PUBLIC SAFETY INTERFERENCE ENVIRONMENT – RAISING RECEIVER PERFORMANCE REQUIREMENTS

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ABSTRACT

Public Safety radios provide "lifeline" communications for Public Safety officers and are expected to work regardless of the RF environment. The RF environment continues to become more crowded with mixed services within and adjacent to the spectrum utilized by Public Safety agencies. The industry is spending over two billion dollars to reorganize the 800 MHz band to separate Public Safety and Cellular Commercial Services operations because of near-far and out-of-band-emission interference impacting mission critical communications. The United States will complete the transition to digital television this year. The D Block and Public Safety broadband services are adjacent to Public Safety narrowband spectrum creating opportunities for near-far and out-of-band-emission interference. The new TV whitespace spectrum provides broadband operation opportunity for Public Safety and Critical Infrastructure but in a difficult RF environment in urban and suburban areas with large number of digital TV transmitters which create extremely large in-band signals. This paper will explore the interference challenges that the Public Safety radios are facing and the impact on future receiver designs. Field experience to mitigate interference in the 800 MHz band with improved radio receiver design will be reviewed and the need for increasing performance requirements of Public Safety radio receivers will be explored.

1. INTRODUCTION

Public safety receiver performance requirements are defined under TIA 603 [1] which was defined when operating environments were simpler. Service bands were homogeneous with simple narrowband waveforms. This changed in the 800 MHz band when cellular services began to use broadband waveforms on the adjacent bands and Nextel cellular service was intermingled with the public service and "business/light" industrial services. Land mobile radio high-site noise limited service was now intermingled with low-site interference limited high density cellular systems. The public safety radios were not designed to handle the near-far interference that was created within their receivers. In order to resolve the rising interference issues in the 800 MHz band, the services were separated at an expense that will exceed $2B. Such conflicts can be anticipated in the future for 700 MHz broadband and cognitive (i.e. TVWS) spectrum unless precautions are taken now. The receiver requirements for public safety will need to improve.

2. INTERFERENCE MECHANISMS

There are three main sources of interference in spectral compatibility scenarios. These are out-of-band emissions, intermodulation and, to a lesser extent, spurious responses. Models for these mechanisms will be used in later sections to determine their affect on performance. This section briefly describes these mechanisms and how they result in interference.

2.1 Out-of-band Emissions

Transmitter emissions that fall outside of the transmitter's channel bandwidth are known as out-of-band emissions (OOBE) or, equivalently, as sideband noise. This noise splatters into the adjacent channels and into other bands, generally getting smaller and smaller in strength as the frequency offset from the transmitter frequency increases.

OOBE enters receivers on other channels and sums with the thermal noise floor of the receiver. The increase in noise power in the receiver requires an equal increase in desired signal power to maintain equivalent signal-to-noise ratio (SNR) and thus causes a reduction in the sensitivity of the receiver. Since the interference is due to noise that is on-channel to receiver, there is nothing that can be done at the receiver to mitigate interference due to OOBE.

2.2 Spurious Responses

It is common for transmitters to have elevated power levels at a small number of discrete frequencies other than the intended transmitter frequency. Likewise, receivers exhibit somewhat elevated sensitivity at a small number of discrete frequencies other than the intended receive frequency.

These are called spurious responses. Spurious responses result from particular design choices such as synthesizer reference frequency and IF frequency. Spurious responses are only problematic in unusual circumstances.

2.3 Intermodulation

Receiver intermodulation (IM) is the mixing of over-the-air signals in a radio's receiver circuitry such that the mix products fall within the IF bandwidth of the receiver and add to its thermal noise floor, thus reducing the sensitivity of the receiver. IM is not due to a transmitter's spectrum but rather it is due to non-linearity in the receiver itself. This type of interference results when the undesired signals entering the receiver's circuitry are large, typically over -50 dBm, and then increases rapidly as the strength of the undesired signals increase.

