International Spectrum Workshop

Wednesday, June 28, 2017, 09:00 - 18:00

Université Paris-Dauphine, Raymond Aron Conference Room

Agenda

09:00 – 10:00 **Breakfast**

10:00 – 10:30 **Welcome & Introduction**
Phil Weiser and Eric Brousseau

10:30 – 11:30 **Session 1: Spectrum Allocation and Metrics**
Moderator: J. Scott Marcus
Presenters: Pierre de Vries, Peter Anker, and Jan Kruys
Readings:
Risk-informed interference assessment: A quantitative basis for spectrum allocation decisions, by Pierre de Vries
Sharing license-exempt spectrum based on multi-dimensional metrics, by Johannes (Jan) Kruys, Peter Anker, Roel Schiphorst

11:30 – 12:00 **Break**

12:00 – 13:00 **Session 2: Assignment and Management**
Moderator: Joëlle Toledano
Presenters: Gérard Pogorel and William Webb
Readings:
Spectrum 5.0 Improving assignment procedures to meet economic and social policy goals – A position paper, by Gérard Pogorel and Erik Bohlin
Managed Unlicensed Spectrum, by William Webb

13:00 – 14:00 **Lunch**

14:00 – 15:00 **Session 3: Next-Generation Spectrum Enforcement**
Moderator: Christopher S. Yoo
Presenter: Pierre de Vries
Commenter: Didier Chauveau
Reading:
A Study to Develop the Next Generation Systems Architecture for Radio Spectrum Interference Resolution, by Spectrum and Receiver Performance Working Group, FCC Technological Advisory Council

15:00 – 15:30 **Break**

15:30 – 16:30 **Session 4: Standards and Public Policy Goals**
Moderator: Howard Shelanski
Presenter: Phil Weiser
Commenter: Martin Cave
Reading:
Addressing Public Policy Goals in the Standards Setting Process: The Case of 5G Wireless Standards, by Dale Hatfield

16:30 – 17:00 **Wrap-up**

17:00 – 18:00 **Reception**

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Participants

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Risk-informed interference assessment: A quantitative basis for spectrum allocation decisions☆

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A R T I C L E I N F O

Keywords:
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Quantitative risk analysis
Radio
Regulation
Spectrum

1. Introduction

Lottery billboards proclaim the huge amounts that punters could win, but they do not reveal the infinitesimal chance of actually winning. Most harmful interference claims work the same way: incumbent services fearing harm from new entrants emphasize the sensational consequences of extreme interference events, but not their low likelihood.

Making a trade-off between the benefits of a new service and the risks to incumbents is at the heart of spectrum policy (see Section 2.1). It has, to date, frequently been qualitative and often based on worst-case scenarios. This paper makes a case for quantitative risk assessments that broaden regulatory analysis from "What's the worst that can happen?" to "What can happen, how likely is it, and what are the consequences?" and can thus provide a stronger evidence base for policy judgments.

Quantitative risk assessment (QRA) is a well-established technique, with an extensive literature and regulatory uses, in industries from finance to food safety, spanning many decades. The method was not explicitly used in spectrum analysis until the work of FCC TAC (2015a) and De Vries (2015), although wider use of stochastic modeling and acceptable interference statistics was advocated in IEEE-USA (2012). The literature and some non-spectrum applications are briefly reviewed in Section 2.2.2.

As illustrated Section 3, QRA complements the customary and well-established practice of worst-case analysis, which is an assessment of interference potential that focuses on a single, high impact scenario where most if not all parameters take extreme values.

QRA has many benefits, such as providing a more complete and nuanced analysis than worst-case assessment; providing a common currency for comparing different hazard types; and providing an objective basis for decision making. Of course, it is also limited in various ways: it requires more data and computation than traditional methods; it challenges the regulatory community to think in new ways, e.g. in using statistics; and it needs complementary perspectives from economics (e.g. cost-benefit analysis) and the humanities (e.g. cultural and psychological perspectives) to augment engineering analysis. The benefits and limitations of QRA are discussed in Section 4.

Spectrum policy makers and managers can begin to incorporate quantitative risk assessment into their procedures immediately—

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no new rules are needed. Recommendations for policy action by regulators and legislators are given in Section 5.

The scope of this paper is limited to regulatory activities, in particular the upfront assessment of harmful interference during rulemaking, not post-allocation activities such as adjudication and enforcement. It also leaves aside important topics such as risk communication, ongoing risk management, and the use of risk analysis in interference disputes and enforcement.

1.1. The MetSat case study

Section 3 will frequently refer to a meteorological satellite ("MetSat") case study. It was developed in a set of closely related papers that will be referred to as the "MetSat Risk Studies": De Vries (2015), FCC TAC (2015b), and De Vries, Livnat, and Tonkin (2016). We will illustrate our method by frequent reference to De Vries et al. (2016).

The case study deals with the reception of signals from Polar-orbiting Operational Environmental Satellites (POES); geostationary satellite services (GOES) in the same band are less vulnerable to interference. MetSat receiving earth stations in the 1675–1710 MHz band need to be protected from harmful interference from cellular mobile devices in the 1695–1710 MHz band, which were assigned U.S. licenses through the AWS-3 auction. Polar satellites are in a low earth orbit and make a usable pass over a given earth station about once a day. Since the received signal is very weak, a satellite is tracked by a large, fixed, high gain dish antenna. The aggregate of all the signals transmitted by cellular mobiles close to the receiver can cause interference. The key regulatory question in the U.S. was: How far away should co-channel cellular mobiles sharing the band be kept from MetSat earth stations to ensure that data used in weather forecasting is successfully received? The exclusion distance was a key element of the resulting band sharing rules.

The exclusion zones proposed in the original NTIA assessment were calculated for co-channel interference using the maximum transmit power of cellular mobiles (NTIA, 2010, referred to for convenience as the "Fast Track Report"). The subsequent report by a working group of the Commerce Spectrum Management Advisory Committee assumed a more realistic range of mobile transmit power which resulted in protection zones reduced by 21–89% (CSMAC, 2013, "WG-1 Report"). Both studies took a worst-case approach that used extreme values for most parameters, and focused only on long-term, co-channel interference. The MetSat Risk Studies, summarized in Section 3, provided a more comprehensive hazards analysis, such as looking at both short- and long-term interference scenarios, and including adjacent band as well as co-channel interference. That results in even smaller co-channel protection zones.

2. Risk assessment and spectrum policy

2.1. The policy context

The insatiable and growing demand for spectrum use rights (so well known that it will not be rehearsed here) leads to a continual process of spectrum re-allocation. More and more applications and devices—of increasing variety, that require ever more spectrum capacity—must be squeezed into ever-more crowded spectrum. This leads to closer packing in time, space, and frequency.

Greater proximity increases the cost of mistakes in allocation or assignment of spectrum use rights, and increases the risk of service breakdowns due to harmful interference. This leads to a tussle between incumbents and new entrants. Incumbents fear that new allocations will harm their services, and aspiring entrants fear that exaggerated forecasts of harm will stymie their plans. At the same time, growing demand means that wide guard bands and protection zones are increasingly hard to justify.

The question of whether a spectrum regulator should allow a new radio service is usually informed by engineering analysis oriented around the worst-case, followed by a qualitative rather than quantitative judgment of risk (De Vries & Littman, 2014). This paper argues for a more rigorous approach: quantitative risk-informed interference assessment.[1]

2.2. Risk assessment defined

Engineering risk assessment sets out to inventory possible hazards and calculate their severity and likelihood. For example, when considering whether to install a burglar alarm system one might consider the various circumstances under which unwanted people might enter your house; how likely each possibility might be; and what harm might befall you in each case, from pranks and petty larceny to assault.

2.2.1. Deterministic methods and worst-case analysis

Before turning to the definition of risk assessment, it is instructive to examine *deterministic methods*. These evaluate risk in terms of scenarios characterized by single-valued parameters. A deterministic approach does not necessarily entail using extreme values, but usually does. A "worst-case" analysis—perhaps more accurately described as a deterministic extreme value analysis, since for any "worst" case one can almost always construct an even worse one—considers the single scenario with the most severe consequence regardless of its likelihood.

[1] Interference is not necessarily harmful. The ITU-R definitions, incorporated in national regulation such as 47C.F.R. 2.1 in the U.S., characterize *interference* as "[t]he effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy", and *harmful interference* as interference that "endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service".

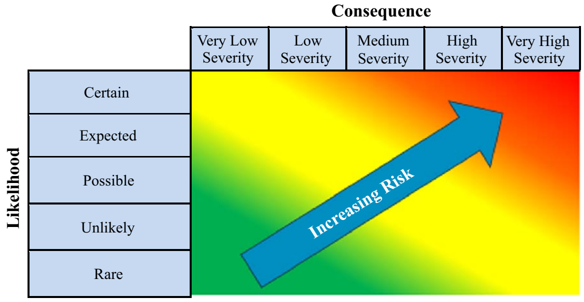


Fig. 1. A qualitative risk chart.

For example (with worst-case instances in parentheses), the hazard posed by a new radio service allocation is often estimated by assuming a potentially interfering transmitter operating at a fixed distance (very close by) at a given transmit power (the maximum legally allowed) to a specific receiver (the least interference-resistant one on the market) over a propagation path with a single-valued attenuation loss (assuming a direct path without any intervening obstructions).

There are cases where an extreme value analysis can be useful. For example, if a particular hazard does not pose a risk even under worst-case assumptions, it can be omitted from subsequent analysis. Conversely, if a hazard poses risks even in the most favorable circumstances, further analysis is needed. However, fixating on a single interference scenario does not accurately represent reality and can lead to false confidence that the resulting rules will avert harm. For example, the worst-case (malicious jamming, say) may be so rare that it can be safely ignored; and a more common but less extreme effect (like a rise in background radio noise) may be more problematic in practice.

As an analogy, when deciding on the amount of domestic protection to buy, most consumers do not plan for a worst-case like home invasion. Rather, they take a view—based on the particular threats in their neighborhood, their need for security, and costs—of various options like deadbolts, burglar bars, intrusion alarms and steel doors.

A worst-case approach is inherently conservative, all too easily leading to rules that severely limit the benefits of new services while giving incumbents more protection than they need. It arguably made sense when spectrum rights were not in such great demand. It is not tenable when high value services have to be squeezed ever more tightly together. There are exceptions where a conservative approach remains appropriate, such as life safety services where interruption is absolutely unacceptable and spectrum protection is the only way to guarantee it.

The FCC has quite often based its conclusions on worst-case analysis, e.g. in the determination of rules for UWB systems (see De Vries and Littman (2014), footnote 2), but has rejected a worst-case analysis on some occasions (Cox & De Vries, 2015). In the MetSat case, relaxing the worst-case assumptions in the Fast Track Report and using the not-quite-worst case assumptions in the WG-1 Report reduced the size of exclusion zones, generating tens of millions of dollars in value (Ward-Bailey & De Vries, 2015).

2.2.2. Quantitative risk assessment

This paper considers *risk* to be the combination of likelihood and consequence for multiple failure scenarios, using the "risk triplet" introduced by Kaplan and Garrick (1981): What can go wrong? How likely is it? What are the consequences? This kind of risk assessment is by its nature probabilistic or statistical.

Risk assessments can be qualitative or quantitative. The likelihood and consequence of hazards are often plotted on a *risk chart*; a generic version of a qualitative one is shown in Fig. 1. High risk hazards are in the top right hand corner, shown in red; they have severe consequences and high likelihoods. Minimal risks, in green, arise from unlikely or rare events with moderate or low severity. Moderate risks occupy the yellow band across the middle of the table. They include both rare events with very high severity, and expected events with minimal consequences.

If both likelihood and consequence can be quantified, quantitative risk charts such as those in Fig. 8 can be plotted. *Quantitative risk assessment* (QRA), also known as *probabilistic risk assessment* (PRA), sets out to answer the three questions above by using numerical estimates of frequencies and consequences to estimate risk. Quantitative assessments help to compensate for poor human intuition regarding probability and statistics (see e.g. Kahneman and Tversky (1972) and Shermer (2008)). QRA, as employed in this paper, explores a range of input parameter values and generates a probability distribution of a consequence metric.[2]

Applying quantitative risk assessment to spectrum yields *risk-informed interference assessment*, the systematic, quantitative analysis of the likelihood and consequence of interference hazards caused by the interaction between radio systems. Such an assessment both informs, and is informed by, a regulator's judgement on what risks are acceptable.

The work is not over once a risk assessment has been done and rules have been made. Risk management is an on-going task; see e.g. the discussion of the International Risk Governance Council's framework in Renn (2008b). While day-to-day spectrum risk management is primarily the responsibility of radio operators, the regulator may intervene—by adjusting rules, say—if the assumptions that underpinned its risk assessment are invalidated by subsequent events and unexpected harmful interference occurs.

[2] Event tree or fault tree analysis—for example, as widely used in the nuclear industry before the adoption of QRA—multiplies single-valued probabilities at the nodes of a fault tree to estimate the deterministic probability of a specific initiating event. The result is a single probability, not a probability distribution.

A spectrum regulator's ongoing risk management responsibilities require further study and are not considered in this paper.

QRA is a well-established technique, with an extensive literature spanning many decades: see e.g. Kaplan and Garrick (1981), Morgan and Henrion (1990), Renn (2008a, 2008b), and Vose (2008). It has been used around the world for decades in regulated industries from finance to food safety, including cases where safety of life is paramount. There are many U.S. examples:

- The U.S. Nuclear Regulatory Commission ("NRC"): The NRC adopted quantitative risk assessment in the seventies. It uses this technique to improve safety decision-making and regulatory efficiency. For more details, see NRC (n.d., 2007, 2011) and Littman and De Vries (2014).
- The U.S. Environmental Protection Agency ("EPA"): Since 1967, the EPA has used risk assessment to characterize the nature and magnitude of health risks from chemical contaminants and other environmental stressors (EPA, 2004).
- The U.S. Food and Drug Administration ("FDA"): The FDA uses risk analysis to ensure that regulatory decisions about foods are science-based and transparent (FDA, n.d.). FDA-iRisk (https://irisk.foodrisk.org/) is a publicly accessible online tool that uses Monte Carlo simulation to estimate the health burden of microbial and chemical hazards in food.
- Other U.S. government agencies and departments using risk assessment methods include the Office of Management and Budget and the Office of Science and Technology Policy; the Departments of Homeland Security, Health and Human Services, and Transport; and the Federal Aviation Administration, NASA and the Occupational Safety & Health Administration.

The method was not explicitly used in spectrum analysis until recently. IEEE-USA (2012) argued for the wider use of stochastic modeling and acceptable interference statistics, and De Vries and Littman (2014) examined the use of statistical risk assessment by the FCC. Littman and De Vries (2014) investigated lessons that the FCC could learn from the use of risk-informed regulation in the nuclear industry. The FCC Technological Advisory Council ("TAC") published an introduction to risk-informed interference assessment (FCC TAC, 2015a), and De Vries (2015) introduced the MetSat case study that will be referenced throughout this paper. The Silicon Flatirons Center organized the first conference on risk assessment in spectrum policy in October 2015 (Ward-Bailey, 2015).

3. Risk-informed interference assessment

This paper divides risk-informed interference assessment into four elements:

1. Make an inventory of all significant harmful interference hazard modes.
2. Define a consequence metric to characterize the severity of hazards.
3. Assess the likelihood and consequence of each hazard mode.
4. Aggregate the results to inform decision making.

This section discusses each element in turn, providing two kinds of examples in each case: inputs and results from the latest MetSat case study (De Vries et al., 2016); and ad hoc examples from a variety of prior interference studies in the literature. The ad hoc examples show that the data and calculations required for a quantitative risk assessment are already common in interference assessment.

3.1. First element: make an inventory of hazards

The first step in quantitative risk assessment is to make an inventory of all expected hazards, that is, phenomena that could but do not necessarily cause harm.

The interaction between two radio systems is affected by the locations of the interfering and affected systems, the characteristics of the transmitters and receivers of the two systems, and the coupling between them. The coupling (that is, the degree to which interfering energy from a transmitter is admitted into a receiver) depends on factors such as antenna gain patterns and propagation loss. A risk assessment uses this information together with measures of service degradation (likelihood and consequences metrics). Fig. 2 summarizes the information needed.

There are many interference mechanisms. For example, service degradation can result from both out-of-band emissions ("OOBE": interfering signals leaking into the affected system's operating channel from transmissions in an adjacent channel or band) and adjacent band interference ("ABI": a service being affected by energy entirely contained within an adjacent channel or band that its receiver cannot reject). Potential sources of interference range from unintentional radiators to maliciously operated transmitters. There may be both single-source interference from a strong transmitter and/or aggregate interference from many individually weak transmitters. Key interference parameters for cellular-into-MetSat interference are listed in Table 1.

Since there are many potential hazards, it is tempting to limit analysis to only the most important ones. In many cases, one hazard dominates—or is assumed to dominate—the analysis. The characteristic hazard in cellular-to-TV interference, for example, is adjacent channel interference (Aegis, 2007).

However, it is imprudent to focus on a single hazard since one may miss important interference modes. For example, the only MetSat hazard investigated in the Fast Track and WG-1 reports was co-channel interference; adjacent channel interference was ignored, without explanation. Fig. 10 shows, however, that adjacent channel interference can, in fact, be a greater hazard. There was more than one hazard in play in the GPS/LightSquared case, although this was not recognized early on (FCC, 2011; GPS Working Group, 2011). The discussion in the early 2000's focused on LightSquared's out-of-band emissions. The decisive dispute of the early

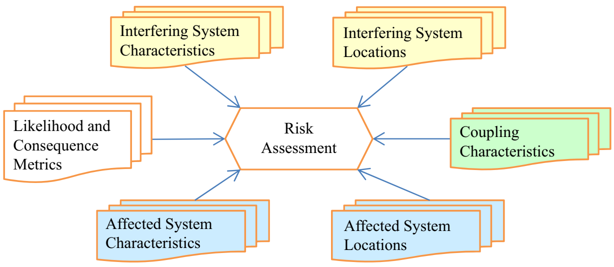


Fig. 2. A simplified representation of the parameters and process needed to perform an interference estimation (TR 46, 2001, Section 4).

2010's that led to LightSquared's bankruptcy, however, hinged on adjacent band interference.

3.1.1. Transmitter characteristics

Fig. 3 shows an example of a transmitter characteristic from the MetSat case: the distribution of the transmit power of LTE cellular mobiles used in the WG-1 Report and the MetSat Risk Studies.

3.1.2. Receiver characteristics

The ability of receivers to reject interference can be characterized using a variety of attributes, including selectivity, adjacent channel and spurious response rejection, intermodulation rejection, and blocking immunity (NTIA, 2003, Table 20).

The key parameters used to characterize MetSat receivers in the Fast Track Report are 3 dB intermediate frequency (IF) bandwidth, and IF selectivity (NTIA, 2010, Appendix A). Receiver performance can vary greatly, as seen in Fig. 4.

The MetSat case is comparatively simple since interference has to be assessed at only a few dozen fixed sites, each with a receiver for which the selectivity is known. In other cases there are millions of receivers, and their performance can vary considerably. Fig. 5 illustrates the wide range in the interference susceptibility of consumer digital television receivers (FCC OET, 2007). In such cases, especially where industry standards cannot be relied on, a statistical distribution of performance values will have to be used.

3.1.3. Transmitter-receiver coupling

The energy transferred from a transmitter to a receiver depends not only on the transmit power and receiver selectivity, but also on the transmitter and receiver antenna gains along the vector between them, as well as losses due to propagation, body attenuation, cables, polarization mismatch, etc.

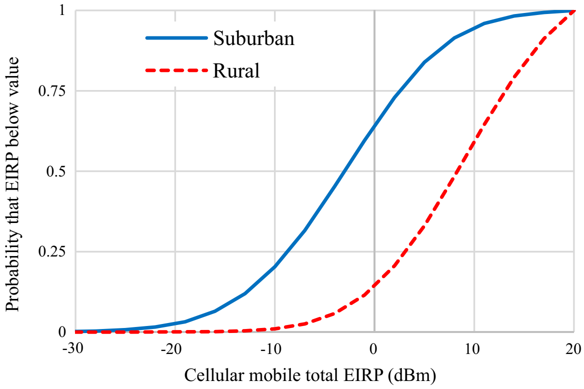
In the MetSat case the receiver antenna gain pattern varies from site to site, and the gain towards a cellular mobile transmitter depends on the pointing direction of the antenna and its height about ground level. A selection of values is given in Table 2; a gain of around 30 dBi is typical, and most antennas are between 17 and 33 m above local terrain.

Propagation losses depend on the propagation path and intervening obstacles, and thus depend on transmitter-receiver distance and terrain. The propagation loss used in a risk calculation will depend on the propagation model that is chosen. There is a long menu of choices, and the results generated can differ quite substantially between models, and from measured values (Phillips, Sicker, & Grunwald, 2012, 2013). For example, Fig. 6 shows the median propagation losses predicted for different ranges for the

Table 1
Parameters affecting co-channel interference between cellular mobiles and weather satellite earth stations.

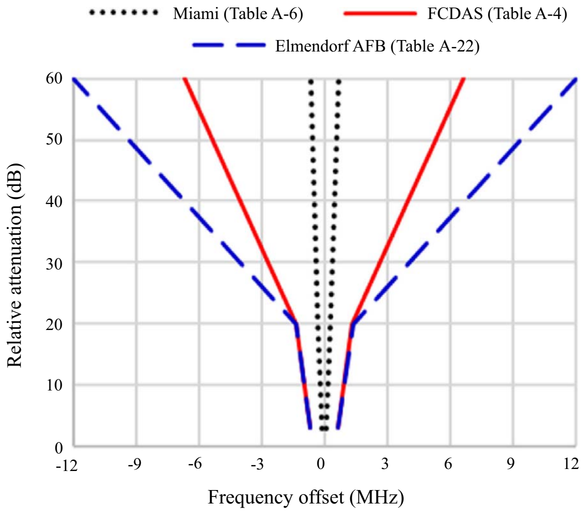
Transmitter characteristics (cellular mobiles)
Transmitted power per mobile device co-channel and out-of-channel
Frequency channel width
Percentage loading of base station by devices transmitting to it
Location and density of mobiles
Location and density of base stations
Receiver characteristics (satellite earth stations)
Receiver center frequency, 3 dB bandwidth, noise figure
Selectivity (i.e. frequency-dependent rejection of adjacent band transmissions)
Transmitter-Receiver coupling (propagation and antenna effects)
Path loss from transmitter to receiver
Additional losses, e.g. body loss, cable loss
Mobile antenna height (assume isotropic gain)
Earth station antenna height, pointing direction (elevation and azimuth), and mainbeam gain

Based on De Vries et al. (2016)



Based on data from CSMAC (2013, Appendix 3)

Fig. 3. Cumulative distribution function of radiated power per handset.



