Illuminating the Road from Engineering and Policy to Radio Regulation

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Abstract

The relationship between engineering practice and technology policy is a perennial question. In this paper, we examine it in the context of the spectrum regulation debate. There is a widely held belief that regulatory and policy decisions can be justified, and indeed quantified, based on hard engineering and science facts. Similarly it is often felt that regulatory and policy domain issues should not stifle innovation by dictating the course of technology development for broadband radio systems. In this paper we strongly argue against such views and contend that key policy decisions in communications must be connected to engineering in a more explicit and nuanced way. We hold that policy makers' belief in "technology neutral" regulation is an illusion; engineering results are often used by businesses and politicians to justify their actions and promote their interests, yet the engineering means to achieve social ends are usually far upstream from political outcomes, and their connection is tenuous. Conversely, wireless communications engineers typically focus on the network protocol stack, ignoring the broader socio-economical context of their work. We show that is useful to consider a more holistic framework for radio system design that includes not just the network protocol layers but also the regulatory and commercial aspects of the technology. Given the inevitable complexity of the decision space in spectrum regulation, we believe that *transparency* and taking a *systems view* are essential for supporting evidence-based decision making around wireless technology policy and spectrum regulation. We ground our work in a technical case study, considering the extent to which engineering results can (or cannot) be used to argue the benefits of unlicensed spectrum allocation in the TV white spaces. We critique the unsophisticated use of spectrum efficiency metrics by providing a framework that demonstrates the many ways in which metrics can be constructed and interpreted. We emphasize the importance of *N-dimensional engineering analysis* to properly reason about the complex technical design space of modern wireless systems, and of the *disclosure of financial interests* by expert interlocutors. We frame our analysis of the relationship between engineering and policy using a *technology circle* which generalizes the seven-layer OSI network protocol stack by adding Layer Zero, the regulatory rules that constrain what may be implemented at the networking layers, and Layer Eight, the business and social practices that are built on the network, and that inform regulatory decisions at Layer Zero. Finally, we advocate the use of a *fail-safe* design philosophy to inform engineering work and regulatory decisions. We believe that our recommendations would make the interaction between wireless engineering and radio regulation more effective, thus strengthening the spectrum regulation and policymaking process.

1. Introduction

Wireless communications technology has become crucial to ensuring economic growth and the welfare of modern society. Radio communication is heavily regulated yet its success is also heavily dependent on new technology. The interaction between spectrum regulation and wireless engineering research and development is thus critical. There is a widely held belief that regulatory and policy decisions can be justified, and indeed quantified, based on hard engineering and science facts. Similarly, it is often felt that regulatory and policy domain issues should not stifle innovation by dictating the course of technology development for broadband radio systems. In this paper we strongly argue against such views and contend that key policy decisions in radio regulation must be connected to wireless engineering in a more explicit and nuanced way.

The relationship between engineering and technology policy is a perennial question. In this paper we will examine the interaction between engineering practice and technology policy in the context of the spectrum regulation debate. Engineering results are often used by businesses and politicians to justify their actions and promote their interests, yet the engineering means to achieve social ends are usually far upstream from political outcomes, and their connection is tenuous. Conversely, wireless communications engineers typically focus on the network protocol stack, ignoring the broader socio-economical context of their work. In reality, there is a complex interplay between modern wireless technology, spectrum regulation, and the economic environment and social goals that ultimately inform policymaking. We thus believe that is important to consider a more holistic framework for radio system design that includes not just the network protocol layers but also the regulatory and commercial aspects of technology. Similarly, although it is well understood and accepted that engineering is an inevitable part of any regulation of technological artifacts, we believe that the way in which the engineering community and its approaches are integrated into the regulatory framework can be improved to better support evidence-based decision making around wireless technology policy and spectrum regulation.

In our view, the heart of the problem lies in the sheer complexity of modern engineering systems and the subsequent complexity and uncertainty of the decision space that spectrum regulators and policymakers are faced with. One cannot predict the results of changes in human institutions like regulation, or complex systems in general, with much if any accuracy. Yet, wireless technology advocates often make a habit of attempting to take lessons from overly simplified engineering models or narrative “success stories”. An apt example from the recent history of wireless technology is the definitive victory of the IEEE 802.11 Wi-Fi wireless networking standard over the competing HomeRF and European HIPERLAN standards; the eventual dominance of IEEE 802.11 was not initially due to its technical superiority, but instead depended on a host of regulatory, market, and business factors (including timing), and things could well have turned out rather differently [1, 2]. However, in retrospect the IEEE 802.11 standard has been held up as an inevitable success story, which the wireless community has been trying to replicate ever since via a proliferation of standards (e.g. IEEE 802.15.1 Bluetooth, IEEE 802.16 WiMAX), with mixed results. A similar story is the phenomenal success of the GSM system as a 2G cellular standard. As in the case of IEEE 802.11, many different factors contributed to the success of GSM, yet the cellular industry (particularly in Europe) has since been strongly pursuing this model of standardization as a proven formula towards wireless technology success [3, 4].

Some of the most recent standardization efforts in this vein are the IEEE 802.22 and the draft IEEE 802.11af standards for operating in unused portions of the TV bands. These standards are emerging as a result of great enthusiasm for using these TV white spaces (TVWS) for extended broadband connectivity, following recent regulatory decisions in the USA and UK allowing such secondary spectrum access [5, 6]. We will illustrate via a technical case study that the success of a Wi-Fi-like deployment in the TV bands is not quite the foregone conclusion assumed by some proponents. We will do so in the context of a more general critique of the unsophisticated use of spectrum efficiency metrics, by providing a framework that demonstrates the many ways in which metrics can be constructed and interpreted. Our case study will emphasize the danger of basing regulatory policy decisions on overly simplistic engineering metrics and analysis[1].

We thus believe that it is prudent to beware simplified success stories and "cargo cult" engineering and regulation. Achieving radio regulation outcomes which best serve the public interest requires a deeper understanding of the complex technical design space of wireless technology and its interaction with policy and commercial aspects. Given the complexity of policymaking, and the complicated technical considerations that need to inform regulation, we believe that transparency and taking a systems view are essential to success. This paper explores these recommendations in turn. Under the rubric of transparency, we discuss the importance of communicating the multi-dimensionality of the technical decision space, and of disclosing the financial interests of expert interlocutors. We provide two perspectives on a systems view of the problem: the use of an integrated view of policy, engineering, and business perspectives (the *technology circle*), and the use of a fail-safe design philosophy to inform both engineering and regulatory decisions.

2. Transparency Recommendation

We believe that the complexity of the decision space that spectrum regulators must deal with calls for an increased transparency in the engineering recommendations that inform such policymaking. In this section we elaborate our transparency recommendation by advocating (i) the use of N-dimensional analysis to more comprehensively represent the design space of modern wireless systems and (ii) disclosure of financial interests by technical experts. We believe that these measures to increase transparency can greatly help the regulator to make better use of engineering evidence submitted in favour of competing wireless technologies and proposed regulatory regimes.

