Improving Spectrum Sharing Interference Criteria: A Survey of a Critical Need for Measurements

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2022 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI) | 978-1-6654-0929-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/EMCSI39492.2022.9889673

***Abstract*—As radio spectrum becomes more congested and more valuable, an increasing number of potential conflicts is occurring between or among disparate systems and services. Such potential conflicts can be related to systems sharing the same band or even the same channel. Because of unwanted emissions (which include out-of-band emissions and spurious emissions), potential conflicts can arise in immediately adjacent bands, and even bands that are far removed from the operating frequencies of the potentially interfering system. We refer to these issues as potential conflicts, because whether a conflict does or does not exist in reality is often far from clear. Such claims are typically based on paper studies that combine interference criteria for a particular service, propagation models, deployment models, usage assumptions, and other factors. The inputs, assumptions, and even the applicability of any or all of these specific factors are debatable, with the potential interferer relying on liberal interpretations, and the potential victim assuming conservative parameters. In the end, often the potential interfering operator concludes with certainty that no harmful interference will occur, and the potential victim operator concludes with certainty that harmful interference will occur. The regulator, which is often understaffed with appropriate resources to perform its own detailed technical analyses, must make a judgment call, which is usually based on a combination of policy goals, politics, and the "loudest voice." Sometimes that judgment call results in overly restrictive requirements that causes inefficient spectrum use, or policies that may in fact lead to harmful interference in actual deployments. In this paper, we make an argument that the current situation could be significantly improved if one or more independent third-party "co-existence labs" were established that can help provide neutral input to regulators on the compatibility between various systems and services in the radio spectrum.**

I. Introduction and Background

The worldwide use of the radio spectrum is increasing at an astonishing rate. The demand for constant connectivity is driving the need for mobile broadband spectrum. Connectivity for typically underserved areas, such as rural areas and remote areas such as open ocean, is driving the development of extremely large constellations of broadband satellites, numbering in some cases in the hundreds of thousands. National defense drives the need for military radar, which often requires wide bandwidths to achieve its resolution and sensitivity objectives. Weather forecasting applications are of pertinent contemporary interest due to an anticipated increase in the number of severe storms, often attributed to climate change. These weather forecasting applications include weather radars as well as active and passive remote sensing systems (space-based and terrestrial). Broadband connections in homes and offices, including for applications such as Internet of Things (IoT), are often provided by unlicensed devices such as Wi-Fi, therefore driving the demand for more spectrum designated for unlicensed use. And the need for extreme bandwidths, such as for 5G systems (and beyond), is driving interest in traditionally underutilized portions of the radio spectrum, such as millimeter-wave (mmW, 30 – 300 GHz), and even terahertz frequencies (300 – 3,000 GHz).

The increase in spectrum use is producing an increasing number of potential conflicts among spectrum users. That is, one system operating on a particular channel in a particular band may be predicted to cause interference to another system that is operating on the same or other frequencies. The following types of interference may occur:

- Co-channel. Two systems operating on the same channel in a band.
- Adjacent-channel. Two systems operating on different channels in the same band.
- Adjacent-band. Two systems operating in immediately adjacent or relatively nearby bands.
- Spurious interference. Two systems operating in bands potentially far removed from one another, such as a victim system operating on a frequency that is a harmonic of the interfering system.

Incidences of concern over co-channel, adjacent-channel, and adjacent band interference are particularly on the rise as disparate systems are being required to share the same band, or operate in nearby bands, due to spectrum congestion and the lack of "clear" spectrum in which to deploy new systems or services. Therefore, an important component of improving the efficiency with which spectrum is used by current and future systems and services is to better understand co-existence among such systems and services. Here, co-existence refers to the ability of various systems and services to operate in the radio spectrum, within the confines of established regulations, without causing interference or burden on one another.

II. The Regulatory Environment

There are several regulatory constructs that relate to the concept of one system or service causing interference to another. It is useful to define these concepts before proceeding. The International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) and many national regulators use the following interference-related definitions [1], [2].

- "Interference. The 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."
- "Harmful Interference. Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations."
- "Necessary Bandwidth. For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions."
- "Occupied Bandwidth. The width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage $\beta/2$ of the total mean power of a given emission. Note: Unless otherwise specified in an ITU-R Recommendation for the appropriate class of emission, the value of $\beta/2$ should be taken as 0.5%."
- "Out-of-band Emission. Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process, but excluding spurious emissions."
- "Spurious Emission. Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions."
- "Unwanted Emissions. Consist of spurious emissions and out-of-band emissions."