Based on data from NTIA (2010 Appendix A)

Fig. 4. MetSat receiver selectivity for HRPT data at various locations.

Extended Hata model and the ITM model with three different terrain roughness parameters Δh, one of them with a correction for suburban conditions.[3]

The coupling between transmitters and receivers can also vary significantly, even for locations that are spatially close to each other. This variation, often called location variability or clutter factor, is typically assumed to be a lognormal distribution with standard deviation of 8 dB (Drocella et al., 2015). There can also be variation due to weather. Fig. 7 shows an example from a different proceeding, known as the "Northpoint case." MITRE (2001) studied potential interference from a hypothetical multi-channel video distribution and data service ("MVDDS") into direct broadcast satellite ("DBS") television receivers. Rain attenuates the satellite signal received by the home system, with high attenuation being less likely than low attenuation. Fig. 7 shows the difference in attenuation probabilities between wet and dry locations as reported in MITRE (2001).

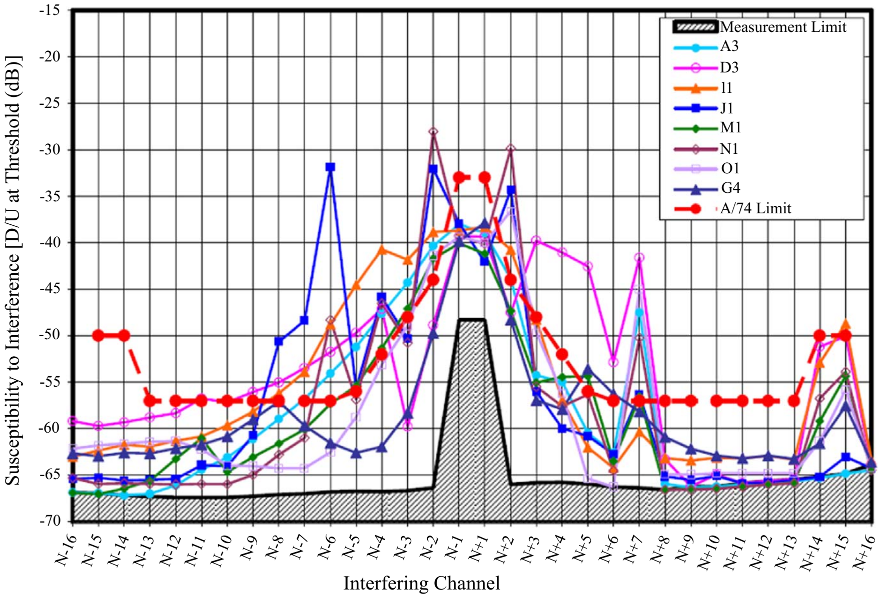
3.2. Second element: define a consequence metric

3.2.1. Choosing a consequence metric

There are many possible consequence metrics that represent the degree of harm caused by interference. One can distinguish three broad categories:

- *Corporate metrics*: Examples include loss in revenue or profit (particularly relevant to the private sector), impact on the ability to complete a mission (particularly for government entities), and increased capital expenditure.

[3] The standard ITM model is calibrated to fit rural areas.



Source: FCC OET (2007), Figure 5-1, "D/U of 8 Receivers at D = -68 dBm on Channel 30"

Fig. 5. Interference susceptibility of DTV receivers.

- *Service metrics*: These measure the quality of the service that the radio link supports. Two broad sub-categories are availability (time period or percentage of outage, number or percentage of households without service, etc.) and quality (measured by bit error rates for mobile data services, range reduction for radar systems, etc.).
- *RF metrics*: Quantities observable in the radio frequency (thus "RF") environment, such as changes in interference-to-noise ratio (I/N), signal-to-interference and/or carrier-to-interference ratios (SINR, C/I), absolute interfering signal level, receiver noise floor degradation, and so on.

Table 2
A selection of MetSat HRPT receiver antenna parameters.

System	Mainbeam gain (dBi)	Height above local terrain (m)
Fairbanks, AK (Table A-4)	43.1	17
Sioux Falls, SD (Table A-7)	31	14.5
Suitland, MD (Table A-5)	29.5	86.8
Elmendorf AFB (Table A-22)	29	33

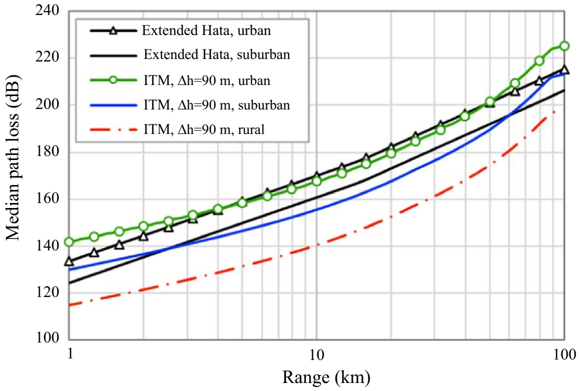
Source: Fast Track Report (NTIA, 2010), Appendix A.

Since harmful interference is defined for regulatory purposes as a service metric of sorts (cf. footnote 1), corporate or service metrics are in principle preferable to RF metrics. However, in practice the mapping of RF metrics to service degradation is at best uncertain, if not unknown. For example, the tenuous link between interference protection criteria (RF metrics) and bit error rates or image quality (service metrics) in the MetSat case is discussed in De Vries (2015, Appendix A).

The MetSat consequence metric used by the NTIA in the Fast Track and WG-1 Reports was an interference-to-noise ratio. It was a binary indicator: all was assumed to be well with I/N below −10 dB, and unacceptable harm was presumed if it exceeded that value. However, the ITU-R Recommendation SA.1026 for the protection of weather satellite systems—the international reference for MetSat coexistence analysis—does not even mention I/N. Rather, it specifies two interfering signal power levels (that depend on system characteristics like data protocol and antenna gain) not to be exceeded more than 20% and 0.0125% of the time, respectively (ITU-R, 2009). The MetSat Risk Studies used the ITU-R criteria as a consequence metric.

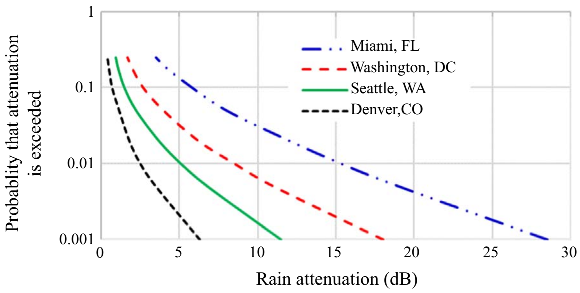
An Ofcom-commissioned study of interference between cellular and television systems used several consequence metrics, including the probability of interference for WiMAX base stations affecting DTT (Digital Terrestrial Television) receivers, and C/I as a function of distance between a mobile WiMAX transmitter and a DTT receiver (Aegis, 2007, Section 2).

MITRE developed several interference metrics in its analysis of interference in the Northpoint case: three metrics of the absolute or relative increase in DBS downlink unavailability, plus the minimum clear-air value of C/I (MITRE, 2001, Section 5.1.1).



Source: De Vries, Livnat & Tonkin (2016)

Fig. 6. Propagation loss predictions for Extended Hata and ITM models.



Based on data from MITRE (2001)

Fig. 7. Rain model results for various U.S. locations.

3.2.2. The importance of baselines

MITRE's use of an increase in DBS downlink unavailability as a consequence metric illustrates the importance of baseline values in evaluating interference consequences. The FCC's MVDDS rules were based on an increase in television unavailability of no more than 10% over the baseline unavailability due to rain attenuation (FCC, 2002, para. 71).

This principle applies in general, even for a traditional worst-case analysis. Interference impact should be judged in the context of the baseline service degradation that occurs in the absence of added interference from a new service. The baseline degradation may be due to pre-existing natural or man-made interference (cf. IEEE, 2008, Section 6.4.4.6). It may also result from non-interference hazards such as operator error, power outages, device misconfiguration, intentional jamming, and device degradation due to vibration, humidity, mold growth, corrosion, abrasion, etc.

In the Northpoint case, MITRE could use an ITU recommendation about signal attenuation due to rain to establish its baseline (ITU-R, 2012). In other cases, the information may be a government secret, commercially confidential, or hard to elicit from incumbents who might worry it will undermine their position that no service degradation of any kind is acceptable. A regulator may need to provide incentives to elicit baseline information. For example, the FCC TAC has recommended the principle that “services under FCC jurisdiction are expected to disclose the relevant standards, guidelines and operating characteristics of their systems to the Commission if they expect protection from harmful interference” (FCC TAC, 2015c); those operating characteristics should include baseline interference data.

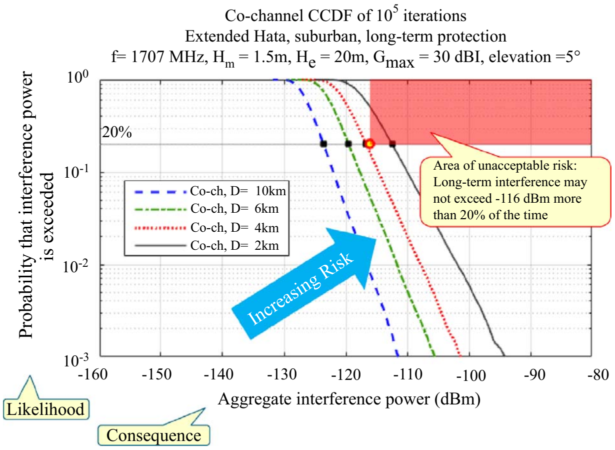
3.3. Third element: assess likelihood and consequence

The next element of the analysis is estimating the likelihood and consequence of each of the posited interference hazards. Wherever possible, probability distributions of hazard-determining parameters should be combined to yield a probability distribution for the consequence metric. If discrete values of parameters must be used instead, the analyst should at least estimate the likelihood that those values will occur.

Rough estimates of severity and likelihood—even just orders of magnitude—will often be sufficient. For example, the Nuclear Regulatory Commission uses orders of magnitude (10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}) for both baseline values and value changes of the two key consequence metrics (core damage frequency and large early release frequency) in its licensing guidelines for nuclear power stations (NRC, 2011, Section 2.4).

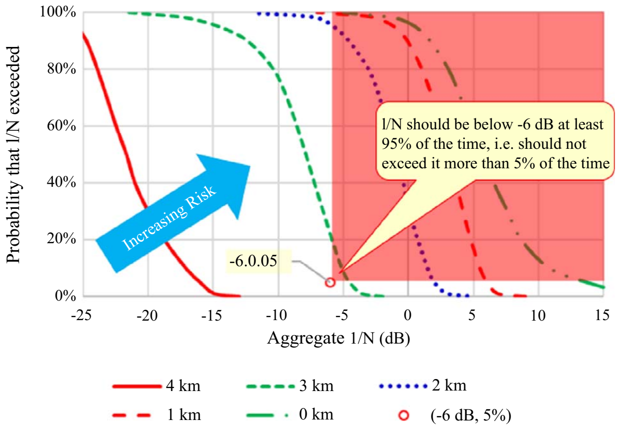
The likelihood of a hazard is the probability of its occurrence over the affected population. An appropriate population for regulatory decisions is likely to be all affected receivers in the region at issue, such as a license area.

A risk chart results when the likelihoods of various consequences are plotted. Fig. 8 is an example from the MetSat case, for the ITU-R SA.1026-4 “long-term” protection criterion that specifies a 5° antenna elevation angle. It shows the probability that the



Source: De Vries, Livnat & Tonkin (2016)

Fig. 8. Exceedance probability for co-channel interference from cellular mobiles into a MetSat earth station. Three candidate exclusion distances. Long-term protection scenario (5° antenna elevation).



Based on data from Drocella et al. (2015)

Fig. 9. Co-channel I/N exceedance probability for various exclusion zone radii around Camp Pendleton.

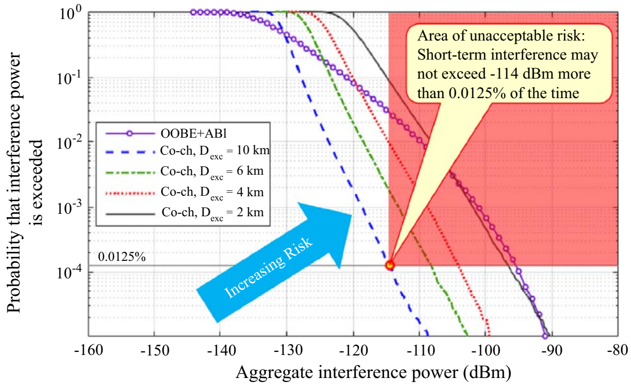
aggregate interfering power from a "sea" of cellular mobiles beyond a particular exclusion distance exceeds a given value for three candidate exclusion distances. ITU-R SA.1026-4 specifies that, for this antenna gain and protection criterion, −116 dBm of aggregate interference may not be exceeded more than 20% of the time. That is met with an exclusion distance of 4 km or greater.

The analysis in Drocella et al. (2015) of ground-based radar exclusion zone candidates in the 3.5 GHz band can be interpreted in terms of risk by designating the aggregate interference-to-noise ratio (I/N) as the consequence metric. Drocella et al. (2015) posit that I/N should be below −6 dB at least 95% of the time, indicated by the little red circle in Fig. 9. This chart, which replots the data in Drocella et al. (2015, Fig. 5) in the format of Fig. 8, shows that these authors effectively reported their results as a risk chart, without describing it as such.

Turning to another of our recurring examples, the results obtained by Aegis (2007) in their DTT simulation study can be represented as a likelihood-consequence pair. Aegis predicted that a TV receiver at the edge of TV coverage would have less than a 0.01% probability of seeing a desired/undesired ratio (C/I) less than (that is, worse than) −20 dB. This likelihood/consequence pair is a risk assessment data point. Using a −30 dB protection ratio, Aegis inferred that "any likelihood of the protection ratio not being met is considerably less than 0.01%".

3.4. Fourth element: aggregate likelihood-consequence results

Once likelihood-consequence data have been collected for the relevant hazards, they can be plotted in an aggregate view that shows their relative risk.



Source: De Vries, Livnat & Tonkin (2016)

Fig. 10. Exceedance probability for co-channel, out-of-band and adjacent band interference from cellular mobiles into a MetSat earth station. Four candidate exclusion distances. Short-term protection scenario (13° elevation).

Risk charts can be used in various ways to support regulatory decisions:

- When making rules, one might plot the likelihood-consequence curves for different potential choices of operating parameters, e.g. transmit power ceiling or exclusion distance. This would generate a family of curves, one for each potential rule set, that would illustrate the risk sensitivity to various levels of operating parameters. Figs. 8 and 9 are examples where the rule choice is between exclusion distances.
- Similarly, one could plot risk curves for various harm thresholds, using e.g. I/N values of −3, −6, and −14 dB to measure severity, and the probability of those values occurring.
- For a given choice of operating parameters and harm thresholds, one could plot risk curves for different interference modes, e.g. out-of-band emission (OOBE), adjacent band interference (ABI), intermodulation, etc. This would help prioritize which failure modes to focus on when choosing operating parameters. Fig. 10 below is an example.

Fig. 10 shows the aggregate interference from three different hazards into a MetSat earth station. In this figure the antenna elevation is 13° corresponding to the ITU-R SA.1026-4 "short-term" interference protection criterion; for the antenna gain under study here, aggregate interference may not exceed −114 dBm more than 0.0125% of the time. Two out-of-band hazards have been included in this risk chart: the OOBE derives from cellular mobile transmissions that spill over into the MetSat receiver's operating channel, and the ABI is cellular power in the adjacent licensed cellular band that the MetSat receiver is not selective enough to reject.

One can observe in Fig. 10 that the 4 km exclusion distance, which was sufficient for long-term co-channel protection as shown in Fig. 8, is no longer sufficient. Exclusion of 10 km or greater is required.

However, the figure also shows that the co-channel interference hazard is far less risky than OOBE or ABI—for which there is no exclusion zone. Both the OOBE and ABI interference hazards fail to meet the ITU-R interference criterion in this scenario. This suggests that considering only co-channel interference, as the Fast Track Report, WG-1 Report and consequent FCC rules did, does not adequately reflect potential hazards. Since there have been no complaints about OOBE or ABI interference into MetSat, it may also mean that the model assumptions used in these studies are unrealistically conservative.

As described in Section 2.2.2, qualitative risk charts are also often used to compare different hazards. Such charts have occasionally been used in spectrum studies. Fig. 11 shows an assessment of risks to the GPS spectrum environment by a working group of the National Advisory Board on Space-based Positioning Navigation & Timing (Ciganer & Hatch, 2014).

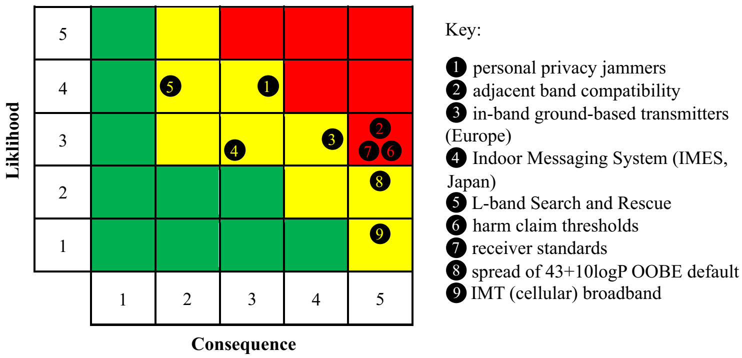
4. The value of quantitative risk assessment

4.1. Benefits

As we have seen in the MetSat case, quantitative risk assessment provides a more complete analysis of risk than using a single-scenario worst-case analysis—in this case, combining co-channel, OOBE and ABI hazards in a single assessment. A single consequence metric for all hazards provides a common currency for comparing different hazards. It also allows the joint consideration of pervasive, low impact interference hazards (such as an elevation of the noise floor that causes small but ubiquitous degradation in service quality) and rare, catastrophic worst-case harms (like malicious jamming of public safety communications during a terrorist attack).

The use of probability distributions rather than single values for interference parameters provides a more nuanced and comprehensive view of the nature of the hazards, and the impact of different regulatory choices. For example, Fig. 8 shows how the risk from different exclusion distances can be compared.

Risk analysis also gives a better picture of what the community of experts knows or does not know, highlighting areas where the



Based on Ciganer and Hatch (2014)

Fig. 11. Perceived spectrum risks to GPS.

public record is inadequate. Examples include treating only co-channel interference in the NTIA MetSat studies, and ignoring adjacent band interference in the early phase of the GPS/LightSquared proceeding. It also highlights the lack of baseline information in all the examples given in this paper except for the Northpoint case.

Most importantly, it provides objective and actionable information to decision-makers. While weighing the benefits of a new service against its adverse impacts on incumbents is ultimately a matter of judgment not calculation, comprehensive quantification of the impact of a new service—and not just the existence of some extreme potential harm—supports good decision making.

4.2. Limitations

No approach is without costs and drawbacks. Quantitative risk analysis usually requires more data on system parameters, more extensive computation, and more familiarity with statistical analysis than a deterministic (let alone a worst-case) approach. This is to be expected since QRA strives for a more realistic representation of the hazards being studied. One should not expect simple answers to complex questions! The analysis may therefore take longer, and require new skills and habits to produce and interpret.

Hazard assessment will always rely on expert judgment and can never be entirely quantitative. For example, the assumptions informing a model and the interpretation of results can always be debated. Engineering analysis is constrained by legal and economic contexts, and the technical analysis in turn influences legal and economic assumptions. It should be emphasized that the approach recommended here is risk-*informed* and not risk-*based*. That is, while technical analysis is an important input into the deliberation process, it is by no means the only factor that influences the final decision. Other considerations include the public interest, the uncertainty associated with the technical analysis, the resources and capabilities of the agency, and legal requirements.

While the definition of risk used in this paper is quite orthodox in engineering, other disciplines offer complementary perspectives. Renn (2008a) provides an excellent review. He proposes four major perspectives. The *first* is that of the natural sciences and technology, using actuarial analysis, causal modeling, or (the approach of this paper) probabilistic risk assessment. The *second* perspective uses economic concepts like the transformation of undesired effects into economic utilities. The *third* is psychological, and addresses the subjective processing of risk information including personal preferences, quirks in the perception of probabilities, and biases such as risk aversion. The *fourth* major perspective is a social and cultural one where undesirable events are socially defined and (in some cases) socially constructed. The use of multiple perspectives would provide a more complete treatment of interference risk. For example, concerns among the public about exposure to electromagnetic fields from cellphones may be best understood from a psychological rather than a technical perspective.

A quantitative analysis of radio interference risk is more complex than a back-of-the-envelope worst-case calculation, and will not give as clear-cut an answer. However, the examples given show that the quantitative, engineering-oriented assessment of risk advocated in this paper is a viable and important step in introducing risk analysis to spectrum policy, which will in turn lead to more productive rules for wireless operation.

5. Recommendations for government action

The experience of the Nuclear Regulatory Commission, the agency that pioneered quantitative risk assessment in the U.S., indicates that regulators need not, and should not, start with a major overhaul of their regulatory approach (Littman & De Vries, 2014). The NRC story suggests that changing an industry's culture takes time, even though some constraints on the NRC—such as the burden of calculating complex nuclear reactor fault trees with the limited computing power of the 80s and 90s—do not apply to the FCC's work. An encouraging lesson is that quantitative risk assessment can be applied successfully even in an industry like nuclear power where safety-of-life is paramount; thus, while national defense and public safety services may not be the first applications of QRA in spectrum regulation, they could also be managed using this approach.

One should expect that it will take the spectrum community some time to become comfortable with this new approach, even given that risk analysis is a very mature technique, and tools are widely available. However, given the value of quantitative risk assessment in maximizing the value of spectrum use, it is important that regulators not delay. In other words: *Start small, but start soon.*

The first step is to get the spectrum community thinking about risk-informed interference assessment. Studies by regulators and stakeholder groups, such as FCC TAC (2015b, 2015a), can get the ball rolling. Regulators should also develop know-how in their agencies and the wider community through in-house and public education such as lecture series, workshops and training courses.