A. N-Dimensional Design Space

There is a strong tendency in the wireless engineering community to characterize the efficiency of wireless networks and systems in terms of a single or very few quantitative parameters. The quintessential example is *spectral efficiency* measured in bits/s/Hz, which is consistently used in spectrum allocation debates and technology advocacy as an ultimate quantifier of the performance of a wireless system. However, any such figure is necessarily based on a plethora of assumptions (e.g. channel model, number of users, traffic load, average

[1] We emphasize that our intention is not specifically to prove or disprove the benefit of TVWS Wi-Fi, but to highlight the inevitable uncertainties and the need for a holistic analysis in engineering arguments put forward in spectrum regulation debates.

or maximum output parameter values, network model, medium access technique, etc.). Thus using such singular metrics *in isolation* is entirely inadequate to properly and fully characterize a wireless system[2].

This preference for presenting simplified quantitative arguments nonetheless seems to be particularly strong when engineers interact with policy makers and must argue about the merits of a given wireless technology in the context of spectrum regulation. Indeed, the legal, policy, and regulator community appear to have a similar fondness for such “authoritative” singular engineering metrics, since this kind of engineering input can give a strong impression of scientific impartiality and thus greatly ease the task of making and defending policy and regulatory decisions.

We believe that basing rational regulatory and policy decisions on overly simplistic engineering metrics and analysis is suboptimal at best, and dangerously misleading at worst. In reality, properly characterizing any complex technical system, which is also under regulatory and business constraints, is difficult and requires a multi-dimensional representation to fairly and fully show the relative strengths of competing solutions in the decision space. The engineering community cannot and should not be expected to provide “magic bullet” numbers to unequivocally justify policy and regulatory choices, since any single metric may be misleading in characterizing the efficiency of spectrum utilization.

Instead, we advocate explicitly considering and presenting analysis from the full ***N-dimensional design space*** of any candidate wireless technology when characterizing the efficiency of spectrum use, in order to systematically spell out the various design tradeoffs inherent in such complex systems. We believe that adoption of such an N-dimensional representation of wireless systems in the discourse between engineers and regulators will serve to greatly improve the transparency of engineering analysis and thus better support rational decision making by those involved in spectrum policy and regulation.

There are a number of fundamental *input* parameters comprising the N-dimensional metric design space of a wireless system, such as channel bandwidth (Hz), operating frequency (Hz), and transmit power (W), along with other important system parameters such as infrastructure cost ($). The metric nature of the space necessitates *quantifiable* inputs, so that it is possible to compute (analytically or via simulation) the *output* efficiency values characterizing the performance of the wireless system, such as throughput (bits/s), latency (s), or coverage (m or m^2). The various parameters could also be interdependent, making the N-dimensional space *non-linear*. A wireless system which spans a large volume of N-dimensional space can be deemed to be *flexible*, whereas physical, engineering, financial, or regulatory constraints might create *exclusion zones* in the parameter space.

We propose that regulators encourage N-dimensional analyses by explicitly requesting that technical filings provide them, and that regulators themselves provide them as a part of the technical justification of their decisions. In particular, we strongly urge technology advocates to resist building their case around the best-sounding singular metric (e.g. aggregate maximum theoretical physical layer throughput) and instead encourage them to put their preferred figures of merit in the context of the full N-dimensional design space as a means of

[2] This is in especially so if used outside the very simple case of characterizing the physical layer of a wireless link under some specific channel assumptions. Characterizing the overall efficiency of a wireless *network* is much more complex, and employing such singular metrics to do so essentially amounts to an abuse of what these metrics where originally designed to quantify at the physical layer.

increased transparency towards the regulator. By the same token, regulators should discount, though of course not ignore, submissions that do disregard the complexity of the subject matter.

Rather than hiding the complexity of modern wireless communication systems behind simplistic metrics, which necessarily presents a distorted picture, we believe engineers should find ways to better represent the true complexity of the technical systems under regulation, in a way which is nonetheless useful and manageable for non-engineers working in spectrum regulation and policy. The first step is to move away from presenting technical arguments in terms of single metrics, towards presenting plots of two-dimensional slices out of the full N-dimensional space. The second step is to move towards the adoption of real-time visualization tools that give the regulator access to the N-dimensional engineering analysis. Such visualization tools would enable both engineers and non-engineers involved in policy and regulation to play with the dynamics of the system and thereby come to a better understanding of the overall design space of the technology under consideration[3].

Although the N-dimensional metric space is a rather straightforward concept, we believe that its importance has not been emphasized enough in the engineering community, perhaps partly owing to its perceived obviousness. An exemplary paper making use of N-dimensional efficiency analysis is the study of various system aspects of LTE in [7]; unfortunately such analyses are rather rare, both in the research literature and in particular in technical arguments put forward in the context of spectrum allocation debates and regulation.

Another likely reason why N-dimensional analysis is not explicitly embraced is the “keep-it-simple” ethos that looms large in many engineering communities. Namely, there exists a culture within engineering which insists that problems should be strictly quantifiable with a small number of numeric parameters. While it is natural and often necessary to employ simplifying models and assumptions in order to proceed with a lot of engineering analysis, it is easy to forget that any single metric is only an abstraction which leaves out a lot of detail in order to provide a useful thumbnail of the studied system. Indeed, as Einstein famously put it, “*everything should be as simple as possible, but not simpler*”. Consequently, a too firmly entrenched “keep-it-simple” attitude becomes incompatible with and resistant to the idea that thorough reasoning about complex techno-economical systems inevitably requires complex analysis, which in turn requires N-dimensional arguments about technical efficiency.

In order to illustrate the concept of N-dimensional design space for wireless systems and demonstrate its importance in conducting a thorough engineering analysis, we present a technical case study of a network of Wi-Fi-like access points (APs) operating in different frequency bands. Recent regulatory rulings by the FCC in the USA and Ofcom in the UK [5, 6] that have allowed secondary access to unused portions of TV spectrum have been met with great enthusiasm for using these TV white spaces (TVWS) for extended Wi-Fi-like connectivity, popularly known as “Wi-Fi on steroids” or “super Wi-Fi” [8, 9]. We demonstrate the importance of N-dimensional wireless system analysis in the context of this ongoing secondary spectrum access debate, by comparing the benefit of TVWS access against Wi-Fi operating in the existing 2.4 GHz ISM and 5 GHz unlicensed bands. Our case study illustrates the danger of basing policy decisions on overly simplistic engineering metrics and analysis. We also emphasize that it is possible to support contrary conclusions

[3] We emphasize that what we envision here are tools that go beyond simple “graphical user interfaces” and afford the user the flexibility of varying different system parameters in order to answer “what if” questions; one could thus even characterize such tools as lightweight simulators.

simply by picking appropriate “sympathetic” cuts through the N-dimensional design space, in a way that showcases the most favourable aspects of the championed technology. It is for this reason that we strongly advocate presenting the whole N-dimensional argument, especially in spectrum policy and regulation debates, as a means of improving the transparency of engineering analysis and providing a more complete and accurate picture of the complex engineering systems under discussion.

