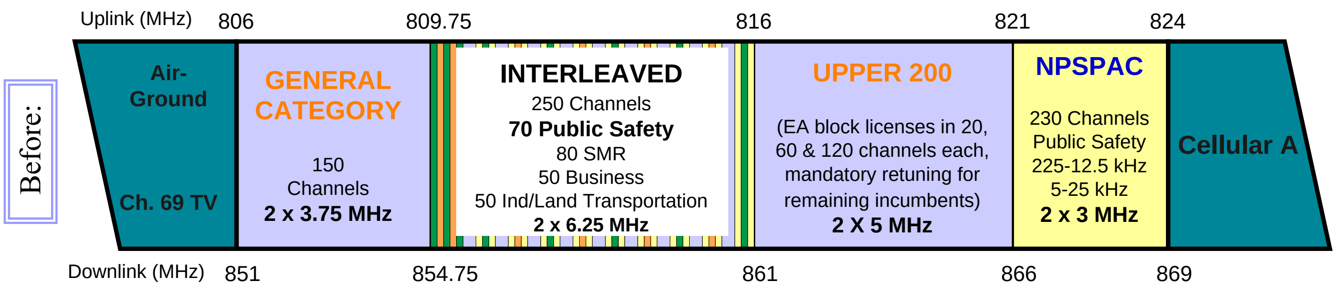
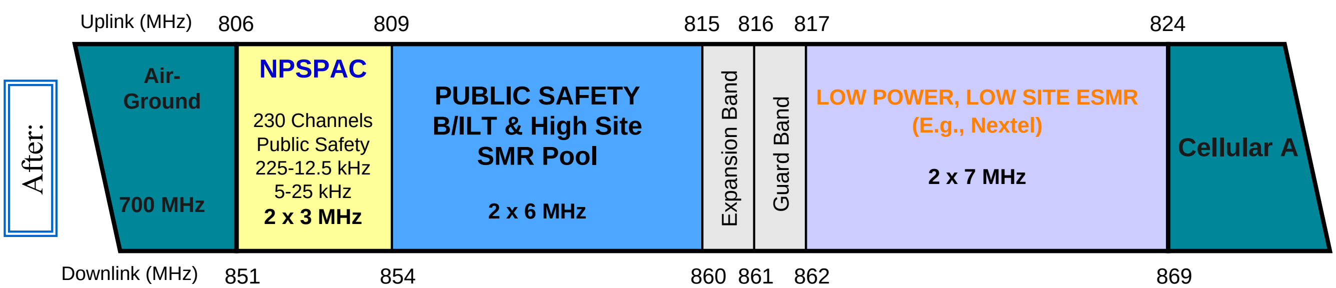
How Does the Consensus Plan Eliminate 800 MHz Public Safety Interference?





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1.0 Executive Summary

On July 8, 2004, the FCC adopted the Consensus Plan, a solution to the longstanding interference problem faced by 800 MHz public safety radio systems [17]. The process that led to this decision started on March 15, 2002 when the FCC released a Notice of Proposed Rulemaking, "Improving Public Safety Communications in the 800 MHz Band, Consolidating the 900 MHz Industrial/Land Transportation and Business Pool Channels (WT Docket No. 02-55)" [5]. As part of this proceeding, a group of seventeen public safety agencies and other interested parties developed the "Consensus Plan" which describes in some detail an approach for rebanding the 800 MHz band (851-869 MHz) with the goal of eliminating harmful interference from cellular operators inside the band (e.g., Nextel) and the A-Band cellular carrier, located immediately above the band [8].

Advocates of the Consensus Plan argued that public safety and cellular radio services are inherently dissimilar and must be separated to eliminate harmful interference [8]. Not all agreed with this assertion. Among other points, opponents of the Consensus Plan argued that the improvements created by adoption of the Consensus Plan, if any, are small and inadequate and therefore the Consensus Plan does not solve the interference problem. One specific criticism is that thousands of potentially harmful intermodulation products still exist after rebanding.

The purpose of this paper is to quantify the interference improvements realized by the Consensus Plan and show specific implementations of the Consensus Plan that will completely eliminate harmful out-of-band emissions and 3rd order receiver intermodulation products from cellular carriers. Specifically, we will show the following:

- The current band plan, with its four public safety/cellular band edges, presents an insurmountable problem. Rebanding is the only effective way to eliminate out-of-band emissions and receiver intermodulation created by Nextel and the A-Band cellular carrier.

- It is true that after rebanding, there are still thousands of potentially harmful intermodulation products.

- These intermodulation products can be eliminated completely through the use of a simple algorithm to create intermodulation-free channel sets at cell sites.

- Co-location interference, created when Nextel and the A-Band cellular carrier occupy the same site or are in close proximity, remains a problem after rebanding. Co-location interference comprises a small fraction of the total problem and it can be eliminated by implementing some simple, low-cost techniques which are only feasible after rebanding.

We also consider the switchable attenuator, proposed by Motorola to mitigate receiver intermodulation interference. When applied to real-world interference measurements, we find that improvements are very small. Furthermore, any improvements realized are sensitive to the value of attenuation applied. Because the optimal attenuation will vary by city and by cell site, one value of attenuation cannot be best under all conditions. We find that the attenuator can only be used when the public safety signal is relatively strong, but the intermodulation problem occurs in practice when the public safety signal is relatively weak.

Contrary to the critics' assertions, rebanding is the only practical way to solve the 800 MHz interference problem. It creates the necessary separation between dissimilar services and makes it possible to completely eliminate harmful out-of-band emissions and 3rd-order intermodulation products.

2.0 Background

To give the reader some background on the 800 MHz interference problem, this section addresses five subjects: an introduction to the physical problem, an explanation of the two main interference types, a brief description of the Consensus Plan, a discussion of IM-free channel sets, and an analysis of a switchable attenuator to mitigate receiver IM.

A. Problem Statement

The Nextel interference problem is an example of the *near-far* problem. Radio receivers operating in the same band or in adjacent bands have limited ability to reject interference. Strong signals from 800 MHz cell sites near the public safety receiver can and do cause harmful interference. The relatively weak signal from the public safety transmitter site, often located miles away, cannot overcome this strong interference. Usually the offending Nextel or A-Band cellular carrier site has relatively low antenna heights, creating strong signals on the street.

The City and County of Denver has faced this problem for over three years. Several interim measures have been implemented by Nextel, to include auto-tune cavity combiners and Nextel site "tuning" to protect Denver control channels from intermodulation. We use the term *tuning* to refer to the selection of intermodulation-free channel sets at Nextel cell sites. These measures have only achieved limited success. A more complete discussion of Denver's experience is found in its report and comments filed with the FCC [9], [10]. It is Denver's position that public safety and cellular radio are inherently dissimilar services and the 800 MHz interference problem cannot be solved until these dissimilar services are separated through rebanding.

When dissimilar services are separated, problems can still occur at band edges. For this reason, public safety should ideally occupy just one continuous band. Today, public safety shares the band 854.9625 - 860.9875 MHz and occupies the band 866-869 MHz (NPSPAC) [12]. Some public safety agencies also use General Category channels from 851 to 854.75 MHz. Even if public safety was the sole user of 855-861 MHz, there would still be four band edges where harmful interference could occur. A better solution is to combine NPSPAC with other public safety channels in a single public safety band. A guard band is still necessary to prevent interference at the band edge, but only one guard band is needed if public safety is moved to the bottom of the existing SMR band.

B. Interference Types

There are many types of harmful interference, including transmitter intermodulation, receiver intermodulation, receiver desense, and passive intermodulation (i.e., "rusty bolt" phenomenon). There are no universally accepted definitions for interference types, so it is necessary to define terms. In the case of Nextel interference, experience has shown that harmful interference occurs in the portable radio's receiver on the downlink (repeater site to portable) and falls into two categories:

- *Out-of-Band Emissions* comprise radio frequency energy that falls outside the assigned channel for the transmitter. Out-of-band emissions include radio carrier harmonics, transmitter intermodulation products, and broadband transmitter "noise" that is typical of digital radio transmitters. A detailed treatment of the effects of out-of-band emissions is found in Appendix A.

- *Receiver intermodulation* is a non-linear combination of two or more interfering signals inside the receiver front-end (low-noise amplifier and/or mixer).

A block diagram for a typical public safety radio receiver is shown in Figure 1. Public safety receivers are vulnerable to receiver intermodulation because the front-end bandpass filter must pass all frequencies from 851 to 869 MHz. Nextel frequencies fall within this same band, so the low-noise amplifier that follows the bandpass filter is exposed to strong interfering signals that can mix within the amplifier.