Second, regulators can set a good example and contribute to the development expertise by using quantitative risk assessment in their own analyses and—importantly—publishing the results. Since this approach complements existing techniques, it can easily be added to the regulatory decision making process. In the U.S. context, for example, the FCC could:

- Quantify likelihoods and consequences in its findings.[4] When framing risk probabilistically and explaining its judgments, the FCC should document both relative and absolute changes in interference impacts, as well as giving the probability of being unaffected by new rules.
- Adopt as common practice the assessment of interference risk against a baseline of current impairments, as used in the Northpoint case (cf. FCC, 2002, 2003).
- Request (ideally, require) disclosure and analysis of both the likelihood and consequence of harmful interference hazards—including existing baseline hazards—in Notices of Inquiry, Notices of Proposed Rulemaking and other consultations.

Third, regulators can pilot the use of quantitative risk assessment in proceedings with limited scope. Applications for site-specific waivers to service rules appear to be a good candidate in the U.S context since they reduce the number of variables the FCC would have to consider and limit the geographic impact of risk-informed decisions (Cox, Minnock, & De Vries, 2014; Samuelson-Glushko Technology Law & Policy Clinic & De Vries, 2016). QRA should not substantially alter the waiver review process, since waivers are regularly opposed and already receive in-depth review from the FCC—meaning they can already take six months or more to process.

Legislators and the executive branch can also play an important role:

- Legislators can make risk-informed assessment an oversight requirement, insisting that regulators and departments use it in reports to the public and legislature.
- When presented with politically charged claims of harmful interference, politicians should avoid conjuring up—or falling for—nightmare worst-case scenarios, and instead make risk-informed assessments.
- They can support and encourage regulators that use risk-informed interference assessments.

In the U.S., various executive orders (OMB, 1996, 2003; POTUS, 2011) under both Republican and Democratic presidents have required risk analysis and cost/benefit analysis. These mandates do not apply to independent agencies like the FCC, but this could be changed either by the President amending Executive Order 12866 and OMB Circular A-4, or by Congress enacting legislation (Carey, 2014).

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[4] At present, the FCC customarily uses probabilistic language without quantification (De Vries & Littman, 2014).

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Sharing license-exempt spectrum based on multi-dimensional metrics

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Abstract

Purpose – *The purpose of this paper is to investigate the possibility to replace radio equipment compliance requirements based on equipment parameters with a set of simple metrics that accurately reflects spectrum utilization and spectrum-sharing efficiency.*

Design/methodology/approach – *The approach taken is to go back to the basic factors that determine radio system behavior in a shared spectrum environment: radio frequency power, duty cycle and frequency occupation. By normalizing these parameters, device specificity is avoided and a statistical perspective on spectrum utilization and sharing becomes possible.*

Findings – *The analysis shows that two technology-neutral metrics would be adequate to govern spectrum utilization and sharing: a spectrum utilization metric and a spectrum-sharing efficiency metric. These metrics form the core of regulatory requirements for shared frequency bands. Each shared frequency band could be assigned criteria based on these metrics that take into account the types of applications for which that band will be used.*

Research limitations/implications – *This work is a first step that identifies the main factors that affect shared spectrum usage from a statistical point of view. More work is needed on the relationship between real-world interference and its abstraction in the spectrum-sharing rules.*

Practical implications – *The metrics proposed could be considered as the basis for a new approach to the regulation of the license-exempt spectrum, and, by extension, as the basis for generic compliance criteria. Their use would facilitate the compliance assessment of software-defined radio technology.*

Social implications – *This work has no direct social implications.*

Originality/value – *This paper combines new work on spectrum utilization criteria with extensions of previous work on spectrum-sharing efficiency into a comprehensive proposal for a new approach to the regulation of the license-exempt spectrum.*

Keywords *Internet of Things, Short range devices, License exempt spectrum, Spectrum sharing, Technical regulations*

Paper type *Research paper*

Abbreviations

AFA	: Adaptive frequency agility;
AMA	: Adaptive medium access;
CSMA/CA	: Carrier sense multiple access with collision avoidance;
DFS	: Dynamic frequency selection;
EIRP	: Equivalent isotropically radiated power;
ETSI	: European Telecommunications Standards Institute;
FCC	: Federal Communications Committee;
LBT	: Listen-Before-Talk;
LTE	: Long term evolution;
MIMO	: Multiple input, multiple output;
OFDM	: Orthogonal frequency division multiplexing;
RF	: Radio frequency;
RLAN	: Radio local area network;
SINAD	: Signal to noise and distortion ratio;

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SIR	: Signal to interference ratio;
SNIR	: Signal to noise + interference ratio; and
TDMA	: Time division multiple access.

1. Background

Although the scarcity of the radio spectrum is well-advertised, practice shows that with proper regulatory constraints and good engineering, the capacity of the radio spectrum may seem almost unlimited. This apparent contradiction arises because radio spectrum can be shared among different users. Spectrum sharing can take many forms, ranging from the tight procedural and operational controls that govern cellular systems operating in a licensed spectrum to the almost free-for-all regime applied to radio spectrum set aside for industrial, scientific and medical use (ISM bands) and certain other license-exempt frequency bands. This paper is mostly concerned with the physical aspects of radio communication; of the logical aspects such as medium access procedures and link-level protocols, only the former are mentioned where relevant.

Spectrum scarcity has become an item on the agendas for many regulatory authorities and spectrum efficiency has become a key spectrum policy consideration, together with technology neutrality and application neutrality. An example of this increased emphasis on spectrum sharing and spectrum efficiency is the Radio Equipment Directive (European Commission, 2014) issued by the European Commission in 2014[1]. It states specifically that "[transmitters] should be so constructed] that potential negative impact on the goals of radio spectrum policy should be limited to such a level that, according to the state of the art, harmful interference is avoided" and that "[receivers have] a level of performance that allows it to operate as intended and protects it against the risk of harmful interference, in particular from shared or adjacent channels, and, in so doing, supports improvements in the efficient use of shared or adjacent channels". Although the language may be less than perfectly clear, the objective behind it can be readily discerned: shared spectrum will be the rule and efficient shared use of spectrum will be necessary.

Currently, European Union (EU) compliance standards (harmonized standards) define classes of equipment with different compliance requirements designed to meet product- or application specifics and the new spectrum efficiency requirements will be implemented in the same way. Because changes to such standards are required whenever a new technology or product has been developed, this practice is anti-competitive: it tends to favor established interests.

The objective of the policy of technology neutrality and application neutrality is to minimize, if not remove, this anti-competitive element in the process of creating harmonized standards – an objective to be kept in mind in the development of compliance requirements for efficient shared use of the radio spectrum.

1.1 Different spectrum-sharing regimes

Sharing spectrum among homogeneous systems, as in the case of cellular networks, can be very efficient, as all sharing parameters – space, time and frequency[2] – are known and under full control of the sharing systems. Common regulatory limits are defined for each parameter and exploited to the maximum extent possible to optimize the system's capacity and, therefore, its earning power.

Sharing spectrum among heterogeneous systems is a problem of a different order. Typical examples of such systems are the short-range devices (SRDs), which are used for a wide variety of purposes, including Internet of Things (IoT) and machine-to-machine (M2M) applications, as well as wireless local area networks (LANs) and other communications applications. SRDs vary widely in terms of emitted radio frequency (RF) power, duty cycle, bandwidth and modulation. RF power levels vary from less than 1 mW to 500 mW, duty cycles vary from well below 0.01 per cent to 100 per cent and bandwidths vary over a similar range. This diversity in products and technologies makes it impossible to predict and control interference among such systems. Further, each system has its own means to optimize its transmission function in such an unfriendly environment and in a way that fits its purpose and application. These means may include adaptive spectrum use that facilitates sharing with other spectrum users. Common technical parameters to ensure optimum spectrum utilization are impossible to define without severely restricting the freedom of systems designers to optimize their products for given applications and conditions.

Other, technology-neutral, means of improving spectrum sharing and utilization by SRDs have to be defined, taking into account the key factors that determine spectrum use. The possibilities for spectrum sharing and efficient use[3] are determined[4] by the transmitter as well as the receiver operating together as a transmission system. Considered in isolation, the efficiency of spectrum use of a system is a function of the transmitted energy level and the level of the energy required at the receiver to successfully decode the energy received. The upper limit for the former is typically the regulatory limit, and the lower limit for the latter is set by the thermal noise level of the receiver and the properties of the receiver circuits. Real products operate somewhere in that range. The density of the information transferred determines the energy per bit and, therefore, the operating range of the system. In practice, this simple picture has to be extended with factors for interfering energy from a variety of other sources, notably other spectrum users and for the properties of the antennas and the propagation environment.

1.2 The heart of the matter

In a shared spectrum environment, two sources of interfering energy must be taken into account: in-band interference and out-of-band interference. The former is caused by other systems operating in the same frequency band; the latter by systems operating in other bands. Such interference may take the form of co-channel or adjacent channel interference, intermodulation effects and receiver de-sensitization.

Co-channel interference may be considered to add to the noise floor of a receiver:

$$SNIR = \frac{P}{N + I} \tag{1}$$

Other forms of interference such as adjacent channel interference, intermodulation and other performance degradation factors cannot be represented in such a simple expression for receiver performance because of variations in receiver design. Instead, a variety of receiver parameters are required to express receiver performance under interference.

The Radio Equipment Directive of the EU (European Commission, 2014) seeks to improve spectrum efficiency through the specification of receiver parameters in standards for regulatory compliance. Examples are receiver sensitivity, adjacent channel selectivity, intermodulation and receiver de-sensitization. Whether this approach works, depends on the context.

Receiver parameter specifications are very much relevant and beneficial for homogeneous equipment operating in a licensed spectrum. Receiver parameters can be specified in detail because the other users of the spectrum and the operating environment are well-known. However, the benefits of *regulatory* requirements for receiver parameters are questionable. Under *commercial pressure*, spectrum efficiency may be taken care of by design, but avoiding inefficient spectrum use that burdens other spectrum users requires constraints on *transmitter* parameters[5].

Whereas receiver parameters play a major role in homogeneous networks, the diversity of license-exempt equipment prevents the conventional approach of setting common criteria for receiver parameters because each product has its particular properties and application. In fact, equipment characteristics vary by a factor 100 or more. This variation would require the specification of product-specific receiver parameters – a practically impossible task that would be always chasing new technology developments. Therefore, a solution must be found that encourages efficient use of the license-exempt spectrum without restricting existing products or technical innovation.

Ideally, regulatory requirements for receiver parameters should be technology-neutral and applicable across a wide range of equipment and applications. In the following sections, two metrics are developed that can be used as elements of a forward-looking regulatory policy for the license-exempt spectrum: the *spectrum load metric* and the *spectrum-sharing efficiency* metric. In combination with limits on RF power, these metrics provide a flexible regulatory regime that is technology-neutral, open to innovation and effective in fostering efficient use of the license-exempt spectrum.

2. Transmitter metrics

"One man's transmission is another man's interference". This truism points toward one possibility to make efficient use of the radio spectrum: constrain transmitters. Generally, this is the focus of regulations for the license-exempt spectrum. The Federal Communications Committee (FCC)'s Part 15 rules (FCC, 2015) do just that and they have been the model for technology-neutral regulatory measures elsewhere.

In contrast, some standards for regulatory compliance are much more restrictive. An example is European Telecommunications Standards Institute (ETSI) EN 300 328 (ETSI, 2015), which specifies in addition to the basic RF parameters, various combinations of limits for a whole range of parameters: duty cycle, minimum transmission time, maximum transmission time, frequency hopping minimum and maximum timings and bandwidths, as well as adaptivity mechanisms and thresholds. Different combinations of properties such as specific mechanisms for medium access adaptivity and duty cycle restrictions confer the right to use higher power levels, whereas at lower power levels, there are no such restrictions.

This standard with its complex requirements and test methods is one example of mandatory compliance criteria that have grown over time as new market entrants sought and obtained "permission" to operate their equipment in a given frequency band. Although aimed at fair use of the radio spectrum, the implications of this detailed regime include a strong preference for existing technologies and products and a barrier to innovation, whereas its benefits are difficult to quantify. Clearly, more generic criteria are needed – criteria that focus on spectrum utilization and sharing efficiency rather than on equipment parameters.

2.1 Radio spectrum as a resource

In an unstructured environment with many different types of equipment being used, interference cannot be analyzed in terms of specific cause and effect. Interference can only be considered in terms of statistical probability, determined by the RF power used, the frequencies affected and the duration of transmissions[6]. Such a statistical approach is inherently technology-neutral. Existing regulatory requirements for a given frequency band determine the total resource available as a resource space with three dimensions: power, frequency and time. A given radio transmitter will occupy only a fraction of this resource space and thus spectrum utilization can be expressed as a fraction that is characterized by three factors: power, frequency and time.

2.2 The spectrum load metric

The product of the three factors – power, frequency and time – defines what might be called the "spectrum load metric"[7]. This metric can be used as a regulatory mechanism: within the constraints defined by a *limit value* for spectrum load, system designers would be free to choose each of the three factors to give the best performance for a given application or purpose. Like other radio properties such as RF power and unwanted emissions, the result would be subject to compliance validation, e.g. by testing or measurement.

Application of this concept makes differentiation unnecessary between fixed-frequency equipment, frequency agile equipment, frequency hopping equipment and low-duty cycle equipment, as is currently the case. Another benefit is the significant simplification of compliance testing.

In the domain of the license-exempt spectrum, there are no known a priori values other than the regulatory limits that apply to the frequency band under consideration[8]. As noted above, RF power levels, duty cycles and bandwidths vary by a factor 100 or more; the implication is that the spectrum load may vary between systems by a factor 1,000,000. Technologies like frequency hopping and fast frequency adaptation complicate the picture further. This variety can be accommodated by normalization: e.g. instead of RF power, RF power spectral density[9] has to be used, which is not dependent on transmitter bandwidth.

The range at which receivers are affected by transmitted power depends on the local power flux density, which varies exponentially with the inverse of the pathloss. This is expressed by the Friis formula for the received RF power due to pathloss:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^{PLE} \quad (2)$$

P_t is the transmit power; G_t and G_r give the gain of the transmitter and receiver antenna, respectively; λ is the wavelength; R is the distance; and PLE is the pathloss exponent. For a given frequency, the wavelength over distance term can be replaced by a constant C. Dropping the antenna gain factors and extracting R gives a formula for how RF power flux density changes with distance under given pathloss conditions:

$$R = C.P_t^{\left(\frac{1}{PLE}\right)} \quad (3)$$

This formula ignores such factors as fading and other signal impairments – which should be taken into account in the analysis of a particular case or condition. The area[10] affected by P_t varies as the square of R:

$$Area = C.P_t^{\left(\frac{2}{PLE}\right)} \quad (4)$$

The same relationship holds for the power spectral density. The duty cycle is typically a dimensionless fraction that needs no normalization, although care should be taken to assess the median value rather than the "maximum". The latter may occur once in a long time and taking the median value rather than the mean value avoids skewing the result toward this maximum. Frequency use – the operating bandwidth – has to be expressed as fraction of the available frequencies.

The resulting expression of the spectrum load metric is as follows:

$$L_{sp} = PD^{\left(\frac{2}{PLE}\right)}.DC_m.U_f \quad (5)$$

PD is the transmitter's power spectral density, PLE is the pathloss exponent and DC_m is the median duty cycle. U_f is the frequency utilization factor:

$$U_f = F_{frac}.P_{col} \quad (6)$$

F_{frac} is the occupied frequency range as a fraction of the available frequency band, and P_{col} is a correction factor for variable-frequency equipment – it is proportional to the number of frequencies in use and gives the probability that a frequency within the operating range is occupied. By expressing PD as a ratio relative to a given maximum and taking the log of the result, the spectrum load metric becomes a dimensionless value in dBs relative to the maximum of all three parameters:

$$L_{spr} = 10\ log\left((PD_{rel})^{\left(\frac{2}{PLE}\right)}.DC_m.U_f\right) \quad (7)$$

Antenna directivity allows a reduction in RF power for the same operating range. This is taken into account by subtracting the azimuth gain in dB from (7):

$$L_{spr} = 10\ log\left((PD_{rel})\left(\frac{2}{PLE}\right).DC_m.U_f\right) - A_{tx} \quad (7a)$$

To put this in perspective: a device that operates at 100 per cent of the allowed RF power at a duty cycle of 10 per cent and using 2 per cent of the available frequency range has a spectrum load factor of −27 dB. This is 1/500th of the theoretical maximum for this hypothetical frequency band. A transmitter with an antenna of 20 dB gain operating at full power with a 100 per cent duty cycle over 20 per cent of a frequency band has approximately the same spectrum load.

The spectrum load metric as expressed by (7) or (7a) is a potentially useful tool for spectrum management purposes. This is addressed in Section 2.4 below.

2.3 Spectrum load and adaptive medium access

Adaptivity in spectrum use – adapting power, frequency or time in response to local conditions – facilitates sharing of spectrum and therefore obviously beneficial to equipment considered in isolation. IEEE 802.11 is one of the extremely successful examples. With the decreasing cost of computational capabilities, adaptivity is likely to spread to all kinds of technologies and applications. There are different forms of adaptive radio device behavior. The most important ones are spectral adaptivity and medium access adaptivity.

Spectral adaptivity may involve a change in modulation, transmission power and/or bandwidth according to the success or failure of past transmissions. Spectral adaptivity starts from a baseline condition – e.g. a given transmission rate, bandwidth and power level – and changes this mix until a balance is reached between the effective transmission rate and probability of transmission success that optimizes the net throughput. As conditions change, these parameters may be adapted to find a new balance point. Spectral adaptivity has major implications for spectrum utilization. From a spectrum utilization viewpoint, the non-adapted transmission rate is the reference for assessing spectrum utilization because it reflects the baseline, i.e. the worst-case behavior at a given throughput. Spectral adaptation reduces the instantaneous spectrum utilization, but it does not affect the baseline value.

Medium access adaptivity – sometimes referred to as polite medium access – avoids collisions with other spectrum users whenever possible[11]. Typically, it involves a temporary change of spectrum utilization in time: e.g. Listen-Before-Talk (LBT) or Detect-And-Avoid (DAA)[12] or a change in frequency (adaptive frequency agility, AFA). A device using LBT will defer its transmissions until the channel becomes available; a device using DAA will defer its use of an occupied channel for a longer time. The difference lies in the conditions applied to the defer procedures, e.g. sensing period, incrementing back-off in time or blocking time for occupied channels. A device using AFA may move to an unused frequency and stay there for some time. In practice, various combinations of DAA- and AFA-like behavior may be implemented that best fit the application and the operating conditions of a particular system or device.

Adaptive medium access (AMA) is sometimes confused with efficient use of spectrum. However, the two are different but in some sense related. The role of adaptivity is to facilitate graceful performance degradation under congestion conditions. Thus, AMA capabilities solve the problem of ensuring sharing of spectrum without imposing unnecessary limits: an AMA-capable device can use the maximum allowed share of the available spectrum resource because it will reduce that use in the presence of other devices.

AMA requires that equipment is aware of other users of the frequency band and that it adjusts its spectrum use accordingly. The rate of this adjustment has to take into account the natural time scale of the adaptation: changing transmission time can be very quick and has no memory – LBT works fine here. Changing frequency does have a strong memory aspect – e.g. time is needed to move a network of devices to another channel.

There is one element that is common to all AMA schemes and that is a threshold for the level of interference or performance degradation caused by interference that causes adaptive action. LBT and other sensing-based schemes measure the interference energy directly; error detection-based schemes may use error rates or feedback from one or more receivers to trigger action. An example of the latter is the RTS/CTS[13] scheme of IEEE 802.11: it avoids a transmission to a receiver that would not successfully receive that transmission.

The spectrum load metric can be used to encourage SRD designers to implement AMA capabilities through the simple expedient of allowing higher spectrum load values for adaptive devices. The threshold below which AMA operation is not required can be chosen to fit the uses of a particular frequency band. This is further detailed in Section 4.2 Recommendations.

It should be noted that spectrum sensing has limited effectiveness. Even among more or less equal devices, it is inaccurate and unreliable, for various reasons. First of all, the sensing threshold must be well above the minimum receiver sensitivity to ensure reliable detection with a suitably low level of false-positives. The implication is a residual non-detection rate. The non-detected transmitters will cause some interference at the receiver targeted by the sensing transmitter. This increases the background noise level in busy networks. The second reason is that in the real world, RF power levels of transmitters vary widely – a laptop computer may deliver 100 mW RF power, while a smartphone may not get out more than a few mW. Generally, transmissions of the former are easily detected, not those of the smartphone, although it may be close to a receiver to cause interference: this is known as “hidden node effect”[14]. The third reason is that the RF environment can be highly variable in time as well as by location. The effects on spectrum sensing are the same as for larger difference in RF power output: pseudo hidden node effects, the accumulation of which may cause severe performance loss.

Maintaining a reasonable degree of equal medium access among a heterogeneous population of spectrum users requires that the transmitter’s interference potential is taken into account when deciding to use the spectrum resource or to defer or switch to another frequency. A high power density affects devices at large distances and therefore it is important to set the threshold for adaptive action accordingly. Duty cycle also affects other spectrum users and thus the product of power density, and median duty cycle reflects the potential interference load L_{int} of a transmitter:

$$L_{int} = PD\left(\frac{2}{PLE}\right).DC_m \tag{8}$$

L_{int} expresses a potential effect that is the same for all frequencies on which a transmitter may be operating and therefore the spectrum utilization factor U_f of expression (7) is not needed in expression (8).

Relative to the allowed maximum power density, the expression changes to:

$$L_{intr} = 10\log\left(PD/PD_{max}\right)\left(\frac{2}{PLE}\right).DC_m \tag{9}$$

Its value can be used for scaling the required threshold for adaptive action, for example the LBT sensing threshold T_{adapt} may be adjusted upwards as transmitter power density – and therefore its interference potential – is reduced, e.g.:

$$T_{adapt} = -(Offset + L_{\mathrm{intr}})\quad \mathrm{dBm/MHz} \tag{10}$$

“Offset” will vary with the frequency band and application type, but the general form of the equation should prove broadly applicable.

Note that, because L_{intr} contains the median duty cycle as well as the RF power density, changing the adaptivity threshold while keeping the power factor constant requires a change in duty cycle. Thus, an AMA device that finds itself blocked from medium access could, at the price of a reduced medium access time, increase its adaptivity threshold without increasing its spectrum load.

Because (9) is linear for a given pathloss, the L_{intr} value can be used for other adaptivity schemes as well. For example, in a scheme based on a threshold in error statistics, e.g. on the raw bit error rate, the value of L_{intr} can be used to lower the threshold in proportion, taking into account that the response of a receiver to interference may be non-linear. This subject needs further work.