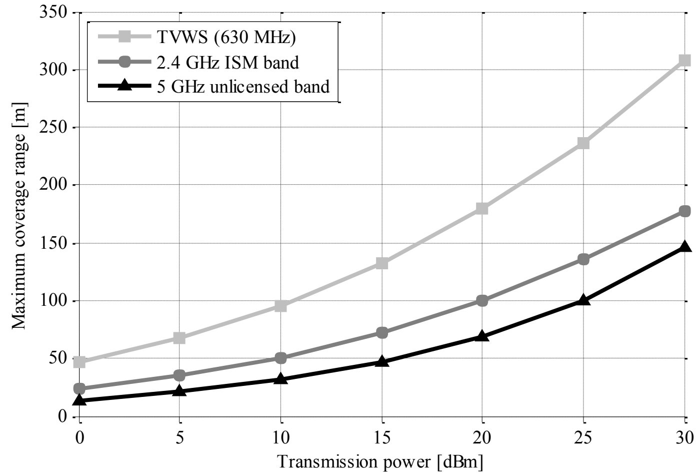
In Figs. 1-3 we show several different two-dimensional slices out of the N-dimensional metric design space of a Wi-Fi-like network of APs operating using the CSMA/CA medium access protocol in different frequency bands (i.e. IEEE 802.11g operating in the 2.4 GHz ISM band, IEEE 802.11a operating in the 5 GHz unlicensed band, and Wi-Fi-like devices operating in TVWS, with the centre frequency of 630 MHz, as planned in the draft IEEE 802.11af standard [10]). Our results were obtained via simulation, for two application scenarios: outdoor urban hotspot deployment and indoor urban use (*cf.* Table I). We assume that the APs employ an auto-rate function, which maps received SINR at the associated user terminal to the raw bit rate provided by the AP (e.g. from 6 to 54 Mbps for IEEE 802.11a/g); the auto-rate function is a piecewise constant function defined by the minimum receiver sensitivity and physical layer spectral efficiency specifications in the IEEE 802.11 standard [11]. We assume each AP in the network randomly selects one of a number of available channels to operate on. As summarized in Table II, in the 2.4 GHz ISM frequency band there are three non-overlapping 20 MHz channels, whereas in the unlicensed 5 GHz band there are nineteen and fifteen 20 MHz channels available for indoor and outdoor use, respectively (in Europe) [11]. In the TV bands, we assume aggregation of three adjacent 8 MHz channels to enable operation on a channel of comparable width (24 MHz). It is well known that the exact amount of TVWS spectrum available for secondary operation varies depending on the geographic location; as one realistic and rather typical example, we use TVWS availability estimates for the German city of Aachen, where four 24 MHz channel chunks are predicted to exist [12, 13]. We take into account the effects of interference and congestion among co-channel APs via the model adopted in [13] which estimates an AP’s downlink throughput as the raw bit rate divided by the number of APs sharing the common contention domain. Further details of the system model used in our analysis may be found in [13], along with extended comments on the benefit of both urban and rural deployments of Wi-Fi in TVWS.

Table I. Wi-Fi system model parameters.

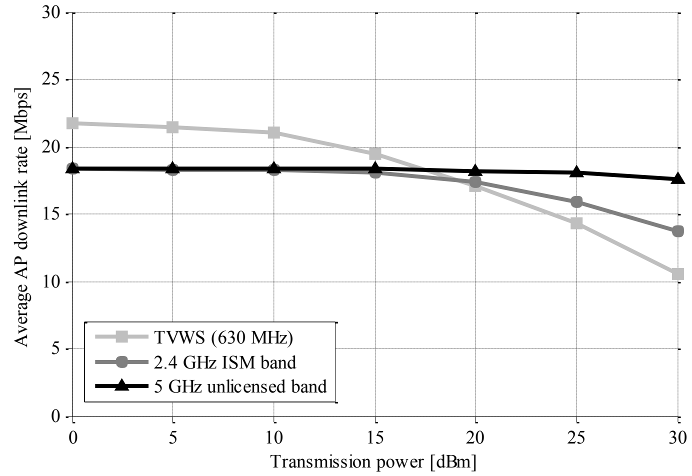
Deployment scenario	**Outdoor urban**	**Indoor urban**
Propagation characteristics (log-distance path loss model)	path loss exponent, $k = 3$	path loss exponent, $k = 4$ and 18 dB wall loss
Density of Poisson point process generating random AP locations	λ =12.5 APs/km^2	λ =125 APs/km^2
Network study area	(2 km x 2 km) in central Aachen	(500 m x 500m) in central Aachen

Table II. Characteristics of different frequency bands for Wi-Fi operation.

Frequency band	**2.4 GHz ISM**	**5 GHz unlicensed**	**TVWS**
Centre frequency	2.4 GHz	5 GHz	630 MHz
Width of AP operating channel	20 MHz	20 MHz	24 MHz (aggregation of three adjacent 8 MHz TV channels)
Number of non-overlapping operating channels available in band	3	19 (indoor) 15 (outdoor)	4 (typical example TVWS availability from Aachen urban study area)



(a)



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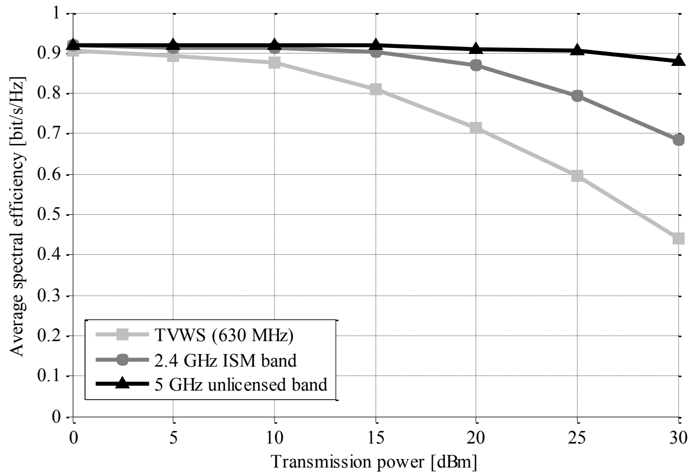
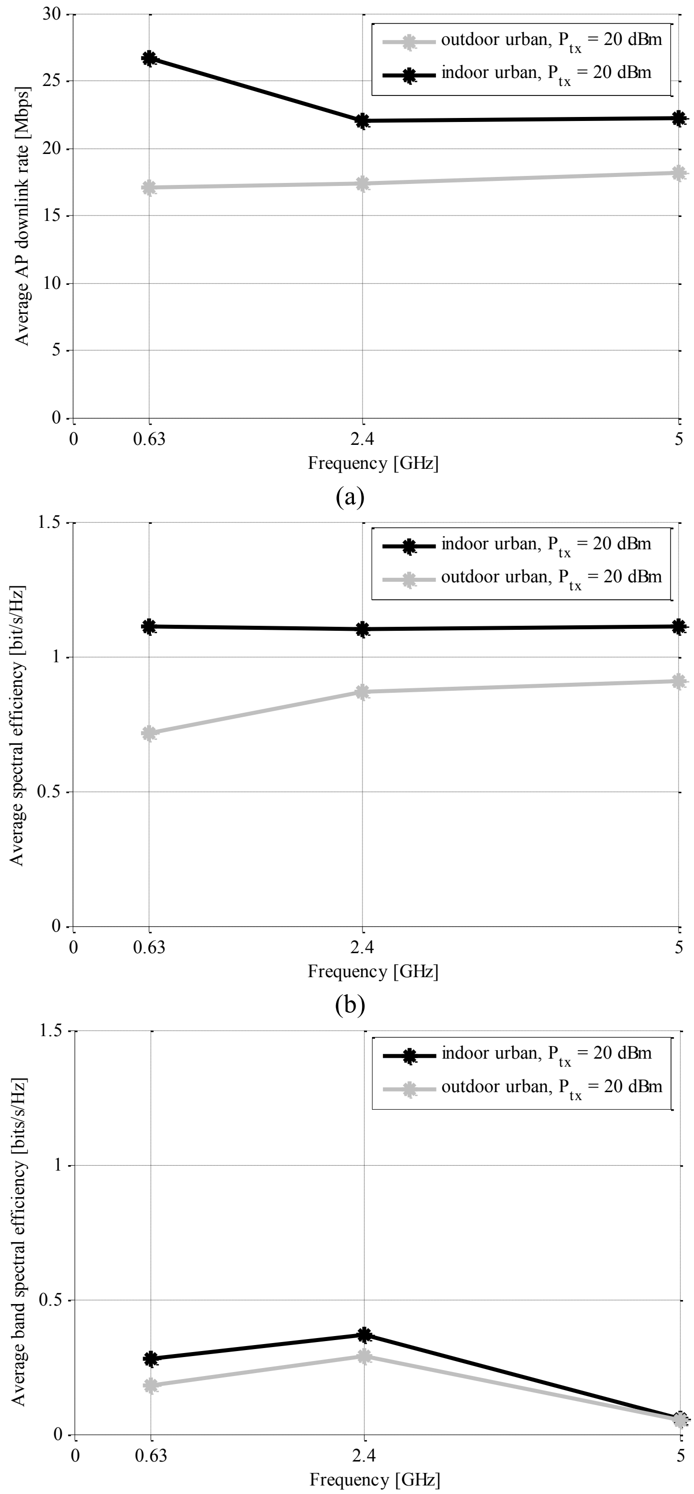


