4 POST-MEASUREMENT PROCESSING

This section describes post processing techniques used to extract channel occupancy statistics. This includes setting the proper detection threshold levels, as well as removing the effects of impulsive noise and measurement system sideband noise.

Although very significant efforts were made in hardware design and field measurement procedures to minimize measurement defects caused by IM, LO noise sidebands, broadband impulsive noise, and other problems, the raw measurement data still contains certain defects from these sources that, for the most part, can be corrected. Since techniques that would have eliminated these defects completely would also have decreased the ability to measure weaker signals, we chose to operate with better sensitivity – anticipating that we could adequately remove most defects with further post-measurement processing. This section describes those efforts to identify and remove the most common types of measurement defects.

All of the post-measurement defect-reduction processing is performed on the saved 1-second, median data (*Channel Power Values*). A key factor in being able to distinguish some of these defects from the good data that they are embedded in is that the entire set of 1-second data is measured simultaneously across an entire 8-MHz IF bandwidth. The 8-MHz bandwidth completely captures the 5-MHz sample of signals that can pass through the 5-MHz (typically) RF bandpass filters in the preselector. That means that the processed data would be expected to include all of the high-amplitude signals that could have caused IM products to appear in the computed *Channel Power Values* – which means that proper modeling could remove most of the IM effects. However, initial analysis of the data showed that IM products from strong signals occurred so infrequently during these measurements that removing them using specialized processing techniques was not warranted.

4.1 Broadband Impulsive Noise

Broadband impulsive noise from electrical machinery or automobile ignition systems is usually seen on scanning spectrum analyzers as a sequence of impulses appearing at more-or-less regularly spaced frequencies across the analyzer display. Actually, the noise impulses are very broadband, but they show up on swept analyzers at whatever frequency the spectrum analyzer was measuring at the instant when the noise impulse occurred. However, the "simultaneous" nature of the 8-MHz IF digital sampling used in these LMR measurements means that either all frequencies show the noise, or none of them do. If the noise impulse occurs during the 1-ms digitizing period, the effect of the broadband noise will be generally present at each of the frequencies in the band of measurement. If the noise impulse does not occur during the 1-ms digitizing period, it will occur in none of the frequencies.

Therefore, impulsive noise can be eliminated in two very effective ways. The first “line-of-defense” against impulsive noise is from the median-of-5 measurement algorithm. Unless at least three of the five independent measurements taken in a 1-second period are contaminated by impulsive noise, the noise will be almost completely eliminated by the median-of-5 processing because these higher power levels occupy the places of the 2 highest readings and are ignored (along with the 2 lowest readings). Therefore, most impulsive noise is eliminated on a real-time basis by the measurement algorithm and is never seen in the recorded median-of-5 *Channel Power Values*.

If the median-of-5 *Channel Power Values* are contaminated with noise, all channels will tend to be similarly contaminated. This allows contaminated *Channel Power Values* to be easily recognized and removed from further data analysis. The noise-contamination algorithm checks to see whether at least 75%[9] of the frequencies in the measured band were 5 dB or more above the arithmetic mean[10] system noise power. If so, that set of *Channel Power Values* is judged contaminated by broadband noise and removed from further processing. Figures 11 and 12 show two sequential measurements, one without impulsive noise and one with, taken 1 second apart (the threshold being 8 dB above the median system noise). The impulsive noise in Figure 12 appears as a substantial momentary increase in system noise, causing that data set to be rejected from any further processing.

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[9] 75% was chosen because it is highly unlikely that 75% of all channels in the band would simultaneously come on line. Because the signal power for each of the channels is measured simultaneously, the impulsive noise is likely to raise the noise floor for, at least, 75% of the channels in the band.

[10] For median-of-5 traces of Gaussian noise there is a 1.5-dB difference between the arithmetic mean and median power – mean being the higher of the two. In this report, both mean and median are used under different circumstances, but each may be translated to the other using the 1.5-dB correction factor.