2.4 Using spectrum load metric as a regulatory mechanism

The conventional approach to regulation of spectrum utilization is to define a set of limits for transmitter parameters. This set typically includes the parameters for RF power and/or RF power density and unwanted emissions. However, some compliance standards also specify duty cycle and/or other timing restrictions and adaptive action (LBT) thresholds[15]. As noted above, such detailed requirements are a two-sided tool: excessive spectrum utilization is prevented but at the price of complex compliance requirements and, by maintaining the commercial status quo, discouraging innovation.

The spectrum load metric offers an alternative that is very effective from a spectrum management point of view but avoids the above costs. The number of parameters required for compliance testing could be reduced accordingly and product testing could be vastly simplified. This would significantly reduce the risk and cost of bringing a product to market.

Another interesting possibility of using the spectrum load metric is the scaling of performance-related criteria such as unwanted emissions: clearly, the impact of unwanted emissions varies proportionally with the interference potential of the transmitter. See also Section 4.2 Recommendations.

3. Receiver metrics

Whereas transmitters emit coded information which occupies a share of the available spectrum resources, receivers capture and decode these emissions. Therefore, assessing spectrum utilization efficiency requires a metric for receiver "performance" as well. This performance depends not only on the level and coding of the received energy (the modulation) but also on distortion of the received signal and the presence of unwanted energy from other transmitters and other sources.

The distortion is determined by the RF properties of the environment, but its impact varies with the modulation and coding of the transmitted signal as well as by the directionality and other properties of the receiver's antenna[16]. This variation affects spectrum efficiency and therefore it should be taken into account in assessing receiver performance[17].

3.1 Basic spectrum-sharing efficiency

The unwanted energy is determined by the presence of other transmitters in the receptive field of the receive antenna. In a dense, heterogeneous population of SRDs, the unwanted energy takes the form of noise-like interference that increases the effective noise floor of receivers.

The single most important factor in spectrum sharing is co-channel interference. In general, interference is a function of three factors: RF power and time (= duration) and the required signal to interference ratio (SIR) at the receiver. Starting from this premise, Kruys *et al.* (2014) develop a *spectrum utilization efficiency metric* and *spectrum-sharing metric* but without consideration of other, off-channel interference sources.

Spectrum utilization efficiency is a measure of how many devices can operate concurrently on the same frequencies in the same geographical space. Whether a device can operate in such an interference-limited environment depends not only on the signal it receives but also on its ability to handle co-channel interference caused by other users of the frequency band. Other factors are bandwidth and protocol efficiency. The ability to handle co-channel interference affects the effective operating area, which is smaller than the nominal area determined by the received signal power in the absence of interference. The ratio between the nominal operating area and the effective operating area is determined by the SIR[18] of the receiver and the number of interferers n under the prevailing pathloss conditions:

$$r_{area} = 10^{\left(\frac{2\left(SIR+10\log\sqrt{n}\right)}{(10.\,PLE)}\right)} \tag{11}$$

Taking into account the directivity of the receiving antenna requires multiplying n by the azimuth aperture factor A expressed in degrees/360 (and which may be the same for transmitter and receiver):

$$r_{area} = 10^{\left(\frac{2\left(SIR+10\log\sqrt{n.A}\right)}{(10.\,PLE)}\right)} \tag{11a}$$

The term $SIR+\sqrt{(n.A)}$ makes it clear that designers have choice between designing for receiver interference resistance and receiver antenna gain in meeting the spectrum-sharing requirements of a given application.

From a statistical point of view, this ratio specifies the reduction in *spectral efficiency* under conditions of interference. Conventionally, spectral efficiency is given in b/s/Hz. Taking into account protocol efficiency as well as the reduction in working area caused by interference from other spectrum users, the *net spectral efficiency* can be written as:

$$E_{net} \leq E_{prot}.\frac{E_0}{10^{\left(\frac{2SIR+10\log\sqrt{n.A}}{10\,.PLE}\right)}} \text{ b/s/Hz} \tag{12}$$

The message in the above expression is that in an interference-limited environment, systems with a lower SIR requirement will perform better than their more demanding cousins.

The s*pectrum-sharing efficiency* M_{se} of a system further depends on the radiated RF power (equivalent isotropically radiated power, EIRP)[19], the bandwidth and the duty cycle – all affect the spectrum resource available to other spectrum users. Because of the variety of devices using license-exempt bands, the RF power has to be normalized and, therefore, power flux density is to be used. This causes the frequency factor to drop out:

$$M_{se} = \frac{E_{prot}.E_0}{DC_m.PD_{tx}.10^{\left(\frac{2.SIR+10\log\sqrt{n.A}}{10.PLE}\right)}} \text{ b/s/mW} \tag{13}$$

DC_m is the median duty cycle and PD_{tx} is the transmitter's power spectral density.

Equation (13) clearly shows that for the same nominal throughput and SIR, a lower power density and duty cycle contribute positively to the efficiency of spectrum sharing. Further, the benefit of multiple input, multiple output technology is clear as well: for the same RF power and SIR, higher transmission rates can be achieved through spatial multiplexing. For cooperative network coding systems which use multiple transmitters for the same message, a factor m has to be added to the denominator – which shows that such systems are not necessarily efficient spectrum users:

$$M_{sen} = \frac{E_{prot}.E_0}{DC_m.m.PD_{tx}.10^{\left(\frac{2\left(SIR+10\log\sqrt{n.A}\right)}{10.PLE}\right)}} \text{ b/s/mW} \tag{14}$$

As noted above, this metric considers only co-channel interference and assumes that the interference is due to spectrum users with the same properties operating under ideal conditions. Practice is more complicated.

3.2 Spectrum-sharing efficiency under general interference conditions

Whereas the SIR is a key parameter for spectrum utilization efficiency, secondary receiver performance factors such as adjacent channel rejection, intermodulation properties and receiver de-sensitization also play a role. However, as noted in Section 1 Background, it is not possible to define common metrics for these secondary factors that would be applicable to a heterogeneous device population.

Changing the perspective to the generated interference and away from the victim reaction suggests the usefulness of a "reference interference profile" that mimics many of the interference effects that are found in practice. This reference profile would necessarily be frequency band-specific because the regulatory parameters of a band itself and its adjacent bands determine interference conditions. A similar concept is the "Interference Limits Policy", which has been proposed by the Technical Advisory Committee of the FCC (TAC, 2014).

A reference interference profile could contain both in-band and out-of-band components. The in-band components would mimic a number of devices expected to be used in proximity – Wi-Fi, Bluetooth and ZigBee come to mind as examples in case of the 2.4-GHz band. For each, a number of transmitters with associated signal levels at a virtual victim receiver could be chosen. Examples of potential reference out-of-band interference signals are the LTE signals into SRDs bands, e.g. the 860-MHz band and the 2.4-GHz band.

Every receiver implementation has its particular response behavior that becomes visible in the degradation of its performance caused by the reference interference profile. This degradation may be offset by various means such as a higher wanted signal or lower data rate at a more robust modulation rate[20]. The former is captured by adding this offset – *RPx* to (12):

$$E_{net} \leq E_{prot}.\frac{E_0}{10^{\left(\frac{2\left(SIR+10\log\sqrt{n.A}+RPx\right)}{10.PLE}\right)}} \text{ b/s/Hz} \tag{15}$$

RP_x is a device-specific value that specifies the increase in the wanted signal necessary to counteract the applicable off-channel interference. A downward adjustment of the modulation to improve robustness is reflected in a lower value of E_O and, therefore, both effects are accommodated by this expression.

The E_{net} metric as defined in (15) is a technical one, which gives an indication of the achievable throughput of a given system under given reference interference conditions. It does not apply to the broader economic or societal aspects of a spectrum use – e.g. a frequency band dedicated to emergency services is heavily underused most of the time. The fact that emergency services are ensured of a reliable communications medium may well be considered efficient from a societal point of view, e.g. because it may minimize loss of life.

Similarly, the interference aspects of spectrum sharing can be added to expression (13) or (14) by means of the same RP_x parameter – this gives the spectrum-sharing efficiency under interference conditions:

$$M_{spe} = \frac{E_{prot}.E_0}{DC_m.m.PD_{tx}.10^{\left(\frac{2\left(SIR+10\log\sqrt{n.A}+RPx\right)}{10.PLE}\right)}} \text{ b/s/mW} \tag{16}$$

This formula is bandwidth-independent provided the interference term RP_x expresses power spectral density. How a wideband receiver handles this interference is captured by the RP_x parameter. Its value depends on many intrinsic receiver factors such as linearity and filtering but also on factors like the coding level of the received signal.

3.3 Real net throughput

To find the actual throughput of a system, given its nominal throughput K_0 – in terms of b/s – in a given amount of spectrum, the latter is multiplied by the efficiency factor E_{net}. The net throughput K_{net} is a function of the raw throughput K_O, the protocol efficiency and the re-use area factor and the interference margin RP_x:

$$K_{net} \leq K_0.E_{prot}.\frac{1}{10^{\left(\frac{2\left(SIR+10\log\sqrt{n.A}+RPx\right)}{10.PLE}\right)}} \text{ b/s} \tag{17}$$

These throughput values are system-specific – e.g. for Wi-Fi, the figures are very different from those for Bluetooth or DECT. However, when normalized to a common channel width or frequency band, they can be used to compare different systems in terms of spectrum utilization efficiency.

Note that the K_{net} value is *area-independent*. In other words, the same throughput value can be achieved on any scale – whether per square meter or per square kilometer. This is relevant for the discussion of spectrum scarcity: given a certain demand for capacity – C_i expressed in b/s/area – and the available spectrum in Hz – the factor that determines a system's behavior under given pathloss and interference conditions – ($SIR + 10log\sqrt{n}.A + RP_x$) – can be derived. The first step is to realize that $C = K/area$ and, therefore, only K is needed as input value.

4. Conclusion and recommendations

4.1 Conclusions

In Europe, spectrum management parameters for SRDs conventionally have been formulated in terms of device parameters. This allowed a given type of device to be put on the market without changes to the parameters and requirements for existing devices. In this process, little, if any, consideration was given to the systems aspects of SRDs. The technical standards for assessing equipment compliance have followed the same model and emphasized limits on specific device parameters as the basis for regulatory compliance.

The systems aspects become apparent if one considers all the factors that play a role in the communication process: from the RF power output of a transmitter and its interference-generating effects to the signal propagation and distortion effects of the RF channel to the performance of the receiver in dealing with the distorted signal while subject to a variety of interfering signals.

However, regulations and compliance requirements for the license-exempt spectrum have lacked these performance aspects and instead have focused on device parameters under the assumption that minimizing interference among devices would be adequate. The recently issued radio equipment directive of the EU (European Commission, 2014) has increased the emphasis on parameters at the expense of losing sight of the broader, systems aspects of efficient use of the radio spectrum. By implication, constraints are imposed that assume – but do not demonstrate – spectrum usage benefits. Instead, these constraints may well prove a hindrance to innovations in radio technologies and their applications. Considering the statistics of wireless devices as interacting systems using a shared resource avoids this.

In this paper, we show that a different approach to regulatory and compliance requirements, based on a systems perspective and suitable metrics for transmitter and receiver performance in shared spectrum conditions, offers many advantages.

The use of these *technology-neutral* metrics allows a metrics-based approach to regulations for shared spectrum that limits ensembles of parameters rather than individual parameters. This approach has two major benefits: it reduces the administrative burden of keeping regulatory requirements up-to-date in relation to new technical developments and, second, it clarifies the relationship between regulatory measures and use of shared spectrum.

The proposed metrics-based approach allows major simplifications in the compliance criteria and in compliance testing. More importantly, it encourages designers to design efficient systems that optimize spectrum utilization for a given application within the constraints imposed by the regulatory framework.

4.2 Recommendations

The current regulatory framework in the EU for license-exempt frequency bands could benefit from a more generic approach that facilitates innovation while ensuring efficient use of the available spectrum.

The current regulation (European Commission, 2013) defines 29 different regulatory definitions for subbands adding up to a total of 96.5 MHz. The band at 2,400.000 to 2,483.500 MHz has four *overlapping* subband definitions with RF power levels of 10 mW to 500 mW that apply to the same set of frequencies. These definitions specify not only power levels but also bandwidth and channel spacing, duty cycle constraints and adaptivity requirements.

This regulatory framework could be very much simplified by defining spectrum utilization criteria for a given frequency band – regardless of the technology or application for which the technology is used. Three primary criteria define the total spectrum resource available – regardless the technology or application:

1. maximum EIRP and maximum power density within that range;
2. the available frequency range in MHz; and
3. the maximum duty cycle allowed – 100 per cent by default.

Three further criteria restrict the way individual systems use the spectrum resource:

4. the maximum spectrum load allowed – L_{spr};

This criterion restricts the share of the available spectrum resource that any device or system can use.

5. the AMA threshold;

This criterion disallows non-AMA operation above a given threshold value of L_{spr}.

6. the minimum spectrum-sharing efficiency required – M_{spe}.

The latter criterion prevents the use of devices or systems that are not able to operate efficiently in shared spectrum in the presence of interference.

Table I gives an example for the 2.4-GHz ISM band. The actual values to be incorporated in regulatory documents require further study.

These primary criteria would form the basis for the compliance requirements and methods of measurement specified in a harmonized compliance standard – developed by ETSI – for SRDs and IoT/M2M systems operating in the 2.4-GHz band.

4.3 Secondary compliance criteria based on spectrum load

The recently issued Radio Equipment Directive (European Commission, 2014) requires criteria for receiver performance to be included in all compliance standards. Defining common receiver criteria for license-exempt equipment is practically impossible due the

Table I Example of regulatory requirements using spectrum load and sharing efficiency for the 2.4-GHz ISM band

Regulatory criterion	*Value*
Frequency range	2,400 – 2,483.5 MHz
RF power (EIRP)	≤100 mW
RF power density (EIRP)	≤100 mW/MHz
Duty cycle	≤100%
Spectrum load share (maximum is 1)	$L_{spr} \leq -15$dB
Adaptive medium access threshold	$L_{spr} \geq -25$dB
Spectrum sharing efficiency (indoor, PLE = 3.3)	$M_{spe} \geq 0.2$

wide range of device properties, device design and implementation costs. Imposing a common set of such criteria on all devices would necessarily be arbitrary and therefore unacceptable. However, there is a close relationship between spectrum utilization and receiver quality. Therefore, scaling the compliance requirements for receiver parameters with the spectrum load offers a potential solution to this conundrum. This scaling can be applied to transmitter requirements as well. For example, the impact of unwanted emissions is proportional to the interference potential of the transmitter. The allowed peak to average ratio of the unwanted emissions could be proportional to the inverse of the interference potential[21]. Taken together, such scaled requirements provide a flexible compliance regime for a wide range of SRDs.

Compared to the rest of the world, Europe has a very complex and restrictive compliance regime for SRDs that discourages innovation and is costly to implement for all concerned. The metrics-based approach to SRD regulations and compliance requirements offers a way forward that fits well with the long-term policy goal of efficient spectrum use while encouraging innovation.

5. Further work

This paper sketches a way forward toward a new approach to spectrum regulations for license-exempt frequency bands. Further work is needed in three directions: the relevance and potential benefits of the proposed metrics for software-defined radio technology; how this metrics-based approach can be used in a context of a risk-informed interference assessment policy now being considered by the FCC – see TAC (2015) and De Vries (2015); and mapping of metrics-based regulatory requirements to technical compliance standards.

Notes

1. The Radio Equipment Directive formally succeeds the Radio and Telecommunications Terminal Directive in June 2016.
2. One could argue that a fourth dimension is relevant: the information dimension that is exploited by, e.g., CDMA systems. However, the use of coding affects the other three parameters and therefore it need not be considered separately.
3. “Efficient use” should not be confused with “effective use”. The former is related to the transfer of information, while the latter is related to the value and purpose of the information transferred.
4. The propagation environment plays a major role because it affects the strength of the received signals and interference at all receivers.
5. In fact, it may be argued that a variation in receiver performance under interference does not affect spectrum efficiency of a system unless that variation affects the behavior of the transmitter.
6. The ability of the receiver to handle interference while processing a wanted signal also affects spectrum sharing. This is covered in Section 3, Receiver Metrics.
7. Kruys (2015) develops the concept of interference load as measure of the demand an active transmitter places on the available spectrum resource.
8. These limits may include antenna directivity factors because these affect the interference area of a transmitter and thus the overall spectrum-sharing efficiency of a system.
9. The term power spectral density is used here to denote the mean RF power per Hz or per MHz of a transmitter, e.g., as measured with a spectrum analyzer.
10. Antenna gain generally maps to antenna directivity. For a given transmitter output, the area affected is approximately independent of the azimuth aperture.
11. Adaptive medium access techniques create a prisoner’s dilemma case for the users of a given frequency band: being polite means being at the mercy of other spectrum users, being not polite denies all users fair use of the spectrum. This principle applies to basic sharing mechanisms like LBT but also to secondary sharing mechanisms like contention window management.
12. A special form of DAA is the radar interference avoidance scheme known as DFS – dynamic frequency selection. This function requires a wireless LAN device to detect the presence of a radar signal and to switch frequency to avoid causing interference into the radar system.

13. See IEEE 802.11-2012, Clause 9.3 for an explanation of the RTS/CTS mechanism.
14. In a homogeneous device population, the hidden node effect is mostly environment-dependent, but when transmitter power levels differ by a factor 10 or more, relative distances become important as well.
15. The FCC's Part15§247 rules contain only RF power requirements (wanted and unwanted emissions) for equipment using frequency hopping and for equipment using "digital modulation" and they do not, contrary to, e.g., EU regulations, impose further restrictions such as the use of specific modes of LBT.
16. Antenna directivity has a major impact on spectrum sharing because it affects the wanted signal and the unwanted signals received from other sources differently. A higher directivity – a smaller azimuth aperture – generally means a smaller number of potential interfering sources.
17. It may be argued that the modulation and coding factors should be considered as properties of the transmitter. However, these factors come into effect mainly at the receiver.
18. SIR usually does not take into account signal distortion due to imperfections of the RF transmission channel. Signal to noise and distortion ratio (SINAD) does take this into account, and therefore, it may be more practically useful to use SINAD instead of SIR. This consideration is left for further work.
19. The EIRP form takes into account the transmit antenna gain and, therefore, its directivity.
20. This is correct only for receivers operating in their linear domain, i.e. significant de-sensitization does not occur.
21. The FCC's Part 15§247 rules provide such a relaxation of the unwanted emissions on the basis of a peak to average ratio limited to 20 dB.

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Spectrum 5.0
Improving assignment procedures to meet economic and social policy goals
A position paper[1]

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There are recurring and even growing concerns in Europe about the pace of deployment of new and future wireless technologies and networks. This can be currently observed for the deployment of 4G. It is to be feared those concerns are even more acute with the future deployment of 5G. 5G is actually to be even more complex in terms of technologies, and comprehensive in terms of services and societal impacts, with the expansion of IoT, M2M, and industry services in addition to residential customer markets. Governments in most countries face "…widespread public dissatisfaction around coverage, particularly outside urban areas." (Ofcom, 2016). In a typical example, however, of the right hand ignoring what is being done by the left hand, some branches of Governments, or Agencies in charge of license assignments, tend to focus exclusively or primarily on maximising the fees they can derive from the spectrum auction procedures which govern spectrum assignment today, with only secondary attention being paid to the now widely observed limitations of this policy tool in achieving broader policy objectives. In the end, the present assignment procedures have not been able to incentivise the

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industry development in the expected manner. There is now a growing body of evidence suggesting that spectrum auctions as they are currently being conducted do not stimulate network investments.

A study by GSMA and NERA (2017) concludes that:
"Statistical evidence shows the impact on consumers and links high price outcomes with:

- Lower quality and reduced take-up of mobile broadband services;
- Higher consumer prices for mobile broadband data; and
- Consumers losing out on economic benefits with a purchasing power of an estimated US$250 billion across 15 countries where spectrum was priced above the global median – equivalent to US$118 per person."

A draft Commission study by PolicyTracker, LS Telcom & VVA (2017) "found that the grouping with the highest auction prices also had the poorest network availability… This questions the common view that operators who pay high prices for spectrum must invest in their networks to make this money back."

Cambini & Garelli (2017) have illustrated the fact that spectrum fees and availability do not have significant impact on operators' revenue and investments.

These empirical studies confirm the analytical assumptions by Pogorel & Bohlin (2016) that pure spectrum auctions aiming at maximising spectrum fees do not serve to stimulate investments and network deployment.

Although most industry and government representatives recognise those facts when discussing behind closed doors, only a few have dared recognise these shortcomings, and publicly come out in favour of a better practice.

The purpose of this position paper is to explore future proof spectrum assignment scenarios that would more harmoniously balance the legitimate goal of the efficient use of spectrum as a limited public resource, with the equally prominent objective of deriving the maximum benefits for the economy that can be expected from investments in wireless network technologies, and putting in place the right incentives for the operators to exploit the potential of future network technologies in fulfilling economic, social and industrial objectives.

We present in this position paper design assignment scenarios in the 5G perspective that would re-balance the auction process, giving full consideration to the investment commitments of the bidders needed to achieve broader economic objectives, alongside the frequency fee paid to the government agency in charge. The 5G political challenges for the EU telecom industry are higher than ever. 5G will serve Industry 4.0, connectivity, cross industry digitisation, and provide the building blocks for the Digital future of Europe.

Re-defining spectrum awards procedures to align incentives with overall policy objectives

In order to circumvent the shortcomings of past spectrum auctions, future spectrum auctions should feature re-balanced spectrum assignment criteria prioritising investment plans of operators and put them at the forefront of public choices.

The Spectrum 5.0 re-balanced competitive procedures would combine:

- investment plans

- with the traditional spectrum fee.

The primary focus of the assignment would be on investment plans. They could be expressed in financial terms of defined as population and/or geographic coverage commitments. In case the government, based on its appraisal of the public interest, sets the assignment conditions at 90-95% coverage, the procedure would resemble a traditional spectrum fee auction. In cases, like early stage 5G deployment, where technology and economic risks and uncertainties are high, NRAs might not want to pre-define coverage obligations. Therefore, the new assignment mode would warrant from the biddeers more substantial steps towards investment.

Different modalities can be envisaged:

1. pure investment and coverage commitments
2. investment amount in escrow to be released along the deployment by the operators

With modality 1, the NRA would have to deal with the delicate issue of measuring the coverage outcomes, as is the case currently in many instances. In this respect, modality 2, keeping investment funding in escrow would have the advantage of reversing the burden of the proof: it would be up to the operators to demonstrate they have complied with their commitments.

