Receiver Performance Technology

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Executive Summary

The growing movement to encourage spectrum sharing will be a significant enabler for cognitive radio systems. However, existing spectrum users have a reasonable expectation that their systems operation will not be impaired by new in-band and adjacent band users. Historically, this has been managed through a variety of standards and regulations primarily focused on transmitter parameters, sometimes with unexpected consequences.

This project identifies the critical receiver performance parameters required in order to enable spectrum sharing systems in existing bands. The current and expected receiver performance criteria for two existing systems, LMR and GPS, are presented, along with methods to apply these criteria to higher level abstractions.

By studying the impact of receiver performance on spectrum regulation, the need to utilize receiver performance metrics in the evaluation of spectrum reallocation or sharing is highlighted. In the case of Nextel interference into Public Safety bands, the unexpected regular pattern of high power in-band channelized transmissions combined with front end nonlinearities of the public safety systems to create challenging interference. Solving this problem required both an increase in receiver performance, system reconfiguration and eventual re-banding of spectrum, and serves as a model to evaluate future in-band spectral re-use. In the case of Light Squared transmissions adjacent to GPS reception, the changing of an adjacent band from a low power satellite to high power terrestrial provided a much higher level of adjacent band interference than was anticipated. Again, a combination of increasing receiver performance along with careful spectrum allocation may provide a path forward for similar systems.

Summarized in the report are the receiver performance characteristics of LMR and GPS systems. Since each of these was designed with different expectations of performance protection, the examples are illustrative of a variety of current and future systems. In both cases, it is seen that careful consideration of receiver performance is essential when new services are introduced in adjacent bands.

With these performance parameters in hand, regulators and system planners can better evaluate the impact of changing spectrum use. By understanding the receiver susceptibility to adjacent spectrum block interference, the impact of reallocation of spectrum can be evaluated. The authors highlight several systems that have explicit or implicit performance expectations and could be impacted by future spectral reallocation. In these cases, it is suggested that a similar study of receiver performance should be pursued to properly evaluate the value and impact of future spectral reallocation.

Receiver Performance Technology

1 Historical Views on Receiver Performance

The radio spectrum is becoming increasingly congested each and every day as new services are being deployed to fulfill the ever growing demand for data. Traditionally, spectrum regulations for one-way or broadcast systems focus on placing restrictions exclusively on transmitters. This can leave the receiver design completely open and a point of vulnerability for interference. Low cost designs will often trade off receiver performance to achieve other goals. With the growth of two-way communication systems and their need for greater spectral re-use, industry specifications have come into play to require a minimum set of performance for both transmitters and receivers.

In the current wireless spectrum plan, the receiver also plays a very important role in interference mitigation; yet a higher sensitivity receiver is required for an efficient operation. The FCC, realizing the issue, has published a recent report[1] on helping efficient use of spectrum and to provide recommendations on avoiding obstacles posed by poor receiver performance to making spectrum available for new services. A recent white paper by GAO[2] also noted that "interference being experienced is widely distributed both geographically and temporally. This would be the case when, for example, widely deployed consumer devices like television sets or handheld wireless devices receiving signals 'over the air' are interfered with by, say, geographically dispersed private land mobile radio, amateur radio transmitters or other wireless devices operating in an adjacent band. Thus the base case would exclude resolution of interference that arises when multiple radio systems (i.e., transmitters and receivers) are co-located at a single antenna site, or on a single tower, or even share a single antenna on a tower." Also, according to the recently published PCAST report[3], the regulation must be carefully developed to facilitate an increased use of new technology while protecting the legacy systems, to have a balanced socio-economic impact while heavily influencing the technological advances and innovations.

In investigating the impact of receiver performance on spectrum and system requirements, two recent radio engineering challenges are worth studying. Even with the well specified performance of mission critical LMR systems, the rapid growth of adjacent cellular operations created significant interference issues that were eventually resolved with further improved receiver performance. Lightly specified receiver performance intersected with changing spectral use to cause unanticipated performance challenges to GPS systems from the proposed

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[1] FCC Technological Advisory Council. (2013, February 6). Interference Limits Policy - The use of harm claim thresholds to improve the interference tolerance of wireless systems. Retrieved July 25, 2013, from http://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf

[2] General Accounting Office. (2013, February). Further Consideration of Options to Improve Receiver Performance Needed. Retrieved from http://www.gao.gov/assets/660/652284.pdf

[3] President's Council of Advisors on Science and Technology. (2012, July). Realizing the Full Potential of Government Held Spectrum to Spur Economic Growth. Retrieved from https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf

LightSquared system. Again, an increase in receiver performance was one of a set of solutions proposed to enable nearby spectral re-use.

1.1 LightSquared / GPS Interference and Mitigation

There have been several calls for receiver performance standards over the past decade. In the interest of maximizing use of the limited resource of spectrum and expanding availability of spectrum available for LTE and other broadband solutions, spectral allocations previously thought unusable or otherwise unavailable are under new scrutiny. This first example deals with the L-band spectrum encompassing the 1525 – 1559 and 1626.5 – 1660.5 MHz band.

Several factors affect the availability and suitability of spectrum sharing in specific allocations. These include 1) Outright reallocation of existing occupants to new bands, 2) Co-existence of new services with existing incumbents with mechanisms to protect the primary incumbents, and, 3) Generalized shared use cases based on geographic, temporal, power restriction, sensing, and other factors. One issue that continues to come to light is that of use of adjacent allocations from the standpoint of receiver protection, and the need for increased receiver performance in light of proposed new services and adjacent channel emissions.