Historically, IM was thought of as individual carriers at particular frequencies inter-modulating such that the products would fall on particular, unfortunate frequencies. The Telecommunications Industry Association (TIA) defines an IM rejection specification, called IMR, using two discrete carriers, one at a frequency offset A from the receiver under test and the other at a frequency offset of 2A. Doing this, a particular IM product, called a third-order product, will land on the test frequency. The amplitude of the IM product is a function of the carrier levels and the receiver's propensity to generate IM products. A low frequency, low deviation modulation is applied to the carrier at frequency 2A. By modulating in this way, the intermodulation product that appears on the desired frequency is an exact copy of the low deviation modulation and, because of the narrowband nature of the modulation signal, will affect only the desired channel.

The procedure is appealing for its simplicity and it was realistic for the time when all channels were narrowband. The signal levels that result in interference are obvious from the test procedure and transmitter sites could easily be evaluated for harmful IM products, which could then be eliminated by carefully choosing frequencies.

Broadband signals change this considerably for a couple of reasons. First, it is impossible to avoid IM through judicious frequency selection since broadband signals can occupy much or all of a band. Further, the IM products produced by broadband signals are themselves broadband and can span the whole receive band. Given this, the traditional frequency management approaches to controlling IM no longer apply.

Figure 1 shows the affect third-order intermodulation on a broadband signal. The red line in Figure 1 shows the signals as they enter a receiver. A narrowband signal, A at frequency F_A, and a 5 MHz broadband signal, B at frequency F_B, are shown. Intermodulation results in signals falling at frequencies $2F_A$-F_B and $2F_B$-F_A. In addition, intermodulation results in broadband spectral components appearing around signals A and B themselves, which increases the probability that intermodulation products will land on the receiver's desired frequency and cause interference.

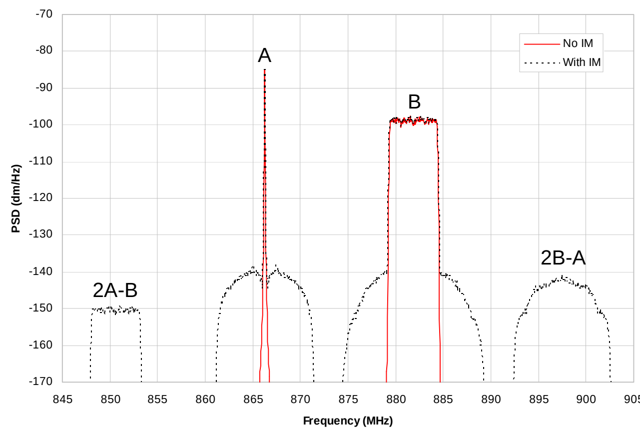


Figure 1 – Spectrum due to intermodulation of a broadband signal.

A property of intermodulation products is that their signal strength varies not in direct proportion to the input signals that cause them, but as a function of the signal strength and the order of the intermodulation product. For example, the third-order product generated in the TIA IMR test increases 3 dB for every 1 dB increase of the input signals. Higher order products exist as well, and the strength of these products start smaller and increase faster than third-order products.

For the most part, interference due to IM must be solved by improving the characteristics of the receiver itself.

3. INTERMODULATION IMPACT ON COVERAGE

Interference can be viewed as degradation to overall system coverage reliability rather than simply a local problem. In this view, interference is considered as another source of outage, just like low signal strength is. In calculating SNR at a point in the coverage area, the interference due to OOBE, intermodulation and the interference due to any other source are added to the receiver's thermal noise power to determine the total noise power. The desired signal power is then divided by the total noise power resulting in a signal-to-noise ratio, which if below a minimally acceptable value indicates that the point is not covered. A system's entire service area can be analyzed tile-by-tile in this manner and an overall system coverage value derived. This is the way systems are designed and tested by Motorola today, where a typical coverage reliability specification is 97% or greater.

The advantage of this approach is that it is quantitative, resulting in a precise value for interference impact. A disadvantage is that users may not accept that all outages are equal, especially since interference sources tend to congregate in populated areas, whereas outages due to low signal strength tend to happen in remote areas.

