time makes it harder to write contracts; that it may be easier to specify the rights up front. Some attendees favored establishing grants in perpetuity, for example, by reference to the real estate market where renewing a housing license every twenty years would be considered absurd.

Finally, it was noted that for existing licenses, the legally established reasonable expectation of renewal of an FCC license amounts to granting the right in perpetuity.

6.4.4.4 Are rights definitions even the problem?

There was some disagreement about whether rights definition was even a problem. One participant felt that FCC right may already be too well-defined. However, another contended that there is almost no understanding of operating rights, which is why it is almost impossible to determine whether Nextel did something right or wrong: Nextel and public safety had clear transmit rights, but how the rights and reciprocal obligation interact with each other is not clear at all. Finally, another attendee felt the problem was insoluble, arguing that dynamic spectrum access approaches would succeed because the frequency managers will throw their hands up at managing adjacent channel and just turn it over to the radios.

6.4.5 Modeling vs. measurement

A shift from defining transmitter parameters to specifying the allowed resulting signal strength, as is done in Ofcom's SURs, raises the question of how a system's performance will be determined. There was a vigorous debate about the strengths and weaknesses of modeling *interference versus making field measurements. The SURs approach uses modeling rather than measurement.*

A modeling skeptic observed that while the predictions of different models sometimes resembled one another, at other times they were dramatically different. Field measurements show dramatic dependence on changing local conditions not taken into account in models, such as whether a parking structure was full of cars or not. Models can contain many variables, and people disagree on which ones are salient.

Models have many degrees of freedom, and arguments are likely about the statistical metrics chosen (e.g. 95% of the time and 95% of locations), the independent variables (e.g. time, space, frequency, power, and environment), the propagation model, and the granularity of the time dimension (is interference measured down to a femtosecond, a millisecond, a second, …).

Further, all models have a bias towards a particular usage scenario. These biases may handicap novel configurations such as packetized versus constant-strength signals, ad hoc networks or increased mobility.

On the other hand, it was argued that modeling has advantages over measurement in terms of speed, cost, and use in a court of law since it provides certainty and a level playing field: everyone will be using the same reference. Measurement shared many of the weaknesses of modeling, since variation makes it practically impossible to define interference accurately at any point in space or time. Further, Ofcom has found that in at least 95% of all its tests, the model prediction is within 6 dB of the measurement. Finally, while models are imperfect, the level of inaccuracy of predicted/specified interference is still orders of magnitude better than could be obtained by just restricting the transmitter power: it's not perfection, but it is better than the current situation.

7 Results of Consensus Poll

An on-line poll of attendees was conducted after the meeting to test areas of agreement quantitatively. Poll participants were asked to rate their position on ten statements using a six point scale: Strongly Agree; Agree; No Opinion; Disagree; Strongly Disagree; Can't answer as framed. Thirteen of the seventeen attendees responded.

The results of the poll are available on the meeting web page, http://www.silicon-flatirons.org/events.php?id=761.[28] They are summarized here.

There was general agreement (most participants responded Strongly Agree or Agree) that:

- "Defining license rights in terms of resulting interfering signal levels is preferable to defining transmitter parameters."
- "Political pressure on the FCC from Congress and interested parties undermines the rights allocation and adjudication process."
- "Clustering similar services and/or rules with similar parameters is a useful regulatory tool."
- "An obligation to accept a certain level of interference should be specified as a complement to the right operate transmitters."

Most attendees disagreed (indicating Disagree or Strongly Disagree) with the following statement:

- "It is better to specify acceptable interference levels by the impact at the service layer, than by interfering energy levels at the link layer."

There was weak agreement (a range of opinions, but a preponderance on the side of agreement) that:

- "The FCC is the best venue for deciding rights disputes (as opposed to, say, courts)."
- "A regulatory regime should have a mechanism for adjusting rights definitions as technology changes."
- "Explicit receiver performance standards mandated and tested by the regulator are a desirable regulatory tool."
- "Defining the maximum interfering signal levels that a receiver must accept (explicitly by rule, or implicitly as a result of a neighbor's SUR) is preferable to receiver performance standards."

There was weak disagreement with the following statement:

- "Rights entailed by current FCC rules are sufficiently well defined to lead to efficient problem resolution when parties are willing."

[28] http://www.silicon-flatirons.org/documents/misc/OOBSummit/PollResults.xls

8 Conclusions

8.1 Consensus and Disagreement

In spite of their varied perspectives, participants reached consensus on a variety of issues. They generally accepted the premise that properly defined rules and rights could shift some of the management burden from regulators to market participants. There was consensus that the advance of wireless technologies and maturing infrastructures had brought the industry to an inflection point where past methods of governance were no longer adequate. The shift to mobile operation and the increasing use of ad hoc rather than centralized networks were accepted as driving forces behind the need for new rules. A holistic, future-oriented approach to solving the problem seemed to resonate, as did the "ecosystem" metaphor.