Regulators often use the specific definition of "harmful interference" when determining whether one system or service is interfering (or predicted to interfere) with another. Unfortunately, the application of the definition of harmful interference is generally open for interpretation from an engineering perspective. Many terms that appear in the definition, such as "endangering," "degrades," "obstructs," "repeatedly," and "interrupts" are not themselves defined in any technical or mathematical sense.

Note that adjacent-channel and adjacent-band interference are typically caused by out-of-band emissions (OOBEs), while spurious interference is caused by spurious emissions. Co-channel interference is caused by signals whose necessary bandwidths overlap.

Regulators use various methods to mitigate the various types of potential interference. For example, the radiated power (Equivalent Isotropic Radiated Power, or EIRP) and occupied bandwidth are usually regulated to mitigate co-channel interference. OOBEs are almost always regulated to mitigate adjacent-channel and adjacent-band interference. Likewise, spurious emissions are usually regulated to limit harmonic emissions and other emissions in distant bands.

III. Interference Criteria and their Establishment

An important component of analyzing whether one system or service (the "interferer") might interfere with another service (the "victim") is the interference criteria that apply to the victim service. For example, a received signal that exceeds a level of X dBm (or X dBm/MHz) on the victim's operating channel, at the input to the victim's receiver, may be claimed to constitute harmful interference to the victim. That signal level may be specified as single-exposure (caused by one interferer) or aggregate (caused by all interferers combined).

Establishing reasonable interference criteria is important: criteria that are too lenient will not adequately protect the victim, while criteria that are too strict will place an undue burden on other spectrum users and result in underutilization of scarce spectrum resources.

A challenge with interference criteria is that they are typically established by the victim service itself, with little or no independent validation. For example, many services have established baseline criteria within the ITU process, in which work on service-specific matters is divided into numerous service-specific study groups and working parties [3]. Examples of interference criteria can be found in the ITU's collection of Recommendations [4]. While the groups invite inspection and comment from other groups, the reality is that each group is very busy with its own work, and often has relatively little time to validate the work of other groups. Further, many interference criteria that apply today were established decades ago, long before many spectrum conflicts existed or were foreseen, so various groups had less incentive to challenge interference criteria created by others, because they were not impacted by those criteria at the time. Nevertheless, established ITU-R interference criteria are adopted by many national regulators, without challenge or validation.

Lastly, interference criteria generally depend on the nature of the interfering signal. For example, the impact of a low duty cycle emission such as Wi-Fi (which typically transmits only a few percent of the time, but over a wide bandwidth) may be very different from the impact of an analog FM dispatch signal, which is a constant duty cycle signal confined to a narrower bandwidth. Interference criteria often fail to distinguish among the specific natures of the interfering signals.

IV. Propagation Models

Interference criteria are only one component of the co-existence analysis. Predicting how strong an interfering signal will be at the victim location relies upon one or more propagation models. Unfortunately, the state of propagation models is not particularly advanced, considering they are heavily utilized to establish spectrum policy and dictate spectrum utilization through regulations established to mitigate harmful interference.

As just one example, the Irregular Terrain Model (ITM) [5] is currently used in two modern sharing scenarios: the U.S. 3.5 GHz Citizens Broadband Radio Service (CBRS) [6], and the U.S. 6 GHz unlicensed band shared with fixed service links [7]. A particularly important component of ITM with regard to spectrum sharing is its prediction of long-path propagation loss caused by tropospheric scatter (troposcatter). ITM bases that component on the Longley-Rice troposcatter mode [8], which was developed based on empirical data acquired more than six decades ago (in the 1950s). Besides the data being acquired a long time ago, it is also sparse in frequency, geography, climate, and many other factors, calling into question its application today to modern and ubiquitous spectrum sharing applications across a wide range of frequencies.

The other challenge with ITM is that it does not include a clutter component, and close-in propagation essentially defaults to free space loss if there is no terrain blockage. In practice, this results in inappropriate predictions in heavily cluttered areas. For example, ITM sees downtown Manhattan as a flat piece of barren terrain, and has no knowledge of the myriad skyscrapers that block propagation paths. A comparison of ITM predictions to actual propagation in an urban environment shows that ITM under-predicted measured losses by an average of 29.8 dB, and that measured loss exceeded predicted loss more than 86% of the time [9].

Clearly, validation of propagation models, and establishment of new clutter-aware models, is a key area for development to improve the efficiency with which spectrum is used and shared.

V. Recent Co-existence Issues

The challenges and shortcomings of our incomplete understanding of co-existence among disparate systems and services has real-world consequences, as exhibited in the following examples.