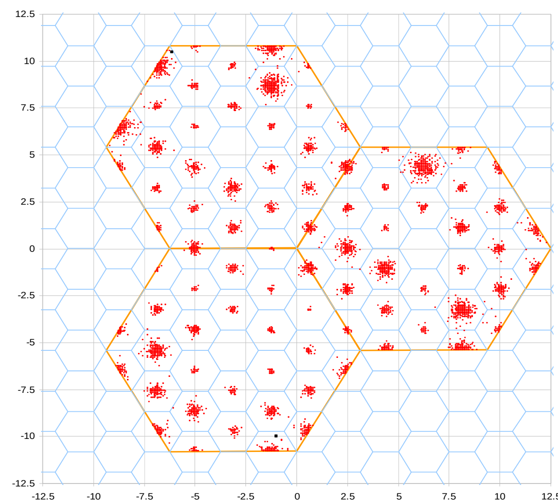
Experience with 800 MHz cellular/PS interference reveals that the system coverage approach tends to understate the perceived interference impact. The holes in coverage around cell sites tend to be small and reduce system coverage by only a small amount, but users tend to be more bothered by and highly critical of these outages.

A further disadvantage of the system coverage degradation model of interference is that, while base-generated interference causes continuous coverage outage at specific locations, mobile-generated interference is temporal in nature and does not clearly map to locations of outage. This is particularly true of mobile-to-mobile interference where interference can occur anywhere in the coverage area if an offending mobile gets close enough to the victim receiver. Likewise, mobile-to-base interference occurs when a mobile operating on a different system is close enough to the base station of the desired system. In these situations, coverage can be thought of as reduced in some average sense related to the frequency of the offending mobile transmitting near the victim mobile or base station. This would be very hard to quantify in any useful way. Thus, the system coverage degradation model of interference applies primarily to base-to-mobile coverage.

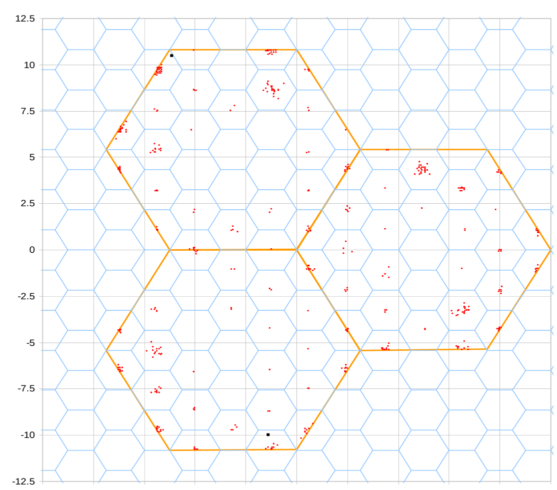
The red dots in Figures 2a and 2b show the locations of coverage outage in a three site public safety system due to interference from intermodulation near broadband sites. The public safety system consists of three transmitter sites, each site covering slightly over 110 square miles, for a total coverage area of slightly over 330 square miles. As such, this represents a small suburban county. A cell system operating in the band adjacent to the public safety system is shown by the light blue cellular pattern. The cell sites are separated by approximately 2.5 miles, which is also typical of a suburban area. There are also red dots in Figures 2a and 2b that show locations where coverage has failed due to low signal strength from the pubic safety transmitters which occurs due to any number of factors that affect radio propagation.

Figure 2(a) shows the outage that results in a public safety receiver that meets a 70 dB intermodulation rejection (IMR) as specified by Telecommunication Industry Association (TIA) Class A standards. The outage clusters around cellular sites because the signal strength near a cell site can be quite high, exceeding -25 dBm in some locations. Some sites are worse than others due to local terrain or land-cover features. Over 5% of the area of the public safety system suffers outage due to intermodulation as shown in Figure 2(a). Figure 2(b) shows the outage that results from the exact same public safety and cellular systems except that the public safety portable receiver meets an 80 dB IMR specification and includes an RF AGC function that attenuates large RF signals. In this case, approximately one-half percent of the area of the public safety system suffers outage due to intermodulation, which meets typical public safety coverage specifications.

These figures show that this type of interference is not temporal in nature but is related to location. It is also generated in the receiver itself so choosing a different frequency at the public safety transmitter is unlikely to be effective at eliminating the interference. This is why it is important that public safety employ high specification portable receivers when operating in a frequency band adjacent to broadband cellular.