Examples of receiver interference from newly-authorized services are numerous and applicable, directly or indirectly, to L-Band options. These include in-band, co-channel incompatibilities such as GLONASS encroachment into passive Radio-astronomy (RA) near 1610 MHz; Out-of-Band Emissions (OOBE) encountered with early Iridium satellites; and, most recently, the proposed use of L-band spectrum straddling Global Navigation Satellite System (GNSS) components such as GPS near 1575 MHz for terrestrial LTE. Specifically, the now-historic example of LightSquared (circa 2011) illustrates the interference potential, the root cause of interference in this specific case, and the proposed solutions. Parallels can be drawn between the LightSquared case and the earlier Nextel 800 MHz interference case as well; the latter will also be discussed herein.

In 2003, modifications to existing rules governing the use of L-band spectrum allocated for Mobile Satellite Service (MSS) were approved by the FCC. Known as the Ancillary Terrestrial Component (ATC) rules, these modifications allowed the use of terrestrial base stations to augment existing satellite services. At the time, the spectrum was assembled through business acquisitions by LightSquared. Initially, the ATC rules authorized base station power levels of up to +62 dBm; Precursor companies to LightSquared had, in 2009, requested regulatory relief to operate at power levels up to 15 kW (+72 dBm). The request was subsequently approved.

The spectrum acquired and available to LightSquared is included within the MSS allocations; specifically 1525-1559 and 1626.5-1660.5 MHz. These allocations surround the GNSS allocation: 1559 – 1610 MHz (including the GLONSS / RA overlap); "Big LEO" (Low Earth Orbit) satellite system complete this segment of L-band allocations operating in the 1610 – 1626.5 MHz portion. Prior to the 2003 allowance of potential ATC use-cases, all operations within the MSS allocations were weak signal based. Originally, typical GPS received signal levels at ground varied between -138 and -159 dBm. Newer generation satellites have increased the on-ground signal level by approximately 10 dB; -128 dBm is now typical for a well-placed

GPS satellite. However, the introduction of high power terrestrial signals into the band was not fully considered by the industry; receiver designs centered on weak signal adjacent band "blocker" performance – signals also emanating from satellite-based systems - with other factors ranked higher. Key factors for GNSS receivers included design for lowest system noise figure concurrent with high gain as to not diminish system sensitivity and additional factors necessary to maintain system noise figure throughout the receiver chain. This implies high (often exceeding 30 dB) low noise amplifier (LNA) gain and minimally-attenuative in-band filtering prior to down-conversion or direct conversion and subsequent digital sampling / correlation blocks. Furthermore, front-end filters were also designed with severe cost, size, and operating temperature restrictions. Much of the cost burden came from the regulatory need to incorporate location services into consumer cellular devices for E911 purposes. While network-based location methods were possible for E911 systems, none were are effective and accurate as the GPS (and other GNSS signals) that provide the most accurate "last outdoor location" fix. Furthermore, these systems often continue to work in residential homes due to low noise figure design of the GPS chipsets as well as the increased on-ground power obtained from newer generation GPS satellites. Since strong signals were not expected by allocation within at least 30 MHz either side of GNSS allocations, bandwidths of low loss filters designed to account for temperature drift during the extremes of indoor and outdoor temperatures encountered were, and remain, 50 MHz or greater. Many products now utilize and incorporate newer and more capable filters, yet legacy products remain with decade-long life spans.

The above E911 example, involving cellular telephony, is similar to other consumer and public safety applications of GPS including in-car navigation, network timing, frequency reference systems, location fix for professional and mission-critical applications, as well as many additional use-cases. Most of these examples utilize only the C/A code of the GPS signal. The bandwidth of the CA code is approximately 2 MHz and is centered at 1575.42 MHz (1540x the 1.023 MHz chip rate). The only other information required by the consumer receiver is the navigation data which is sent at a 50 Hz rate. Therefore, these applications could make use of a narrower RF filter; such filters are now available, and being incorporated into newer designs as mentioned above. There are, however, other applications wherein the full 20 MHz channel bandwidth is important. These include Aviation / Navigation system, defense applications, and hybrid use-cases such as precision farming. Direct use of the full 20 MHz channel information is by authorization only; however, aspects of the spectral signature of the full 20 MHz channel can be taken advantage of to provide much higher precision than that available through use of the C/A code only. Precision farming applications take advantage of signal exploitation and, arguably, accounts for 10 billion dollars (US) in energy savings, reduction of waste, and advancing green farming through precision of application of fertilizers and chemicals.

It can be argued that the GNSS community should have realized that use of the ATC rules, not only in 2003 when originally adopted, but also in 2009 when augmented to allow additional power, would impact GNSS services negatively. But, in early 2011, the full impact of the proposed use-case had yet to be understood and studied. Early testing of ATC systems quickly indicated disruption of GPS services. The industry soon realized that strong blockers in adjacent allocations could, and would, severely impact continued GNSS services.

The problems associated with the proposed ATC service inauguration are at least three-fold: 1) A strong adjacent channel signal can block reception of the weak signal (blocking within the GPS receiver due to dynamic range limitations), 2) Strong signals mixing at the base station site due to poor / deteriorated mechanical issues at the associated base site may generate unwanted OOBE emissions which, in turn, interfere with GPS signals, and 3) Receiver-generated IM issues may occur due to non-linearities within the LNA and subsequent stages of the GPS receiver that fall within the GNSS spectrum. In the case of the proposed LightSquared system rollout, all three were theoretically possible. Case 1 and 3 are related; the mechanism are somewhat different but are both derived from non-linear action, or protection thereof, of the LNA and mixer stages of the GPS/GNSS receiver.