All agreed that the interference conflicts were rooted in the co-existence of different technical architectures and conflicting commercial interests, whether due to changes in the use of a band, unforeseen new operating requirements or unexpected variances in the ability of receivers to reject interference. Conflicting interests are particularly likely in adjacent bands with different service rules. Declining receiver quality due to CMOS integration of front-ends created a particular challenge – more work is needed on this topic.

Broad support emerged for defining license rights in terms of resulting interfering signal levels, as exemplified by Ofcom's SURs, rather than in terms of the customary rules on individual transmitters.[29] Some participants expressed doubts about Ofcom's use of models, rather than measurement, to determine whether interference had occurred.

The role of receiver performance when harmful interference is experienced was a recurring theme. There seemed to be broad support for taking receivers into account more explicitly when drafting rules, e.g. by regulating resulting signal levels rather than transmitter power. Discussants divided on whether receiver standards[30] were necessary, and on whether the degree of interference that a receiver needed to reject should be defined explicitly in rules, or implicitly (as the aggregate of rules applicable to operators in adjacent frequencies).

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[29] Other alternatives to the traditional approach, such as the Australian "space-centric" management method, were not presented. For an exposition of this approach, see e.g. Michael Whittaker (2007), *Space-Centric Management: A General Solution for Equitable Access to Radio Spectrum Space under Conditions of Flexible Use*, available at http://www.itu.int/osg/spu/STN/spectrum/workshop_proceedings/Background_Papers_Final/Michale%20Whittaker%20-%20space_centric_management_spu(mjw).pdf. For a critique of the SURs method from this perspective, see Michael Whittaker (2007, updated), "Commercial Certainty in Spectrum Right Formulation", available at http://www.futurepace.com.au/CCMar.pdf

[30] Receiver standards imply that devices must pass tests defined by the regulator; they are distinct from reception parameters do not entail such tests. For example, receiver standards might specify selectivity or adjacent channel rejection; reception parameters might specify the maximum interfering signal levels that a receiver must accept.

There was lively discussion about using dynamic spectrum access (DSA) technologies to significantly mitigate out-of-band problems, since a DSA radio can select a new channel when an out-of-band problem occurs; they also inspire new regulatory approaches , including shifting the determination of interference harm from the radio layer to overall system behavior.

There seemed to be consensus that scenarios had to be used to inform the creation of rules, and that they encoded assumptions, some of which would later be found to be wrong or obsolete. The clustering of similar services, also known as zoning, follows from a scenario approach, and garnered support from most attendees.

Most, but not all, attendees agreed that the problems exemplified in the case studies were due to poorly defined rules.

While the institutional frailties of the FCC – including unpredictable time frames for decisions, a low priority on enforcement, and a tolerance for squatter's rights – elicited spirited debate, no consensus emerged about the causes. There was general agreement, though not consensus, that political pressure on the FCC from Congress and interested parties undermined the rights allocation and adjudication process. There were differing opinions, with a preponderance of support, for the proposition that the FCC was the best venue for deciding rights disputes as opposed to, say, courts.

Attendees did not reach consensus about whether rules should be revisited periodically, e.g. as technology shifts, or whether license terms should be limited or indefinite. However, almost all participants agreed that a regulatory regime should have a mechanism for adjusting rights definitions as technology changes.

8.2 Case Studies

Each case study highlighted different aspects of the conflict engendered by inter-channel interference.

Difficulties in the 800 MHz band were difficult to resolve because public safety's entitlement to inference protection was not clear enough to force Nextel to change its operation or require public safety to change its architecture. There seems to have been a conflict between two rights: public safety's right to interference protection for its receivers, and Nextel's right to deploy transmitters in a topology different from services which shared the band, while still operating them at licensed power. Clearer *ex ante* definitions of both receiver protection rights and transmit rights – for example, defining both in terms of resulting signal strength throughout the license area – could have highlighted the contradictions in rights allocations before they were made.

WCS/SDARS was a different kind of fight: both parties wanted new rights, and they used claims of interference to their extant rights as leverage. The lack of resolution in WCS/SDARS is not necessarily an indication of poor rights definition, however, since the conflict concerned the creation of new rights. Both sides seem happy to drag out the *status quo*. However, the fact that both felt that they were more likely to get new rights through the politicized process of recourse to the FCC rather than through mutual negotiation points to an institutional problem.

The third case study addressed whether rights to be given to AWS-3 licensees would cause harmful interference with AWS-1. It thus has aspects of both the preceding cases: a lack of clarity over the meaning of extant rights, and a political tussle over the creation of new rights. This case suggests that although the transmitter rights of AWS-1 licensees were clear, their interference protection rights were not.

8.3 Outstanding Questions

The case studies suggest a taxonomy of inter-channel interference conflicts (Table 2; a particular case can contain more than one kind of conflict). Analysis of more cases, and a more detailed analysis of rights definitions, will surely generate refinements.