(a)



(b)

Figure 2 – Areas of outage in a public safety system due to thermal noise and broadband intermodulation for a 70 dB IMR specification public safety receiver (a) and an 80 dB IMR specification public safety receiver with an automatic RF AGC function “(b)”.

4. 800 MHZ INTERFERENCE EXPERIENCE

Interference from cellular systems in the 800 MHz cellular band (869-894 MHz) to public safety systems in the 800 MHz land-mobile radio (LMR) band (851-869 MHz) began to surface in the late 1990s. Evidence built over time that the relatively low antenna height and high transmitter power of cellular systems resulted in signal levels in the vicinity of some cell sites strong enough to exceed the IMR specifications of typical public safety portable units. Because of the proximity of the cellular band it is impractical to reject all cellular signals with RF filtering. The problem was compounded by the collocation of the Nextel cellular system at many cellular sites resulting in strong narrowband signals in the 800 MHz LMR band which inter-modulated with the broadband signals in the cellular band, producing a broad spectrum of interference. While the problem existed at only a small percentage of cell sites, the large number of cell sites resulted in numerous instances of interference.

Field tests conducted and simulation models developed at that time showed that the majority of interference instances could be mitigated by the use of RF AGC in the public safety portable receiver. RF AGC can be as simple as an attenuator placed in front of the receiver and switched in and out in response to signal strength measured in the IF filter of the portable receiver. Recall that the strength of intermodulation products vary in proportion to the order of the modulation product in addition to the strength of the signals that cause the product. So when a 15 dB attenuator is switched into the receiver path the third-order intermodulation products are reduced by 45 dB while the desired signal is only reduced by 15 dB. In this way, switching in attenuation can improve the signal-to-noise ratio.

A 15 dB attenuator was found to be very effective at eliminating interference from intermodulation as long as the strength of the desired signal was sufficient to allow the attenuator to be switched in. To mitigate interference in the areas where 15 dB of attenuation would cause outage due to low desired signal strength, IMR was increased to 80 dB. Between these two approaches, intermodulation interference would have been virtually eliminated from the 800 MHz LMR band.

The experience gained through the cellular/PS interference problems of the 800 MHz band indicated that increasing the IMR specification of the PS receiver to 80 dB, utilizing an automatic RF attenuator in the PS receiver front-end, and reducing preselector bandwidth to the minimum necessary to cover the PS band eliminated a very high percentage of IM interference cases.

5. 700 MHz BROADBAND

The impact of interference between LTE and public safety narrowband in the Upper 700 MHz band is also of concern. The Upper 700 MHz band plan and the primary interference scenario is shown in Figure 3. This scenario assumes FDD technologies deployed with base transmit in the 746 MHz – 776 MHz band and mobile transmit in the 776 MHz – 806 MHz band.

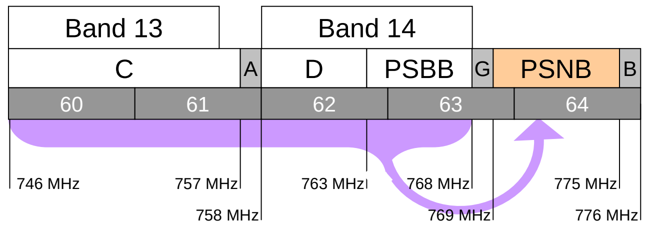


Figure 3 – Upper 700 MHz band plan and primary interference scenario

The primary concern is intermodulation due to strong signals from the broadband base stations in Blocks C, D and the public safety broadband spectrum. The likelihood of strong narrowband carriers in the public safety narrowband block is much less than occurred in the 800 MHz band when Nextel shared the band with public safety. Still, IM from the adjacent broadband allocations will cause intermodulation products that may interfere with narrowband public safety operations.

Figure 4 shows the spectrums that result in the public safety portable receiver when operating close to a broadband site where all three blocks, C, D and public safety broadband, are transmitting. The attenuation of the public safety portable's preselector is responsible for the shaping seen on the spectrum in the C Block. The power level assumed is -30 dBm, which is a high signal strength but not uncommon near cell sites.