Other defining elements in the assignments should be considered. Assessing the relationship between a specific frequency band and the network deployment are no different from the current situation. There will also be a need to account for different use cases: 5G in general, and IoT, in particular, have different use cases, with different coverage definitions.

Moreover, the network evolution over a long period will have to be articulated with investment plans and the duration of the license. To make the bids comparable, investments over time will be summed up at present value, accounting also for the evolution of network costs.

What spectrum fee should be paid to the government?

Fees should be paid for the use of spectrum as a limited resource. We could consider various methodologies:

- % of investments
- % of expected income
- pre-defined fee.

Monitoring and compliance

One key element is the compliance of bidders in the implementation of the investment objectives in their bids. A major risk is the potential divergence between ex ante commitments and ex post outcomes. While traditional auctions are based on ex ante expectations including auction fees, the investment promotion auction design is based on carefully designed rules of behaviour and follow-up monitoring. To make sure that investments are indeed taking place, institutional arrangements should be designed to ensure the compliance to commitments, and to cope with potential shortcomings.

The task of monitoring the implementation of the selected license holders will not be much different from what is currently performed by NRAs. Some flexibility should be allowed on investment plans, taking into account changing economic conditions. Coverage obligations should be fulfilled, and the present value of the scheduled investments maintained. A degree of flexibility of investments in specific bands is warranted: the commitments cannot be band specific over the long period.

The issue of reverting back unused or under-used frequencies if the commitments are unfulfilled needs to be considered, as is the case for past spectrum assignment procedures.

Positive short term and long term impacts at telco, industry, government budget, and macro level

The results of the alignment of public policy and industry strategies can be expected to be positive.

- MNOs will know precisely what is expected in the terms of their license, allowing them to define their business model and strategy. The fee paid to the government will lose its central status, and be considered as a normal counterpart of the use of the spectrum resources. Funding by banks, especially the EIB, could be made easier. Better consideration could be devoted to entrants with infrastructure investment plans.
- The public will benefit from the faster deployment of new networks, faster diffusion of new services, increased incomes of all industries, and the government from corresponding taxes. Coordination, incentives and public policy initiatives, especially regarding verticals can be positively considered.
- Focus on investments has positive impacts on R&D, technology and standards,

The European dimension

Member states have different starting points, but convergence and consistency are essential for the digital single market, in terms of rules, timing, and conditions. The re-balanced spectrum awards framework corresponds to an EU wide perspective, and can be proposed as a best practice.

Conclusions: The value of spectrum resides in its use by the economy and society

To put it bluntly, and contrary to the hot air common wisdom, spectrum has no value in itself. Its value resides exclusively in the contribution Its use makes possible for society and the economy.

It is not too late to think about spectrum awards for 5G in this perspective. Spectrum auctions 5.0 should put an end to the case by case lottery of successive spectrum assignments. It should pave the way for a consistent, less stochastic, system of putting spectrum usage at the service of society, by smoothing spectrum fees, in a manner connected to global usage and in line with the continuity of technological evolutions.

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Managed Unlicensed Spectrum

William Webb, June 2017

Introduction

Unlicensed spectrum is only very loosely managed. Rules of access such as maximum power levels and duty cycles aim to regulate behaviour to a limited degree but by necessity are set in place before a band is put into use. Database approaches such as those proposed for TV white space can be more proactive by dynamically changing whether access is allowed but do not seek, for example, to minimise interference between unlicensed users.

For many, the lack of management is one of the key attractions. With little control over what can be deployed, innovation can occur and spectrum access is enabled for all. Most would judge unlicensed spectrum to have been a great success with widespread and growing usage of Wi-Fi, Bluetooth, myriad connected home devices and much more. Hence, the idea of imposing some kind of management control might be seen as contrary to one of the founding principles on which unlicensed access has been built.

In this paper, we look at whether there may be some cases where management is appropriate and some mechanisms that can be deployed to achieve it without compromising the attributes that have made unlicensed spectrum so attractive.

Why management might be appropriate in some cases

Broadly, management of spectrum is only appropriate where interference is a problem. If there is no interference then there is no need for management. If we look at some unlicensed usage we might categorise interference problems broadly as follows:

Interference not a problem	Interference can be problematic
Cordless telephones (own spectrum)	Wi-Fi in dense areas
Wi-Fi in less dense areas	Wide-area IoT solutions
Bluetooth	Drones
Home connectivity	RFID
Car door openers	
Wireless keyboards, mice, etc	

Simplistically, interference tends not to be an issue where one of the following holds true:

- The usage has its own unlicensed spectrum (eg cordless phones in Europe).
- The density of usage is low, such as outside urban areas.
- The solution is highly tolerant of interference, such as Bluetooth where frequency hopping provides excellent interference rejection.
- The usage is very short range such as wireless keyboards.

Interference tends to become problematic where:

- The density of usage is high, such as Wi-Fi in conference venues.
- The range required is long, such as wide-area IoT solutions with a range of 5km or more.
- The power levels are very low, such as RFIDs, where any interference is problematic.

This paper concentrates on two case studies to demonstrate the benefits of a solution and show what might be implemented before drawing some general conclusions.

1. The use of Wi-Fi where uncoordinated frequency planning between Wi-Fi nodes can halve the spectrum efficiency, and where new technologies such as unlicensed-LTE might cause future problems.
2. Wide area IoT connectivity where many uses are unlikely because of concerns over being able to guarantee a quality of service level in unlicensed spectrum.

Wi-Fi

For most people, their experience of broadband connectivity is via a Wi-Fi connection. In the home almost all computing devices, tablets and smart-phones are Wi-Fi connected rather than being plugged into a wire connected to the home gateway. Approximately 80% of all our mobile data consumption is via Wi-Fi and over 80% of all our computing devices have Wi-Fi connectivity but no cellular connectivity.

In some cases, Wi-Fi can form the bottleneck in the delivery of higher speed content. If the connection to the home is 100Mbits/s but the Wi-Fi connections only support 10Mbits/s due to congestion, interference or weak signals then the higher speed of access to the home is of limited value. In congested areas such as apartment blocks, shopping malls, train stations and conference centres, the level of interference between Wi-Fi nodes can be such that data rates fall below 1Mbits/s. If Wi-Fi congestion were to rise then many attempts to deliver faster broadband would not succeed. With ever more Wi-Fi nodes deployed then a rise in congestion is very likely.

Reduced data rates in Wi-Fi can be caused by three effects:

- Low signal level caused by being far from the router.
- Congestion caused by many devices accessing the same router.
- Interference between routers.

The solution to the first two problems is to install more routers to provide greater coverage and capacity, but as more routers are installed interference rises. Hence, reducing interference between routers is critical to enabling improvements in Wi-Fi data rates.

In cellular systems, central planning of the radio frequency assigned to cells ensures neighbouring cells do not interfere and that devices are attached to the optimal cell. In most Wi-Fi systems this decision making is decentralised with each router selecting what it believes is the best frequency and each device attaching to its preferred router: often according to whether it has attached to that particular one in the past. This decentralised approach works well when router density is low and each router is able to find a free channel. However, it works poorly when there are insufficient channels and in some cases algorithms may actual make matters worse as routers “fight” against each other for optimal channels.

The solution is some degree of centralisation of the management of router frequencies and device selection of routers in those areas where there is a high density of routers. This centralisation could be local, covering only a single building or dense area, or it could be regional or national. However, this centralisation is complicated by the fact that routers are owned by many different parties. For example, in a block of flats, each flat owner will likely own a router. In a train station, each of the shops and restaurants may own their own routers. In a city centre there may be a mix of routers owned by mobile operators, by third-party Wi-Fi providers, by city councils and by office tenants. None of these may wish to take the lead in providing centralised planning. In this situation a third-party or agreed shared mechanism is needed that can control the access points, the device attachment and deliver an optimised service for the benefit of all. Achieving this requires:

- Standardisation such that each router knows how to contact the centralised manager, is able to provide information in a standard format on frequency usage and the manager knows how to direct the router to act.
- The emergence of a trusted third party or trusted shared solution to provide this management function.
- Appropriate central planning solutions that deliver optimal results.
- Wi-Fi frequencies as free as possible from interference from non-Wi-Fi devices since interference that could not be controlled would complicate the central planning process.
- The participation of all, or almost all, routers in an area in the scheme – if only a small subset participate there will be limited benefits[1].
- An appropriate business model to cover any costs that arise, complicated by the fact that few currently pay for delivering Wi-Fi and that there are few immediate advantages for the first to join the scheme.

Elements of many of these already exist. The standard TR-069 enables Wi-Fi nodes to send information to a remote management unit and to receive instructions in return. Companies such as Vodafone already manage the routers that connect to their broadband lines using this standard, planning frequencies throughout homes. Some airports manage Wi-Fi frequencies, requiring franchise owners on the airports to link their Wi-Fi routers to a central unit. Software solutions that can be embedded within routers and central planning algorithms have been suggested and trialled by commercial and academic entities. But operation at scale across routers owned by different parties is rare and would require significant leadership to achieve.

For example, EcoWi-Fi – a commercial venture – claims to be able to improve Wi-Fi data rates by up to 130%. Aoifes, the company developing EcoWi-Fi, is hoping to partner with ISPs and router manufacturers, targeting home deployments of Wi-Fi routers. Their solution comprises additional software embedded in routers and a cloud-based central management system. Another approach is termed Empaticradio and has been developed by academics in Norway and aims for peer-to-peer communication between routers with limited need for centralised management. Instead routers aim to decide between themselves as to the best approach. Alternatively, organisations such as Assia have proprietary solutions that aim to optimise the performance of individual routers in the presence of interference, claiming over 100% performance improvement[2].

Concerning the emergence of either a trusted third party to manage the central database or a peer-to-peer solution there appears to be two significantly different approaches:

- A centralised database owned by a legal entity (eg a company, Government) that registers routers and manages their key parameters.
- A peer-to-peer solution where routers self-discover other nearby routers and using cloud-hosted software collectively determine their optimal frequency allocation.

At this stage there is no clear preference between these – and indeed both could potentially co-exist as long as there was some cooperation between them. If there is central management then in the

[1] It is not clear as to what percentage of routers would need to participate to realise the majority of the benefits. There is anecdotal evidence that it is not necessary to achieve 100% but further study is required to understand the minimum percentage that would make the undertaking worthwhile.

[2] Simulations performed by the author suggest similar levels of gains in eg dense residential areas.

first instance confidence will be improved if a third party is sanctioned by Government, a regulator or some similar entity. This could be as part of a procurement process to provide management to Government-owned routers.

Where there is a cost then options might include:

- Owners of Wi-Fi routers paying a monthly fee for the central planning approach.
- Government paying the central planner for the benefits it provides, perhaps from revenues arising from spectrum auctions, fee payments or similar.
- A small fee being attached to fixed line usage to cover central Wi-Fi planning since most fixed lines will have an attached Wi-Fi router.
- Router manufacturers funding the third party through a small increase in the cost of routers.

The business model would need to ensure that it sufficiently incentivised those organisations that already manage groups of routers to partake in a wider management process. The peer-to-peer approach may have fewer costs making the business model less critical, but key players will still need some form of incentivisation.

Implementing a solution of this sort is complicated by the fact that there are already many deployed routers and that it might not be possible to locate and update these remotely. Hence, it may require gradual churn and replacement of devices. This means there is very little benefit from early adopters so if they have to pay any fee they may decide to wait until the majority of devices have enrolled into the solution. If all make this decision, then the solution is never successful.

Further study is required to determine the best way to resolve this start-up problem. Some areas that might merit investigation include:

- Opening a new band, or partial band (eg at 5GHz) and requiring all routers using this band to have central management.
- "Seed-funding" the process such that Government or others provide the funding needed to enable the introduction of the solution to the point that the benefits were clear. (At this point the initial funding could potentially be repaid.)
- Local initiatives such that, eg, all the residents in a particular area were encouraged to enrol in a relatively short timeframe.

Internet of Things

IoT connectivity broadly divides into short-range in the home, office or factory; and long-range for devices that need connectivity outdoors. The latter include systems like smart metering, connected trash-cans, asset tracking, smart parking sensors, agricultural sensors and much more.

Current solutions to long-range or wide-area connectivity fall into two categories often referred to as licensed and unlicensed. Licensed solutions are those deployed by the mobile operators in their licensed spectrum. These have been developed within 3GPP and comprise LTE-M and NB-IoT. Simplistically, LTE-M is more appropriate for devices with substantial batteries or mains power, while NB-IoT is better for the low-power and lower-functionality devices. Some mobile operators, such as Vodafone, are planning aggressive roll-out of licensed solutions across their network in 2017 and 2018.

Unlicensed solutions have predominantly been developed as proprietary technologies by companies such as Sigfox or the LoRa technology developed by Semtech, or standardised technologies such as that from the Weightless SIG, and are deployed by a wide range of different entities in unlicensed spectrum. Some deployments are campus-wide self-provision, whereas others are national networks deployed by operators such as Sigfox and their affiliates. Whether both licensed and unlicensed solutions will continue to exist and the balance of traffic between them is unclear. Some believe that the mobile operators have such a compelling advantage in terms of coverage and branding that they will dominate the market. Others think that the relatively high cost of cellular-compatible modules and cost-structure of the operators will result in licensed solutions only being used for the most valuable of connections. Some look to the world of personal connectivity where a mix of licensed cellular solutions and unlicensed Wi-Fi solutions are in use.

Predicting the outcome appears near-impossible at this point. However, there is a risk of a default to a sub-optimal outcome if both licensed and unlicensed solutions are not available for operators and users to select from.

One of the key problems for unlicensed deployments is a lack of suitable spectrum. Most unlicensed spectrum is configured for short-range devices which communicate infrequently. Therefore, it has limits on transmitted power and on duty-cycle, often as low as 1%. A wide-area IoT solution typically comprises a base station which needs to transmit for somewhere between 10% and 50% of the time and could benefit from using relatively high power levels, although terminal devices generally will only need 1% transmission time and be low-power. However, relaxing the duty cycle and transmit power could increase interference[3].

A second problem is that the compromises made in system design to enable low-power devices to communicate over many kilometres, can make the systems vulnerable to interference. For example, recent reports suggest that the LoRa solution can experience a rapid reduction in performance as interference from other technologies increases. Some solutions may fail completely if that have no way of feeding back to the device the need for a change in parameters due to interference[4].

A solution to these issues would be a different set of spectrum-access rules for wide-area IoT solutions. Ideally, these would be accompanied by spectrum dedicated to unlicensed IoT operation. For example, higher powers and unlimited duty cycles could be allowed if operators agreed to central coordination which delivered a fair division of the spectrum across networks in a manner that optimised their performance. This might segregate technologies known to have poor co-existence while frequency planning technologies that can co-exist.

Not only would this enable the deployment of networks that might otherwise not be possible, it would go some way towards reassuring potential users of the network that significant interference issues would not occur in the future, especially if dedicated bands were provided.

The management probably needs to be centralised – unlike Wi-Fi where peer-to-peer management might be viable. It could be Government owned, commercial or run by a not-for-profit standards body or similar. Possible models include dynamic spectrum sharing databases. Because this is an emerging area and because the number of players is relatively small then the start-up problem is minimal and the business case unlikely to be an issue.

[3] There are compromise positions – for example Ofcom allowed a 10% duty cycle for base stations where the location was registered with the regulator.

[4] For example, the Sigfox solution has no significant downlink and hence no way of changing device behaviour. Devices will continue to transmit regardless of whether their communications have any chance of being received.

Implications and conclusions

This paper has suggested that while managed unlicensed spectrum is not needed nor appropriate in many cases, there are important situations where it could make a material difference. Indeed, given the critical role of Wi-Fi and the future potential of IoT to transform society and address some of our key challenges, even small differences in spectrum efficiency or increases in potential use cases could deliver huge societal benefits.

Where it is needed, there are different issues and ways to achieve solutions. In Wi-Fi, peer-to-peer self-organisation might be viable, in IoT changes in spectrum access parameters when utilising a centralised database might be preferred. Some of the key attributes of the two solutions are summarised in the table below.

Parameter	**Wi-Fi**	**IoT**
Voluntary or obligatory?	Voluntary, although the start-up/free-rider problem needs addressing	Obligatory if enhanced spectrum access to be allowed
National or international?	Could work on a national basis but given the international nature of equipment supply, best addressed internationally	National, set by each regulator, although economies of scale helped if multiple regulators adopt same approach
Getting started	Could happen without Government or regulatory involvement, eg by Wi-Fi Alliance	Needs regulatory lead
Timescales	Could be prolonged	Needs to ideally happen in the short-term

There are strong grounds for trialling managed unlicensed solutions in both these cases in order to assess the role management might play in the future.

Biography

William is the CTO at OpenSignal, the world-leader in crowd-sourcing of mobile connectivity information. He is also CEO of the Weightless SIG, the standards body developing a new global M2M technology. He was President of the IET – Europe's largest Professional Engineering body during 14/15.

He was one of the founding directors of Neul, a company developing machine-to-machine technologies and networks, which was formed at the start of 2011 and subsequently sold to Huawei in 2014 for $25m. Prior to this William was a Director at Ofcom where he managed a team providing technical advice and performing research across all areas of Ofcom's regulatory remit. He also led some of the major reviews conducted by Ofcom including the Spectrum Framework Review, the development of Spectrum Usage Rights and most recently cognitive or white space policy. Previously, William worked for a range of communications consultancies in the UK in the fields of hardware design, computer simulation, propagation modelling, spectrum management and strategy development. William also spent three years providing strategic management across Motorola's entire communications portfolio, based in Chicago.

William has published 15 books, over 100 papers, and 18 patents. He is a Visiting Professor at Surrey and Southampton Universities, an Adjunct Professor at Trinity College Dublin, a Board member of Cambridge Wireless, a member of the Science Advisory Council at DCMS, other oversight Boards and a Fellow of the Royal Academy of Engineering, the IEEE and the IET. In 2015 he was awarded the Honorary Degree of Doctor of Science by Southampton University in recognition of his work on wireless technologies and Honorary Doctor of Technology by Anglia Ruskin University in honour of his contribution to the engineering profession. His biography is included in multiple "Who's Who" publications around the world. William has a first class honours degree in electronics, a PhD and an MBA.

A Study to Develop the Next Generation Systems Architecture for Radio Spectrum Interference Resolution

Prepared by:

Spectrum and Receiver Performance Working Group*
FCC Technological Advisory Council

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Preface

This preliminary Statement of Work for a Study to Develop the Next Generation Systems Architecture for Radio Spectrum Interference Resolution was prepared by the Spectrum and Receiver Performance Working Group of the FCC's Technological Advisory Council (TAC) and approved at a meeting of the TAC membership on March 9, 2016. This document was prepared to encourage the FCC, other government agencies and the academic and private sectors to facilitate the undertaking of such a study by (a) cooperating in refining and completing the Statement of Work, (b) identifying potential funding sources, (c) establishing a governing structure for overseeing the accomplishment of the work, and (d) identifying potential performers of the tasks identified. The urgent need for the study is described in the Statement of Work included herein. The TAC recommends that the FCC work on its own account, and with other government agencies and the academic and private sectors, to facilitate the undertaking of such a study by engaging in the four activities identified above

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A Study to Develop the Next Generation Systems Architecture For Radio Spectrum Interference Resolution

1. Introduction and Background

The exponential growth in demand for access to and use of the radio spectrum is well documented. It is being driven by (a) a combination of more users using more devices and often consuming more bandwidth per device and (b) the requirements of emerging radio-based systems designed to offer new services important to both government and civilian users. An example of the former is the growth in mobile data. A frequently cited annual report from Cisco Systems[1] stated that global mobile data traffic has grown 4,000-fold over the past 10 years and almost 400-million-fold over the past 15 years. It went on to report that mobile data traffic in 2015 grew by 74 percent globally and by 55 percent in the U.S. The report cites a host of reasons for current and future growth, including the dramatic increase in the amount and technical quality of video traffic conveyed due to the proliferation of advanced multimedia uses. In a recent forecast, Gartner, Inc. projected that the Internet of Things (IoT) would be the fastest growth sector in terms of radio emitters and would reach 21 billion devices by 2020.[2] Other examples of rapidly emerging radio services are new types of aeronautical and space systems including, among many others, unmanned aircraft systems (UAS) and Low Earth Orbiting (LEO) satellites. All of these new systems offer the potential of significant public benefits, but also often present unique challenges in terms of interference issues in both transmitting and/or receiving. Adding to the challenge of trying to accommodate intentional radiators is the growing presence of other electrical and electronic devices that unintentionally or incidentally emit radio waves or that are susceptible to the increased density of radio waves that are present.

From a high-level perspective, spectrum management techniques used in response to this explosion in demand include (a) increased densification in both the frequency dimension (e.g., through reduced guard bands) and the space dimension (e.g., through increased frequency reuse) and (b) following the vision set forth in a 2012 Presidential Council of Advisors on Science and Technology ("PCAST") Report,[3] facilitating dynamic sharing in the time, frequency and space dimensions through the use of sophisticated Spectrum Access Systems that rely upon geo-location data-bases and/or spectrum sensing for their operation.

While these approaches, along with more traditional approaches such as using more sophisticated modulation and signal compression techniques are laudable, they change in fundamental ways the vulnerability of the associated systems to both intentional and

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[1] Cisco. (2016, Feb. 3). *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020* [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.pdf

[2] Gartner. (2015, Nov. 10). *Gartner Says 2.4 Billion Connected "Things" Will Be in Use in 2016, Up 30 Percent from 2015* [Online] Available: http://www.gartner.com/newsroom/id/3165317

[3] President's Council of Advisors on Science and Technology. (2012, Jul.). *Report to the President: Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth* ("PCAST Report") [Online]. *Available at* http://go.usa.gov/k27R

unintentional interference. Although it is hoped that largely voluntary collaboration and coordination between and among Federal agencies and the private sector entities involved will be effective in preventing and resolving most interference incidents in an increasingly dynamic shared spectrum environment, fast and effective interference resolution actions will still be needed in cases involving malicious and non-malicious intentional interference that present an immediate threat to the safety of life and to mission critical systems. Incidents involving unintentional interference (or interference produced by incidental radiation) that pose an immediate threat to the safety of life and mission critical systems or which causes harmful interference to other systems or services may require similar, direct regulatory intervention.