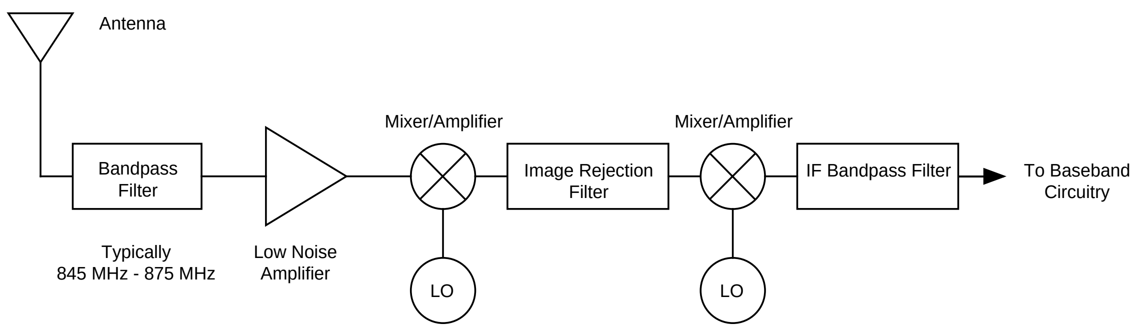

Figure 1 - Typical Public Safety Receiver Front-End

Mathematically, an intermodulation (IM) product between two interferers with frequencies f_1 and f_2 can be represented by the following general equation:

$$f_{im} = nf_1 + mf_2$$

where n and m are non-zero integers. The order of the product is simply the sum of the absolute values of the coefficients, $|n| + |m|$.

For example, two interferers operating at 861.4875 and 862.4875 will create the following third-order intermodulation products inside the 800 MHz band:

2 (861.4875 MHz) - 862.4875 MHz = 860.4875 MHz

$$2\,(862.4875 \text{ MHz}) - 861.4875 \text{ MHz} = 863.4875 \text{ MHz}$$

An important rule-of-thumb for two-transmitter 3rd order products is that the products will fall exactly $|f_1 - f_2|$ below the lower frequency (f_1) and above the higher frequency (f_2).

Third-order products can also be created by three carriers. These products have the form A + B - C rather than 2A - B. Three-carrier products are more numerous than two-carrier products because there are $N(N\text{-}1)(N\text{-}2)/2$ total three-carrier products and only $N(N\text{-}1)$ two-carrier products, where N is the number of transmit frequencies. Assuming equal amplitude fundamentals, three-carrier products are 6 dB stronger than two-carrier products [11].

In general, given a set of potential interfering frequencies that fall within the range $[f_{min}, f_{max}]$, no third-order product can fall farther than $|f_{max} - f_{min}|$ below f_{min} or above f_{max}. Mathematically, we can state a sufficient condition to preclude 3rd order IM products as

$$f_r < 2f_{min} - f_{max} \text{ or } f_r > 2f_{max} - f_{min}, \quad (1)$$

where f_r is the nearest receive frequency requiring interference protection. This principle is shown graphically in Figure 2.

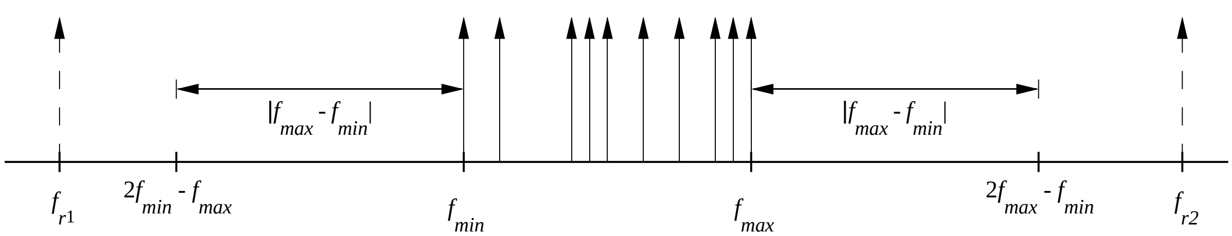

Figure 2 - Range Limits of 3rd Order IM Products

Thus, a simple way to eliminate receiver intermodulation is to first create a guard band between dissimilar services and then ensure frequency sets for the interfering service (e.g., Nextel) have a span no greater than the span of the guard band. Because guard bands waste spectrum, it is important to limit the number of band edges between the two dissimilar services so only one guard band is required.

For typical public safety receivers, receiver intermodulation is not a problem unless the interfering signals exceed -50 dBm *and* the desired signal is relatively weak. Because public safety receivers have passbands that include the entire 800 MHz band (851-869 MHz), interfering Nextel signals are not attenuated at the receiver front-end.

Laboratory measurements show that 5th and higher order intermodulation products are much weaker than 3rd order products (in some cases, 25 dB weaker) [9]. Thus, it is reasonable to focus mitigation efforts solely on 3rd order products.

Some engineers use the term "receiver overload" to describe strong interfering signals at the radio receiver that do not have the mathematical relationship to create harmful intermodulation products. These interferers may compress the front-end amplifier, activate automatic gain control circuits (AGC) and degrade the receiver sensitivity. Laboratory measurements of several of Denver's M/A-COM portable and mobile receivers show that receiver overload is a minor problem and the dominant problem is receiver intermodulation. In other words, the public safety receiver is robust in the presence of a single strong interferer, but vulnerable to multiple interferers if they create intermodulation products that fall on active frequencies.

C. The Consensus Plan

The Consensus Plan seeks to eliminate harmful 800 MHz interference from cellular carriers primarily through a rebanding of the 800 MHz band. Today, the band consists of four subbands as shown in Figure 3 ("Before").

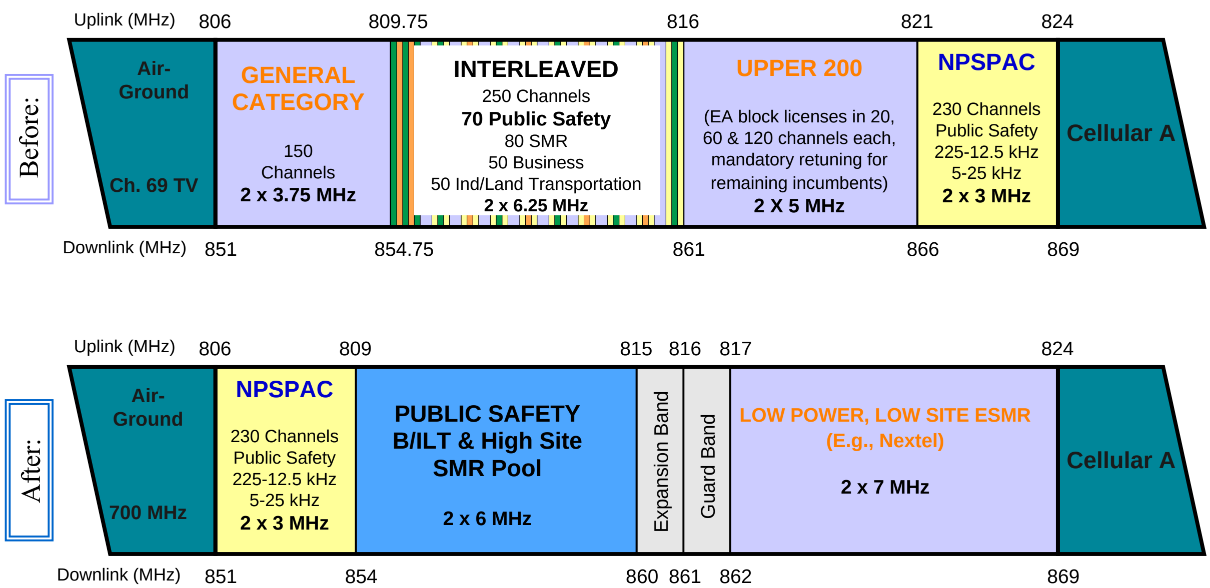

Figure 3 - Consensus Plan Spectrum Allocation[1]

Note that public safety channels occur in the interleaved band and in the NPSPAC band. Interleaving alone creates insurmountable problems, but the four band edges also create

[1]The 2 MHz between 860 and 862 MHz is subdivided into an Expansion Band (860-861) and a Guard Band (861-862). No public safety system is required to remain in or relocate to the Expansion Band; although they may do so voluntarily. The level of protection afforded in the Expansion Band creates the effect of a pseudo-guard band.

problems. The proposed rebanding in Figure 3 (“After”) reduces the band edges from four to one and effectively creates a 2 MHz guard band where Nextel has agreed to certain significant service restrictions. This pseudo-guard band has a twofold purpose: it allows bandpass filters at the cell site to roll off and it enables Nextel to create channel plans with intermodulation products that fall in the guard band, but not on public safety channels.

D. Creating IM-Free Channel Sets Without Rebanding

We have already shown that a straightforward way to eliminate third-order IM products on public safety channels is to separate dissimilar services by a guard band and then limit each sector’s channel set to a narrow band that is no wider than the guard band. This solution requires rebanding. But is it possible to create IM-free channel sets under the existing conditions with four band edges, no guard bands, and interleaved channels? Practical experience in Denver shows that it is not possible to create IM-free channel sets without eliminating large numbers of Nextel and A-Band cellular channels. To see why this is true in general, let’s consider the theoretical aspects of the problem:

Some researchers have developed methods for creating intermodulation-free channel sets, but they assume that interfering frequencies and frequencies to be protected are in the same set. An application where this condition might apply would be simplex channels. See [2], [3] and [4]. In our case, the frequencies to be protected (e.g., 70 public safety channels) do not contribute to the IM products and must be treated separately from the cellular carrier’s channels. Our problem is more complex and we are not aware of any method for creating IM-free sets other than trial-and-error.