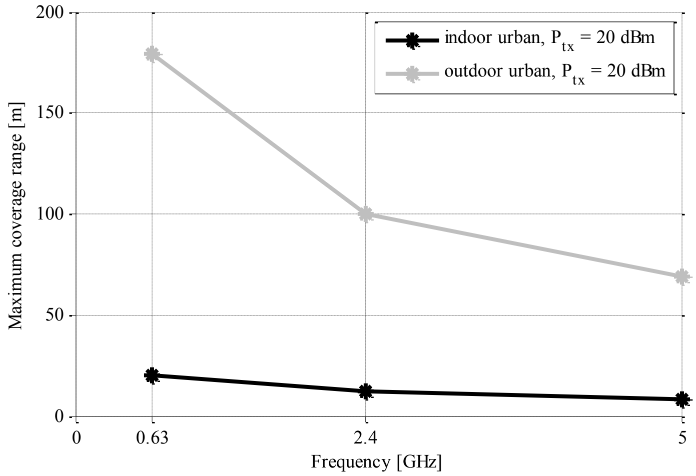
(c)

Figure 1. Slices out of the N-dimensional space analysis of a Wi-Fi-like wireless network operating in different frequency bands for the outdoor urban scenario, showing the effect of varying the AP transmission power on: (a) maximum (cell-edge) AP coverage range, (b) average AP downlink rate (for a single user, averaged over the coverage area of the AP), and (c) average spectral efficiency (average AP downlink rate normalized by the width of the channel occupied by the AP).



(c)

Figure 2. Slices out of the N-dimensional space analysis of a Wi-Fi-like wireless network operating in the outdoor and indoor urban scenarios, showing the effect of varying the centre operating frequency on: (a) average AP downlink rate (for a single user, averaged over the coverage area of the AP), (b) average spectral efficiency (average AP downlink rate normalized by the width of the channel occupied by the AP), and (b) average band spectral efficiency (average AP downlink rate normalized by the width of the frequency band used by the network).



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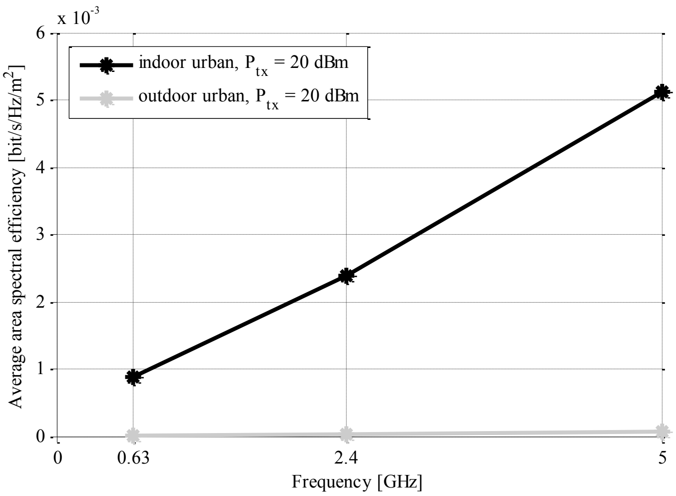

(b)

Figure 3. Slices out of the N-dimensional space analysis of a Wi-Fi-like wireless network operating in the outdoor urban and indoor urban scenarios, showing the effect of varying the centre operating frequency on: (a) maximum (cell-edge) AP coverage range and (b) average area spectral efficiency (average AP downlink rate normalized by the width of the channel occupied by the AP and the size of the AP's coverage area).

Let us consider Fig. 1, which shows plots of several output efficiency metrics as the AP transmission power, P_{tx}, is varied for a Wi-Fi network operating in the outdoor urban scenario. Fig. 1(a) demonstrates that for a given power budget, the coverage range of the wireless system increases as the operating frequency is decreased, in accordance with the better wireless propagation properties of lower frequencies. The results in Fig. 1(a) thus support the claims by advocates of "super Wi-Fi" and "Wi-Fi on steroids" of achieving a greatly increased range when operating in TVWS compared to the existing unlicensed bands (e.g. for P_{tx} = 20 dBm, 1.8 and 2.6 times higher compared to 2.4 GHz and 5GHz, respectively). However, the results in Fig. 1(b) show that this increased range at a lower operating frequency comes at the cost of substantially decreased AP throughput. The Wi-Fi network exhibits this tradeoff due to its contention-based medium access technique, whereby the extended AP range in TVWS leads to a larger number of overlapping AP contention domains, which in turn significantly degrades performance due to congestion.

These results illustrate the danger of basing policy decisions on overly simplistic engineering analysis and singular metrics. Following the FCC's 2010 ruling allowing unlicensed secondary access to unused portions of TV spectrum, FCC Chairman Julius Genachowski released the statement: "*We know what the first major application [of TVWS spectrum] will be: super Wi-Fi. Super Wi-Fi is what it sounds like: Wi-Fi, but with longer range, faster speeds, and more reliable connections*" [9]. It would appear that this claim of "super Wi-Fi" by early advocates of uncoordinated access to TVWS was a result of a very simplistic calculation of range at the lower TV frequencies, without taking into account that this also increases the interference radius, which lowers throughput due to congestion, especially if a CSMA/CA type of medium access is employed. The proponents of a "plug-and-play" Wi-Fi-like system in TVWS thus presented an unrealistically optimistic case in support of the FCC's regulatory decision to open up the UHF frequencies for unlicensed secondary use. This is a clear example of the danger of employing a singular metric and overly simplistic engineering analysis to construct misleadingly attractive arguments in a spectrum regulation debate.