Although the techniques outlined above for keeping up with the explosion in spectrum demand have created radio spectrum interference resolution challenges, many of the same, underlying technological developments that make them possible have also led to dramatically improved capabilities for detecting, classifying/identifying, locating, and reporting sources of interference. In combination, these developments suggest an urgent need for a study that uses modern system engineering tools, analyses, and techniques to develop a vastly improved and better coordinated next generation systems architecture for interference resolution.[4] The need for such an architecture is further propelled by the following:

- Existing and future resources for detecting, classifying/identifying, locating, reporting, mitigating and remediating interference are and will, as a practical matter, continue to be scattered across multiple entities, both public and private.

- Budgetary constraints on public entities (e.g., federal agencies) and cost minimization pressures on commercial entities, suggesting the need to avoid unnecessary duplication of facilities and functions.

- The need to automate interference resolution systems in order to speed responses to serious interference incidents and to reduce costs.

- Recent changes in Federal Communications Commission (FCC) enforcement strategies and priorities as reflected in its recent Order addressing Enforcement Modernization.[5]

Failure to develop the next generation systems architecture could lead to unnecessary and costly over-laps in interference monitoring and location equipment and personnel or, at the other extreme, gaps in equipment and personnel that would slow and reduce the effectiveness of responses to serious interference incidents involving the safety of life and property and homeland defense. Such an architecture would facilitate the ability of today's radio spectrum interference

[4] In the systems engineering design process, systems architecting refers to "the partitioning of a system into components, the defining of interfaces among these components and the processes that govern their changes over time." See Robinson, C. (2013, Apr.). *Big 'A' Systems Architecture* [Online]. Available: http://dau.dodlive.mil/files/2013/04/Robinson.pdf. Systems architecting is also explored in more detail in Section 4.g below.

[5] Federal Communications Commission. (2015, Jul. 16). *In the Matter of Reorganization of the Enforcement Bureau's Field Operations*, FCC 15-81 [Online]. Available: https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-81A1.pdf

resolution systems to evolve efficiently and effectively in the face of rapid technological changes.

Finally, the lack of a next generation systems architecture and any associated inability to (a) limit the number of incidents of harmful and disruptive interference and (b) resolve them quickly when they do occur, could also undermine the value of dynamically shared spectrum to commercial entities and the willingness of Federal government agencies to share their spectrum. This would put into serious jeopardy the presidential goal of making an additional 500 MHz of spectrum available for commercial use by 2020[6] and result in the loss of the substantial economic and social benefits associated with further advances in wireless systems and services.

2. Objective

The objective of this study is to develop the next generation systems architecture for radio system interference resolution in spectrum management that is responsive to the challenges and opportunities outlined above and described in more detail in Section 4 below.

3. Scope of Work

The terms "spectrum management," "interference resolution," and "enforcement" are broad in scope and sometimes ambiguous. For the purpose of this study, spectrum management is defined to include both the organizations (such as regulators, multi-stakeholder groups, trade associations and operators) and activities (from rulemaking to monitoring and remediation) that strive to obtain maximum value from the use of wireless devices, systems and services. Among other things spectrum management includes making rules (not only about radio operation but also the allocation and assignment of operating rights), ensuring that the rules are observed, and taking market structure into account where it affects the public interest. For the purpose here, the term interference resolution is defined to mean the elimination of interference between one radio operator and another, including cases where there is mutual interference. Interference resolution can be done by the operators themselves, or it may involve remediation and/or prosecution by the FCC. Interference resolution is thus a part of spectrum management.

The term enforcement has both broad and narrow meanings. In the broad meaning, it refers to interference resolution activities such as those undertaken by the FCC Enforcement Bureau. Those activities can be broken down into a variety of functions, such as monitoring – the observation of radio signals and detection, identification and location of interferers; adjudication – deciding whether observed interference is culpable; remediation, also called enforcement – terminating harmful interference by informal or formal action such as educating operators or imposing fines and seizing equipment. Enforcement is thus one of the tools for interference resolution and it can refer to wide range of activities or just remediation actions alone. To resolve this ambiguity, in the context of this study, enforcement is defined to mean the wide range of

[6] B. Obama. (2010, Jun. 28). *Presidential Memorandum: Unleashing the Wireless Broadband Revolution* [Online]. Available: https://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution

activities associated with interference resolution while remediation is defined to mean the much narrower set of education and punitive activities.

Activities associated with interference resolution are typically divided into two categories – *ex ante* and *ex post* (that is before and after the fact). *Ex ante*, in this context, refers to preventative measures taken in advance to eliminate or minimize subsequent incidents of radio interference. *Ex post* refers to actions taken after interference occurs. Examples of *ex ante* activity include making appropriate rules; authorizing equipment to ensure that devices operate in compliance with the rules or, say, educating the public about the negative consequences of buying and using an unapproved cellular radio jamming device. An example of an *ex post* measure would be a punitive, remediation action taken against the user of such a device once it had been put into service. The focus of the study proposed herein is on *ex post* systems and activities associated with interference detection, classification/identification, location, reporting, mitigating, and remediation.[7]

In Section 1 above, a distinction was made between non-malicious intentional interference and unintentional interference. An example of intentional interference without malicious intent would be an employer who uses an unauthorized device to jam cellular signals to prevent employees from making cellular calls or texting while engaging in hazardous activities. An example of unintentional interference would be interference inadvertently produced by an improperly aligned transmitting antenna lobe. The remaining category is malicious, intentional interference that conceivably could be produced by individual criminals, organized crime groups, foreign powers or non-state actors using unauthorized devices. While the focus of the study proposed herein is on non-malicious intentional interference and unintentional interference, the systems developed under the next generation systems architecture would obviously be of significant value in interference detection, classification/identification, location, reporting, mitigation, and remediation which is associated with both malicious intentional and non-malicious intentional interference.

Without resorting to formal technical definitions, the terms Electromagnetic Compatibility (EMC) and Electromagnetic Interference (EMI) are associated with unintended interference that may arise when electrical and electronic (i.e., telecommunications) equipment are operated in close proximity to each other. Under such circumstances the interference may not enter the receiving equipment through the antenna input jack but, for example, through other forms of coupling between the interference source and the receiver. A specific example would be electromagnetic energy that enters a receiver though a poorly shielded enclosure or via an associated power cord. EMC/EMI analyses and spectrum management are closely related but different disciplines and the focus of the study proposed herein it is on the latter rather than the former.

[7] Although the focus of the study is on *ex post* interference resolution activities, it is obvious (a) that there is a tradeoff between devoting limited resources to preventative activities versus punitive activities taken after-the-fact and (b) that much can be achieved by well-researched and well-grounded sharing studies conducted and acted upon in advance of deployment. The Federal Communications Commission's Technological Advisory Council recently developed a set of basic principles that should be considered in carrying out such decisions. See FCC Technological Advisory Council, Spectrum and Receiver Performance Working Group. (2015, Dec. 11). *Basic Principles for Assessing Compatibility of New Spectrum Allocations* [Online]. Available: https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

4. Specific Tasks/Key Activities

In carrying out the study, the performer shall execute the seven tasks described below. While the tasks are listed separately and sequentially, it is recognized that, realistically, all portions may be carried out in parallel and in an iterative fashion to produce the final deliverable – the next generation systems architecture for radio system interference resolution.

a. Document the Traditional Radio System Environment

The changing environment for interference resolution is illustrated by noting that, in the not too distant past, radio communications systems (i) typically operated in the analog mode with a very limited number of modulation methods or waveforms and used a single or limited number of (often) narrowband channels that were fixed or manually selected rather than dynamically assigned, (ii) utilized high power transmitters with high antenna sites that produced signals that were easy to detect and locate using relatively unsophisticated, manually operated spectrum monitoring and direction-finding systems, (iii) were typically noise limited rather than interference limited, (iv) were licensed by the Commission (or authorized by NTIA in the case of government systems), and regularly transmitted unique identifying information (e.g., call letters) in the clear and (v) transmitted the associated information content itself in the clear or in a form that was otherwise easily decipherable. Moreover, end-user devices had very limited processing, storage and display capabilities and had no means of ascertaining their location. Finally, unapproved transmitting devices designed for deliberate jamming were not widely available.

The purpose of this task is for the performer to document the traditional radio system environment including not only traditional communications systems but also other spectrum consuming systems such as radar and radio astronomy. This will provide a historical context for recent technological changes such as the migration from analog to digital modulation techniques in modern systems. In performing this task, the performer may rely upon the TAC White Paper dated May 29, 2014 entitled "Introduction to Interference Resolution, Enforcement and Radio Noise"[8] while conducting its own literature reviews and interviews or utilizing other research techniques.

b. Study and Document the Changes Occurring in the Radio Environment and the Challenges Associated with Them

In contrast to the traditional radio system environment described immediately above, the situation today is vastly different in nearly every respect. For example, many radio systems (i) increasingly operate in the digital mode using a myriad of complex waveforms that dynamically adapt to changing channel conditions while operating on multiple, dynamically

[8] D. N. Hatfield et al. (2014, Jun. 10). *Introduction to Interference Resolution, Enforcement and Radio Noise* [Online]. Available: https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting61014/InterferenceResolution-Enforcement-Radio-Noise-White-Paper.pdf. See also D. Hatfield. (2014, Mar. 31). *Keynote Remarks for WSRD SSG Workshop V: Understanding the Spectrum Environment: Data and Monitoring to Improve Spectrum Utilization* [Online]. Available: https://www.nitrd.gov/nitrdgroups/images/d/dd/Understanding_the_Spectrum_Environme_-_Hatfield_-_keynote_remarks.pdf

assigned broadband channels scattered over numerous bands that may be shared with other services on an active basis, (ii) often transmit at low power and low elevations from hundreds of antenna sites in order to provide the necessary capacity (through frequency reuse) to communicate successfully with millions of highly mobile end user devices consuming and producing a rapidly increasing amount of broadband information (iii) are typically interference-limited rather than noise-limited especially in congested suburban and urban areas (iv) are often unlicensed (e.g., in the case of Wi-Fi networks) or licensed by rule rather than on an individual basis and are not required to transmit unique identifiers (e.g., call letters or their equivalent) or communicate in the clear (e.g., without scrambling or encryption) (v) transmit the information content itself in "noise like" digital formats so that it is difficult to detect and to decipher and hence to classify or identify interfering signals for interference resolution purposes. Furthermore, because of the increased demand for spectrum capacity, widely deployed nomadic and mobile systems are moving higher up in frequency in the radio spectrum – e.g., above 3 GHz and even into millimeter wavelengths.

Individually and in combination, the characteristics of these modern wireless systems present significant challenges to the relatively unsophisticated, manually operated spectrum monitoring and direction-finding systems used in traditional interference resolution activities. The dynamic nature of the modern wireless systems, the normal variability associated with radio propagation conditions, and the increased mobility of end user devices results in interference being highly intermittent in terms of time, space and frequency; furthermore, the shorter ranges associated with the use of lower power and higher frequency bands makes spectrum monitoring and direction-finding problematic from a limited number of fixed and mobile locations. From an end-user (and service provider) perspective, the noise-like characteristics of aggregated intentional and unintentional interference from multiple sources may manifest themselves as sporadic decreases in capacity rather than as an outright, easily distinguishable disruption of service. The interference resolution challenges are further compounded by the wider availability of unapproved transmitting devices designed for deliberate jamming.

These challenges are elaborated upon at some length in the TAC "Introduction to Interference Resolution, Enforcement and Radio Noise" White Paper referenced earlier while some specific challenges, such as temporary transmitter or receiver intermodulation, are dealt with in a more recent TAC paper entitled "Basic Principles for Assessing Compatibility of New Spectrum Allocations."[9] The purpose of this task is for the performer to build upon these reports in order to create and document a more in-depth and comprehensive understanding of the interference resolution challenges that are created by densification and an increasingly dynamic shared spectrum environment. A clear, in-depth and comprehensive understanding of these challenges is essential to the development of the next generation systems architecture for radio system interference resolution that is the ultimate objective of the entire study.

c. Identify, Analyze and Document Improved Capabilities for Detecting, Classifying/Identifying, Locating, Reporting, Mitigating, and Remediating Interference

[9] G. Lapin et al. (2015, Dec. 11). *Basic Principles for Assessing Compatibility of New Spectrum Allocations* [Online]. Available: https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

While the developments described immediately above present significant challenges to traditional methods used for interference resolution, going forward the same or related underlying technological advances that produced them also hold great promise in terms of increasing the speed, efficiency and efficacy of interference mitigation and avoidance techniques. To take a simple example, the technology that enables frequency agility that can create harmful and hard to locate transient interference can also be used by the victim of that interference to evade it by moving to another channel or even another band.

More broadly, the falling cost and increased performance of digital signal processing, the increasing capacity and falling cost of computer memory, and the development of increasingly powerful mathematical algorithms have facilitated the expansion of sophisticated systems for interference detection, classification/identification, location, reporting, mitigation, and remediation. Such modern systems can significantly outperform the relatively unsophisticated, manually operated spectrum monitoring and direction-finding systems used in traditional interference resolution activities of the past.

For example, individual analog spectrum monitoring systems were severely limited in terms of (a) the amount of information on the radio frequency environment that they could collect, analyze in real-time, and store for later analysis and (b) their ability to share their information and analyses in a cooperative fashion with other, similar systems. Modern digital systems, on the other hand, are not only capable of collecting, displaying and storing signal amplitude information but phase (timing) information over wide-swaths of spectrum as well. That is, the monitoring systems (e.g., vector signal analyzers) are able to capture, analyze and store essentially all of the raw – i.e., I/Q[10] – information in an "RF spectrum snapshot" of the radio environment at a location[11] and the wider availability of broadband communications facilities allows the aggregation and analyses of spectrum monitoring data from multiple locations.

Furthermore, the reduced size, weight, primary power requirements and development costs (e.g., through the use of Software Defined Radio – SDR – techniques) of these advanced monitoring devices facilitate their being carried or mounted on various physical platforms ranging from satellites, to aircraft, to drones/UAVs, to fixed, high antenna tower sites, to low towers or poles, to ground based vans or other moving vehicles, to transportable packages that can be left at fixed location on a temporary basis, and to hand carried portable units. Each of these evolving platforms or form factors has a potential role to play in developing the next generation system architecture for interference resolution.

For instance, aircraft mounted monitoring equipment can be (and is being) used to detect multi-channel signal leakage from cable television systems – leakage that may cause interference to over-the-air commercial and governmental radio services. It can also be used to verify the coverage of terrestrial (e.g., commercial) mobile radio services and to monitor background noise level changes over broad geographic areas. Spectrum monitoring equipment mounted on drones

[10] I/Q [(I)nphase / (Q)uadrature] data shows both the changes in magnitude (or amplitude) and phase angle of a sine wave.

[11] The collected information could be for one entire band or for one channel within a band and it could be for one or more antenna directions/sectors and polarity (e.g., horizontal or vertical).

can be used for similar purposes over smaller areas and in reacting to specific interference incidents. There are already a number of "spectrum observatories" operating from high, fixed antenna sites in multiple locations that are useful for general spectrum occupancy studies as well as arrays of low antenna sites that are being distributed around critical installations such as governmental facilities or major transportation hubs to protect the perimeter against interference intrusion on critical frequencies. Ground-based vans and SUVs have traditionally been used for spectrum monitoring purposes by the FCC, NTIA and other government agencies such as the FAA (as well as commercial service providers for drive testing), while portable units with direction-finding capability have been the mainstay for locating an interference source once its general location is known.

The TAC White Paper entitled "Introduction to Interference Resolution, Enforcement and Radio Noise" referenced earlier noted that the rapid growth in "intelligent" end user devices with greater signal processing power, expanded memory capacity and online connectivity into the Internet raises the possibility of using crowdsourcing as a way of improving interference resolution activities. The FCC is currently using crowdsourcing techniques to gather anonymous data from the smartphones of thousands of volunteers in order to better assess broadband performance nationwide.[12] The FCC Speed Test, as the app is known, could be expanded on a voluntary basis to include utilizing smartphones or more specialized devices to detect, store and report information on suspected interference on a near real-time basis if needed. The information collected from end user devices could be combined with other information gathered by the end user's service provider from within the associated network (e.g., information on dropped calls or interrupted data connections) to detect, locate, report and assist in determining the cause of intruding or harmful interference.

More sophisticated spectrum monitoring platforms and equipment can be used in three other important ways as well:

First, as noted before, the dynamic nature of modern wireless systems, the normal variability associated with radio propagation conditions, and the increased mobility of end user devices results in interference being highly variable in terms of time, space and frequency. Accordingly, long term, manned monitoring is inefficient and significant improvements in efficiency and effectiveness can potentially be obtained by engaging in automated monitoring and remote reporting from locations and in frequency ranges that are of special interest because of interference concerns. By using the information from the automated systems, efficiency and effectiveness can be improved by dispatching interference resolution personnel only at times when more is known about the characteristics of the interference.

The same type of monitoring approach can also be used to establish a baseline knowledge of the signals present in a given area and band of interest under normal, uncongested conditions. The monitoring system(s) can then be used to more readily and automatically detect, classify/identify, locate and report on any intruders under abnormal conditions. Note that this information may not necessarily come from a separate standalone monitoring system. It could also come from a

[12] For a description of the FCC's Measuring Broadband America program see *Mobile Broadband America* [Online] Available: https://www.fcc.gov/general/measuring-broadband-america

spectrum analyzer connected to an application specific receiver actually handling live communications traffic from, for example, one sector of a commercial mobile radio system antenna.

Second, and related, measurements made by more sophisticated spectrum monitoring platforms and equipment can be used not only in their normal role of detecting intentional and unintentional interference, but also to provide feedback to the system causing the interference to allow it to automatically adjust its operation to mitigate the interference. In engineering terms, this changes interference management among users in a shared spectrum environment from an open loop system to a closed loop system. Operating on a closed loop basis would allow the stations to be operated closer to each other in terms of frequency separation, transmitting times and spatial separation.

Take the latter, spatial separation, as an example. Radio propagation conditions along a path from an interfering transmitter's output to a victim receiver's input can vary significantly, depending upon a host of factors, including changes in atmospheric conditions and in natural and manmade clutter[13] along the path between the two. In the VHF and UHF regions of the spectrum, certain atmospheric conditions can cause a propagation phenomenon called "ducting" that can result in abnormally strong signals at certain times of the year over certain paths. In some regions of the spectrum, signal strengths (and hence the resulting interference) will vary as crop conditions or the condition of deciduous trees along the radio path change with the season. With a closed loop system, when changes in conditions produce interference the system producing the interference could be instructed to reduce power, change its antenna characteristics, or take other measures to mitigate the interference. Such near-real-time changes could produce significant gains in spectrum efficiency in bands with cooperative sharing arrangements.[14]

Third, I/Q information collected from one or more different sources can be used for *ex post* forensic analysis to determine the root causes of a particular interference incident. This would work in a similar way to how flight data recorders or "black boxes" are used to give investigators clues to the causes of accidents associated with commercial aviation. The results of the forensic analyses could be used not only for de-confliction and remediation purposes but also for developing *ex ante* rules and regulations to reduce the occurrence of such interference incidents in the future. For example, if the harmonics from transmitters operating in a particular service regularly cause interference to systems operated in harmonically related spectrum, the rules regarding the radiation of such spurious emissions could be adjusted accordingly through a normal notice and comment rulemaking proceeding at the FCC.

The paragraphs above provide an introduction to how the falling cost and increased performance of digital signal processing, the increasing capacity and falling cost of computer memory, the development of increasingly powerful mathematical algorithms, and related developments have

[13] In addition to terrain, manmade structures, trees, large bushes and other vegetation (or, more generally land uses/land cover or "clutter") can cause radio signals to weaken significantly as they travel from one location to another. The associated, incremental loss in signal strength is referred to as "clutter loss."

[14] This would be particularly true in situations where the spacing is based upon an *a priori* worst-case analysis intended to reduce *ex post* risk of interference or to allow the entity producing the interference to make *ex* post modifications to its system without going through protracted negotiations or regulatory proceedings.

increased the availability or potential availability of sophisticated systems for detecting, classifying/identifying, locating, reporting, mitigating and remediating sources of interference. The purpose of this task is for the performer to conduct a more comprehensive and in-depth study of these emerging systems. The primary objective of the task is not to gauge the ultimate technical and operational value of any particular system or collection of systems, but, rather, how their existence might inform or guide the development of the next generation systems architecture for radio system interference resolution that is the ultimate objective of the entire study.

d. Identify Current and Evolving Radio Spectrum Interference Resolution Requirements

The next generation interference resolution system must be architected in a way that supports the functionality necessary on an *ex post* basis to prevent or mitigate the effects of harmful interference on wireless systems. There are at least four complicating factors that must be considered in developing the architecture:

First, the effects of harmful interference can range from endangering or disrupting critical navigation and timing systems such as GPS/GNNS over a wide area to affecting only a handful of commercial end user devices operating in a limited area. A further complicating factor is that the same functionality (say interference detection) that is critical to preventing and mitigating specific instances of harmful interference is also useful in discovering areas, frequencies and/or times where interference is approaching but has not exceeded harmful levels thus allowing preventative steps to be taken in advance of actual harm. Or, even lower in priority, the same functionality can be used to find and document underutilized spectrum that might be a candidate for reallocating or sharing.

Second, as alluded to before, certain geographic areas (e.g., transportation hubs) and/or services (e.g., GPS) may have specialized systems dedicated to detecting, classifying/identifying, locating and reporting encroaching interference. Choosing a balance between using specialized versus more general purpose interference resolution systems is a fundamental one from a systems engineering and architectural standpoint as is the extent to which the two interact in a cooperative fashion with each other to reduce costs or improve performance.

Third, in certain shared spectrum bands, spectrum is (or will likely be) managed by a Spectrum Access System (SAS) on essentially a real-time basis. The details of these SAS systems will vary depending upon the characteristics and requirements of the sharing services/systems in different bands. The point here is not to describe the details of these evolving systems but simply to note that the SAS systems may have available to them certain information (e.g., information gleaned from spectrum sensing) that may be useful to the more general purpose interference resolution system, and that the general purpose system may be able to help the more specialized system if the latter is impacted by interference from systems that are not under its control.