Unfortunately, an exhaustive trial-and-error search for IM-free channel sets is not practical because the number of combinations is too large. Consider that for a set of N transmit frequencies, there are $N!$ ordered sequences to check.[2] Nextel has 366 licensed channels in Denver. If we just consider the 97 Nextel channels in the interleaved subband (854.7375-860.7875 MHz), there are $97! = 9.6 \times 10^{151}$ ordered sequences. Even if we consider just one sector of 15 channels at a time, there are

$$\binom{366}{15} = \frac{366!}{(366-15)!15!} = 1.6 \times 10^{26}$$

ways to select 15 channels from a set of 366. But many sequences, perhaps most, may result in the same IM-free channel set.

We can’t check all ordered sequences, but we can learn some important behaviors by considering examples. We first need an approach to finding an IM-free channel set given a

[2] $N! = N(N-1)(N-2) \cdots 3 \cdot 2 \cdot 1$

set of *N* transmit frequencies.

One approach is the following:

Step 1: Select one of the *N*! ordered sequences of transmit frequencies.
Step 2: Select the first channel in the sequence, *A*.
Step 3: Select the second channel, *B*.
Step 4: Compute 2*A*-*B* and 2*B*-*A* products.
Step 5: If either product falls on one of the public safety channels, delete B from the list.
Step 6: Select the third channel, *C*. If *B* is still in the list, compute both three-carrier and two-carrier third-order combinations of *A*, *B*, and *C*.
Step 7: Continue until all channels in the ordered sequence have been checked and any that create IM "hits" are eliminated.

At the end of this process, the surviving channels form an IM-free set. Note that the first channel in the sequence is always in the resulting IM-free set (if one exists). Thus, if the first channel is a particularly bad choice, the IM-free set will be small.

Let's consider some examples:[3]

<u>Example 1 - Nextel Interleaved and Public Safety</u>: Given the 97 Nextel channels in Denver that fall in the interleaved subband (See Appendix E), find an IM-free set for the 70 public safety channels (per FCC 90.617).[4] The first frequency in the sequence is critical in this example. If we start with 854.7375 MHz, we find the IM-free set has only *three* frequencies: 854.7375, 854.8125, and 855.4375. If, on the other hand, we start with 854.8125 and place 854.7375 at the end of the sequence, we get an IM-free set of 30 frequencies. Clearly this is an improvement, but Nextel will not be satisfied using only 31% of its channels.

This example assumes IM products of interest fall precisely on frequency. Because a 3rd order product has a nominal bandwidth of three times the fundamental frequency bandwidth, a more realistic scenario is to place a window of at least 25 kHz on either side of the IM product. When we do so, the IM-free set reduces from 30 to only 9 channels, or less than 10% of the original set.

<u>Example 2 - Nextel Denver Channels and Public Safety</u>: Now consider all 366 of Nextel's licensed frequencies in Denver as potential interferers to the 70 public safety channels. If we start with Nextel's first channel, 851.0125 MHz, we get an IM-free set of 114 frequencies. Interestingly, none falls in the band 853-863 MHz which includes the interleaved channels. In other words, because we started at the bottom of the 800 MHz

[3]Pericle Communications hs written a computer program to make the calculations required for these examples.

[4]This example is primarily of academic interest because out-of-band emissions preclude the use of most interleaved channels, regardless of the IM situation.

band, the IM-free channel set requires a *de facto* band separation and guard bands at the two edges (855 and 861 MHz).

Example 3 - A-Band Cellular and NPSPAC: Given the 199 A-Band cellular channels below 875 MHz, find an IM-free channel set that protects the 230 NPSPAC channels. Because A-Band cellular IM products will not in general fall on the center of a NPSPAC channel, use a one-sided window of 12 kHz.[5] If we start with 869.04 MHz, the IM-free set has only *four* frequencies: 869.04, 869.07, 872.16, and 872.19 MHz. Of course, starting at the band edge is probably a poor choice.

Example 4 - A-Band Cellular and NPSPAC, Reverse Order: Re-do example 3, but place the cellular channels in reverse order, starting with 874.98 MHz. Now the IM-free set has 100 channels, but they are the sequential channels from 872.01 to 874.98 MHz. Because this band is less than 3 MHz wide and starts 3 MHz above the highest NPSPAC channel, we have essentially created a guard band. In other words, we would get the same result by applying the simple rule developed earlier in this section. In fact, by running any of non-interleaved cases where cellular (Nextel or A-Band) is adjacent to public safety, we find the only apparent feasible solution is one where a *de facto* guard band is created.

These examples are not exhaustive, but we can still draw two important conclusions:

- Under the existing 800 MHz band plan, IM-free channel sets are small relative to the number of licensed channels. In other words, large numbers of Nextel and A-Band cellular frequencies are not usable if third-order products are to be eliminated.

- The largest IM-free channel sets are created when guard bands exist at band edges.

E. Switchable Attenuators

In Motorola's Docket 02-55 filings of May and June, 2003, the company proposed the use of an automatic switchable attenuator to reduce or eliminate harmful 3rd order IM products in the public safety receiver [14], [15], [16]. The basic concept is not new. It is well known that an attenuator will reduce receiver-generated 3rd order intermodulation products by 3 dB for every 1 dB of attenuation [13]. Thus, a large improvement in intermodulation performance is achieved for a small loss in receiver sensitivity.

While the basic theory is sound, the implementation of a switchable attenuator is far from certain in a dynamic, multipath fading environment. In Appendix B, we treat this problem in some detail and conclude that the benefits of an ideal switchable attenuator are small and a practical attenuator is likely to do more harm than good.

[5] Thus, we capture the nearest intermodulation product, but for simplicity, we don't fully consider the bandwidth of the product.

In the case of OOBE, the switchable attenuator reduces the OOBE interference by the same amount it reduces the desired signal, leaving the *C/I* unchanged. It does not provide a 3:1 improvement as it does in the intermodulation case. Therefore, the switchable attenuator provides no improvement of OOBE and only degrades the sensitivity of the receiver by the amount of the attenuation.

3.0 Frequency Re-Use Plans in Cellular Networks

Cellular radio networks are inherently frequency *re-use* networks. Frequency re-use enables the cellular carrier to maximize spatial call density (calls per square kilometer) by organizing co-channel cell sites according to a cellular pattern. The particular re-use pattern depends on the minimum carrier-to-interference ratio (*C/I*) required by the cellular airlink standard. The original analog FM cellular network, developed by Bell Labs in the 1970s, required a minimum *C/I* of 17 dB and used an *N*=7 re-use pattern [1]. An *N*=7 pattern is shown in Figure 4. Other commonly used re-use patterns are *N*=3 for GSM and *N*=1 for CDMA.

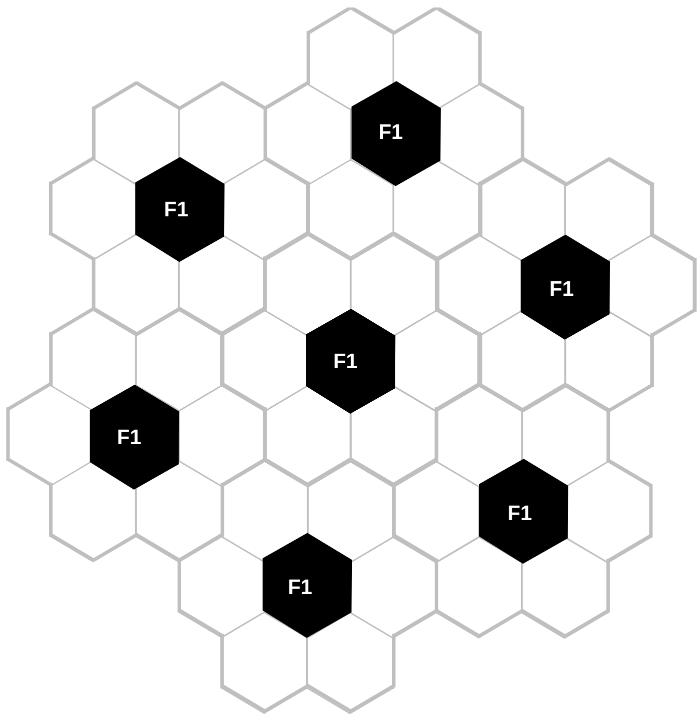

Figure 4 - *N*=7 Cellular Pattern
(Cells using "F1" frequency set are co-channel)

Nextel employs Motorola's iDEN digital cellular airlink standard. iDEN uses Time Division Multiple Access (TDMA) with 25 kHz-wide channels. Specific details of this airlink standard are proprietary, but Nextel engineers tell us that an *ad hoc* re-use pattern is used. In other words, the re-use pattern may vary between *N*=3 and *N*=12, depending on the propagation environment and antenna sectoring scheme used in a particular market. Further, unless cavity combiners are used at the cell site, Nextel can combine any combination of licensed frequencies, including adjacent channels (i.e., minimum channel spacing of 25 kHz). This flexibility will be important after re-banding because it enables

Nextel to create IM-free frequency sets simply by limiting the range of frequencies used in each sector. This subject is treated in detail in later sections of this paper.