U.S. Citizens Broadband Radio Service (CBRS). As mentioned, CBRS relies on the ITM model to protect incumbents (both military radar and civilian fixed-satellite service receive-only earth stations) from harmful interference (predominantly co-channel). CBRS shares the band on a secondary basis with these incumbents.

The use of ITM, particularly its troposcatter predictions, has produced extremely large areas in which CBRS devices must be considered for their contribution to aggregate interference into incumbents. For example, the area of consideration for 50 W EIRP (maximum) CBRS devices causing interference to Navy radars operating up to 200 km off the coast extends as much as 450 km inland. Does a 50 W device operating in the mountain valleys of West Virginia really have a chance of causing interference to a gigawatt Navy radar operating 200 km off the coast of North Carolina? ITM says yes, but its troposcatter predictions have never been thoroughly validated, so no-one really knows. We do know that neither the Navy nor the satellite earth station operators have ever reported a single case of interference caused by CBRS, so anecdotal evidence indicates that the incumbents are well-protected, and may be over-protected, and therefore valuable CBRS spectrum resources may be wasted.

U.S. 6 GHz Unlicensed Band. The U.S. recently allowed the use of the 5925 – 7125 MHz band (the "6 GHz band") by low-power indoor (LPI) unlicensed devices on a secondary basis to tens of thousands of fixed point-to-point links and electronic news gathering portable operations. The Federal Communications Commission (FCC) determined that the power limit of the devices, combined with being indoors only, would mitigate any significant risk of interference to the incumbents. The FCC also allowed the use of higher-power unlicensed devices, both indoors and out, in certain portions of the band, as long as those devices are managed by a centralized Automated Frequency Coordination (AFC) system that is aware of incumbent operations and can manage co-channel interference from the unlicensed devices into co-channel fixed links in the area. However, some incumbents were concerned that the FCC did not properly assess the risk of interference caused by LPI devices, and filed a federal lawsuit to keep LPI devices from being deployed under the current rules. The incumbents mostly lost that lawsuit [10], but their concern over potential interference remains.

With regard to higher-power operations under AFC system management, incumbents and unlicensed proponents continue to disagree over appropriate parameters for such things as reliability and confidence inputs to ITM, and the amount of loss that can be assumed by an AFC system to be caused by buildings when an unlicensed device is located indoors.

3.7 GHz Service and Aviation Radio Altimeters. The U.S. cleared the 3700 – 4000 MHz portion of the C-band satellite downlink band and re-allocated the 3700 – 3980 MHz portion for 5G mobile broadband. In 2020, mobile operators bid over $80 billion for the spectrum, and agreed to pay more than $10 billion to clear the satellite incumbents out of the band. All told, the winning bidders have well over $90 billion invested in the band and were supposed to bring operations in certain markets in December 2021, with most of the rest of the markets available by December 2023.

Before deployments began in December 2021, however, the U.S. aviation authority (the Federal Aviation Administration, or FAA) began expressing very strong concern over the impact that these 5G systems will have on radio altimeters. Radio altimeters are radars on the underside of planes that provide accurate height above ground during an instrument-guided approach to an airport. Radio altimeters operate in the 4200 – 4400 MHz band, which is more than 220 MHz away from the 5G mobile broadband systems. Nonetheless, the FAA was sufficiently concerned that they threatened to close down certain major airports during instrument landing weather, because they were concerned that the radio altimeters might not work or, worse, report the wrong height.

As is typical, 5G operators are certain that harmful interference will not occur, pointing to studies they have conducted and the use of these same bands in other countries [11]; while the FAA and the aviation industry are certain that harmful interference will occur, based on their own studies and analysis [12]. Operators have agreed to a temporary reduction in transmit power near airports while the situation is further analyzed.

This spectrum issue has become so important and so relevant to the public that it has been reported on by network news programs [13], and appeared on the front page of multiple major newspapers, including The Wall Street Journal [14].

5G and 24 GHz Weather Satellites. For the past several years, operators of passive (receive-only) weather satellites operating in the 23.6 – 24 GHz range have expressed concern over adjacent band emissions from 5G systems operating in nearby bands. For example, the U.S. FCC auctioned the 24.25 – 24.45 and 24.75 – 25.25 GHz bands for 5G services in 2018. The weather satellites observe natural thermal emissions from the atmosphere and the ground, and use these data to create forecasts, including forecasts of hurricanes and other important weather phenomena. Their observations are very sensitive to interference, because the strength of natural thermal emissions is quite low. Various regulatory discussions (both national and international) have ensued regarding the necessary limits on OOBEs from 5G systems to avoid corrupting the weather data, but no definitive determination on the potential impact to the satellites and their forecast products has yet been made.