In Case 1, the combination of a high gain LNA, wide (50 MHz) bandwidth filtering prior to the LNA, and limited dynamic range of the GPS receiver cause the strong out of band signals to act as blockers. The desired GPS signal is effectively suppressed into noise by the dynamic range of the various receiver stages (generally, this occurs within the LNA stage) and reception is impaired or outright impossible. During live-air testing of the proposed system in Las Vegas (2011), many GPS receivers were simply blocked over much of the coverage range of the base station ATC transmission (in that case, a LTE waveform); blocking was shown to occur in some GPS receivers in excess of 1 km radius from the base station. However, some experimental designs were also tested that showed blocking in the sub-50 m range. This exemplifies that improvements are possible for that class of receiver. In addition, if multiple channels are utilized within by the ATC base station site, these multiple RF signals can “mix” within the LNA of the GNSS receiver causing locally-generated IM products that fall directly within the passband of the GPS signal. At least one LightSquared proposal for frequency use raster included the potential for generation of these products within the GNSS receiver. Again, field testing during live-sky measurements indicated the existence of such products and reduction or failure of GPS reception as a result.

In addition, limited testing of full bandwidth (20 MHz) GPS receivers also took place and additional, extensive testing was undertaken at government sites. These tests indicated that blocking was a much greater issue, and far more difficult to eliminate. The mechanisms were identical to those of consumer devices but the 10-fold increase in necessary bandwidth of the receiver highlighted the problem.

In all examples of Case #1, the issue is generated locally within the GNSS receiver. It is not the intent of this section to ascertain whether the issue could have been fully resolved; it simply describes the extent of the problem encountered.

In Case #2, when multiple channels are co-located, as Lightsquared initially proposed, at each base station cell site, inadequate filtering and PA protection, the existence of other transmission equipment on site, or even passive mixing of signals within inferior antennas can cause inter-modulation (IM) components to be generated at the transmission site. These low level IM signals can exist within the 20 MHz limited of the GPS band centered on 1575.42 MHz. They are then radiated and, even if generated at low levels, can act to block the weak GPS signal. LightSquared took extensive measures to insure that such products were not generated. This included bandpass filtering at the output of each PA that well exceeded regulatory and necessary parameters. Taking measures such as those undertaken by Lightsquared at their base sites are a critical step towards insuring compatibility with adjacent services but they do not guarantee it. As many sites are shared by multiple users today, system design must take into account the multiple tenants at a given site, along with proper site engineering and installation, to guarantee that total emissions from the site are contained within acceptable levels form the overall site. This may include the need for stricter OOBE limits from a site if adjacent service requirements warrant it. In the case of Lightsquared, the impact of Case #2 potential was never fully developed; tests were dominated by Case #1 and Case #3 issues.

Case #3 manifests itself identically to Case #2; however, the IM products are generated within the GPS receiver due to non-linearity of the device: When multiple channels are simultaneously broadcast at the ATC base station site, these multiple RF products can "mix" within the LNA of the GNSS receiver causing locally-generated IM products that fall directly within the passband of the GPS signal. At least one LightSquared proposal for frequency use raster included the potential for generation of these products within the GNSS receiver. Field testing during live-sky measurements (2011 time frame) indicated the existence of such products and reduction or performance, or failure of GPS reception entirely, as a result.

Case #3 can be theoretically solved by pre-filtering the receiver input such that only GPS signals are passed. For consumer devices which utilize only the 2 MHz C/A code, realizable filters that conform with size requirements required by these devices are currently available, albeit with a degradation of noise figure, thus sensitivity, of approximately 2 dB. The issue becomes far more difficult to resolve when the entire 20 MHz signal bandwidth is utilized for precision agriculture, aviation, and defense use-cases among others. In the case of the original LightSquared proposal, the guard-band between the proposed upper downlink channel and the GPS full channel lower limit was as little as 6 MHz; with tests performed utilizing an 10 MHz guard-band. Since maximum signal levels observed during the 2011 live-air tests exceeded -15 dBm at the GPS receiver input, some 75 dB of additional rejection is required to assure proper operation of equipment designed to meet the international harmonized aviation filter requirement RTCA/DO 229 (illustrated below).

In addition to the receiver and site design considerations – all of which need to be accounted for in reallocation and/or shared allocation proposals – other factors were also ignored by all involved industries and parties in general. Included in these additional criteria are the need to fully understand international standards and regulatory practice. In the case of ATC use of MSS allocations, regulatory standards issues within the aviation industry were also either ignored initially or, at a minimum, underestimated. The aviation industry utilizes the full extent of the GPS signal running the gamut from flight navigation to assisted landing. Interference with GPS signals can become a terminating factor. The aviation receiver industry builds compliant receivers to international standards. One such standard is DO-229, the harmonized GNSS mask of the International Civil Aviation Organization's (ICAO) Standards and Recommended Practices (SARPS).