Early cellular systems used cavity filter combiners so many base station transmitters could share a transmit antenna. Cavity filter combiners require a minimum channel separation to work because of the finite roll-off of the filter. A rule-of-thumb for minimum separation is 250 kHz. For closer channel spacing, other combining techniques are used, such as linear amplifier combining (LAC) and hybrid combining.

4.0 Analysis

Recall there are two types of harmful interference under consideration: out-of-band emissions (OOBE) and receiver intermodulation. Our analysis will consider both types under three categories: Nextel, A-Band cellular, and co-located. Please note that our examples will focus on the 70 public safety channels (Part 90.617) and the 230 NPSPAC channels, but the same general principles and conclusions apply to other channels, including the General Category channels (851.0125 - 854.7625 MHz), where many public safety users operate.

A. Nextel Interference

Nextel out-of-band emissions cannot be eliminated without rebanding. To see why, consider the spectrum allocation in Denver, Colorado which is typical of other cities. In Denver, Nextel is licensed for 166 channels between 851 and 861 MHz and 200 channels between 861 and 866 MHz. Of the 166 channels in the lower part of the band, 97 fall in the same subband occupied by 20 of Denver's public safety channels (855-861 MHz). Because of the way this subband is interleaved, every one of Denver's channels is 150 kHz or closer to at least one of 81 Nextel channels in this subband. It is not feasible to filter frequencies closer than 150 kHz with cavity combiners, so there is no practical solution to this problem other than rebanding.

The second type of interference is receiver intermodulation. An interleaved band makes it impossible for Nextel to create IM-free channel sets without discarding large portions of its spectrum, which it is under no obligation to do under the existing FCC rules. We already considered the problem of creating IM-free channel sets, but we did not quantify the number of IM products that occur with channel sets that are *not* IM-free. To better understand the extent of the problem, it is useful to calculate the number of potential intermodulation products that occur on the 70 public safety channels in the interleaved band. Consider two cases: before and after rebanding.

<u>Case I - Status Quo in Denver, Colorado (typical)</u>

In Denver, Nextel is licensed for 166 channels from 851 to 861 MHz and 200 channels from 861 to 866 MHz ("upper 200") for a total of 366 channels.[6] If we compute the third order products that fall directly on the 70 public safety channels in the interleaved sub-band (per FCC 90.617), we get the following results:

[6]Because of the FCC's Part 90 rules on co-channel interference in the SMR band, some of these frequencies may not be usable at all locations within the metropolitan area. For this analysis, we make the simplifying assumption that all frequencies are available. The 166 channels in the 851-861 MHz subband were provided to us by Nextel in 2002 and are subject to change as the company acquires more spectrum.

Total 3rd order products:	1,942,536
Type 2A-B:	7,097
Type A+B-C:	1,935,439

Note that the vast majority of products are of the type A+B-C. For this case, the distribution of IM products over the 70 public safety channels is roughly uniform. The mean number of IM hits per channel is 15,903. The minimum, maximum and standard deviation are 8,873; 21,817 and 3,264; respectively.

Case II - Post Rebanding (applies nationwide)

Now Nextel is limited to 280 channels, all in the band from 862 to 869 MHz. If we consider the 70 existing public safety channels, we get the following results:

Total 3rd order products:	364,460
Type 2A-B:	4,416
Type A+B-C:	360,044

Thus, rebanding reduces the number of potential IM products by 81%. But there are still too many for interference-free operation. Our goal and measure of success is *no* 3rd order IM products on public safety channels.

IM Products as a Function of Frequency. Let's examine the distribution of IM products as a function of frequency to see if there are any patterns that can be exploited to create IM-free frequency sets.

After rebanding, the distribution of IM products over the 70 public safety channels is non-uniform. The number of products rises exponentially as the receive frequency increases toward the boundary at 862 MHz. This behavior is shown in Figure 5.

We can also plot the distribution of IM products as a function of transmit frequency. This plot is shown in Figure 6.

The purpose of plotting these two distributions is to try to identify any obvious patterns or groups of frequencies that are either unaffected (receive) or do not contribute to IM products (transmit). There are virtually none. We see from the two plots that there are only two IM-free frequencies in the receive set and none in the transmit set. Also, the number of IM hits per frequency is very high (in the thousands) in almost every case.

So, the critics are correct on this point: There are still thousands of potential intermodulation products after rebanding.

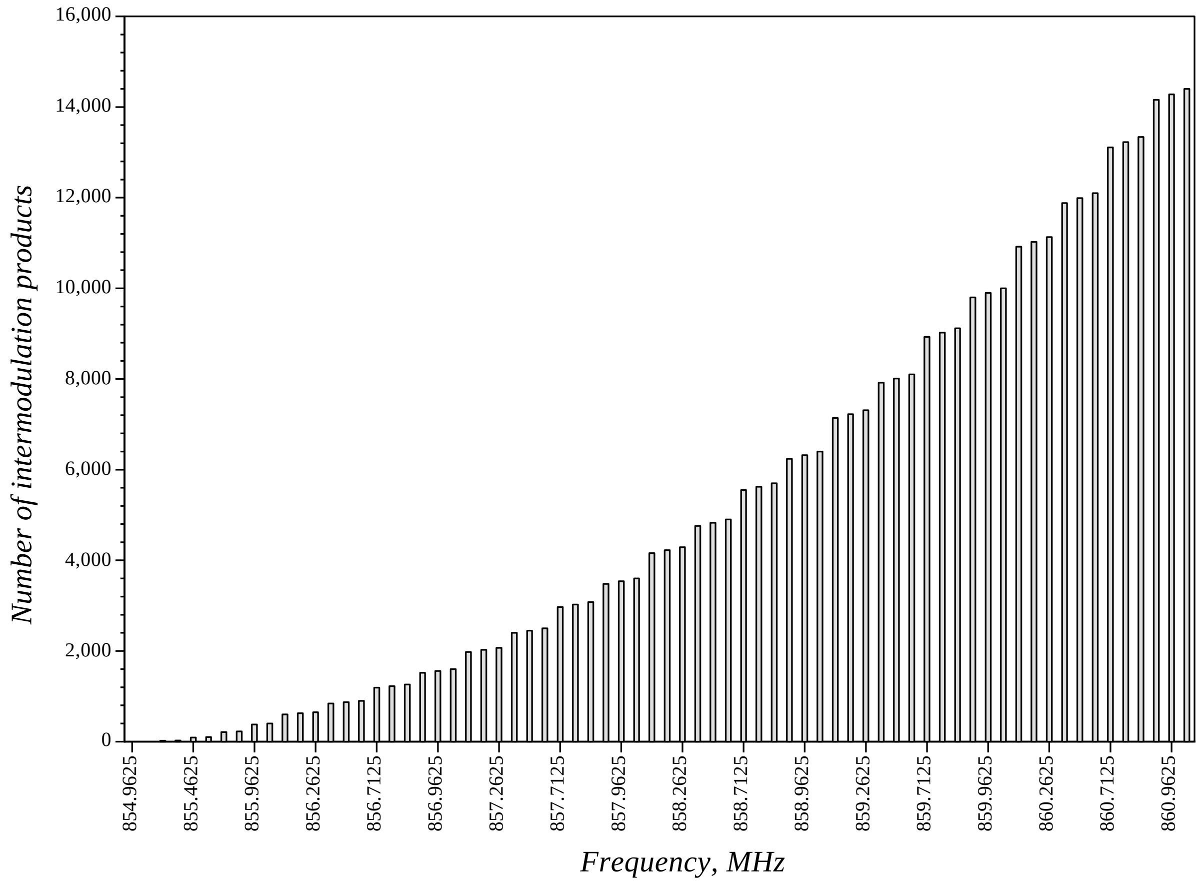

Figure 5 - 3rd Order Products Falling on Each Receive Frequency (Case II)
(These are the 70 public safety channels per FCC 90.617)

The only practical solution is to limit the cellular carrier's frequency set to narrow bands that cannot create IM products outside the guard band. We know from Section 2 that by doing so, we can *completely* eliminate 3rd order IM products on public safety channels. This approach is only feasible after rebanding when there is contiguous spectrum. But how do we do so without severely limiting Nextel's use of their spectrum? We answer this question in Section 5 of this paper.