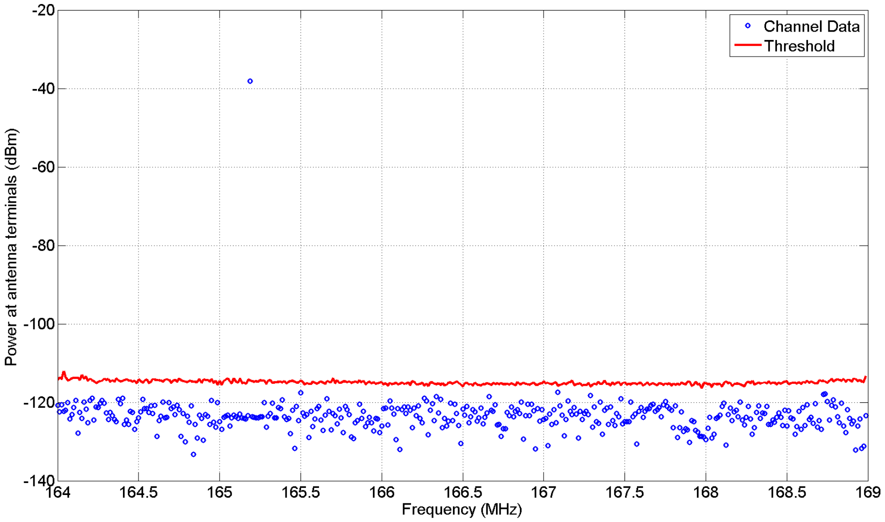

Figure 11. One-second sample without impulsive noise.

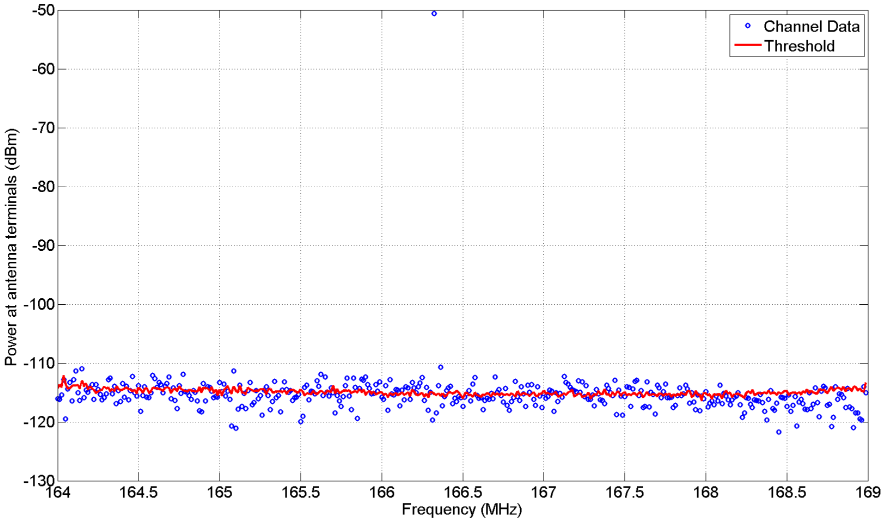

Figure 12. One-second sample with impulsive noise.

While every effort was made to minimize the effects of noise, there were occasional periods when impulsive noise raised the power in the entire band enough for individual channels to exceed the detection threshold but not high enough to trigger a “data discard.” It is difficult to determine precisely how often this occurred but it may have occurred enough to skew the mean usage values somewhat towards higher than expected usage values.

4.2 Noise Sidebands

Noise sidebands, due to either the measurement system local oscillator phase noise, jitter of the ADC, or sideband characteristics of the windowing function (and sometimes transmitter phase noise), can cause apparent signals adjacent to the channel occupied by a strong signal. In the case of these measurements, the noise sidebands produce additional apparent adjacent-channel signals for any real signal at least 60–70 dB above the system noise level. These additional responses decrease at the rate of about 0.5–1.0 dB per channel, for channels further away from the strong signal, and eventually these additional responses disappear below the measurement system noise. Because of the nature of these additional responses, they cannot be removed by using real hardware IF bandpass filters.