Fourth, there is a need to distinguish between interference data that are collected principally for routine occupancy, mitigation and de-confliction purposes, for example, and interference data that are intended to be used in formal remediation proceedings that may lead to legal sanctions such as fines, cease-and-desist orders, forfeitures, equipment seizures and even criminal prosecution. Clearly interference data collected in the pursuit of formal remediation proceedings must be handled even more scrupulously and issues such as data integrity, chain of custody, privacy, security and provenance must be addressed. Data integrity, in this context, refers to maintaining and assuring the accuracy and consistency of data between the time when it is collected until it is used in an administrative or court proceeding. It is essential to ensuring that the data presented at the proceeding have not been tampered with or corrupted.[15]

These four complicating factors suggest very different requirements for the next generation interference resolution system. The purpose of this task is for the performer to gain a more in-depth and comprehensive understanding of these requirements by finding and analyzing more detailed information about both the specialized and general purpose systems from the FCC, NTIA, and other agencies. This shall include understanding the underlying mission requirements and environments that are being addressed as well as identifying and analyzing the associated functional requirements and design constraints. Similar to the fourth task described in Subparagraph 4.c., above, the primary objective of the task is not to judge the appropriateness of these itemized requirements but, rather, to determine how their existence might inform or guide the development of the next generation systems architecture for interference resolution that is the ultimate objective of the entire study.

e. Identify, Analyze and Document Privacy Issues Associated with the Development of the Next Generation Systems Architecture for Radio Spectrum Interference Resolution

Section 4.c above described sophisticated new and improved systems and platforms for detecting, classifying/identifying, locating and reporting interfering signals. These developments promise vast improvements compared to the relatively unsophisticated, manually operated spectrum monitoring and direction-finding systems traditionally used for interference resolution purposes. However, proposals for the wider use of some of these more sophisticated systems and platforms may raise new privacy issues, the resolution of which may influence or constrain the development and deployment of these advanced solutions.

The traditional monitoring systems used for interference resolution were largely based upon spectrum analyzer technology that measured the received power versus frequency over a frequency range determined the capabilities of the instrument. While these scalar measurements were and are useful in characterizing some aspects of the desired and undesired (interfering) signals, scalar measurements of received power versus frequency are inadequate in terms of handling modern broadband signals which may be intermittent or “bursty” in character and which are likely to use complex modulation schemes and waveforms. By themselves, instruments using scalar measurement are unable to extract the information content from a received signal and thus provide a degree of privacy for the generators of the desired and undesired signals.

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[15] Information on interference incidents collected by private sector or non-governmental actors presents different issues than evidence collected by an entity like the FCC which is charged by federal statute with enforcement. Also, evidence collected by automated versus manual techniques may present special issues in terms of system requirements.

Given the increasingly wide variety of desired and undesired signals and unintended and incidental radiation that may be encountered in interference resolution activities today, increasingly sophisticated monitoring systems that include vector signal analyzers or real-time signal analyzers are evolving. These evolving systems can provide significant advantages in terms of detecting, classifying/identifying, locating and reporting on interference by being able to capture, store, and analyze on a real-time or forensic basis *all* of the raw (I/Q) information from a wide swath of spectrum in a given location and direction.[16] Coupled with modern SIGINT[17] capabilities, these increasingly sophisticated spectrum monitoring systems can be used to classify/identify interfering signals for interference resolution purposes but the same type of capabilities can also be used to provide the raw bit streams associated with the end user's voice, data, image or video traffic. This bit stream may include identifying information (e.g., the equivalent of call-letters) sent in the clear (or not), meta-data providing information on the content being carried including, perhaps, its source and destination, and the content itself which may or may not be encrypted.

Such techniques could be extremely valuable in terms of interference resolution by, for example, allowing the identification of the unique signature of particular interfering device or class of devices (say the power supply of a lamp fixture from a particular manufacturer) or, using the decoded meta-data, identification of the base station antenna sector from which interference is being received. But these potentially powerful benefits must be balanced against the possibility that, barring some form of constraints, the end user's voice, data, image or video content and sensitive meta-data associated with the content may be monitored and exposed. The implications of such a loss of privacy may be different depending upon whether the monitoring is being done by a private sector or public sector entity and whether the interference is merely a temporary annoyance at one extreme or intentional, malicious interference that presents an immediate threat to the safety of life and property and homeland security at the other extreme.[18]

The purpose of this task is for the performer to identify, analyze and document such privacy issues and the contexts in which they might arise. The objective of the task is not to make judgments about the proper balance between privacy and security, but, rather, to convey how privacy concerns might influence or constrain the development of the next generation systems architecture for interference resolution that is the objective of the entire study.

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[16] Up until recently, the amount of I/Q information that could be stored and electronically transported was severely constrained. This limited the real-time bandwidth that could be recorded and how long the recording lasted. These practical constraints reduced potential threats to privacy but the falling cost of digital storage and broadband digital transport have significantly reduced these restrictions. For example, it is now possible to collect hours of I/Q information with a real-time bandwidth of 100s of MHz over a frequency range into the tens of GHz.

[17] SIGINT (signals intelligence) is information gained by the collection and analysis of the electronic signals and communications of a particular target.

[18] For an overview of legal and ethical issues associated with the collection of real Internet traffic see W. John et al., "Passive Internet Measurement: Overview and Guidelines based on Experiences," *Computer Comm.*, vol. 33, no. 5, pp. 533–550, Mar. 2010. (link to full text). For a focused article on the legal aspects of spectrum monitoring see P. Ohm et al., "Legal Issues Surrounding Monitoring During Network Research," *ICM '07 Proc. 7th ACM SIGCOMM Conf. on Internet Measurement*, San Diego, Calif., 2007, pp. 141–148.

f. <u>Identify, Analyze and Document Potential Cybersecurity Issues Associated with the Development of the Next Generation Systems Architecture for Radio Spectrum Interference Resolution</u>

The changes envisioned in moving from today's system for interference resolution to the next generation version that takes into account the profound changes in the RF environment described earlier will inevitably lead to increased (or at least significantly changed) exposure of the system to cybersecurity threats and vulnerabilities.[19] Elements that might be included in the next generation interference resolution architecture are SAS systems, specialized and general purpose monitoring systems operated by various entities, and a host of others. Considering these elements and some recent interference/remediation issues, a number of threats can be easily postulated. For example, the FCC maintains more than 40 specialized, publicly accessible data-bases several of which are essential or at least useful in interference resolution. These include data-bases associated with licensing, radio call signs, equipment authorization and antenna structures.

Consider the first, licensing. If monitoring reveals a signal of interest in a band, a threshold question is whether or not the station is licensed or authorized to operate there. If the license data-base is compromised, a response to a query by the operator of the monitoring equipment could indicate that the station is licensed or authorized to operate in the band when, in fact, it is not. A compromised call letter data-base could lead to similar results. In either licensed and unlicensed bands or services, interference may be produced by the operation of illegal, unapproved equipment or devices. This means that a field agent or other person investigating an interference incident may be misled if the equipment data-base has been compromised. Finally, the FCC's antenna structure registration data-base can be useful in locating potential sources of interference and gaining access to the antenna site if needed. A compromised data-base could impede this process. Similar threats are associated with data-bases (e.g., the Government Master File) operated by NTIA and individual federal agencies.

The purpose of this task is for the performer to (a) research and assess cybersecurity threats associated with the migration to the next generation systems architecture for interference resolution, (b) develop and document insights that will help guide and inform the development of the next generation systems architecture to be carried out in the next task, and (c) provide requirements on that architecture based upon the assessment and insights. In carrying out this task, the performer should take advantage of cyber risk management strategies work already done – or being done – in the communications area including the NIST's Cybersecurity Framework (ICF), the National Initiative for Cybersecurity Education (NICE), the FCC's Communications Security, Reliability and Interoperability Council (CSRIC), numerous activities of the Department of Homeland Security and more focused network security work being conducted by industry/academic groups such as the Wireless Innovation Forum.[20]

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[19] For a useful taxonomy of communications jamming techniques that are associated with the widespread availability of SDR technology, see M. Lichtman et al., "A Communications Jamming Taxonomy," *IEEE Security & Privacy*, vol. 14, no. 1, pp. 47–54, Feb. 2016.

[20] For a substantial amount of well vetted information that is directly relevant to this task, see FCC Task Force on Optimal PSAP [Public Safety Answering Point] Architecture, Working Group 1, *Cybersecurity and Next Gen Systems: Optimal Approach to Cybersecurity for PSAPs* [Online]. Available: https://transition.fcc.gov/pshs/911/TFOPA/TFOPA_WG1_Cybersec_Next-Gen_Systems-042915.pdf

g. <u>Develop the Next Generation Systems Architecture for Radio Spectrum Interference Resolution</u>

The purpose of this final task is for the performer to develop the Next Generation System Architecture for Radio Spectrum Interference Resolution building upon the insights and analyses contained in the six previous tasks (a. – f.). In the first phase of this task, the performer will develop a high-level conceptual architecture and framework within which detailed design can take place. Upon review and agreement of the governing body overseeing the accomplishment of the work, the performer will develop the more detailed architecture by identifying and specifying the major hardware and software components that will comprise the system, the functions to be performed by each of those components, the interfaces among these components, and the associated protocols that allow the components to communicate with one another using the interfaces.[21]

It should be recognized that the details of the architecture will vary depending upon a host of factors, many of which have been touched upon earlier. The architecture will depend upon whether the band and adjacent bands in question are statically or dynamically shared and with whom (federal only, federal and non-federal, or non-federal only), whether they are unlicensed or licensed/authorized, and what constitutes harmful interference for each of the involved services. Further, it should be recognized that, while sophisticated Spectrum Access Systems that rely upon geo-location data-bases and/or spectrum sensing hold great promise in terms of facilitating interference resolution, they are still largely in their development phases and mostly untested at scale. This means that many systems critical to the safety of life and property and to homeland defense will not have the potential protection of these systems for several years, and, in the interim, they still must be protected from harmful interference in the face of the challenges such as densification and intentional jamming of the types described in the report cited in Footnote 20. Thus it is essential that the performer in developing the next generation systems architecture for interference resolution take into account the protection of existing systems that are important to not only to the nation's social and economic well-being, but also to the safety of life and property and homeland defense.

5. Period of Performance

TBD

6. Deliverables

TBD

7. Cost and Resources

TBD

[21]For perhaps the best explanation of the ideas surrounding systems architecting, see M. W. Maier and E. Rechtin, *The Art of Systems Architecting,* 3rd ed. Boca Raton, FL: CRC Press, 2009.

Addressing Public Policy Goals in the Standards Setting Process:
The Case of 5G Wireless Standards

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Introduction

The wireless industry is undergoing a massive transformation in which today's 4G systems and emerging 5G systems[1] are evolving to meet both the exploding demand for ubiquitous broadband data in general and more specialized demands spread across numerous vertical markets. These specialized demands include Fixed Wireless Access Services, Commercial Wireless Mobile Voice and Data/Internet Access Services, Internet of Things (IoT) Services, and Broadband Public Safety (e.g., FirstNet) and Other Mission Critical Services. This massive transformation is accompanied by an equally significant movement by telecommunications operators to adopt virtualized and programmable networks based upon Software-Defined Networking (SDN), Network Function Virtualization (NFV) and Cloud Technologies.

These transformations include changes in network architectures. The <u>choice</u> of a particular architecture for a public network has implications that stretch far beyond its internal technical and economic performance. Such engineering design choices, for example, open versus closed architecture, and centralized versus decentralized computer networks, could facilitate or impede legislatively mandated or widely agreed upon public policy goals. In this paper, we will consider whether and how public policy goals are addressed in the international standards setting process. We will also examine whether and how the views of all interested stakeholders—industry, government, academia, and civil society—are represented at each stage of the standards development process.

1 For brevity, evolving 4G systems and emerging 5G systems will be collectively referred to as 4G+/5G systems.

I. Background

The emerging 4G+/5G systems are described in many fora, including in reports from Technological Advisory Council (TAC) Working Groups of the Federal Communications Commission (FCC), Commerce Spectrum Management Advisory Committee (CSMAC) Subcommittees of the National Telecommunications and Administration (NTIA) of the U.S. Department of Commerce, and in the many reports and other materials cited therein. Those descriptions will not be repeated or summarized here but, rather, it should be noted that they involve dramatic changes in the network architectures involved. That is, they involve changes in how the network is decomposed into hardware and software modules, the functions performed by each of these components, the interfaces among these components, and the associated protocols that allow the modules to communicate with one another using the interfaces.[2] These massive developments will guide the evolution of both fixed and mobile broadband networks for decades to come.

As described in the Introduction and immediately above, the technology transformation to 4G+/5G networks will have a dramatic impact on network architectures. It has long been recognized that choices of network architectures have important implications for public policy. Just as legal codes or regulations, market forces and social norms control or guide human behavior, so do network architectures. Hence, network architectures are an important component of both national and international policy. As philosopher Bruno Latour expressed it, shaping network architecture is "politics by another means" and, as Larry Lessig said so succinctly, "code is law."[3]

While systems engineers are well aware of the importance of network architectures in determining the technical and economic performance of a given network, the choice of a particular architecture for a public network also has implications that stretch far beyond its internal technical and economic performance.

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[2] *See, e.g.*, Federico Boccardi, Robert W. Heath, Angel Loranzo, Thomas L. Marzetta & Petar Popovski, *Five Disruptive Technology Directions for 5G*, 52 IEEE Comm. Mag., no. 2, Feb. 2014 at 74-80, *available at* http://ieeexplore.ieee.org/document/6736746/.

[3] Lawrence Lessig, *Code: Version 2.0*, at 1 (2nd ed. 2006).

For example, not only does the selection of an architecture have an impact on the overall cost/performance delivered to the public, it can also influence the ability of different firms to compete using the network and thereby significantly increase or decrease the pace of innovation. A case-in-point would be an architectural choice that might facilitate or impede the ability of a Mobile Virtual Network Operator (MVNO) to offer retail wireless communications using the wireless network infrastructure of a mobile network operator on a wholesale basis.

Thus, one of the most critical choices is picking how open or closed the architecture should be. Network designs based upon appropriate hardware- and software-based network elements (i.e., appropriate modularity), and upon open architecture principles and standardized (as opposed to proprietary) interfaces between and among network elements, can facilitate competition.[4] But they can also raise issues of, *inter alia*, diminished investment incentives, network security, and privacy.

Another critical design choice involves the computing functions that are carried out using the network.[5] Network computing functions can be carried out or, said another way, applications can be executed, on a decentralized or centralized basis. Decentralized functions use "peer-to-peer" connections.[6] Peer-to-peer computation employs distributed resources such as computer processing power, data storage and content, and network capacity (bandwidth) to perform the network computing function in a decentralized manner. In contrast, centralized network computing exists when the majority of the necessary functions are carried out at, or

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4 The advantages and disadvantages of open versus closed architectures have been explored in numerous policy and regulatory proceedings and in academic and other scholarly papers. Those advantages and disadvantages are widely understood and will not be explored in detail here. *See, e.g.*, Ashish Shah, Douglas C. Sicker, Dale N. Hatfield, *Thinking About Openness in the Telecommunications Policy Context*, Paper Presented at The Thirty-First Telecommunications Policy Research Conference 13 (Sept. 20, 2003), *available at* https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2060641.

5 The generic term for this type of design is network computing. Network computing is defined as the use of computers and other devices in a linked network (e.g., the Internet), rather than as unconnected, stand-alone devices. Network Computing, TECHNOPEDIA.COM, https://www.techopedia.com/definition/23619/network-computing.

6 Peer-to-peer computation is "a communications model in which each party has the same capabilities and either party can initiate a communications session." Peer-to-peer systems distribute computational tasks over multiple clients. *Peer-to-Peer Technology,* NEWTON'S TELECOM DICTIONARY (25th ed. 2009).

obtained from, a remote centralized location. A major distinction between a decentralized and centralized network computing function is that, in the latter case, there is a mandatory centralized point or node through which all the data on the network must access or pass.

A simple example of a decentralized network computing function is a basic push-to-talk connection between two end user devices.[7] In this simple case, the end users' devices could establish the connection on a peer-to-peer basis using their respective addresses. No centralized coordination would be required. A simple example of a centralized network computing function is the retrieval of content such as music from a centrally located data storage device in the classic client – server model. In this case, the mandatory centralized point which distinguishes the centralized computing function is the server because all data on the network must access it. As in the case of picking how open or closed the architecture should be, the advantages and disadvantages of a centralized versus decentralized network and computer architectures will not be explored in detail here. For present purposes, however, it merits emphasis that such peer-to-peer connections are critical for public safety wireless communications, which rely on such connections in emergency response scenarios.

II. Reasons for the Proposition to Be Addressed

A. *Standards Setting Organizations*

In the case of 4G+/5G systems, the design choices elaborated upon above are being made or influenced by a vast range of technical standards setting organizations (SSOs) broadly defined. For our purposes here, this vast array of entities can be organized into three categories:

- Traditional telco-oriented Standards Development Organizations (SDOs) like ITU-R, BBF, and ETSI etc.
- Traditional Internet-oriented SDOs like the IETF and W3C, etc.
- Less traditional Open Source Projects/Consortia like Open Compute Project (OCP), OpenStack, OpenDaylight, Open Network Operating

[7] Push-to-talk communications systems require the user to "press a button to talk and stop pushing the button to listen. . . . Push to talk is used in two-way radio dispatch systems . . . ," including those used by first responders. *Push-to-Talk*, NEWTON'S TELECOM DICTIONARY (25th ed. 2009).

System (ONOS), OpenSwitch, and Central Office Reimaged as a Data Center (CORD), etc.

4G+/5G standards are being defined by the 3rd Generation Partnership Project (3GPP) which unites seven telecommunications standards development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC) and produces reports and specifications that define 3GPP technologies.[8] It is anticipated that the final specifications developed by 3GPP will be submitted to the ITU's International Mobile Telecommunication (IMT) system process for standardization in the 2020 time frame.[9]

It may be useful to distinguish between SSOs that are organized by governments themselves, like the traditional telco-oriented standards setting organizations (e.g., the European Telecommunications Standards Institute (ETSI)), versus entities in which governments play no special role, like the traditional Internet SSOs (e.g., the Internet Engineering Task Force (IETF)) and Open Source Projects/Consortia (e.g., Apache Software Foundation). Each type of organization has different origins, focus, procedures, governance structures, traditions, and cultures. Stakeholders desiring an architectural change to support a particular capability may need to choose from among the three categories of technical standards organizations described. For certain stakeholders, going through the traditional SDOs may provide more certainty, wider acceptability, and a better cultural fit. However, pursuing this route may result in a longer time-to-market and greater rigidity as stakeholders may struggle to tailor the results of the standards development process to a product rollout in a particular national market.

In competitive markets, time-to-market and agility in terms of changing offerings are often critical to success. Stakeholders with greater knowledge and resources may hedge their bets by participating in both formal SDOs and private

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[8] *See* 3GPP: THE MOBILE BROADBAND STANDARD, http://www.3gpp.org (last visited Apr. 5, 2017) (the seven standards development organizations are: Association of Radio Industries and Businesses (ARIB), the Alliance for Telecommunications Industry Solutions (ATIS), China Communications Standards Association (CCSA), European Telecommunications Standards Institute (ETSI), Telecommunications Standards Development Society, India (TSDSI), Telecommunications Technology Association (TTA), Telecommunication Technology Committee (TTC)).

[9] *See generally* ITU TOWARDS "IMT FOR 2020 AND BEYOND", http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx (last visited Apr. 7, 2017).

voluntary SSOs. In this case, private, voluntary SSOs act as gap fillers between the time of a market need and when the formal standard is actually adopted.

Another complicating factor, produced by the convergence of network architectures and service offerings, is already occurring and will doubtlessly accelerate with the evolution of 4G and the emergence of 5G. Convergence increases the number of stakeholders seeking to influence the critical design choices to their benefit and thereby significantly increases the complexity of the relationships between and among them. For example, a service provider offering less advanced telemetry and SCADA services on other platforms and in different frequency ranges or an end user consuming such services today may desire to influence 4G+/5G critical design choices associated with the provision of IoT services.[10] That desire would be prompted by the existing provider or end user being interested in utilizing the 4G+/5G platform rather than less advanced, existing platforms and services.

Not only is there a vast range of technical SSOs, each with their own origins, focus, procedures, governance structures, traditions, and cultures, making critical engineering design choices regarding future network architectures, the associated stakeholder groups -- industry, government, academia and civil society -- have different and often conflicting incentives guiding their participation in those fora as well as varying abilities to influence the choices being made. One result of these differences is that stakeholders are often put in the position of having to choose between what is best for them and what is best for the system as a whole. For example, while corporations may want to be viewed as good corporate citizens, as an end in itself or to court favorable treatment in later regulatory or policymaking proceedings, their directors and officers owe fiduciary duties to their stockholders. These duties create incentives for the directors and officers to support SSO decisions that may give their corporation a market advantage (perhaps by increasing the value of their own intellectual property), and further, to oppose choices that may increase their costs without offsetting compensation.

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[10] Supervisory Control and Data Acquisition (SCADA) systems are "used extensively by power, water, gas, and other utility companies to monitor and manage distribution facilities." *SCADA Protocol*, NEWTON'S TELECOM DICTIONARY (25th ed. 2009). SCADA systems often allow for the collection of telemetry information or "status information on a remote process, function or device." *Telemetry*, NEWTON'S TELECOM DICTIONARY (25th ed. 2009). Internet of Things (IoT) is a "computing concept that describes the idea of everyday physical objects being connected to the internet and being able to identify themselves to other devices." *Internet of Things (IoT)*, TECHNOPEDIA.COM, https://www.techopedia.com/definition/23619/network-computing.

Consequently, there can be no assurance that the resulting choices are optimum in terms of technical and economic performance or the achievement of important public interest goals. David Burstein, a respected editor of an industry newsletter named DSL Prime, recently asserted that even though SSOs, like 3GPP, attract brilliant engineers to define their standards, these groups "have to deliver what the most powerful companies want," while "Africa, Latin America, and the *public interest* are largely ignored."[11] (*Emphasis Added).*

B. Public Policy Goals

In its deliberations leading up to its recommendations to the FCC in 2015, the TAC, via its Future Game Changing Technologies (FGCT) Working Group, identified the following ten examples of legislatively mandated or widely agreed upon public policy goals in the U.S. context:

1. Next Generation 9-1-1
2. Disability Access
3. Next Generation Enforcement
4. Lawful Intercept
5. Network Security
6. Public Safety/Mission Critical Services
7. Outage/Performance Reporting
8. Intellectual Property Protection (DRM)
9. Privacy
10. Transparency and Openness

In identifying these public policy goals, the FGCT Working Group noted that many of them would be affected by programmable networks and what they referred to as 4G+/5G internationally established architectures, standards and specifications.[12] These public policy goals mostly result from the observation that, in economic terms, their production exhibit positive externalities. A positive externality is said to exist if the production and consumption of a good or service benefits a third party not

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11 Dave Burstein, *CTO Blanco: LTE Can Replace Much "5G." Time to Slow Down*, 5G WIRELESS NEWS, May 6, 2017, http://fastnet.news/index.php/88-sp/306-latest-issue.
12 Presentation Slides for September 20, 2016 Meeting of the Federal Communications Commission Technology Advisory Committee at 89, https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting92016/TAC-Presentations9-20-16.pdf.

directly involved in the market transaction. With a positive externality, private returns are less than the social returns from the transaction. So, for example, producers of IoT devices or services may make them less secure to lower their own costs and thereby inadvertently impose economic risks on society as a whole by making the overall network less robust from a cyber security standpoint. Or, said the other way, a producer of IoT products or services will offer less robustness than is socially desirable because some of the benefits of a more secure product or service may largely accrue to others. Similarly, a service provider may be reluctant to facilitate lawful intercept ("wiretapping") by absorbing additional costs when the assumed benefits would accrue to others.