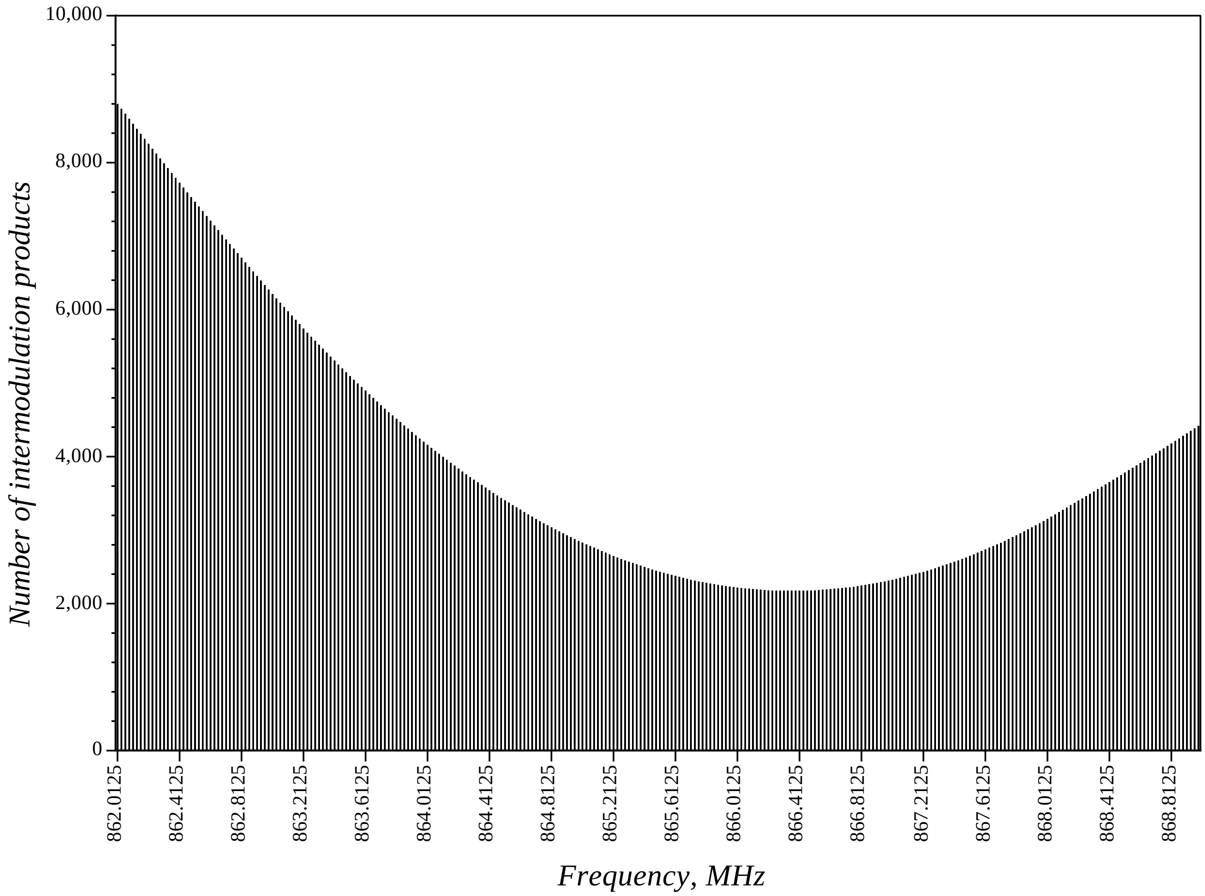

Figure 6 - 3rd Order Products Attributable to Each Transmit Frequency (Case II)

B. A-Band Cellular Carrier Interference

The A-Band cellular carrier operates in the bands 869-880 MHz and 890-891.5 MHz. The NPSPAC band falls immediately below, occupying 866-869 MHz. Most of the new portable and mobile public safety radios employ bandpass filters that begin to roll off at 875 MHz. Frequencies above 875 MHz will be attenuated and third-order products in the receiver will be further attenuated by a 3 to 1 ratio in dB. Thus, we are mostly interested in cellular channels that fall below 875 MHz. AMPS, CDPD, and TIA-136 airlink standards employ 30 kHz channels in this band. GSM and CDMA employ 200 kHz and 1.25 MHz channels, respectively. In Denver, the A-Band carrier employs AMPS, TIA-136 and GSM.[7]

[7]GSM introduces signal characteristics that both increase and decrease the likelihood of harmful interference. The 200 kHz GSM channel creates an intermodulation product with a wider bandwidth, increasing the probability an intermodulation product will overlap a Denver channel. Relatively high-power and high-duty cycle data services such as GPRS and EDGE also increase the likelihood of harmful interference. However, there are fewer GSM channels than TIA-136 channels and GSM requires a smaller *C/I* than TIA-136 for the same level of performance. Also, GSM uses downlink power control which only recently appeared in TIA-136 systems.

Let's consider the case of 30 kHz channels. There are 199 30 kHz channels between 869.04 and 874.98 MHz. Most NPSPAC channels are spaced at 12.5 kHz and in general, IM products created by cellular channels will not fall precisely on the center of a NPSPAC channel. Because the nonlinear mechanism that creates IM products is a multiplication in the time domain, it must be a convolution in the frequency domain. Convolving two or three radio carriers in a third order product causes the bandwidth to increase to roughly three times the original bandwidth. To make a fair comparison between A-Band cellular interference and Nextel interference, we must create an interference "window." For this discussion, we will use a window of 12 kHz. Thus, unless an IM product falls on the center of a NPSPAC channel, the product will affect two NPSPAC channels simultaneously.

The first 199 cellular channels alone cannot create IM products on any of the 70 public safety channels in the 855-861 MHz band because the 6 MHz span (869-875 MHz) does not exceed the 8 MHz gap between public safety and A-Band cellular. Only the NPSPAC channels are affected.

Case I - Status Quo (nationwide)

There are 199 A-Band cellular channels that are potential interferers. If we compute the third order products that fall within 12 kHz of any of the 230 NPSPAC channels we get the following results:

Total 3rd order products:	991,202
Type 2A-B:	12,775
Type A+B-C:	978,427

Note that whenever an IM product affects two NPSPAC channels simultaneously, it is counted twice. With almost 1 million potential IM products on public safety channels, the potential impact of the A-Band cellular carrier is comparable to Nextel's impact on the 70 public safety channels in the interleaved band.

Case II - After Rebanding (nationwide)

After rebanding, all NPSPAC channels will move to the 851-854 MHz subband. It is impossible for any of the first 199 cellular channels to create 3rd order products in this subband or in the 854-861 MHz band. OOBE is eliminated by existing bandpass filters at the cell site. Thus, rebanding eliminates both OOBE and receiver IM for the A-Band cellular carrier when not co-located with Nextel.

C. Co-Location Interference

Co-location of Nextel and the A-Band cellular carrier introduces new receiver intermodulation products. Even if both carriers operate with IM-free channel sets, there are still intermodulation products between the carriers that will fall on public safety channels. Rebanding alone does not solve this problem.

For example, consider the following co-location scenario:

- Nextel's sector operates within a 1 MHz band from 864 to 865 MHz
- The A-Band sector operates within a 3 MHz band from 869-872 MHz

Alone, neither carrier can create 3rd order IM products below 861 MHz. However, if strong signals from both carriers appear in the receiver front-end simultaneously, harmful IM products can occur in a wide band from 856 to 861 MHz, affecting 60 of 70 public safety channels.[8]

Consider a more specific example: Assume Nextel and the A-Band carrier are operating with the channel sets shown in Table 1.

Table 1 - Co-Location Example

Nextel	A-Band Carrier
863.0125	869.04
863.1125	869.46
863.2125	869.88
863.3125	870.30
863.4125	870.72
863.5125	871.14
863.6125	871.56
863.7125	871.98
863.8125	872.40
863.9125	872.82
864.0125	873.24
864.1125	873.66
864.2125	874.08
864.3125	874.50
864.4125	874.92

Again, in isolation, each carrier's channel set is IM-free, but co-location creates hundreds of IM hits. The results of the IM study for the 70 public safety channels (855-861 MHz) is the following (window = 12 kHz):

[8]The low frequency in this range is found from 2(864) - 872 = 856. The high frequency is found from 2(865) - 869 = 861.

Total 3rd order products:	427
Type 2A - B:	31
Type A + B - C:	396

Note that even with a relatively small number of channels (30 total), the number of IM products falling on public safety channels is over 400. These products are spread nearly uniformly across the 70 public safety channels. The mean number of hits per public safety channel is 6. The minimum, maximum and standard deviation are 0, 15, and 3.5, respectively. Only seven of 70 channels had zero hits.

Thus, a small number of interferers creates a large number of harmful IM products. With many A-Band carriers using dynamic channel allocation with large channel sets, it does not appear practical for Nextel and the A-Band carrier to jointly select compatible channel sets except perhaps in a few isolated cases.

The situation improves after rebanding. Assuming channels above 875 MHz are adequately attenuated in the receiver front-end, one solution to co-location interference is to restrict Nextel's frequency set at co-located sites to 867.5 to 869 MHz (60 channels). The entire span is then 867.5 to 875 MHz or 7.5 MHz total. Under this condition, third-order products cannot fall below 860 MHz and therefore cannot affect public safety channels in the fully protected spectrum (851-860 MHz).

5.0 Solutions

In previous sections we showed that OOBE and receiver intermodulation cannot be eliminated in any practical way without rebanding. We also showed that rebanding alone does not solve the problem because thousands of potential intermodulation products still exist after rebanding. Instead, rebanding creates a situation where filtering to eliminate OOBE and the creation of IM-free channel sets are feasible. In this section, we propose specific implementations of the Consensus Plan that completely eliminate OOBE and receiver intermodulation on public safety channels.

Our proposed solutions address the three categories of interference: Nextel, A-Band cellular carrier, and co-location interference.