TABLE 2
A TAXONOMY OF RIGHTS CONFLICTS

1) One or both parties claim their rights are being infringed.
    a) They disagree on the facts: e.g. competing test results. (Example: AWS-3.)
    b) They agree on the facts (which may include estimates of potential interference by envisaged operations), but
        i) One (or both) contends that the other does not have such rights: rights are poorly defined. (Example: deployment of terrestrial repeaters beyond scope of experimental license by SDARS.)
        ii) Both parties have the rights they claim, but the rights are contradictory, i.e. both can operate in the terms of their license but harmful interference can still result. (Example: 800 MHz.)
        iii) One or both parties are seeking new rights to operate that exceed their current rights. (Examples: mobile WCS operation; SDARS terrestrial repeaters.)
2) The harm claimed is not covered by the rights as currently defined: e.g. arguments over the consequences of new rights issuances. (Example: AWS-3 rights to generate interference into AWS-1)

This summit focused on the technical basis of inter-channel interference. It is clear that a more detailed analysis of the legal rights asserted by parties, and their interpretation by the FCC, would be worthwhile. A near-term opportunity for further work includes analyzing the property rights claims in the case studies in much finer detail. There is also a need for more analysis to determine where the most likely regulatory challenges would arise after a transition for pervasive mobile and ad hoc operation, and the implications of the extensive network assets that have been built for some services.

On the technical front, the debate did not deal in any depth with non-linear receiver effects like desensitization and intermodulation issue; further analysis of this area is required.

Transmitter masks are just as important for managing inter-channel interference as receiver performance attributes like selectivity and dynamic range. A participant observed after the meeting that while the discussion covered receiver performance in some detail, transmitter attributes were mentioned only in passing. A balance needs to be struck between receiver and transmitter requirements; making one more stringent allows the other to be worse, while yielding the same interference protection. There is a complex technical and cost relationship between transmitter mask values and receiver selectivity/linearity values required for some desired out-of-band isolation. These trade-offs may be explicit or implicit, as when scenarios are used to devise SURs. Parameter choices can have far-reaching consequences; for example, the transmitter masks being required from unlicensed devices in the TV white spaces are so demanding that they may limit use of this allocation.

While this discussion focused on a number of specific cases and also considered general trends, it did not create a framework to decide which types of interference issues should be dealt with through rules and regulations, and which should be negotiated by the parties. It also did not consider in detail whether, where or how existing institutions currently fail, or will fail, to solve these problems.

One participant observed that there would always be moments in the regulatory process when rights would be up for grabs. A group such as this could try to define where the ambiguities might lie, and where there is sufficient clarity to move forward.

Finally, a number of questions of rights definitions were raised but not resolved, including whether absolute technology neutrality is necessary, desirable or feasible; whether future proof ex ante definition of rights was possible; and the appropriate use of scenarios in defining rights.

9 Attendees

Ken Baker	Scholar in Residence, Interdisciplinary Telecommunications Program, University of Colorado at Boulder
Ira Barron	Baseline Telecom (The 800 MHz Transition Administrator)
Brad Bernthal	Associate Clinical Professor of Law, University of Colorado at Boulder
Pierre de Vries	Senior Adjunct Fellow, Silicon Flatirons Center
Kathleen Hamm	Vice President of Federal Regulatory Affairs, T-Mobile
Dale Hatfield	Executive Director, Silicon Flatirons Center; former Chief of the FCC Office of Engineering and Technology
Paul Kolodzy	Kolodzy Consulting; former Chair of the FCC Spectrum Policy Task Force
Mark McHenry	President and CTO, Shared Spectrum Company
Scott Marcus	Senior Consultant, WIK Consult GmbH
Preston Marshall	Director, Information Sciences Institute, University of Southern California; former Program Manager, DARPA XG Program
Bob Matheson	Former Deputy Director of the NTIA Institute for Telecommunication Sciences (ITS) and Head of the ITS Spectrum Division
Susan Ness	Susan Ness Strategies; former FCC Commissioner
Greg Rosston	Deputy Director, Stanford Institute for Economic Policy Research
Doug Sicker	Assistant Professor, Computer Science, University of Colorado at Boulder
Ed Thomas	Engineering and Technology Policy Advisor, Wiltshire & Grannis LLP; former Chief of the FCC Office of Engineering and Technology
Scott Wallsten	Vice President for Research and Senior Fellow, Technology Policy Institute (on leave); currently Economics Director for the FCC National Broadband Task Force
William Webb	Head of Research and Development, and Senior Technologist, Ofcom

10 Abbreviations

AWS	Advanced Wireless Service (FCC)
BAS	Broadcast Auxiliary Service (FCC)
DSA	Dynamic Spectrum Access
FDD	Frequency Division Duplex
IF	Intermediate Frequency
LMR	Land Mobile Radio (FCC)
LNA	Low-noise amplifier
OOBE	Out-of-band emission(s)
RF	Radio Frequency
SDARS	Satellite Digital Audio Radio System (FCC)
SMR	Specialized Mobile Radio
SUR(s)	Spectrum Usage Right(s) (Ofcom)
TDD	Time Division Duplex
WCS	Wireless Communications Service (FCC)