VI. The Role of Co-Existence Labs

All of the foregoing discussion points to the need for more robust analysis of the potential for harmful interference from one service into another. Typically, such analyses are conducted on an ad hoc basis, and only after conflict arises. Predictably, the interferer concludes that no harmful interference will occur, while the victim concludes precisely the opposite. Each sides' analyses are strongly informed by their respective agendas.

What is needed is the creation of one or more neutral third-party arbiters that are properly resourced to conduct the necessary technical studies such that they are able to adequately quantify the risk of interference on a statistical basis, from which informed decisions by regulators can be better made. The purpose of the work would be, in part, to provide mathematical and statistical meaning to the prediction of "harmful interference." Such arbiters would fulfill the role of "co-existence umpires." A co-existence lab would perform the following functions, among others:

- Hire skilled engineers and spectrum managers to design and conduct necessary studies
- Conduct laboratory tests to analyze and quantify the impact of various interfering signals to a victim system, considering co-channel, adjacent channel, adjacent band, and spurious impacts
- Conduct tests in environments consistent with actual deployments to determine how the laboratory results can best be applied to real-world scenarios
- Use the data to create a matrix of interference criteria that considers a variety of interferers and victims
- Work with experts in difficult-to-parameterize interference scenarios (for example, passive services) to analyze existing interference data to determine if such data can be used to empirically develop accurate interference criteria
- Conduct tests to validate propagation models, and help understand and quantify their limits. For example, conduct long-term tests of long-range propagation across a variety of frequencies, geographies, and environments, and examine the respective importance of troposcatter mode vs other long-distance modes, such as anomalous propagation by ducting, sporadic E, and other modes.
- Develop improved propagation models that take into account the improving quality and coverage of clutter data, such as building and foliage polygons being acquired by major tech companies.
- Conduct propagation tests to validate new clutter models.
- Publish the results of all studies
- Provide unbiased input to domestic and international regulators

Ideally, the work of a co-existence lab, as proposed, would be conducted by technical staff of regulatory agencies and other government labs. In reality, there are challenges with this approach. First, the government is typically under-resourced with appropriate technical staff. Such staff members are involved in numerous different proceedings at any given time, and there is not sufficient technical personnel to conduct a deep dive in all of the various proceedings simultaneously. Second, the regulator itself is also not always neutral. In some governments, the regulatory agencies are lead by political appointees who may have certain goals or objectives that they want to see implemented, and the staffs that report to such individuals are not always able to freely express their technical concerns about certain issues. Third, sometimes the need for co-existence analysis only arises at the time a regulator begins a proceeding on a certain issue, and the time to conduct thorough analyses may exceed the time that the regulatory agency has available to conclude the proceeding (for example, based on a legislative deadline). A co-existence lab will build a library of results that can be relied on when needed or, worst-case, the lab will be more nimble than the government and can conduct technical analyses more quickly than an under-resourced agency can.

The funding model and structure for a co-existence lab should be carefully considered. To remain neutral, a lab should not rely upon direct funding from industries with vested interest in the outcome of the lab's work. Ideally, the lab would be funded by the national government, either through the national regulator or through appropriate research funding agencies. Because the results of the work of a co-existence lab would be of international interest (due to the international aspect of spectrum use and regulation), perhaps a joint funding model among multiple governments, with the lab's work spread among multiple countries.

While the lab should not rely upon funding from entities with vested interest in its work, it should include an advisory council with representatives of all the different types of spectrum users. The lab would seek advice from such experts but would not be beholden to implement the advice of any specific interest.

The work of the lab should be open and transparent. Results should be published and freely available in the open literature. With appropriate constraints, observers should be allowed to view tests being conducted. The lab should be willing to consider collaborating with interested parties when appropriate, but the tests and their results should not be inappropriately influenced by any party, including national and international regulators.

While the lab should be thorough and accurate, it must be nimble, and it should avoid creating "analysis-paralysis." It should also be willing to conduct revised studies whenever new developments arise, or whenever field experience may indicate shortcomings in prior results.

VII. Conclusion

As spectrum becomes more congested and bands become more crowded, better analyses of the parameters under which different services and systems can co-exist are needed. Unfortunately, most such analyses today are conducted by the respective proponents. A respected third-party lab that can study co-existence issues from a neutral perspective is needed in order to help ensure that incumbent operators do not suffer harmful interference, while new entrants are not unnecessarily constrained such that scarce spectrum resources are wasted.

Acknowledgments

This research was funded by the National Science Foundation (Grant No. 2030243 and Grant No. 2037850).

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