A. Nextel Solutions

After rebanding, the solution to OOBE is straightforward. Each of Nextel's transmit antenna sectors should have a cavity bandpass filter designed to pass 862-869 MHz and reject all frequencies below 860 MHz by at least 45 dB. Such a filter is well within the state-of-the-art and several U.S. manufacturers are capable of supplying them for reasonable cost.

The solution to receiver intermodulation is also straightforward. Our objective is to create channel sets using all of Nextel's rebanded channels (280 total) without creating any 3rd order IM products on or adjacent to a public safety channel. For each Nextel channel set with a minimum frequency, f_{min}, the maximum frequency, f_{max}, must obey the following rule:

$$2f_{min} - f_{max} > 860 \text{ MHz} \qquad (2)$$

There are numerous feasible solutions to this problem. Using a 7-cell, sectored re-use pattern with 280 total channels, Nextel only requires 280/7/3, or 13 channels per sector. A 3-cell reuse pattern requires 31 channels per sector. For an iDEN system, 3-cell reuse is likely to be worst-case. We know that Nextel can combine adjacent channels on the same sector antenna. Thus, thirteen channels require only 325 kHz and thirty-one channels require 775 kHz. But the proposed effective guard band is 2 MHz, so feasible solutions must exist.

Some potential frequency sets are listed in Table 2.

Note from Table 2 that we have limited the range of frequencies in each cell site (3 sectors total) so IM products that would occur between sectors still fall above 860 MHz. Thus, a public safety receiver operating in the overlap region between sectors is still protected.

Table 2 - Potential Frequency Sets (Compatible with N=3 Reuse) (A,B,C = cell, 1,2,3 = sector)						
Set	**Span**	**Channels**	**fmin (MHz)**	**fmax (MHz)**	**Lowest IM Sector (MHz)**	**Lowest IM Cell (MHz)**
A1	675 kHz	27	862.0125	862.6625	861.3625	860.0125
A2	675 kHz	27	862.6875	863.3375	862.0375	
A3	675 kHz	27	863.3625	864.0125	862.7125	
B1	825 kHz	33	864.0375	864.8375	863.2375	861.5875
B2	825 kHz	33	864.8625	865.6625	864.0625	
B3	825 kHz	33	865.6875	866.4875	864.8875	
C1	825 kHz	33	866.5125	867.3125	865.7125	864.0375
C2	825 kHz	33	867.3375	868.1375	866.5375	
C3	850 kHz	34	868.1625	868.9875	867.3375	

Channel sets A1, A2 and A3 have less than 31 channels, but these sets can be assigned to relatively low-capacity sites. Nextel does not assign the same number of channels per sector today and it won't after rebanding, so this is unlikely to be a limitation. Also, we doubt that any sectors in the United States have more than 27 channels today.

Table 2 is only one feasible solution. There are literally hundreds of practical solutions that meet Nextel's capacity needs while fully protecting public safety from all 3rd order IM products. Any channel set that obeys Equation (2) within a sector and between adjacent sectors is a feasible solution.

B. A-Band Cellular Carrier Solutions

When not co-located with Nextel, the A-Band cellular carrier is essentially off-the-hook after rebanding. OOBE and receiver IM are eliminated, assuming portable or mobile receivers with filters that roll off at 878 MHz or below. Most new receivers have filters that roll off at 875 MHz.

If the public safety agency operates older radios (some don't roll off until 890 MHz), and A-Band carrier interference is a problem, there are two obvious solutions:

- Limit channels in the offending sector to 869-878 MHz
- More generally, limit the range of channels to $[f_{min}, f_{max}]$, where $2 f_{min} - f_{max} >$ 860 MHz. This is not a cumbersome limitation given the 9 MHz separation between bands.

C. Co-Location Solutions

Co-location of Nextel and the cellular A-Band carrier is still a problem after rebanding because new IM products can be created between the two carriers. Limiting either carrier to narrow bands does not guarantee IM-free interference. In fact, the number of potential cross-products is quite large. Fortunately, most cell sites are not co-located. In Denver, only a small number of co-located sites are creating harmful interference.

The problem cannot be ignored, however. One solution is to limit Nextel's channels at co-located sites to 867.5-869 MHz as proposed in the previous section. Another potential solution is an external bandpass filter at the portable or mobile radio. Rebanding makes such a filter practical. A similar filter was proposed in part by MT Communications in comments submitted to the FCC in the fall of 2003 [6]. Bandpass filters using dielectric or surface acoustic wave (SAW) technology are already available off-the-shelf in small footprints. Although filters with passbands of 806-862 MHz probably don't exist today, after rebanding the market for such filters will be large and it is likely that manufacturers will be willing to provide suitable products. Using existing filter specifications as a guide, one should expect 2.5 - 3.5 dB of loss through such a filter [7].

The main advantage of such a filter is it does not require the purchase of new radios or even factory modification of existing radios. Instead, we envision a small coaxial adapter, perhaps 1/2 inch high, that attaches to the radio between the antenna port and the antenna. Different versions would be needed for different radio models (e.g., SMA, BNC, TNC, etc.). An improvement on this design is an integrated version with antenna and filter in one package. A conceptual block diagram is shown in Figure 7.

Summarizing, an external bandpass filter offers these advantages:

- It eliminates co-location and A-Band cellular interference by attenuating signals above 868 MHz (assuming comparable roll-off to today's filters)
- It is inexpensive, potentially less than $10 each in quantity
- New radios are not required
- No internal radio modifications are needed
- It can be installed easily by the user
- The device is passive and unlikely to fail

Alternative solutions include replacement of the existing receive filter in the radio or possibly re-tuning the filter for some older radios with tunable filters. For owners of newer Motorola radios with a varactor-tuned filter, the filter may be tunable without hardware modifications to the radio. Motorola should be consulted to determine feasible options.

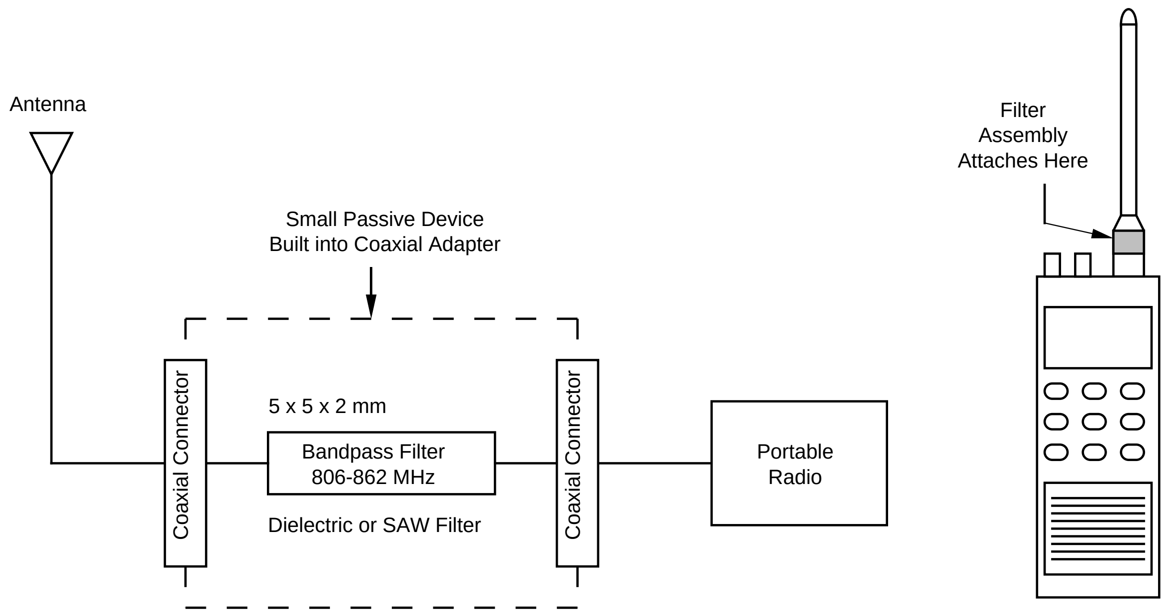

Figure 7 - External Bandpass Filter

6.0 Conclusions

Previous studies, including field measurements in Denver, Colorado, have shown that rebanding, as specified in the Consensus Plan, is the only practical way to eliminate out-of-band emissions and receiver intermodulation from 800 MHz cellular carriers [9], [10]. Critics of the Consensus Plan argue that the plan does not solve the interference problem completely because thousands of harmful intermodulation products still exist after rebanding. The purpose of this paper was to quantify the improvements created by rebanding and suggest specific implementations of the Consensus Plan that completely eliminate out-of-band emissions and 3rd-order intermodulation.

It is true that thousands of harmful intermodulation products *could* be created after rebanding, but only if Nextel constructs poor channel sets at its cell sites. Rebanding creates band separation and contiguous spectrum that together make it possible to completely eliminate harmful out-of-band emissions *and* receiver intermodulation. To prove this point, we have constructed a specific frequency plan that is intermodulation-free. Our suggested plan is just one of hundreds of feasible plans, so Nextel has great flexibility in the use of its licensed spectrum. In contrast, the existing band allocation, with interleaved channels and four public safety/cellular band edges, makes it impossible to achieve this goal.