C. Civil Society Groups

Civil society groups (e.g., public interest groups) that (a) operate outside the government and for-profit sectors of the economy and (b) pursue goals that, if achieved, provide benefits to the public at large, might normally be counted on to advocate for architectures, standards, or specifications that would facilitate the achievement of public policy goals through regulatory or other forms of intervention such as public-private partnerships. However, civil society groups may be limited or precluded from doing so by a host of factors:

First, because of the sheer number of government and private sector organizations that are involved in developing architectures, standards, and specifications for 4G+/5G systems, or at least attempting to influence them (e.g., 5G Americas[13]) or other closely associated policy/regulatory issues (e.g., spectrum availability), it is effectively impossible for a civil society group to determine where, in an organizational sense, all the design choices are being made that could facilitate or impede the achievement of important public policy goals.

Second, even if a civil society group is able to identify which organizations are involved in developing architectures, standards, and specifications for 4G+/5G

[13] According to its website, 5G Americas is an industry trade organization composed of leading telecommunications service providers and manufacturers. The organization's mission is to advocate for and foster the advancement and full capabilities of LTE wireless technologies and their evolution to 5G, throughout the ecosystem's networks, services, applications and connected devices in the Americas. *See* 5G AMERICAS, http://www.5gamericas.org (last visited Apr. 6, 2017).

systems or that are attempting to influence them, they may not be able to participate in their deliberations because of governance issues. That is, a civil society group may not be eligible for membership in, say, an industry-led trade or private SSO.[14]

Third, in the case that the civil society group is able to identify key organizations and is eligible for at least some form of membership in them, the cost of participating in terms of membership fees and/or the cost of participating in long, in-person meetings in foreign locations may make participation impractical from a financial standpoint.[15] Although growing broadband accessibility has facilitated more interactive remote participation options, the inherent technical complexity of the subject matter and associated deliberations may still present a challenge to civil society groups who do not have the financial resources to properly staff multiple in-person meetings with qualified technical experts. Civil society groups may also face constraints in terms of developing very specialized talent (whether engineers, lawyers, economists or otherwise) who have expertise in, for example, spectrum policy and disability access and have the connections to and trust of the organization (authenticity).

Fourth, participation by civil society groups in organizations that are involved in developing architectures, standards, and specifications for 4G+/5G systems may be constrained by the lack of transparency at each of three stages of the standards development process; namely, proposal for the standardization activity, technical work on the standard's design, and approval of the draft standard.[16] Obviously, if a

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14 *See infra* Appendix A.

15 See Adrian Scrase, Draft Summary Minutes, Decisions and Actions from 3GPP PCG Meeting#36, 3GPP (Apr. 28, 2016), http://www.3gpp.org/DynaReport/TDocExMtg--PCG-37--32036.htm (follow the second hyperlink labeled PCG37_02 and see sections 3GPP Support and 3GPP Working Hours on pages 3-5). Additionally, a sample of 2017 3GPP meetings and their locations highlights the extensive resources required for in-person representation: June—3GPPSA2#122 in San Jose Del Cabo, Mexico; May—3GPPCT1#104 in Zhangjiajie, China; 3GPPSA6#17 in Prague, Czech Republic; 3GPPSA1#78 in Porto, Portugal; April—3GPPPCG#38 in West Palm Beach, United States; 3GPPSA4#93 in Busan, South Korea; 3GPPRAN5-TTCN Workshop#37 in Sophia Antipolis, France; 3GPPCT4#77 in Spokane, United States; March—3GPPSA#75 in Dubrovnik, Croatia. ETSI Calendar of Meetings, 3GPP (last visited Apr. 7, 2017), https://portal.etsi.org/webapp/meetingcalendar/.

16 *See* Olia Kanevskaia, *Technology Standard-Setting Under the Lens of Global Administrative Law: Accountability, Participation and Transparency of Standard-Setting Organizations*, Tilburg Law and Economics Center (TILEC) Discussion Paper No. 2016-016, at 13-19 (2016) (describing the three stages of standards development as proposal for standardization, technical work on the standard's design, and approval of the draft standard).

civil society group does not get adequate and timely notice and appropriate supporting information at each of these three stages, the effectiveness of their participation will be significantly reduced.[17]

One may argue that, in the case of 3GPP, any concerns of civil society groups or the general public could be considered when public input is sought at the final stage of the process, namely, when the 3GPP draft recommendations move to the formal approval stage at the ITU. But, as a practical matter, the possibility of negotiating a change to the recommended standard to accommodate civil society group concerns after years of deliberation is problematic at best. Moreover, the openness and transparency of the ITU's final standards adoption process has sometimes been called into question because it may limit participation by individuals and civil society groups including public interest groups.[18]

As discussed above, civil society groups face significant financial and technical challenges in trying to advocate architectures, standards, and specifications that would facilitate the achievement of public policy goals like the ten identified by the FGCT Working Group of the FCC's TAC. It is instructive to note that one of those public policy goals, ensuring that the architectures, standards, and specifications for 4G+/5G are responsive to the specialized needs of Public Safety/Mission Critical Service providers, is being supported in the U.S. by the Public Safety Communications Research Program (PSCR).[19] The PSCR, notably,

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17 Transparency in terms of (a) the pros and cons of the design choices being made and (b) the processes leading up to those choices (e.g., in terms of the pros and cons of alternative design choices considered), builds trust in the outcomes among stakeholders and is likely to lead to wider acceptance of the choices when they are adopted. It also increases the legitimacy of the standards setting organization involved. Joe Waz & Phil Weiser, *Internet Governance: The Role of Multistakeholder Organizations,* 10 J. ON TELECOMM. & HIGH TECH. L. 331, 343-344 (2012); *see also* Phil Weiser, *Entrepreneurial Administration,* U. OF. COLO. L. LEGAL STUD. Research Paper No. 16-11 (2017).

18 *See* Grant Gross, *Groups Say ITU's Transparency Efforts Aren't Enough*, PCWorld from IDG (Jul. 16, 2016, 1:47 PM PT), http://www.pcworld.com/article/259337/groups_say_itus_transparency_efforts_arent_enough.html; *see also* Olia Kanevskaia, *Technology Standard-Setting Under the Lens of Global Administrative Law: Accountability, Participation and Transparency of Standards-Setting Organizations,* Tilburg Law and Economics Center (TILEC) Discussion Paper No. 2016-016, (2016).

19 The Public Safety Communications Research Program (PSCR) is a joint effort between the National Institute of Science and Technology (NIST) and the National Telecommunication and Information Administration (NTIA) both of which are units of the U.S. Department of Commerce.

has the financial and technical resources to focus on a particular public policy goal whereas, with respect to other public policy goals (say, accessible for people with disabilities), no such group may exist.[20] Consider, for example, that the public safety community is fortunate and appreciative to have PSRC representing their interests before standards bodies, with one leader noting that the PSRC staff "…has traveled the world over going to 3GPP meetings and going from a point where we thought public safety was going to be and we'd never get anything done. Three or four years later, we're right at the top."[21]

Civil society and even governmental groups (e.g., from smaller countries) that desire to advocate architectures, standards, and specifications that would facilitate the achievement of other public policy goals in the list, say disability access or privacy, may also fear being "buried under a whole bunch of commercial concerns."[22] Unlike PSRC though, they may lack the financial wherewithal, technical resources and the necessary status to participate not only in 3GPP and subsequent ITU proceedings, but also in the myriad of other related Internet-oriented and Open Source SSO activities. Without their participation, the gap between the

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Much of the PSCR's efforts are focused upon FirstNet. FirstNet is an independent authority within the NTIA that holds the spectrum licenses for a "much-needed nationwide interoperable broadband network that will help police, firefighters, . . . and other public safety officials stay safe and do their jobs. . . . [FirstNet] is charged with taking all actions necessary to build, deploy and operate the network." PUBLIC SAFETY, https://www.ntia.doc.gov/category/public-safety (last visited April 9, 2017).

[20] In addition to having the necessary financial and technical resources to participate in SSO activities, PSCR, as a component of a recognized national standards organization (NIST), does not face potential membership issues like those faced by public interest groups and individuals.

[21] Note that Tetra and Critical Communications Association (TCCA) of the UK is a Market Representation Partner (rather than a Member Organization) of 3GGP. Like the PSCR, TCCA is also concerned with ensuring that 3GPP meets the unique needs of public safety/mission critical service providers. *See The TCCA*, TCCA, https://tandcca.com/tetra/the-tcca/ (last visited April 9, 2017); *Partners*, 3GPP, http://www.3gpp.org/about-3gpp/partners (last visited April 9, 2017); Kevin McGinnis, *Remarks at FirstNet Technology Committee Meeting* (Jun. 2, 2014), *available at* http://www.firstnet.gov/content/board-meeting-june-2014 (follow "Technology Committee - June 2014 (MP4, 86 MB)" hyperlink; *see also* NIST, PUBLIC SAFETY BROADBAND REQUIREMENTS AND STANDARDS PROJECT DESCRIPTION, https://www.nist.gov/programs-projects/public-safety-broadband-requirements-and-standards-project-description.

[22] Kevin McGinnis, *Remarks at FirstNet Technology Committee Meeting* (Jun. 2, 2014), available *at* http://www.firstnet.gov/content/board-meeting-june-2014 (follow "Technology Committee - June 2014 (MP4, 86 MB)" hyperlink; *see also* NIST, PUBLIC SAFETY BROADBAND REQUIREMENTS AND STANDARDS PROJECT DESCRIPTION, https://www.nist.gov/programs-projects/public-safety-broadband-requirements-and-standards-project-description.

social returns and private returns associated with other legally mandated or widely accepted public policy goals may not be closed.

Lastly, it should be realized that there are often important tradeoffs that must be made between the public policy goals in the list. An example would be the ease and scope of lawful intercept versus privacy considerations. Civil society and governmental groups may well disagree among themselves on what is the best tradeoff. But domestic U.S. proponents and opponents of a particular tradeoff both face the same problem – how can they influence the outcome of standards-making processes that are increasingly diverse and internationally driven?

D. Ability of Domestic Entities to Act Unilaterally

Finally, and even more important from a U.S. domestic perspective, technological and marketplace changes both within the Information Communications Technology (ICT) market itself and within the broader international business market for goods and services, have arguably reduced the ability of domestic entities to act unilaterally in the development of ICT standards and increased the technical and economic penalties for doing so. In the early days of cellular communications, the U.S. market for wireless communications was large enough and isolated from the international marketplace well enough to permit the U.S. (and North America) to go its own way to an extent that is not feasible today. This can be illustrated through four examples:

First, early generation cellular telephones were heavy, bulky and consumed lots of battery power. They were permanently mounted in vehicles or carried about in heavy bags ("bag phones"). There was little chance that an end user would take the wireless telephone itself outside the U.S. or North America and hence there was little need to create end user devices and supporting infrastructure that would allow international roaming. This is in sharp contrast to the situation today where end users expect to take their phone, tablet, or laptop computer to another country or region and have it perform as well as at home.

Second, while even in the early days it was important to be able to communicate across international borders, the interfaces and associated protocols were relatively simple because only voice, text and rudimentary data needed to be conveyed. As transnational and global companies with sophisticated voice, data, image, video and multimedia communications requirements grew, the need for seamless broadband interoperability grew with them. Using one standard in one country or region and a different one in another can increase costs (e.g., for interface adapters that are used to compensate for different physical and software standards) and penalize performance.

Third, in the early days of cellular communications, the North American market was large compared to the total, worldwide market. Today, this is no longer true. For example, in terms of Internet usage, while Internet penetration is still high in the North American market compared to Asia (88.1% versus 44.7% respectively), the absolute number of Internet users is vastly different (320M versus 1.9B respectively). Moreover, the lower penetration rate suggests that the potential for growth is greater in Asia than in the U.S./North American market.[23] While the U.S. market is obviously still desirable, it is not as important as it once was and, hence, again arguably, U.S. market requirements are comparatively less important internationally than they once were. This means that choosing a unique standard that would facilitate the achievement of U.S. legislatively mandated or widely agreed upon public policy goals may result in the loss of cost benefits associated with worldwide economies of scale and potentially exacerbate interoperability issues among countries or regions.

Fourth, in the early days of cellular communications, U.S. firms, Motorola and AT&T (including, at the time, AT&T's equipment designed by Bell Labs and manufactured by Western Electric), played a substantial role in the manufacturing of equipment but, over time, that business shifted to the Nordic firms Ericsson and Nokia. More recently, actual manufacturing has shifted again—this time away from Ericsson and Nokia/Alcatel-Lucent, and towards Chinese firms such as Huawei and ZTE.[24] Dave Burstein, cited earlier, recently said, "When I started DSL Prime, the U.S. was the dynamic world leader in telecom. We are now mostly an also-ran."[25] It could certainly be argued that the Nation's declining role in telecommunications

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23 INTERNET WORLD STATS, http://www.internetworldstats.com/stats.htm (*last visited* Apr. 7, 2017).

24 Justin Fox, *Huawei Conquers the World, Except the U.S.*, BLOOMBERG VIEW, July 26, 2016, https://www.bloomberg.com/view/articles/2016-07-26/huawei-conquers-the-world-except-the-u-s.

25 Dave Burstein, Editorial, FASTNET NEWS, February 18, 2017, http://fastnet.news/index.php/88-sp/306-latest-issue.

manufacturing further diminishes the ability of civil society groups to advocate through them in favor of architectures, standards, and specifications that would facilitate the achievement of public policy goals like those itemized above.[26]

III. Proposition to be Addressed

For the reasons expressed in Section II., the FCC, and other government agencies as appropriate, should, with the support of the new Administration and relevant Congressional Committees, reassess how they relate to SSOs.[27] *Specifically, the appropriate agencies should take steps to ensure that domestic legislatively mandated or widely agreed upon public policy goals are addressed in the international standards setting process and that the views of all interested stakeholders—industry, government, academia, and civil society—are represented at each stage of the standards development process.*[28]

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26 For example, ATIS represents a wide coalition of telecommunications and high tech companies. Most ATIS companies do not manufacture telecommunications equipment and merely purchase such equipment from international vendors outside the United States. ATIS Members, ATIS (last visited Apr. 13, 2017), https://www.atis.org/01_membership/members/. ATIS members have reduced incentives to push international standards organizations to incorporate nation-specific public interest features that raise the costs of deploying and maintaining telecommunications networks. Equipment manufacturers, faced with implementing international standards in actual products, are unlikely to adopt nation-specific tweaks unless the feature is a product requirement for deployment in certain markets.

27 OMB Circular A-119 explicitly provides for federal agency participation in SSOs including voluntary consensus bodies and notes that such participation "can be an important contribution to ensuring balance is achieved." *See* OMB Circular A-119, Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities, 27 (Jan. 27, 2017), https://www.nist.gov/sites/default/files/revised_circular_a-119_as_of_01-22-2016.pdf; *see also* Revision of OMB Circular No. A-119, Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities, 81 Fed. Reg. 4673 (Jan. 27, 2017), https://www.gpo.gov/fdsys/pkg/FR-2016-01-27/pdf/2016-01606.pdf.

28 *See* Presentation Slides for September 20, 2016 Meeting of the Federal Communications Commission Technology Advisory Committee at 91-94, https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting92016/TAC-Presentations9-20-16.pdf (recommending that the Commission "establish[] an 'excellence' program around future end-end networks & systems," "undertake an updated assessment of fundamental US societal needs, priorities for economic growth and organizational structure, informed by in-depth insight into industry impact of systemic SDN/NFV/Cloud technology-driven changes" and "establish and maintain a living '5G watch list' of priorities and essential needs for the US market,").

IV. Acknowledgements

In preparing this paper and arriving at the proposition to be addressed, the author benefited greatly from communications with many colleagues, especially those that also served as members of the FCC's Technological Advisory Council and those that are affiliated with the Silicon Flatirons Center for Law, Technology and Entrepreneurship at the University of Colorado at Boulder. For both editing and substantive help, the author is particularly indebted to two Research Assistants, Galen Marston Pospisil and Alexander Joseph Vetras, both students in the University of Colorado School of Law.

Appendix A: Membership Requirements for Standards Setting Organizations

The membership requirements for three categories of SSOs (traditional telco-led, internet related, and open source) shed light on the concern that civil society groups may not be able to participate in SSO deliberations because of governance requirements. First, representative of traditional telco-led SSOs, The Alliance for Telecommunications Industry Solutions (ATIS) requires their full-time members to pay a minimum of $5,000 in annual dues regardless of the member's revenue.[29] Once a member's combination of North American revenue and Non-North American revenue meets a certain threshold, these dues incrementally increase.[30] While only organizations with Full, or ATIS membership, must pay dues, not all organizations are eligible for Full Membership status.[31] ATIS lists several examples of organizations that only qualify for Affiliate Membership: "associations, educational institutions, and PSAPs [(public-safety answering points)]."[32] Although both Full Members and Affiliate Members can hold voting rights, the memberships come with major differences in eligibility for leadership positions. ATIS states: "Affiliate ATIS Member Company representatives…shall not serve as leaders of Forums" and additionally, they "shall not serve as leaders of Subtending Committees or Subcommittees."[33]

29 *See* ATIS Dues Calculator, ATIS (last visited Apr. 7, 2017), http://www.atis.org/DuesCalculator/CalcDues.aspx/.
30 *Id.*
31 Join ATIS, ATIS (last visited Apr. 7, 2017), http://www.atis.org/01_membership/becomemem.asp/.
32 *Id.*
33 Operating Procedures for ATIS Forums and Committees, ATIS, 2-3 (2015), http://www.atis.org/legal/Docs/OP/atisop.pdf.

In contrast, the IETF, an internet related SSO, explains that it has "no formal membership, no membership fee, and nothing to sign."[34] To participate, a newcomer just needs to join a mailing list. Because there is no formal membership for IETF, decisions are not made by voting, but rather by a "general consensus" from those people on a particular mailing list.[35] That being said, the IETF concedes that "[i]f you really want to get results, you probably need to attend some meetings. . . ."[36] And they add that "[t]his isn't free; apart from travel and hotel costs, there is a meeting fee."[37] Thus, while the IETF may be more accessible up front than ATIS, real influence again seems to come with a price tag. Further, the IETF must operate based on the vague idea of "general consensus," while ATIS's memberships allow for a definitive ballot system, albeit at the expense of a more organic, or at least more open, leadership selection process.

Third, the OpenDaylight Project (ODP), which serves as a representative of an open source SSO, sets forth a mix of the guidelines found in the structures of ATIS and the IETF. ODP has six classes of membership: "Platinum Members, Strategic End-User Members, Gold Members, Silver Members, Individual Committer Members, and Associate Members."[38] While there are no fee requirements to join ODP, its voting process is greatly influenced by paying members. For example, Platinum Members who have met all of their fee and membership obligations are given the power to appoint a director on ODP's board, and if they choose, they can also nominate their chosen director to be an officer of ODP.[39] Additionally, Platinum Members can appoint and maintain a representative on the Technical Steering Committee (TSC).[40] Without paying a fee, however, the only membership options available are the Individual Committer and the Associate Member. And of these two, only the Individual Committers can vote among themselves to elect a maximum of two directors to join the board.[41] ODP promises that "[t]he Board and the TSC will use common voting methodologies and ensure

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34 Getting Started in the IETF, The Internet Engineering Task Force (last visited Apr. 9, 2017), https://www.ietf.org/newcomers.html.
35 *Id.*
36 *Id.*
37 *Id.*
38 Open Daylight Bylaws, OpenDaylight (Jul. 23, 2014), https://www.opendaylight.org/bylaws.
39 *Id.*
40 *Id.*
41 *Id.*

no single vendor or group establishes a controlling number of votes on the Board."[42] Nonetheless, it seems clear that the automatic appointments of a Platinum member, as well as other privileges given to paying members, create barriers to any non-paying member who wishes to influence the ODP's ultimate design choices.

[42] *Id.*

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Optional Readings

1. FCC Technological Advisory Council, Spectrum and Receiver Performance Working Group, 2015, *Basic Principles for Assessing Compatibility of New Spectrum Allocations*.

2. Kanevskaia, O., 2016, *Technology Standard-Setting Under the Lens of Global Administrative Law: Accountability, Participation and Transparency of Standard-Setting Organizations*, Tilburg Law and Economics Center (TILEC) Discussion Paper No. 2016-016.

3. Koutroumpis, P. and Cave, M., 2017, *Auction Design and Auction Outcomes*.

4. Kruys, J., 2017, *Technology Agnostic Regulation for License Exempt Spectrum*.

5. Murphy, C. N. and Yates, J., 2015, *Afterword: The Globalizing Governance of International Communications: Market Creation and Voluntary Consensus Standard Setting*, Journal of Policy History, 27(3), pp. 550-558.

6. Naudts, B. et. al., *2016, Deploying SDN and NFV at the speed of innovation: toward a new bond between standards development organizations, industry fora, and open-source software projects*, IEEE Communications Magazine, 54(3), pp. 46-53.

7. NTIA, 2016, *Commerce Spectrum Management Advisory Committee (CSMAC)*, 5G Subcommittee, Final Report.

8. Riihijärvi, J., Mähönen, P., and de Vries, J. P., 2017, *Measurement Procedures for Design and Enforcement of Harm Claim Thresholds*, Proc. of IEEE DySPAN 2017, Baltimore, USA.

9. Tsilikas, H., 2016, *Collaborative Standardization and Disruptive Innovation: The Case of Wireless Telecommunication Standards*, Max Planck Institute for Innovation and Competition Research Paper No. 16-06.

10. Weiser, P., 2017, *Entrepreneurial Administration*, University of Colorado Law Legal Studies Research Paper No. 16-11.