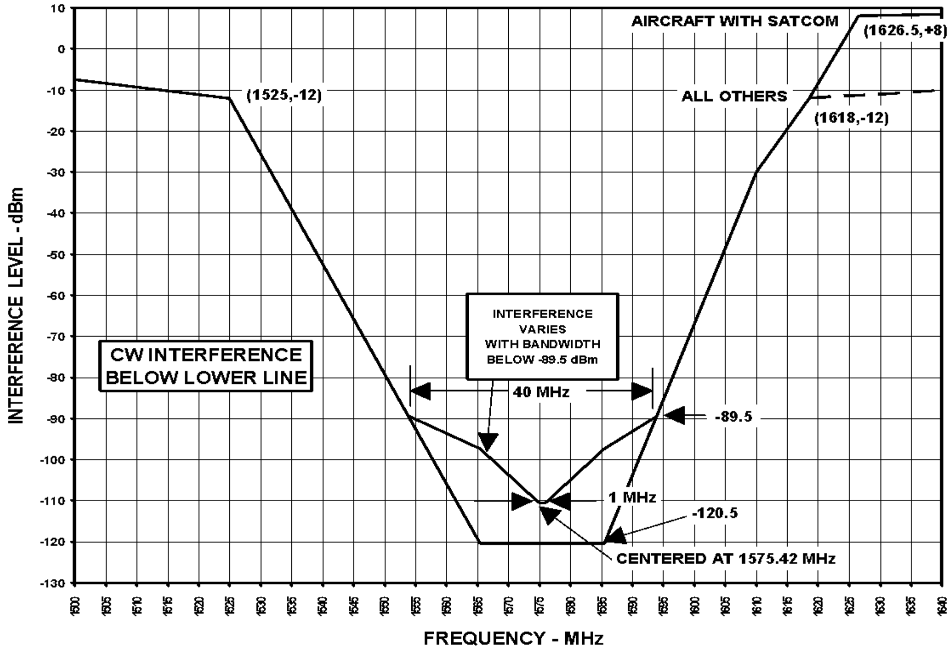

Figure 1: Civil Aviation GNSS Receiver Standards[4]

Clearly, one cannot expect to operate at the band edge (1559 MHz), or within approximately 20 MHz of it, even for low power radiated signals if protection of wideband GNSS receivers is to be expected using the current receiver practices in the aviation industry. Review and drafting of next generation standards for the aviation industry is expected to occur in 2018. While it is unclear as to whether increased protection against out of band emitters will, or even can, be incorporated into a revised standard, additional signals will be expected to be included into any revised standard; bandwidths of GPS/GNSS receivers will undoubtedly increase. Only the slope of the filter can be influenced, within physical and practical limits, to allow additional out of band power to be tolerated. Furthermore, the life expectancy of equipment in the aviation industry easily exceeds a decade or more; plans to allow shared use or reallocation of spectrum adjacent to GNSS allocations will require, at a minimum, a sunset period for the current industry to adapt and prepare. The international impact (in the aviation industry at a minimum) will also play a key role in future use of this L-band allocation.

The misunderstanding of all current use-cases of GPS during the 2011 timeframe and an ATC band plan that attempted to efficiently utilize as much of the GNSS spectrum as possible, coupled with the assumption by the GPS industry that no strong signal blockers would exist within the GNSS allocation, created the perfect storm.

The use of L-band MSS spectrum for terrestrial LTE service is once again being addressed by LightSquared during 2015/16. A new band-plan has been proposed; essentially taking the 1545-1555 MHz downlink allocation off the table – at least initially. In addition, a new downlink

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[4] Graph from public presentation "Civil Aviation GNSS Receiver Standards", Christopher J Hegarty, D.Sc.; FCC Workshop on GPS Protection and Receiver Performance; June 20, 2014.

allocation at 1670 – 1680 MHz is also part of the proposal. Extensive testing is currently underway to confirm that the revised test plan will protect existing GPS receivers. Furthermore, LightSquared has engaged with the GPS industry to ensure that existing products are adequately protected while improvements are considered for new GPS receiver designs. Additional restrictions on Power Flux Density on ground, LTE base site antenna patterns and protection of full bandwidth GPS service including the aviation industry are also under consideration.

Future use of the MSS bands under ATC-like regulation will certainly come to fruition some day. The events that played out from 2001 through the current date merely show that many critical factors must be taken into account as we search for additional spectrum. Receiver performance is but one key item; a timetable towards implementation with sunset periods to allow the industry to prepare and allow existing hardware to be replaced, minimum protected receiver criteria agreed upon by all interested parties, and protection of critical incumbents, with active participation by those incumbents, is paramount towards successful use of future spectrum allocations in our congested radio spectrum.

1.2 The Impact of Broadband Signals Upon IM Generation: The 800 MHz Nextel Example

Historically, IM performance measurement of a narrowband receiver has followed the practices put forth in TIA 603[5]. Section 3 details such measurements and practice in detail.

With the rapid expansion and densification of broadband services offered in the 700, 800, and 900 MHz bands today, plus the future expansion into 600 MHz as well as additional bands above 1 GHz, the generation of IM within a receiver due to non-linearities within the receiver front-end has become a critical issue. Just as in the example of LightSquared, there are historic examples of unexpected consequences due to the combined effects of co-mingled services and the use of status quo receiver performance criteria by incumbents of adjacent channel allocations. Whereby existing specifications detail the expected performance of narrowband service when additional narrowband blockers are present, the use of high power, broadband signals – particularly when deployed at relatively low antenna heights – create an additional subset of concerns and problems. Solutions are available, and resolution is within reach, however, receiver performance is, perhaps, the largest contributor towards successful deployment of additional service – particularly in adjacent allocations.

During the SDR Forum 2009 Conference (December 1 – 4; Washington, DDC), a presentation (add footnote) detailed the then-new issues arising from the emission of broadband signals. While the paper discusses, in detail, issues anticipated in TVWS, it also addressed lessons learned from the then current Nextel 800 MHz deployment and anticipated concerns regarding D-block and adjacent narrowband public safety systems.

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[5] https://global.ihs.com/doc_detail.cfm?&rid=GS&item_s_key=00144319&item_key_date=830929&input_doc_number=TIA%20603&input_doc_title=

Receiver design of the early 2000 timeframe dictated 70 dB IMR (inter-modulation rejection ratio) as specified by the TIA Class A standards. Furthermore, front ends were designed assuming that the strongest off-channel signal present at the antenna port would present less than -50 dBm for any individual signal present at the receiver input. With the careful system planning, that occurred through coordination of system geographical placement based upon the narrowband spectrum allocation that existed a decade or more ago, detrimental IM was usually avoided. The fundamental thesis was that all signals were approximately equivalent in bandwidth; the generation of 2A-B and 2B-A IM products were accurately predicted and dealt with. Broadband signals, such as multi-carrier transmissions such as multiple OFDM signals, can mix with themselves as well as other narrowband and broadband signals to generate blankets of interference that cannot be avoided through simple planning.