After rebanding, a simple algorithm is sufficient to preclude harmful 3rd order IM products: Select a range of frequencies, $[f_{min}, f_{max}]$, such that

$$2f_{min} - f_{max} > 860 \text{ MHz}.$$

Nextel and the A-Band cellular carrier should apply this algorithm to each cell site's channel sets.

Another concern with post-rebanding is the presence of cross-carrier intermodulation products between Nextel and the A-Band cellular carrier at co-located cell sites. Although co-location sites account for a small fraction of problem cell sites, our experience in Denver shows that the problem does occur and requires attention. Rebanding also helps this problem. Rebanding makes it possible to install filters at the public safety radio receiver to attenuate signals from the A-Band cellular carrier. After rebanding, public safety occupies spectrum from 851 to 860 MHz. The 9 MHz between public safety and the A-Band cellular carrier is sufficient to achieve the required filter attenuation and eliminate cross-carrier intermodulation products at the public safety receiver.

To add this filter, it is not necessary to replace the public safety radio receiver or even make internal modifications to the radio. Instead, a low-cost external filter can be fabricated and installed at the antenna port to effectively eliminate cross-carrier intermodulation products. The external bandpass filter is an inexpensive and powerful solution, but it is only feasible after rebanding.

Advocates of the "Balanced Plan" argued that technical fixes can be applied to individual cell sites on a case-by-case basis to solve this problem. First-hand experience in Denver and other cities shows this is simply not true. We also find that the problem is not static; new problem sites appear almost monthly. Chasing interference problems diverts valuable resources from the public safety agency's core mission. Without rebanding, the public safety agency is sailing in a ship that continues to spring leaks and the shoring only partially plugs each hole. As seen in the FCC filings, most public safety agencies believe that 800 MHz interference would eventually put a police officer or firefighter in a life-threatening situation.

Without rebanding, the problem would not go away. Public safety radio and cellular radio (including Nextel) are fundamentally dissimilar services. To gain greater spectrum efficiency, cellular operators are following a trend of more cell sites, lower antenna heights, and more indoor wireless systems. These short antenna heights and indoor systems put strong interfering signals on the street and inside buildings where police officers and firefighters must operate. The public safety radio system will continue to operate from one, or at most a handful of tall sites because the economies of scale and the number of frequencies do not exist to make a cellular architecture feasible. Thus, without rebanding, the public safety agency would always be faced with the near-far problem and the problem would only worsen with time.

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8.0 About the Authors

Jay M. Jacobsmeyer, P.E. is president of Pericle Communications Company, a consulting engineering firm headquartered in Colorado Springs, Colorado. He holds BS and MS degrees in Electrical Engineering from Virginia Tech and Cornell University, respectively, and has over twenty years experience as a field engineer and researcher. Before co-founding Pericle Communications Company in 1992, he served for nine years with the United States Air Force and three years with ENSCO, Inc. He continues to serve as an Air Force Reserve officer. His technical papers have appeared in *IEEE Transactions on Communications*, *IEEE Journal on Selected Areas in Communications*, and in twelve IEEE conference proceedings. Jay Jacobsmeyer has served as principal investigator on four government research projects, one for the U.S. Navy and three for the National Science Foundation. He is a senior member of IEEE, a member of the Association of Federal Communications Consulting Engineers (AFCCE), and a licensed professional engineer in the State of Colorado.

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Appendix A - An Analysis of Out-of-Band Emissions

By George W. Weimer, P.E.

Transmitter out-of-band emissions (OOBE) comprise transmitter intermodulation, broadband phase noise, and other spurious emissions that are unavoidable by-products of the signal generation process. Figure A.1 is a spectrum analyzer trace of a typical Motorola iDEN signal. Note that out-of-band emissions are roughly -60 dBc.

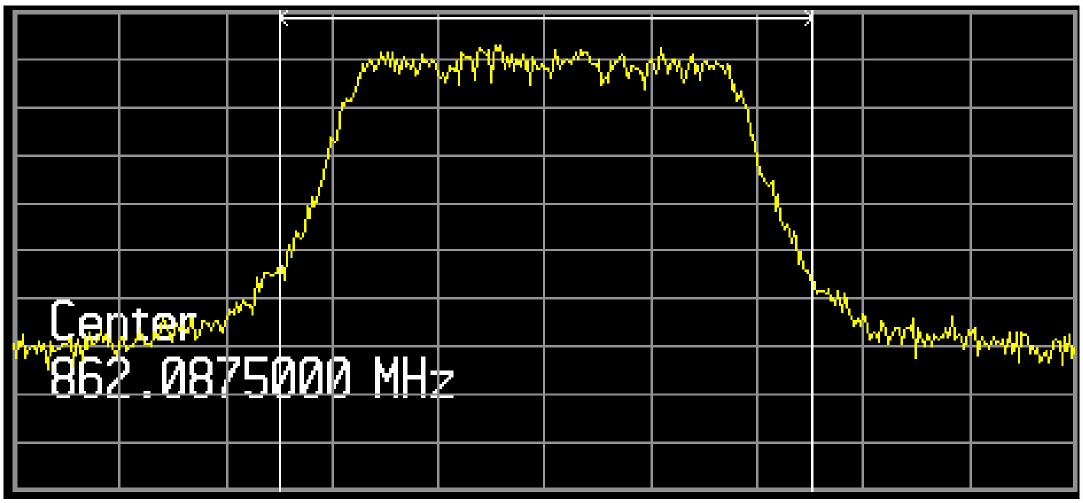

Figure A.1 - Typical Spectrum Analyzer Trace of iDEN Signal
(From Agilent E4401B, 10 dB per vertical division, 5 kHz per horizontal division,
Resolution Bandwidth = 1 kHz, Video Bandwidth = 10 kHz)

Out-of-band emissions are a problem for the public safety radio receiver when the level of transmitter "noise" generated by the Nextel or A-Band cellular base station transmitter is comparable to or greater than the receiver's thermal noise threshold.[9] The receiver thermal noise threshold in dBm is given by

$$P_{th} = 10\log_{10}(kTB) + 30 + NF, \qquad \text{(A.1)}$$

where k is Boltzman's constant (1.38 x 10^{-23} Joules/°K), T is the receiver noise temperature in °K (usually 290° K), B is the noise equivalent bandwidth in Hz (typically 15 kHz for a 25 kHz channel), and NF is the receiver noise figure in dB (typically 10 dB).

The receiver *sensitivity* in dBm is given by the following equation:

$$P_{th} = 10\log_{10}(kTB) + 30 + NF + (C/N)_{req}, \qquad \text{(A.2)}$$

[9]We use the term transmitter noise as it is widely used in the industry. The reader should be able to differentiate transmitter noise from receiver thermal noise from the context.

where $(C/N)_{req}$ is the required carrier-to-noise ratio in dB to achieve the desired figure of merit (e.g., 12 dB SINAD for analog, BER $\leq 10^{-3}$ for digital). Under static conditions, typical receiver sensitivities fall in the range -116 to -122 dBm. Corresponding receiver thermal noise thresholds are in the range –121 dBm to –127 dBm. Any out-of-band emissions that appear at the public safety portable radio receiver near the thermal noise threshold or greater will degrade receiver performance.

All public safety system designs employ an additional margin to establish the intended service reliability under the expected channel conditions and path losses. If noise from external sources enters the receiver, the net result is an increase in the total noise (thermal noise threshold plus OOBE), and therefore the performance margins must be applied to the total noise in the receiver, not just to the thermal noise threshold.

A typical transmitter noise plot for an actual Nextel iDEN antenna sector is shown in Figure A.2. Figure A.2 is a plot of the ratio (in dB) of OOBE power in a 25 kHz channel to the power in one iDEN carrier. Note that OOBE are cumulative from the three active carriers on this sector.