Similarly, we note that by considering Fig. 1(b) in isolation, one could still claim that operating Wi-Fi in TVWS does indeed result in "*faster speeds*" compared to existing Wi-Fi, if the transmit power is under 20 dBm (i.e. up to 1.2 times higher throughput in TVWS compared to the 2.4 and 5 GHz bands). Of course, this higher throughput is simply the result of a 20% wider AP operating channel assumed for the TVWS analysis (24 vs. 20 MHz). This is clearly represented in Fig. 1(c), where the average AP rate is normalized by the channel width to give a measure of average spectral efficiency; thus for the analyzed deployment scenario of relatively dense outdoor urban AP deployment, existing Wi-Fi consistently outperforms operation in TVWS in terms of effective spectral efficiency. Thus by judicious choice of metric, one can show either TVWS "beating" the higher bands at 15 dBm transmit power in terms of average AP downlink rate in Fig. 1(b), or "losing" in terms of average spectral efficiency in Fig. 1(c).

This distinction between Figs. 1(b) and (c) might seem obvious and even trivial. On the contrary, we believe that it serves as a very good example of just how easy it is to obscure important system information, intentionally or not, when presenting an argument in favour of a given wireless technology by using only a select few engineering metrics. It is thus imperative to carefully consider the full N-dimensional design space when comparing candidate wireless systems, as a means of gaining insight into the true dynamics of these complex technical systems and reaching well-informed conclusions about the relative benefits of an advocated technology. While the exact elements in the set of applicable design parameters may well be debatable in any given case, an engineering submission should include *all* those that its authors think apply.

Fig. 2 further demonstrates how our interpretation of the relative efficiency of a wireless system can change depending on which projection we select from its N-dimensional design space. Fig. 2 shows, for two different deployment environments (indoor and outdoor urban), the effect of varying the operating frequency of the Wi-Fi network on three closely related efficiency metrics: average downlink rate in Fig. 2(a), average spectral efficiency in Fig. 2(b), and average *band* spectral efficiency[4] in Fig. 2(c). Firstly, comparing the shape of the curves for indoor and outdoor deployments in Fig. 2 demonstrates just how very scenario and environment dependent our conclusions about the efficiency of a wireless system are. This underlines just how essential it is that the use case scenarios underlying engineering analysis

[4] Namely, this metric would attempt to quantify the spectral efficiency of the entire frequency band, by dividing the average downlink rate achieved by the width of the frequency band the network operates on (e.g. for the 2.4 GHz ISM band, 60 MHz (3 x 20 MHz), as shown in Table 2).

are carefully detailed and disclosed in spectrum policy and regulation arguments, and fully represented via N-dimensional engineering analysis.

Secondly, it is readily evident from the different shapes of the corresponding performance curves in each subfigure of Fig. 2 that we would reach completely different conclusions about the best frequency band to operate in depending on our choice of metric. For example, for the outdoor urban scenario, Figs. 2(a) and (b) indicate that the 5 GHz band is the best to operate in, whereas Fig. 2(c) indicates that it is the least spectrally efficient band. Similarly, for the indoor urban scenario, Fig. 2(a) shows that TVWS outperforms the 2.4 GHz band, whereas the results in Fig 2(c) indicate the opposite, and Fig. 2(b) shows the two bands to be equivalent. This clearly illustrates how using slightly different engineering metrics can lead to divergent conclusions. This naturally prompts the question of which spectrum efficiency metric is the "right" one. Indeed, a recent draft white paper by the FCC Technical Advisory Council alone lists over 25 different spectrum efficiency metrics [14]. Our emphatic answer is that there is *no right singular metric* which can provide a complete characterization of the system, precisely because each axis in the N-dimensional space provides only a partial view of the system as a whole. Given the complexity of N-dimensional design space, it is possible to calculate "hard engineering numbers" in support of virtually any desired conclusion or advocated technology. For the sake of transparency, we advocate instead presenting the full N-dimensional analysis to aid properly reasoned decision making in spectrum policy and regulation[5].

In this vein, we also emphasize the inadequacy of "fractional" spectrum efficiency metrics to robustly capture the multidimensionality of the metric design space of wireless systems. Comparing Fig. 3(b) with Fig. 2(b) shows what happens when we replace the bit/s/Hz spectral efficiency metric with the bit/s/Hz/m^2 *area* spectral efficiency metric. For example, for the indoor urban scenario, operating at the highest frequency band of 5 GHz now appears to be markedly more efficient than the lower bands (*cf.* Fig. 2(b) which shows no significant difference between the bands). The underlying reason for this new view of the system is revealed in Fig. 3(a), namely that lower operating frequencies are associated with a higher AP coverage range and consequently a lower per-area spectral efficiency. This example underlines that even fractional spectrum efficiency metrics cannot replace a proper N-dimensional analysis of the wireless system.

In fact, we believe that such an approach is fundamentally misguided, as attempting to condense information from multiple dimensions into singular measures inevitably leads to dimensional reduction. Sometimes such a "compressive mapping" from a higher to a lower dimensional space keeps the essential picture of the system intact, but in other cases distortions are created, as illustrated by Fig. 3(b). Importantly, dimension reduction is a one-way operation: once we have cut out some of the information, we can no longer reproduce the multidimensional view using the fractional efficiency metric only. In other words, fractional spectrum efficiency metrics are also not the magic bullet for compactly quantifying the efficiency of wireless systems that the engineering and regulator community might wish for. From the point of view of regulation and business analysis, this means that at the very least one has to insist on knowing the premises based on which the "compression" was done. In

[5] One should also note that implementation issues are a part of the N-dimensional space. Although many design and efficiency parameters can be evaluated analytically or via simulation without taking into account implementation challenges or imperfections, this is not always true. Often one also has to consider actual selection of implementation methods, which can lead to different results and particularly highly different system costs, thus greatly affecting conclusions regarding the feasibility of a candidate technology.

fact, we believe that in certain regulatory and policy debates we ought to require that the analysis and premises themselves be disclosed (i.e. mathematical analysis); the outcome of the engineering analysis alone, as represented by a few suitably chosen numbers along with some advocacy statements is simply not transparent enough.

B. Disclosure of Interests

The decision space spectrum regulators have to grapple with is very complex, not least because of the multi-dimensionality of the technical design space of wireless technology which is discussed above. We have proposed the use of N-dimensional technical analysis as a means of more fully representing the design tradeoffs inherent in modern wireless systems, and thus better supporting rational decision-making in spectrum regulation. To further increase the transparency and usefulness of engineering analysis that informs spectrum regulation, we also advocate that engineering recommendations for spectrum policy should be accompanied by a disclosure of financial interests. We believe that this would help the regulator to better judge the credibility of evidence supplied by proponents and to assign relative importance to various technical arguments in favour of competing solutions in the complex decision space.

Those filing engineering petitions in the context of spectrum regulation should always disclose their sources of financial support. This is in fact in line with well-established principles of engineering ethics, as expressed in the second article of the IEEE Code of Ethics: "*avoid real or perceived conflicts of interests whenever possible, and … disclose them to affected parties when do they exist*" [15]. We believe that this recommendation, although accepted in theory, is very often ignored in practice in the process of adversarial rulemaking in spectrum regulation. We emphasize however, that we advocate it here not as a matter of engineering ethics *per se*, but instead as a matter of increased transparency in spectrum regulation, which will lead to regulation outcomes which better serve the public good.