As wideband and broadband services expanded, the inadequacy of narrowband IMR measurements quickly came to light. This was the lesson learned from interleaving of Nextel services, as well as wideband and broadband signals replacing analog and relatively narrowband GSM services in the adjacent cellular spectrum, with narrowband carriers – both in-band and in adjacent bands.

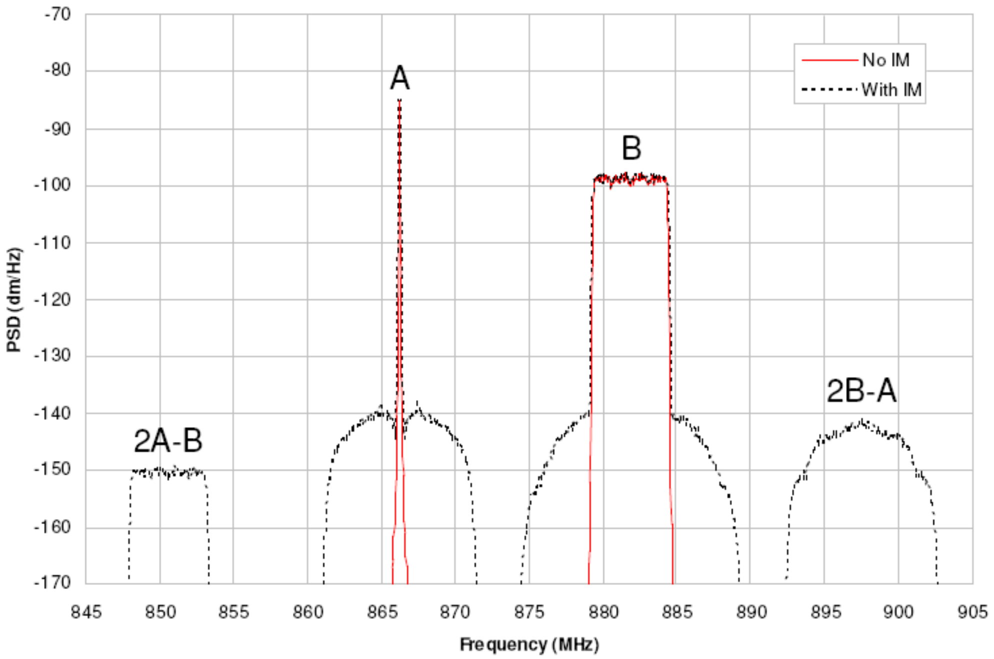

Figure 2: Multiplicative effect of IM generation within a narrowband receiver due to the presence of a nearby broadband signal.

The broad shoulders of IM products generated within the receiver indicate the extent to which services might be denied due to masking of desired signals. IM of this nature caused interference and denial of service issues with public safety narrowband as well as private land mobile services operating in the 800 Mhz allocation. Ultimately, the solution was to re-band services such that public safety had a well-protected allocation buffered by shard private land mobile and additional public safety services. Furthermore, additional guard-band was also created to further reduce the impact of aggregated carrier Nextel services. The result was a multi-year process that carried a price tag of over $2 billion dollars (US). And, it was only a Band-Aid. It solved the short term problems but did not fully address future issues including those associated with the current deployment of broadband LTE in the 800 MHz cellular bands. Fortunately, manufacturers also realized that the then-current IMR specifications were not sufficient to mitigate problems moving forward. To that end, at least some product is now offered that exhibit 80 dB IMR specifications.

While the above figure is illustrative of the generation of IM products within the typical narrowband receiver (70 dB IMR) of the day, it did not anticipate the very large broadband signal levels that accompany most broadband service near the base radio site today. The FCC limits Power Flux Density such that the maximum Power on Ground to which the victim receiver is exposed can be as high as -15 dBm (as opposed to the -50 dBm assumption of a decade ago). The 800 MHz band currently has no restrictions on PFD at ground level outside of the RF Exposure limits imposed by OET 65.

Furthermore, the cellular industry has recently petitioned the FCC for modifications[6] to the regulations concerning cellular telephony in the 800 MHz band. Currently, unlike the 700 MHz bands, there exists no Power Flux Density limit at ground level. The cellular industry has petitioned to modify the current regulations to allow a Power Spectral Density rule to supersede the current Radiated Power rules as systems migrate to LTE. This will result in additional radiated power from each site; hence, additional adjacent band power levels entering the adjacent band service devices. Manufacturers are now assessing the increase of interference zones that will occur from these proposed regulatory modifications.

To illustrate this further, the next figure illustrates, using a 2009 snapshot of the DTV allocations in the City of Madison, WI, the performance of a 70 dB IMR receiver. As a result of the limited IMR performance of this receiver, the apparent noise floor is quite high. The actual noise floor is shown in Figure 3 shows the theoretical noise floor of these measurements with a green line, and the blue line shows the measured noise signal from the 70 dB IMR receiver. It is clear that, while receiver performance of that nature may have been acceptable prior to the mass deployment of 6 MHz broadband signals, the broadband signals create a broader range of intermodulation products in the receiver. This is not limited to DTV modulation types. Other broadband signals will show a similar rise in the artificial noise floor in a low IMR receiver.