Since the noise sideband responses can affect a large number of additional channels, it is especially important to remove these false signals. These noise sideband responses are eliminated by measuring the levels of a typical noise sideband response and generating a "mask" that shows how much signal power to subtract (in linear form) from each channel located adjacent to a strong signal. Fortunately, this mask is typically quite stable and predictable. Unfortunately, the mask is probabilistic – having an amplitude distribution similar to Gaussian noise instead of giving a single value at each frequency. This means that 5–10 dB extra power must be subtracted to reliably discard the noise sideband responses. The major problem with subtracting so much additional signal power is that this process may also discard some real (but weak) signals located near the strong signal. Figure 13 shows the effect of noise sideband responses on measured signal levels, as well as the effectiveness of the algorithm in removing this signal contamination.

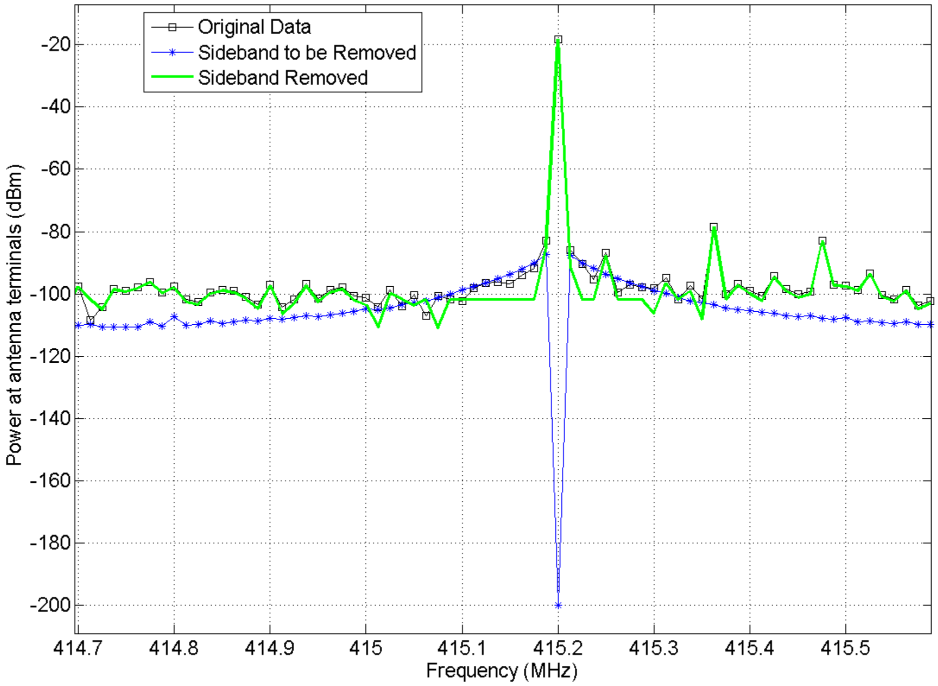

Figure 13. Removal of LO noise sidebands.

4.3 Detection Thresholds

Once imperfections due to impulsive noise, and sideband noise are removed, the next step is to determine the presence of real LMR signals. Determining channel traffic reduces to the problem of determining the portion of time that a signal is detected on the channel. The obvious way to determine whether a signal is present on a channel is to measure the received signal power. If the measured received signal power is substantially higher than some appropriately-selected threshold value, the channel must contain a signal. If it is substantially lower than this threshold value, the channel probably contains only system noise – or possibly noise plus a very weak signal. For our purposes, a signal below system noise is not likely to provide usable service to the LMR user, and therefore it should not be counted as real traffic at the measurement site.

The selection of an exact detection threshold presents some trade-offs. If a very low detection threshold is selected (i.e., close to system noise), some statistically expected noise bursts will occasionally exceed the selected threshold and cause a certain amount of usage to appear on all radio channels (even unused channels). On the other hand, if a much higher detection threshold is chosen, some weak (but functionally usable) signals may be left uncounted by the analysis program. The actual threshold level selected for determining channel usage is therefore a compromise between noise-caused false usage (low detection thresholds) and missed usage of weaker signals (high detection thresholds). In some cases, local external background noise can exceed the system noise, changing the optimal detection threshold level. Some quantitative insights to the selection of a detection threshold can be obtained by considering the amplitude probability distribution (APD) [1] for measurement system noise only. Figure 14 shows an APD for multiple single samples of system noise (solid line) and for multiple noise samples processed as median-of-5 values (dashed line). The solid line shows the expected straight line for Gaussian noise, using the "Rayleigh" graph scaling. The vertical scale is in "dB, relative to the median power." Therefore, both lines cross the "0 dB value" at the 50% point. The arithmetic mean level of power for the unprocessed system noise is about 2 dB above the median value. The graph shows how much of the time system noise is found at various amplitudes. For example, the graph shows that system noise will be 10 dB above the median value about 0.1% of the time. This means that if a detection threshold was selected at 10 dB above the median noise value (8.5 dB above the arithmetic mean noise power), a channel with no real signals would be expected to show a usage of about 0.1% – since the system noise alone exceeds the 10-dB level 0.1% of the time.