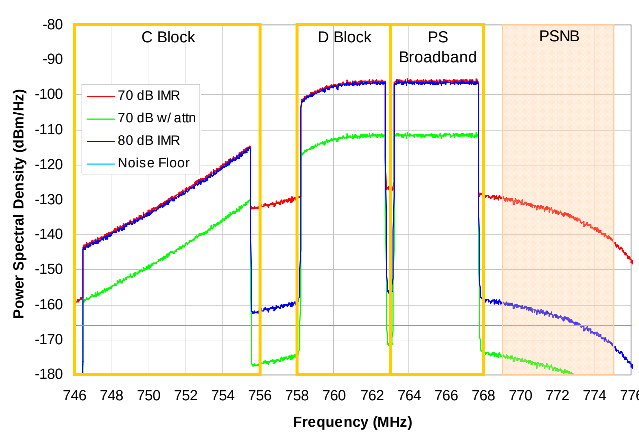


Figure 4 – Spectrum of intermodulation products generated in a public safety portable receiver assuming -30 dBm received signal strength.

The interference in 70 dB IMR public safety receiver, shown as the red line in Figure 4, is equivalent to a more than 30 dB rise in the receiver's noise floor. The green line shows that switching in 15 dB of attenuation reduces the intermodulation products by approximately 45 dB, at which point they are well below the noise floor of the receiver and will have no affect. Since the loss of the attenuator also reduces the signal strength of the desired transmissions, it cannot be used when the desired transmission's signal strength is within 15 dB of threshold. For these cases, the use of an 80 dB IMR receiver, shown by the dark blue line, significantly reduces the intermodulation products. Again the use of both the 80 dB IMR receiver and the RF AGC are required to reduce the incidence of interference due to intermodulation.

6. TVWS

TVWS is newly allocated spectrum that requires some measure of cognitive capability in the transceiver to gain access. The intent of this section is to address at a high level the IM performance required of the receiver so as not to degrade the link range available when using a TVWS channel. Since a Public Safety application is being considered here for the TVWS environment, the communications channel could be as narrow as 12.5 kHz in bandwidth to potentially several MHz wide. Therefore all the simulations will use a 12.5 kHz resolution. The environmental conditions in TVWS vary significantly and covering all of them is beyond the scope of this section; therefore, only the representative market of Madison, WI will be considered here. Being less congested than some of the major markets, it easily reveals how damaging poor radio performance is and how to correct it.

The overarching requirement for operation in TVWS is to not interfere with the incumbent TV stations and licensed microphones. To accomplish this, Motorola has developed a program, called TCAT, which queries the FCC's database and applies widely accepted propagation equations to determine which channels can be used as TVWS and at what power [2]. TCAT indicated that the channels available for 4 W usage in Madison WI. were 14, 15, 16, 17, 28, 29, 30, 34, 35, 36, 40 41, 42, 43 45, 46, 47, 48.

Madison, as typical of many cities, locates their DTV transmitters on one or two relatively high towers. Madison's antennas are at 400 m and 450 m HAAT. Therefore, if the receiver has one large DTV signal at its input from this tower, all the DTV signals from this tower are likely to be large. Another characteristic of DTV transmitters is they often use multi-bay antennas which narrow the elevation beam width. The antenna height and the directivity of the multiple bays tend to reduce the field strength near ground level close to the antenna and increase it at distances further away from the antenna. This makes for relatively constant field strength, maybe ± 10 dB, over a relatively large radius of perhaps 10 km. For the TVWS receiver this means that if there is degradation in performance caused by the DTV transmitters generating IM in the receiver, this degradation is going to limit the performance over a relatively large area around the transmitter unlike the localized outages described earlier.

Figure 5 shows the simulated spectrum derived from measured data of Madison WI. Power in dBm for a 12.5 kHz resolution bandwidth detector is shown on the vertical axis and the horizontal axis is the center frequency of the detector in MHz. A horizontally polarized antenna 10 ft above average terrain was used to collect the data at the following location:

TV Tower Location: 43° 03' 21" N 89° 32' 6" W
Test Location: 43° 04' 56" N 89° 32' 27" W
Distance: 1.70 miles / 2.74 km (170° bearing from test location to tower)

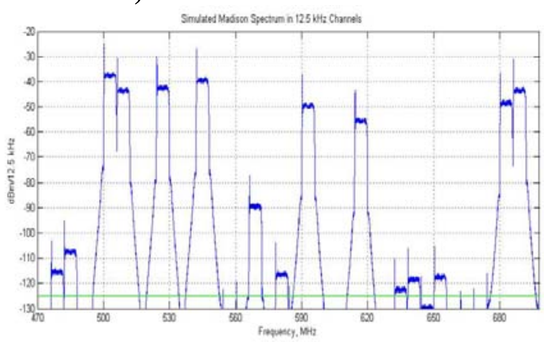


Figure 5 – Simulated Spectrum of Madison with 12.5 kHz resolution bandwidth.