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[6] http://transition.fcc.gov/Daily_Releases/Daily_Business/2014/db1110/FCC-14-181A1.pdf

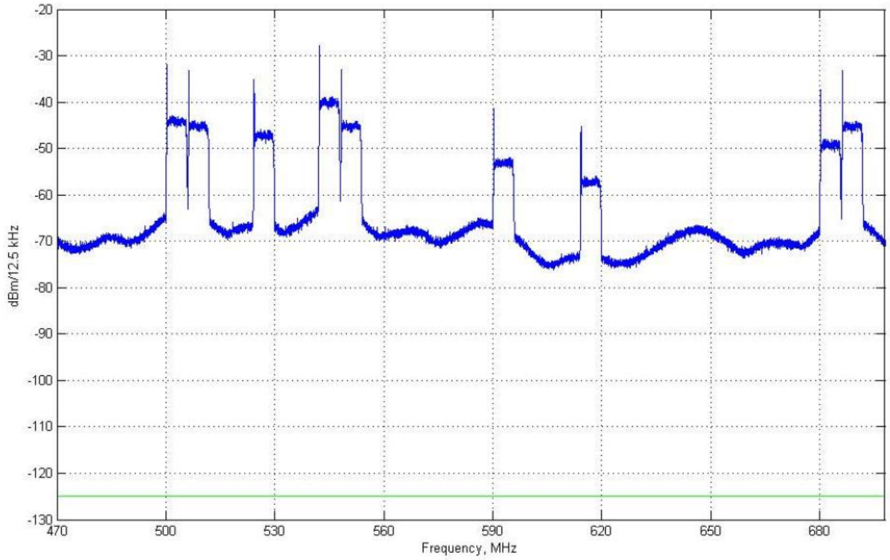

Figure 3: 70 dB IMR receiver observing DTV allocations in the City of Madison, WI

While raising the RX IMR performance to 90 dB is a difficult objective to meet in a portable receiver, it can significantly improve performance. If this level of performance could be accomplished, the results are quite different as seen in Figure 4 below. The perceived noise floor shows nearly zero rise over theoretical except for cases with extremely strong undesired signal sources.

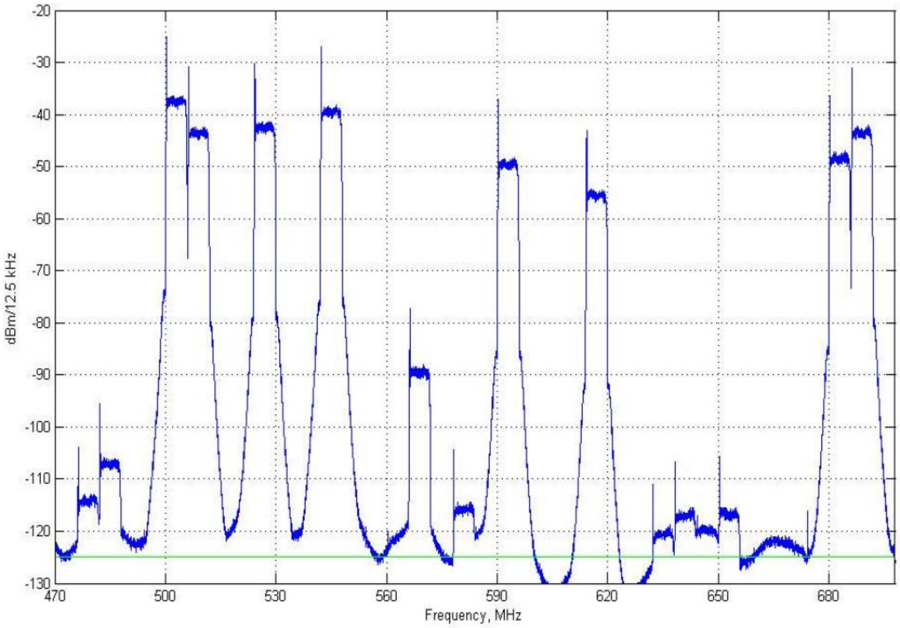

Figure 4: 90 dB IMR receiver observing DTV allocations in the City of Madison, WI

Today, the industry is, in general, producing product that is far superior to the 70 dB IMR specifications present in the mid-2000's. But, they are not yet to the point of producing 90 dB

IMR radios, and it is unclear if this goal can be practically met. Battery life and several other factors make this a difficult goal to achieve.

2 LMR Receiver Performance Details: Current Narrowband Measurement Criteria

(Please note, Section 3 pertains to in-band, narrowband performance that is achieved due to current receiver standards.)

Land Mobile Radio standards have addressed interference concerns through specification of receiver performance in TIA and ETSI standard practice requirements documents. Because of the dense packing of diverse systems, successful deployment of land mobile technology is based on predictable minimum receiver performance. While these specifications represent minimum performance standards, industry participants differentiate based on performance above these minimum levels. Through evaluation of these standards and tests, insight into the application of receiver harm thresholds to LMR bands can be derived.

The fundamental receiver parameters specified in TIA and ETSI standards for Land Mobile Radio systems are described below, and summarized in Table 1.

- Receiver Sensitivity is the level of desired signal required to achieve a minimum decoded communication quality. For analog FM reception, this would typically correspond to 12 dB SINAD. APCO Project 25 digital LMR systems typically specify 5% decoded BER. The receiver sensitivity is typically specified as an absolute signal value, but it is computed as an implementation offset above the theoretical noise/performance floor.

- Adjacent Channel Rejection (ACR) is measured by injecting a specific test signal located one channel offset away from the desired reception channel. The ACR protection level is the injected signal level that incurs a 6 dB receiver sensitivity degradation above the standard. This measurement is done above and below the desired signal. Because LMR system are not synchronized, additional measurements will capture ‘offset’ ACR levels that represent the slight frequency offsets between channels.