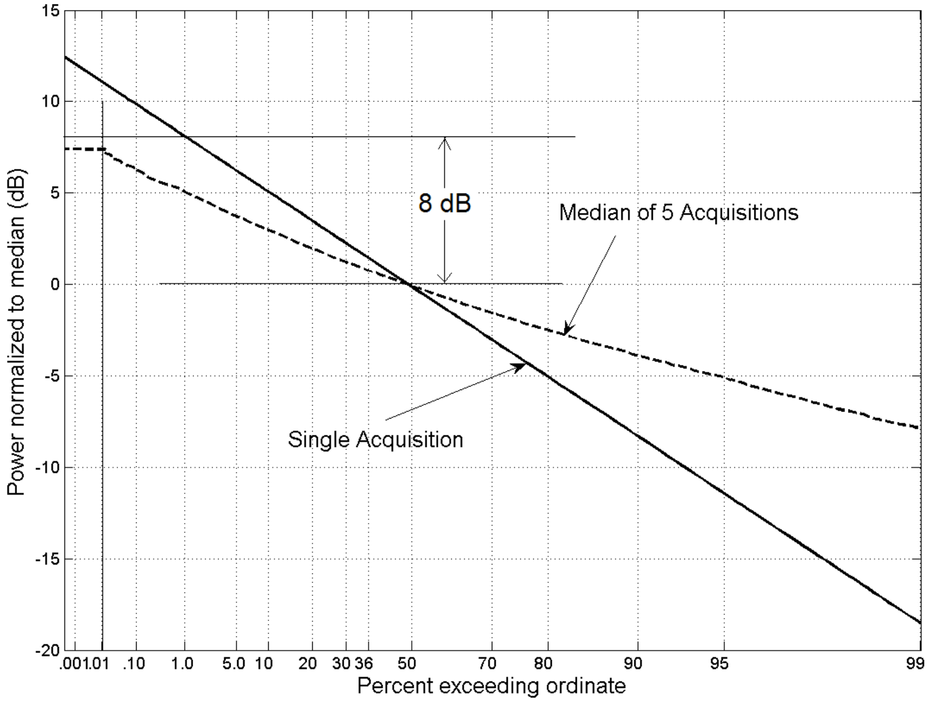

Figure 14. APD of system noise.

On the other hand, if all measurements are processed with a "median-of-5" routine, system noise appears to have an APD described by the dashed line. (The horizontal left-hand part of the curve is an anomaly caused by an insufficient number of measurements; assume that the actual dashed curve extends the general shape of the remainder of the line.) The dashed line is more horizontal (i.e., has fewer high-dB or low-dB samples), because the median-of-5 process requires that at least 3 of the 5 measurements be as large as the indicated value (versus only 1 of the 5 measurements for the single-measurement statistics). Therefore, large variations are less likely for the median-of-5 process. This allows the detection threshold value to be set closer to the median noise value without increasing the probability of false usage readings. For example, allowing 0.1% of false usage readings, the median-of-5 data occupancy threshold could be set near 6 dB, nearly a 4-dB improvement over the individual readings.

Presumably, this detection threshold could be improved even more by taking the median of even more readings – possibly a median-of-11 or median-of-21 readings. However, this would have considerably increased the measurement time and would eventually cause some problems with measurement of short messages. It should be noted that this median-of-5 process is also believed to have removed much of the amplitude variation due to signal modulation techniques and to have almost completely removed any effects from external impulsive noise which might otherwise be falsely detected as LMR signals.