There are a variety of options for putting our disclosure of interests recommendation into force, including explicit regulatory requirements and self-imposed professional norms. The regulator could require that anyone who files a submission also disclose who is funding their work. This could be limited to filings of fact, such as the engineering analysis itself lending support to advocacy for a candidate wireless technology or spectrum allocation regime. We note that there are clear precedents for such a procedure in other domains under regulation, such as the financial disclosure regulations of the FDA (Food and Drug Administration) in the USA. The FDA has instituted a process requiring disclosure of financial interests in order to alert its staff to potential bias in submitted evidence and reliability of clinical data [16]. We believe that spectrum regulation bodies could also benefit from such an approach. Spectrum regulators would ensure that the financial interests of investigators that could affect the reliability of engineering data submitted are identified and disclosed by the applicant. This would in turn minimize the risk of bias in the considered engineering evidence and help the regulator to make well-reasoned and objective decisions which best serve the public interest.

We note, however, that instituting such a requirement by the regulator would likely necessitate a long and involved legislative process. An alternative option would be for the engineering profession to enact this recommendation via self-imposed professional norms and standards of best practice. As discussed above, such guidelines already exist on paper [15], and explicitly apply the requirement of avoidance of conflict of interest to not only "real" but also “perceived” conflicts. However, the IEEE code of ethics does not provide any guidance on what is to be done after disclosure or what professional consequences would follow a failure to properly disclose a conflict of interests [17]. Interestingly, a similar issue recently emerged among economists in the wake of revelations that there is a grave lack of disclosure of affiliations and financial interests when writing academic papers and providing congressional testimony on financial regulatory reform [18]. In January 2011 a group of 300 economists signed a letter urging the American Economics Association (AEA) to adopt a code of ethics; none of the members of the AEA ethics committee were among the signatories, and the panel subsequently formed to collect input on a code of ethics from the 18,000 AEA members, chaired by Nobel prize-winning economist Robert Solow, received only a dozen responses [19]. We urge the wireless engineering community to resist similar apathy and instead truly understand and embrace the importance of strengthening their professional rules of conduct. We believe such an effort would greatly benefit the transparency and effectiveness of the spectrum regulation process.

We believe that any company filing a petition to the spectrum regulator should explicitly state whether they have a financial interest in the outcome of that petition; however such financial interests are arguably already clear in many cases (e.g. filings by a cellular operator or equipment vendor). We in particular emphasize the responsibility to disclose financial interests for those advising the regulator as independent experts, such as engineering researchers or institutes submitting expert opinion in the role of *amicus curiae*. Indeed, as the complexity of the engineering questions in spectrum regulation is high, there is good reason to encourage the research community to become more involved in independently filing engineering opinions to the regulator. This would require a change in perspective of the academic community, where such activity is not normally considered as a particularly important part of academic service. Engineering professional and academic societies, such as the IEEE, could help instigate this change of attitude by creating programs through which engineers can provide *pro bono* service to regulators as independent consultants. We believe that this would increase the transparency of argumentation and advocacy in spectrum regulation debates by strengthening the objectivity of arguments put forward in favour of various candidate wireless technologies and spectrum allocation regimes[6].

3. Systems View Recommendation

There exists a complex interplay between modern wireless technology, spectrum regulation, and the economic environment and social goals that ultimately inform policymaking. We believe that this calls for engineers and regulators to adopt a true *systems view* of these complex systems and interactions in order to deal with, evaluate, and properly argue about new wireless technologies and proposed regulatory regimes. In this section we elaborate our systems view recommendation by proposing a framework for articulating the relationship between engineering and policy (via the *technology circle*) and by advocating the use of *fail-safe* principles in the development of engineering recommendations and spectrum regulation.

[6] We also note that regulators and policy makers should be aware of the different mechanisms that are in place in the engineering community that can sometimes limit the comprehensiveness of engineers’ advice. A good example is that, due to patent infringement laws, several companies limit (even forbid) their research engineers studying patent documents and filings. Although this is done as a means of limiting legal exposure, it naturally also generates some bias on the state-of-the-art knowledge.

A. Technology Circle

We have discussed the inevitable technical complexity of modern wireless technologies, which calls for the use of N-dimensional design space to properly represent these engineering systems. Aside from the many quantitative parameters that characterize wireless systems, there are a lot of further arguments that influence candidate technologies, but are difficult, if not impossible, to quantify. Namely, the N-dimensional technical design space is only a subset of the overall multi-dimensional *decision space* within which spectrum policy and regulation are constructed, which is comprised of *both quantitative and qualitative considerations*. The N-dimensional design space is well-suited to representing the quantitative aspects of the overall techno-economical system under regulation, but it cannot incorporate any additional qualitative arguments related to social, business, economical, environmental, and political concerns which have a strong bearing on technology development and regulation.

For example, spectrum policy debates often involve arguments regarding "innovation" and "competition", such as the often-stated claim that unlicensed technologies foster innovation. Some proponents of this view attempt to quantify it using the metric of revenues generated [20]. However, aside from this being an unreliable and incomplete measure of the impact of spectrum allocation on "innovation", such a metric would be a poor argument for unlicensed, as the revenues from licensed cellular communications are enormous. We believe that such arguments are instead a part of the *qualitative* evidence in the decision space, and as such it is fundamentally misguided to attempt to quantify them and incorporate them into an overall mathematical optimization; clearly judging their importance and credibility simply belongs to the domain of policy debate.

Wireless communications engineers typically focus on network protocol stack, ignoring the broader socio-economical context of their work. We believe that it is useful to consider a more holistic framework for radio system design that includes not just the network protocol layers but also the regulatory and commercial aspects of the technology. We thus propose the *technology circle* (Fig. 4) as a means of explicitly articulating this relationship between engineering and policy. Our technology circle generalizes the seven-layer OSI network protocol stack by adding Layer Zero, the regulatory rules[7] that constrain what may be implemented at the networking layers, and Layer Eight, the business and social practices that are built on the network, and that inform regulatory decisions at Layer Zero.

Examples of engineering parameters that are directly affected by choices at Layer Zero include: maximum transmit power limits, access control rules, licensed vs. unlicensed spectrum allocation, and paired vs. unpaired spectrum allocation (FDD vs. TDD architecture). Business models and social practices at Layer 8 in turn affect choices at Layer Zero as well as the network stack itself. One example of such influence of Layer Eight factors on technology

[7] We note that Layer Zero could also be defined more broadly as any kind of regulation that sets constraints on the engineering systems that operate within it (e.g. privacy regulation affecting what is allowed at the application layer 7), where we would alternatively draw the technology circle with Layer Zero being at the centre of the circle, touching all the other layers.