- Intermodulation Rejection (IMR) addresses interference from multiple in-band narrowband signals. Strong signals can mix in the receiver, creating on-channel interference. In fielded systems, intermodulation in the receiver will occur between numerous signals and in difficult to predict combinations. To conduct this test in a meaningful and repeatable manner, two equal level test signals, offset at 50 and 100 kHz offset from the desired channel, are introduced to the receiver under test. The signal level that degrades the receiver noise sensitivity by 3 dB is the measured IMR level. Because the performance varies between different classes of receivers, this specification is often tiered for mobile, portable and base station systems.

- Blockage Rejection is the resistance of the receiver to strong adjacent band signals. This often occurs at the band edges between disparate systems, or when there is a significant near-far variation for in-band systems. As before, this test is conducted by injecting a single strong test signal as a defined from the desired signal, and observing the level of the test signal when 3 dB of receiver sensitivity degradation is observed. This specification is also tiered for mobile, portable and base station systems.

The fundamental land mobile radio requirements considered for this analysis include those from the Telecommunication Industry Association and the European Telecommunications Standards Institute that relate to narrowband private land mobile service. These specifications, listed below, address the receiver performance requirements for narrowband 12.5 and 25 kHz systems with a variety of air interfaces.

- TIA 603d – Analog FM Speech
- TIA 102.CAAB – APCO P25 Phase 1 Systems
- TIA 102.CCAB – APCO P25 Phase 2 Systems
- ETSI 300-086 – Analog FM Speech
- ETSI 100-113 – Digital Data & Speech Systems

Table 1 summarized the previously detailed receiver performance requirements in each of these standards. While each set of requirements does not specify all measurements, or may specify them in different manners, by looking at the whole set, an overall set of receiver requirements can be synthesized. Also, a trend of improving receiver performance in intermodulation rejection can be observed as the underlying systems evolved.

Table 1: Fundamental Receiver Parameters Specified in TIA and ETSI Standards for Land Mobile Radio Systems

	TIA102.CAAB (P25 Phase 1)	**TIA102.CCAB (P25 Phase 2)**	**TIA603d (Analog Speech)**	**ETSI 300-086 (Analog Speech)**	**ETSI 300-113 (data/digital speech)**
Reference Sensitivity (Static)	-116 dBm (3.1.4)	-116 dBm (3.1.4)	-116 dBm (3.1.4)	shall not exceed an e.m.f. of 6,0 dBµV under normal test conditions, and an e.m.f. of 12,0 dBµV under extreme test conditions (5.2.1)	Paragraph 8.1.3
Reference sensitivity (Faded)	-108 dBm (3.1.5)	-108 dBm (3.1.5)	Not specified	Not Specified	Not specified
Adjacent Channel Rejection dB (Analog)	NA	NA	>20 kHz BW: 75/75/70 Base/mob/port 15 kHz BW: 65 dB 12.5 kHz BW: 45 dB	70 dB for >=20 khz Ch Separation (5.2.5) 60 dB for 12.5 kHz ch separation	NA
Adjacent Channel rejection (Digital)	60 dB (C3.1.7)	60 dB (3.1.7.1)	NA	NA	Pargraph 8.6.3
Cochannel rejection	<9 dB (3.1.8)	<9 dB (3.1.8)	90/90/80 base station/mobile/port	Between -8,0 dB and 0 dB for channel separations of 20 kHz and 25 kHz; Between -12,0 dB and 0 dB for channel separation of 12,5 kHz. (5.2.4)	paragraph 8.5.3
Digital Offset Adjacent Channel rejection	< 9 dB/kHz (3.1.7.2)	47 dB (3.1.7.2)	NA	NA	Not specified
Offset Channel Selectivity Analog (dB)	NA	NA	>20 (3.1.7)	Not specified	NA
Intermod rejection (dB)	75/70/80 mob/port/base station (3.1.10)	75/70/80 mob/port/base station (3.1.10)	75/75/70 base station/mobile/portable (3.1.9)	70/65/65 base/mob/port (5.2.7)	-37/-42/-42 bas/mob/port (paragraph 8.7.7)
Blocking rejection (dB)	Not Specified	Not Specified	90/90/80 Base station/mob/port(3.1.21)	84 dB for 3 dB desense (5.2.8)	-23 dBm (paragraph 8.9.3)
RX Spurious Rejection (dB)	80/70/90 mobile/port/base station (3.1.9)	80/70/90 mobile/port/base (3.1.9)	75/75/70 base station/mobile/port (3.1.8)	70 dB (5.2.6)	-37 dBm (paragraph 8.7.7)

Considering these standard measures of receiver performance, a summary diagram indicating their spectral relationships can be seen in Figure 5. On the spectral chart, the red lines indicate the areas where the spectral levels are defined based on the receiver performance standards. While the diagram in Figure 5 shares some similarities to the harm claim threshold diagram some differences are worth noting.

The LMR specifications are intended to specify the protection levels for individual receivers, not the overall band. Since the LMR bands do not have defined guard bands, the expectations of the industry is that receivers can be utilized very near the band edges. It seems reasonable to apply this spectral model at the upper and lower band edges to allow it to be applied to the reasonable amount of out of band signals that would be tolerable.

Since LMR standards seek to manage the interference between similar systems in nearby spectrum, their typical interference source is another narrowband signal. The harm thresholds model utilizes general power spectral density. Adapting the two-tone intermodulation rejection and the single tone blocker performance will require simulation to compare these results to systems that resemble wideband spectral occupancy.