In order to achieve a probability of no greater than 0.01% that an instantaneous system noise level will exceed the median system noise (as specified in Table 5), a minimum threshold of 8 dB above the median system noise was chosen for processing. This means that, at the minimum threshold, there is a probability of only 0.01% that system noise could give a false indication of an LMR signal. Additional higher thresholds were also chosen for processing for the purpose of displaying statistics on multiple threshold levels.

Due to TV Channel 7 out-of-band emissions, a correction to the minimum detection threshold is applied in the spectral region between 170.7–174 MHz. Figure 15 shows the median of multiple median-of-5 *Channel Power Values* in the frequency range 169–174 MHz. Because some of the out-of-band emissions from TV Channel 7 have a power as much as 10 dB above the threshold, the minimum detection threshold (where the threshold is 8 dB above the median system noise – square symbols in Figure 15) is not sufficient to exclude noise that could be falsely construed as LMR signals. Therefore, in the region between 170.7–174 MHz, the minimum detection threshold is determined by adding 9 dB to arithmetic mean noise power that is due to TV channel 7. This modified threshold is represented in Figure 15 by the solid line. Analysis of the TV out-of-band emission statistics showed that this modified detection threshold would allow the TV out-of-band emissions to be mistaken for LMR signals only in 0.01% of the measurements.

Throughout the analysis, statistics are reported for various thresholds – the minimum threshold, as well as several thresholds at 10 db intervals above the minimum. Because the minimum detection threshold in the region between 170.7–174 MHz has been increased by as much as 15 dB due to Channel 7 out-of-band emissions, all thresholds above the minimum detection threshold are set so that at no point is the threshold less than any other preceding "lesser" threshold for the same frequency channel. Because the detection threshold, especially the minimum threshold, is not constant across the frequency channels, threshold values given for statistical analysis are stated in terms of "mean" threshold power.

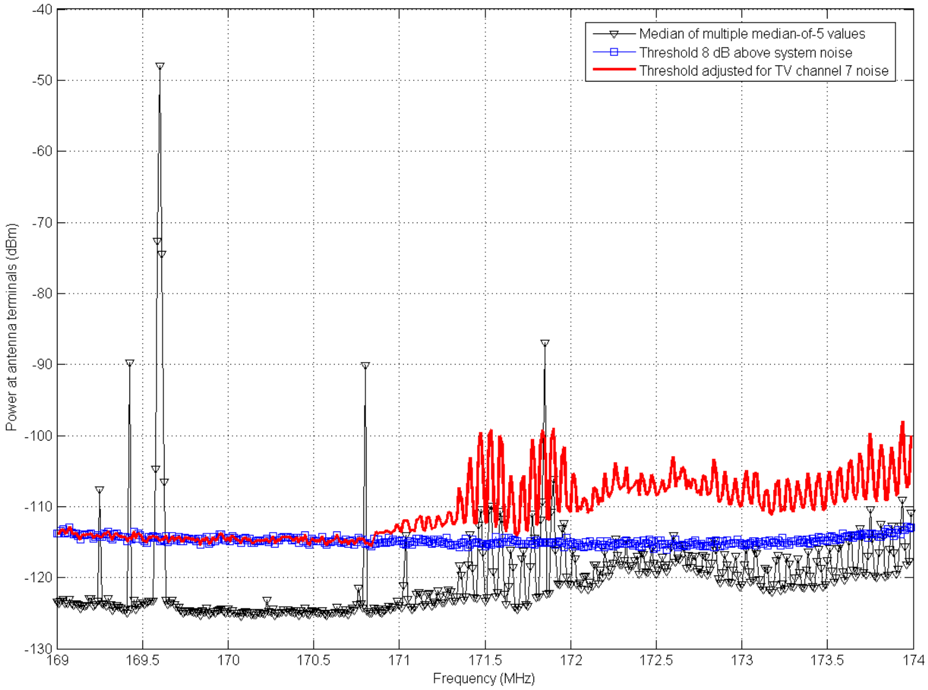

Figure 15. Thresholds and median of multiple median-of-5 data acquisitions.