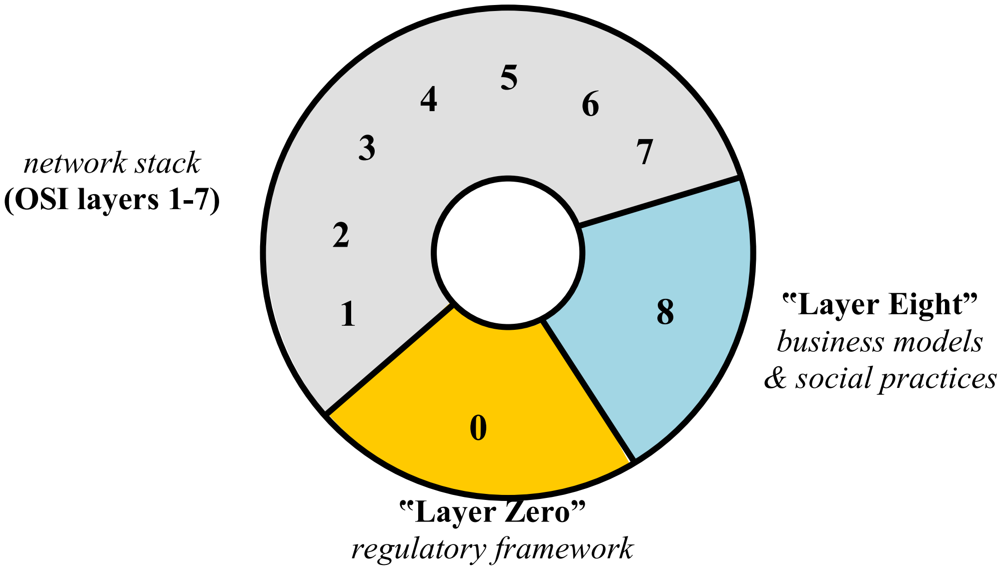

Figure 3. From a network stack to a technology circle: stakeholders must explicitly consider the mutual influence of wireless technology, the spectrum regulatory framework, and the commercial and societal setting.

development is evident in the contrast between the open standards culture of the IETF Internet engineering community and the hierarchical, treaty-driven process favoured by the ITU and governments.

Therefore, there is no such thing as purely technology-neutral regulation, or policy-independent technology. In the course of spectrum regulation debates it is crucial to holistically consider not only the technical aspects of wireless technology but also the many further inevitable non-engineering factors of influence, such as regulation, politics, and the business and social environment. It is this mutual dependence between engineering and policy that our technology circle emphasizes, as a means of providing a more holistic framework for telecommunications technology development and encouraging a systems view in spectrum regulation and policymaking.

In order to holistically consider this techno-economical decision space of spectrum regulation, it is important to adopt a thoughtful and transparent approach of incorporating both quantitative and qualitative evidence into policymaking and spectrum debates. In line with our earlier transparency recommendations, we believe that this at the very least requires resisting the urge to quantify all arguments and collapse the entire decision space into simplistic "magic bullet" numbers (which would then be used to justify policy decisions while hiding away a complex web of arguments and considerations underlying the decision, some technical, others economical or political).

Beyond urging both engineers and regulators to be aware of the mixed nature of the decision space, we recognize that a systematic decision-making framework for synthesizing qualitative and quantitative considerations may be of benefit in spectrum regulation and policymaking. To the best of our knowledge no such recommendations exist yet in the field of technology policy and it is outside the scope of this paper to propose any such comprehensive framework. Instead, we urge those involved in spectrum regulation to investigate the use of qualitative and quantitative methods in other fields and see how and where similar techniques might be useful in technology policymaking. For example, some work has recently emerged on systematically reviewing qualitative and quantitative evidence to inform policymaking in healthcare, as well as on combining such mixed research methods in medicine [21, 22].

In general, it is difficult for engineers to connect social and economic goals to engineering solutions. This is unsurprising given engineering work is inherently upstream from political outcomes, and their connection is tenuous. However, engineering is also rather underequipped and unprepared for dealing with non-quantitative problems in general. Indeed, the father of deductive logic Aristotle also separately laid down the rules of rhetoric as a way of reasoning about non-quantitative evidence. We believe that this is an area that requires more development in the context of technology regulation. There are examples of other disciplines to which engineers can look to, which have thought coherently about how to systematically incorporate qualitative arguments into their complex decision spaces and decision-making processes, such as the fields of economics and design [23, 24]. We believe that there is a great deal yet to be learned about developing more sophisticated ways of combining qualitative and quantitative arguments in spectrum policy.

To enable a holistic view of wireless technology and regulation, we also strongly believe that it is imperative for spectrum regulatory agencies to have access to systems knowledge across the entire technology circle. In spectrum policy, lawyers and RF engineers currently dominate in regulatory advisory roles. The traditional expertise of those advising policy makers and regulators must be broadened in order to achieve a true systems view of the spectrum policy decision space. To this end, *systems engineers* should be recruited to comment on spectrum regulation issues beyond pure RF engineering and the physical layer, such as the overall efficiency of wireless networks given different media access techniques, coordinated vs. uncoordinated network access, and centralized vs. distributed network control. The same holds for business people (e.g. management consultants) who can bring expertise in decision-making that integrates technical and commercial considerations.

We recommend that regulatory bodies should have independent staff as a means of providing such a systems view and thus strengthening the spectrum rulemaking process. There are different ways to provide such capabilities. For example, in the case of technical staff, regulators could have a substantial in-house engineering division, hire independent experts as consultants, team up with engineering research institutions, or have rotating engineering positions such as the CTO position at the FCC. Undoubtedly, a different combination of these tools is likely to be most effective in different regulatory environments. Regional regulatory agencies are best equipped to develop the right framework – the important issue is that such a framework is adopted and that the need for it is well understood.

Finally, we emphasize that it is imperative for the regulator to have both technical and non-technical staff who are savvy on the interactions between all the different layers of the technology circle. It is not sufficient, as has largely been common practice thus far, for engineers to simply feed numbers from commissioned technical analysis to lawyers and economists, who then get on with the big-picture task of making regulatory rules. We note however that this does not necessarily require individuals whose expertise covers the entire technology circle in full detail. The desired systems view can also be achieved using a team of experts in the separate areas, provided that: (i) there is enough overlap between their expertise so that they can make sense of each other's thinking and (ii) there are process, institutions, and incentives which actively foster such interdisciplinary work.

B. Fail-Safe Engineering & Regulation

We have recommended the use of an N-dimensional representation to more fully characterize the technical design space of modern wireless systems. We have furthermore proposed the technology circle as a framework for articulating and reasoning about the many further inevitable dependencies of wireless technologies on non-engineering factors such as politics, regulation, and the business and social environment. Given this immense complexity of wireless engineering, spectrum regulation, and in particular their intersection, we acknowledge that it is impossible to know the exact outcome and effect of any given spectrum policy, except in hindsight. In fact, we believe that the aim in spectrum regulation should not be to find the perfect policy, but instead to aim for policies that can quickly reveal themselves to be flawed and can be changed if they are. The best response to a complex, uncertain, and ever-changing situation is to accept it and aim at *resilience* rather than efficiency. Any diagnosis and prescription should always be provisional and made with the knowledge that it might have to be changed. In this sense, policymaking is an eternal experiment [25]. We therefore propose that both engineers and regulators should apply *fail-safe* principles to their recommendations for spectrum policy and regulation. Engineers should strive to make technical recommendations that lead to regulatory decisions that can be easily revisited and corrected, whereas regulators should develop effective methods of carrying out such reassessments and readjusting their decisions accordingly.

We start by recognizing that complex situations and problems have multiple correct answers. A recent example in spectrum regulation is the different set of rules adopted by the FCC in the USA and Ofcom in the UK for allowing secondary access to TVWS. In short, the FCC has regulated fixed limits on the permitted secondary transmit power and allows secondary device operation outside an exclusion zone which is a fixed distance away from the primary protection contour. In contrast, Ofcom has opted to define a fixed amount of harmful interference to the primary system and then calculate the allowed secondary transmit power, which can take any value, at different locations accordingly. In time we might find that one of these two distinct engineering solutions to enabling TVWS exploitation is superior to the other, or that neither of them provide a sufficient regulatory basis for making TVWS spectrum access a success.