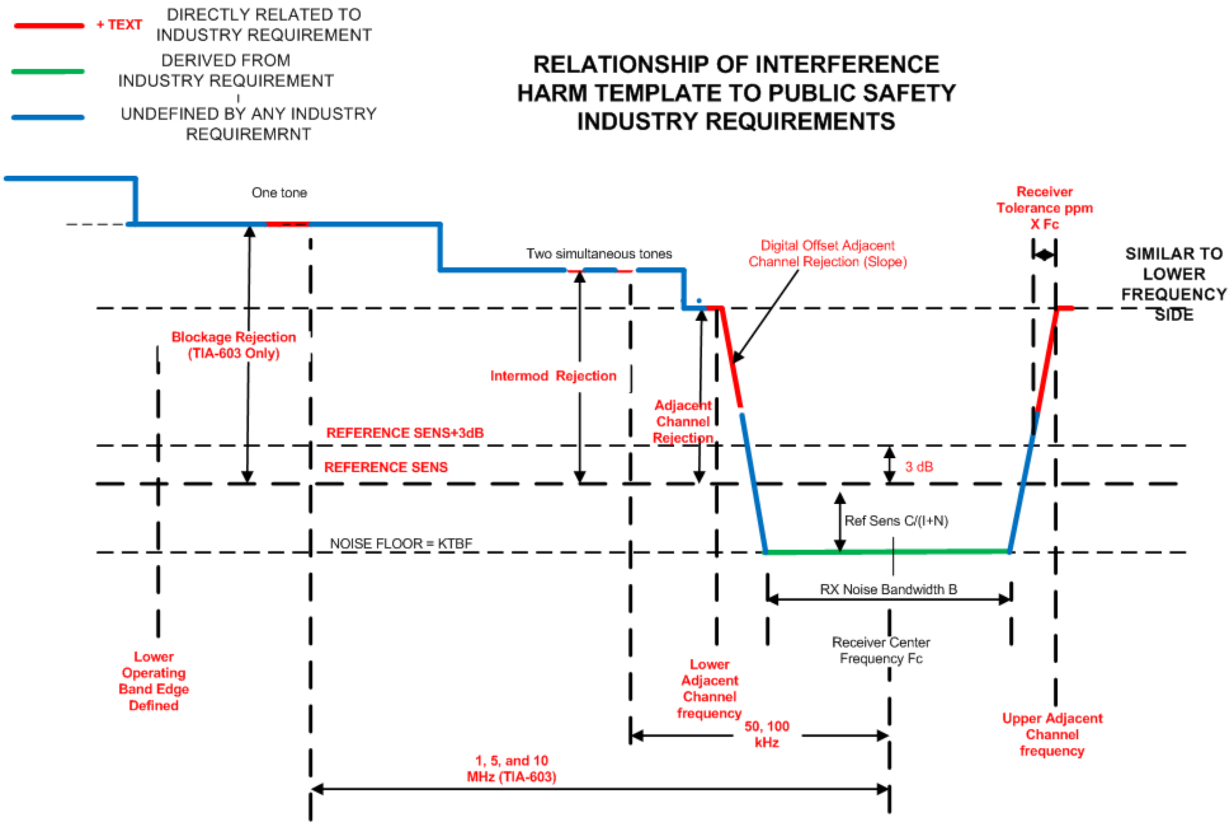

Figure 5: Relationship of Interference Harm Template to Public Safety Industry Requirements

By evaluating the LMR receiver performance specifications, the following observations relevant to the interference harm threshold model can be made:

- The most critical receiver performance specifications that relate to interference harm limits are the receiver sensitivity, two tone IMR levels, and one tone blocking performance. While the adjacent channel protection level is relevant at the band edges, because of the tight filtering in these products, it is only relevant for a small amount of spectrum at the band edges.

- Each of these measurements allows a worst case degradation of receiver sensitivity. However, it is expected that not every worst case scenario will be present simultaneously in useful deployments. In the case of interference harm limits in adjacent bands, it can be reasonably assumed that the amount of allowable receiver sensitivity degradation could be persistent. As a result, it seems that a level well below the 3-6 dB floor rise would be more appropriate.

- The difference between close-in intermodulation rejection and blocker performance susceptibility is substantial. Since the IMR performance is more stringent close in to the desired signal/band edge, this argues towards a two step tiered interference harm limits model that has greater protection closer to the band edge between services.

- The differences between discrete tone interference and other spectrally shaped interference remains for future studies. An appropriate power factor needs to be determined to relate broad flat spectral shapes to the discrete tone measurements of LMR systems.

3 Conclusion & Summary

As regulators and manufacturers plan for new models to share and allocate spectrum, it is key that the performance of current and future receivers are an integral consideration in this process. As seen in the historical examples in this document, the performance of receiver systems can limit the ability of spectrum to be successfully reallocated and shared.

For any given system, receiver performance is not going to be static. Receiver performance can and will improve over time and with market pressures. The Lightsquared/GPS interference issue has motivated the GPS industry to consider their receiver performance for new designs. The Nextel 800 MHz example highlighted a similar challenge, and encouraged the LMR industry to increase the IM performance of their device receivers. While these changes are not instantaneous, they can provide a timeframe for improving receiver performance to enable changing spectral use in the future. When a long term spectrum reallocation plan is considered, it would be greatly helpful to have a industry forum, such as the Wireless Innovation Forum,who would bring together industry and regulators to map these technical improvements, and identifying timeframes at which sufficient performance goals could be met.

Setting and defining these receiver measurement criteria is a challenging task. The LMR Receiver Performance example provides one insight into how receiver performance might be specified for systems in general. The fundamental parameters of sensitivity, adjacent channel rejection, intermodulation rejection and blockage rejection provide a set of measurable parameters that allow modeling of the receiver, assuming interference to self-similar signals. This works well in a homogenous system, but is more challenging when evaluating interference from dramatically different system types. However, with modelling, it should be possible to extend these straightforward measurements into a model of the impact of additional types of interference that is amenable to simulation. This would enable direct measurement of receiver performance parameters identified above to be utilized via simulation to model the impact of interference from a new, potentially unanticipated spectral allocation.