As can be seen in Figure 5, at about 40 dB below the flat top portion of the individual channel spectrum, spectral regrowth starts to bleed into the adjacent channel. This is the OOBE emissions limit of the transmitter allowed by the FCC (See CFR 47 Part 73.622). The simulator was set to generate the FCC's maximum allowed off-channel emissions for the following graphs. The noise floor for a 12.5 kHz bandwidth receiver with an 8 dB noise figure is shown by the green line in Figure 5.

The expectation of a white space transceiver is that it finds the channel with the best RF link available. If the receiver was perfect, any place the spectrum falls below the green noise line and is available for transmission based on TCAT data would give a communications link only limited by the environment. This allows one to use the lowest transmitter power to get the desired range or QoS. There are several spots in the spectrum that could be used, but the initial guess would be to use channels 45-47 which are frequencies 656 MHz to 674 MHz.

The spectrum in Figure 6 shows a simulation of the spectrum after the IM generated by a 70 dB IMR receiver with an RF block filter in front of the receiver covering the total UHF TV band. For those more familiar with IIP3 instead of IMR, the conversion is:

$$IIP3 = 10\log_{10}(kTB) + NF + 3(IMR + C/I_{min})/2.$$

For NF = 8 dB, C/I_{min} = 11 dB, and B = 12.5 kHz (i.e. APCO 25), this results in an IIP3 of -3.5 dBm for a 70 dB IMR radio.

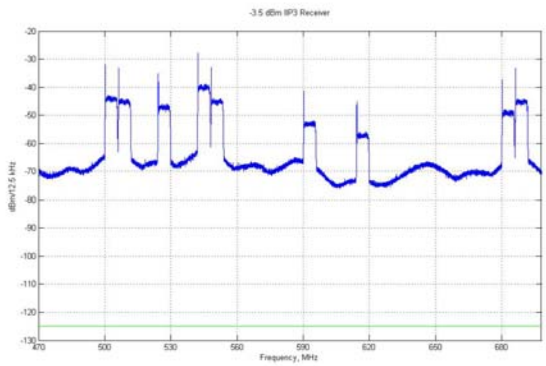


Figure 6 – Madison Spectrum in 70 dB IMR Receiver

The vertical scale is the power in dBm in a 12.5 kHz detector (APCO25 channel). The performance in the desired communications region around 656 to 674 MHz, which used to be limited by the receiver noise, is now at least 50 dB worse due to the IM products generated in the receiver. Another way of looking at this is that the receiver effectively has a 58 dB noise figure. The transmitter needs an extra 50 dB of power for the same link range. This gives a visual indication of how damaging IM products can be.

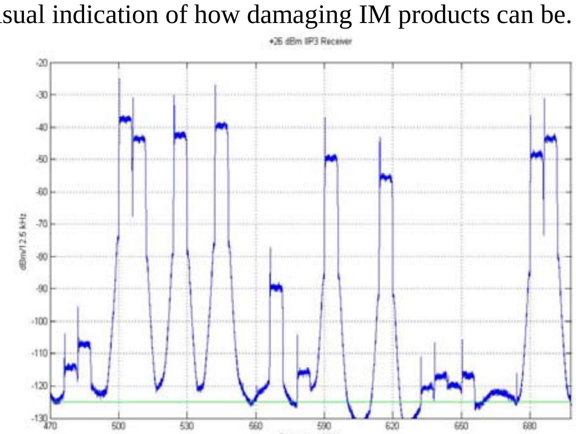


Figure 7– Madison Spectrum in a 90 dB IMR receiver

Clearly a 70 dB IMR receiver is inadequate for this application.