Importantly, just because a given regulatory decision or engineering recommendation did not achieve its aims in hindsight, this does not mean that the regulator was neglectful or ignorant at the time of the decision being made. We believe that the most productive way spectrum regulators can deal with changing conditions and complex situations is to improve the resilience of their decisions by devising means to revisit and correct them when necessary.

In fact, since policymaking is always an experiment and spectrum allocations can and do fail, we need ways to gracefully recover from failed experiments. Importantly, since experiments are the essence of progress, we must not stop them. The institutional problem we face in this regard is that creating rules creates constituencies to protect them, even if they turn out to cause net social harm. To address this, we believe that, just as a method for allocating spectrum is required, so too is a method for *de-allocating* spectrum. Since it is much harder to take action than to forbear, we recommend that regulators should make rules that sunset: spectrum allocations should expire at a predetermined date unless renewed.

We recommend not only that assignments (e.g. licenses) should expire, but also that the allocations on which they are based should do so. The time of renewal can then be used to also change the rules if necessary, but not between renewal dates [26]. Indeed spectrum licenses have fixed terms, and we propose that the same time limit should be applied to unlicensed assignments. Fixing a time in the future to check whether the premises of a given regulation were correct is important since only the passage of time can validate (or invalidate) these premises. This type of approach would be particularly useful when a given spectrum allocation holds great promise but it is very uncertain whether this potential will be realized, such as when the technology or market are changing rapidly, as in the case of TVWS regulation [27].

To this end, we also propose that regulators should ask stakeholders to describe, in a quantified manner, how the projections their advocacy is based on can be validated or refuted in the future. This would provide a basis for fair reconsideration of spectrum regulation decisions at a later date. This recommendation is thus also aimed at increasing the objectivity of arguments put forth in spectrum regulation debates and is inspired by the principle of falsifiability that is at the core of the scientific method. For instance, rules could state that if the assumptions based on which the regulation was argued for are not met, the basis for the rulemaking was not valid, which can then trigger a reconsideration or withdrawal of the rules.

Moreover, we believe that regulators should design "rules that learn" based on this. Namely, as part of the justification for a rule given in a regulatory order, the regulator should specify which parameters ought to be monitored as indicators of whether things might not be going according to plan. These flag parameters should be defined in line with input obtained from the stakeholders prior to the rulemaking and subsequently tracked to signal a potential need to revisit the regulation. Of course, putting such a regime into force is likely more easily said than done, since new spectrum rules, once enacted, inherently create interest groups invested in their preservation. Nonetheless, we believe that adopting such a process would enable the regulator to at least restrain some of the more hyperbolic claims by proponents of candidate wireless technologies, and thus aid in creating and maintaining well-reasoned spectrum regulation which best serves the public interest.

We advocate that *resilience* – the ability to adjust or roll back rule decisions – also be made a central design criterion for engineering policy recommendations. We strongly urge engineers advising those involved with spectrum policy and regulation to use fail-safe design methods in their proposed engineering solutions. Of course, this does not mean that failure is impossible or even improbable, but merely that the design aims to mitigate the consequences of failures. In the context of the complexity and uncertainty of spectrum policy and regulation, engineers should aim for approaches that can be adjusted rather than trying to get it right the first time (with the immense risk of getting it wrong and being unable to fix it). An example of such engineering flexibility in the context of TVWS spectrum regulation would be the design of white space spectrum access databases that can shut down secondary devices or change the operating rules if the need arises. Interestingly, some existing engineering and policy solutions are better in this regard than others. For example, the approach adopted by Ofcom for their TV whitespace databases lends itself more easily to fail-safe resilience, since the database issues secondary power limits, rather than these being hardcoded in regulation as in the case of the FCC. So, if it turns out that the primary TV system requires more protection, it is straightforward to change the degradation probability based on which the allowed power levels are calculated in the database without changing anything in deployed secondary devices. In the FCC case, the devices themselves would have to change their power ceilings, which is almost certainly impractical. In fact, it appears that even though a common FCC mantra is to try simple rules and come back to change them later, in practice they are generally hard to change (*cf.* UWB spectrum allocation [28]).

Moreover, we encourage the engineering community, when making spectrum policy recommendations, to aim for robust solutions which require a minimal number of parameter values to be chosen by the regulator; the number of variables involved almost always grows and it is much easier to adjust a few parameters, given the complex interplay between them (as evidenced by our discussion of the N-dimensional design space and the technology circle). Similarly, we believe that engineers should aim for generic solutions that do not lock in technology or service scenario assumptions. A paradigmatic example of the benefit of this approach are the generic broadband rules in the FCC Part 15 rules.

Finally, we urge engineers to recommend rules for spectrum regulation that "learn", as elaborated above. Engineering analysis submitted to the regulator should show how the recommended solution would change as assumptions vary, and how the validity of the premises used in the analysis could be subsequently tested and potentially refuted. Of course, pure advocacy is the route of least resistance; all good engineers instinctively engage in debate to find the truth, but it takes constant vigilance to maintain this perspective in the midst of the commotion of adversarial rulemaking. In particular, we encourage engineers to focus on analyzing the less self-evident effects of *non-linear* changes to their assumed parameters and consider the impact of changing qualitative assumptions, such as the relative weighting of the social goals of providing rural coverage vs. urban capacity.

4. Conclusions

In this paper we have examined the interaction between wireless engineering practice and radio regulation. We have argued that there is a complex interplay between modern wireless technology, spectrum regulation, and the economic environment and social goals that inform policymaking. Given the resulting complexity of making rational, evidence-based spectrum policy decisions, we have recommended increased *transparency* and taking a *systems view* as important means of making this interaction between wireless engineering and radio regulation more effective.

We have argued that increasing the transparency of argumentation and advocacy in spectrum regulation debates would greatly contribute to strengthening the objectivity of arguments put forward in favour of various candidate wireless technologies and spectrum allocation regimes, and thus strengthen the spectrum regulation and policymaking process. To this end, we have discussed the importance of *N-dimensional engineering analysis* to properly represent the complex technical design space of modern wireless systems, and of the *disclosure of financial interests* by technical experts.

We have further argued that the unavoidable complexity of the decision space regulators must grapple with calls for the adoption of a true systems view of these complex techno-economical systems and interactions, on the part of both engineers and policymakers. To this end, we have proposed a framework for articulating the relationship between wireless engineering and the "soft" issues of spectrum policy (the *technology circle*), and advocated the use of a *fail-safe* design philosophy to inform engineering recommendations and regulatory decisions.

We believe that adopting our recommendations of increased transparency and taking a systems view would enable the engineering profession to contribute more fully to the perennial debates on wireless technology policy and spectrum regulation, in the interest of better serving the public good. In fact, since wireless technology has come to play such a key role in ensuring the prosperity and welfare of our information society, we believe that a commitment to more effectively engaging with spectrum policy and regulation is now truly a part of a wireless engineer's professional duty to society:

> *"A scientist has to be neutral in his search for the truth, but he cannot be neutral as to the use of that truth when found. If you know more than other people, you have more responsibility, rather than less."* – C. P. Snow

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