The spectrum plot shown in Figure 7 is for a hypothetical 90 dB IMR receiver. The extra 20 dB of IMR or 30 dB of IIP3 lowers the IM distortion products by over 50 dB for the same input signal level. Therefore, the IM distortion that was -70 dBm per 12.5 kHz at 668 MHz has been reduced to -121 dBm, which is very close to the -125 dBm per 12.5 kHz noise floor of the receiver. Comparing Figures 5 and 7 shows that, at least for Madison, a receiver with slightly better than 90 dB IMR would have no degradation in link range caused by IM in its reception channel even if the RF was only block filtered.

The use of a bandpass preselector to remove as many of the IM generators from the desired incoming signal as possible is another way to improve the effective dynamic range. There are many approaches for RF filtering, from using large manually tuned cavities to MEMS switched capacitors. All of the approaches have advantages and disadvantages and covering them is beyond the scope of this paper. However, it is informative to investigate the receiver performance within the bounds of a practical varactor tuned 2 pole filter.

A Butterworth filter with a 3 dB bandwidth of 8% of the carrier frequency or 50 MHz wide was chosen to filter the incoming spectrum of Figure 5. This is a practical tradeoff between several parameters including filter insertion loss and filter-generated IM with normally used components. This is not to say a narrower filter couldn't be used to provide more attenuation of the IM generators, but simply that the insertion loss would go up and the IM3 performance of the filter itself could become a concern [3] [4].

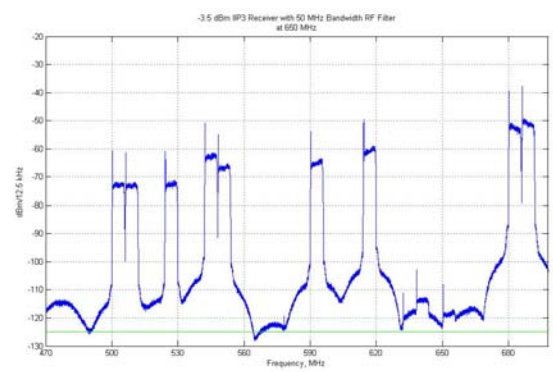


Figure 8 – Spectrum after filtering with 70 dB IMR receiver

Figure 8 shows the spectrum with filtering. The RF filtering has greatly reduced the IM products of the receiver around the spectrum hole which is just above 656 MHz. IM in the first two channels of this hole is still around 6 to 8 dB higher than the noise floor of the receiver. The IM being generated in the receiver due to the 683 MHz station degrades the link range in the 671 MHz channel another 15 to 20 dB. If the receiver's performance was increased to 75 dB IMR the IM in 659 MHz and 665 MHz channels would fall below the receiver's noise floor. The downside of filtering beyond the cost, possible IM, insertion loss impact on noise figure, and tuning of the RF filter is that the simultaneous reception bandwidth of the receiver has been limited to the 50 MHz surrounding 650 MHz.

The usage of TVWS brings the opportunity of new spectrum with the requirement of non-interference with the incumbent users of that spectrum. There are some rural areas in which the spectrum is almost totally open to usage as TVWS and all that is required of the receiver is to have a good NF and some measure of RF filtering. However, as this section of the paper has shown, if the goal is reliable service in small cities and urban areas the receiver performance becomes very important. Even an APCO 25 receiver with 70 dB IMR was shown to degrade the channel resulting in no communications conditions, poor QoS or the base stations needing to be much closer together than would be the case with better receivers.

7. SUMMARY

The RF environment for LMR has changed significantly since the original TIA receiver specifications were determined. Heterogeneous services in the 800 MHz band and the introduction of broadband waveforms in the cellular band created an interference environment significant enough to require rebanding 800 MHz. The 700 MHz D-Block and PSBB spectrum adjacent to the PS narrowband will be problematic with radios designed for the TIA receiver specifications. It has been shown that increasing the IMR specification level to 80 dB would have mitigated the need for 800 MHz rebanding and will reduce potential interference at 700 MHz. TVWS is a new spectrum opportunity, and cognitive radio, in general, will require radio designers to focus on solutions that exceed today's LMR radio receiver designs

8. REFERENCES

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