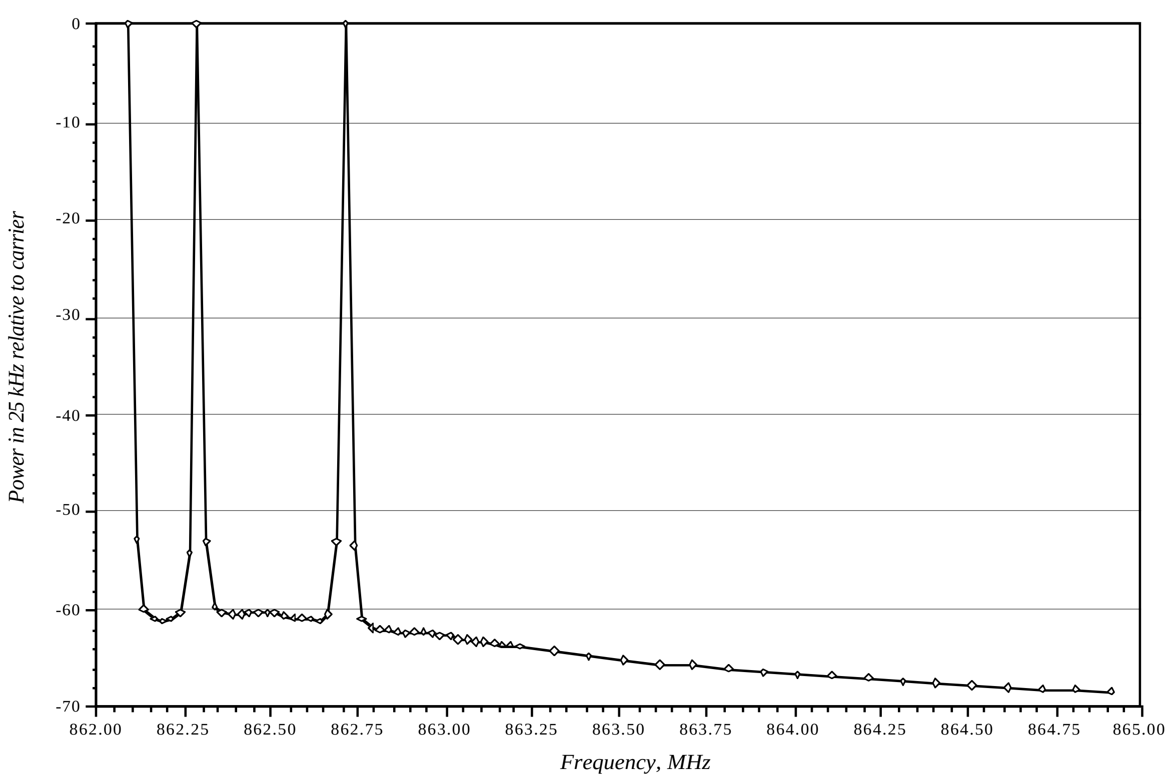

Figure A.2 - Power in 25 kHz Relative to Power in One Occupied iDEN Channel (Measurements Collected Using Channel Power Measurement Routine on Agilent E4401B Spectrum Analyzer)

Some rules of thumb can be gleaned from Figure A.2:

- OOBE from single carriers are -53 dBc on adjacent channels (25 kHz)
- OOBE are -60 dBc for close in, non-adjacent channels
- Several MHz from the carrier, OOBE are still no better than -68 dBc
- OOBE are cumulative, so sectors with many iDEN channels will have higher OOBE

At this point the reader may ask what are typical levels in the public safety receiver given the path loss from the cell site transmit antenna to the receiver? Analyses have been performed for a distance of 1,600 feet from the Nextel cell site based on an ERP of 100 watts (50 dBm) and the 47CFR90.210(b) emission mask requiring 63 dB noise suppression.

This 1,600 feet equates to 85 dB free space loss (at 850 MHz) between transmit and receive antennas. Note that free space loss is a good assumption for this problem as the receiver is normally close to the cell site when interference occurs and the path is roughly line-of-sight. Using this data, we get the following results:

- Nextel's on-channel power at the portable antenna port is approximately –35 dBm, assuming -2 dBi effective antenna gain. Comparable levels have been verified in the field at several interference sites.

- Nextel's OOBE from a single transmitter at the portable antenna port is approximately –98 dBm based upon –35 dBm on-channel power minus 63 dB required transmitter out-of-band emissions attenuation.

- Based on the public safety portable receiver thermal noise threshold, the degradation is between 26 and 32 dB from a single Nextel transmitter.

- Transmitter noise from multiple Nextel transmitters used in the same sector is additive, therefore, two transmitters will increase the degradation by 3 dB (for a total degradation of 29 dB to 35 dB), four transmitters by 6 dB, eight transmitters by 9 dB, and so on.

This noise produced by the Nextel transmitter falls on the portable receiver's intended receive frequency and therefore passes through the receiver's bandpass and IF filters. Thus, it cannot be filtered at the portable receiver without also filtering the intended public safety signal. As stated in the FCC filings and also herein, individual transmitter filtering at 150 kHz or less is ineffective. However, after rebanding, Nextel and public safety channels are no longer interleaved and highpass filters at the output of Nextel's transmit combiner can attenuate transmitter noise on public safety frequencies by the additional 45 dB or more required in the Consensus Plan.

Appendix B - The Switchable Attenuator

By Jay M. Jacobsmeyer, P.E.

In Motorola's Docket 02-55 filings of May and June, 2003, the company proposed the use of an automatic switchable attenuator to reduce or eliminate harmful 3rd order IM products in the public safety receiver [14], [15], [16]. A switchable attenuator to mitigate receiver intermodulation is not a new concept. It is well known that an attenuator will reduce receiver-generated intermodulation products by 3 dB for every 1 dB of attenuation [13]. Thus, in theory, a large improvement in intermodulation performance is achieved for a small loss in receiver sensitivity. For example, a 6 dB attenuator reduces 3rd order products by 18 dB while degrading the receiver's sensitivity by only 6 dB. But a switchable attenuator is only useful if the desired signal is strong enough to withstand the loss in receiver sensitivity. To be of practical use, the receiver must continuously measure the desired signal and switch *out* the attenuator whenever the signal drops below a predetermined threshold, S_{th}.

While the basic theory is sound, the implementation of a switchable attenuator is far from certain in a dynamic, multipath fading environment. The purpose of this appendix is to quantify the attenuator's benefits under real-world conditions and show why an automatic switchable attenuator is so difficult to realize in practice.

The Switchable Attenuator. From Motorola's filings, we gather that the proposed switchable attenuator would use the following basic algorithm:

1) Construct an automatic switchable attenuator with fixed attenuation, A, in dB.
2) Measure the desired signal level, $S(t)$, using RSSI or other known methods[10]
3) If the measured signal, $S'(t)$, is greater than S_{th}, leave the attenuator in the circuit
4) If $S'(t)$ is less than or equal to S_{th}, switch out the attenuator.

Note that this algorithm does not require the receiver to measure the interfering signal, only the desired signal. Because harmful interfering signals are likely to be present only part of the time, it is important that the attenuator be removed from the circuit when the desired signal is weak. Otherwise, receiver sensitivity is unnecessarily degraded and the coverage area shrinks significantly.

One can envision many variations on this basic algorithm. For example, the designer may wish to introduce a time constant to prevent the attenuator from rapidly switching back-and-forth under persistent weak signal conditions. Alternatively, some hysteresis might be desirable to achieve the same effect. Because the algorithm as described above measures signal level and not carrier-to-interference ratio (C/I), it may fail in the presence of broadband interference (i.e., OOBE). To address this problem, the designer might

[10] RSSI = received signal strength indicator, usually measured at IF, often with the aid of an AGC amplifier.

choose to measure packet-error rate on the control channel (or digital traffic channel) rather than RSSI because packet-error rate is a better measure of mean carrier-to-interference ratio. Packet-error rate is also a preferred metric when IM is very strong because an RSSI circuit may unwittingly measure the amplitude of the IM product rather than the amplitude of the desired signal.

Unfortunately, packet-error rate is not directly applicable to a analog voice channel. Under dynamic channel conditions, a measure of the packet-error rate on the control channel may not accurately reflect signal quality a short time later when the user is assigned to an analog voice channel.

These technical hurdles are difficult enough, but the more fundamental problem is the difficulty getting an accurate, timely estimate of desired signal level or *C/I* in a dynamic, multipath fading environment. Because the estimate must be acquired from a time-varying, noisy channel, the threshold, S_{th}, must be a compromise between intermodulation mitigation and sensitivity degradation. If S_{th} is set too low, the algorithm will fail to switch out the attenuator when it should. If S_{th} is set too high, the algorithm will switch out the attenuator at times when it is needed.

Clearly, a practical estimator will have implementation losses. These implementation losses are only acceptable if the theoretical improvement is quite large to begin with. Otherwise, the net improvement after implementation loss may be zero or worse. The theoretical improvement depends largely on the distribution of signal and interference levels in the vicinity of the interfering cell site. If the distribution is favorable, many locations will benefit from the theoretical attenuator. If not, very few will benefit. The best source for these distributions is real-world measurement data, which we have for Denver.

Let’s first consider attenuator performance with a perfect estimator.

Performance With a Perfect Estimator. Even a perfect estimator presents problems, especially if the attenuation is as high as 20 dB, as some have suggested.[11] Consider a typical public safety receiver with a receiver noise threshold of –121 dBm. In multipath fading, the required *C/N* to achieve a DAQ of 3.4 is 20 dB, assuming an FM receiver operating on a 25 kHz channel with 5 kHz peak deviation [13, Annex A]. So, the effective receiver sensitivity is –101 dBm without the attenuator. With the attenuator, the effective receiver sensitivity increases by the attenuator value of 20 dB to -81 dBm. Therefore, assuming a perfect estimator, the threshold value for switching is S_{th} = -81 dBm. But does the IM problem even occur with desired signals this strong?

To answer this question, let’s consider a real-world example. Examining the measured data from the five co-location problem sites in Denver, we find that locations with harmful receiver IM interference *rarely* exceed -81 dBm [9]. Typical signals in problem areas are

[11] Motorola proposed 15 dB in [15].

much lower. For example, at the intersection of Yale & Colorado, there were 94 discrete locations with harmful interference (defined as $C/I < 20$ dB and $C > -101$ dBm) and *none* of these had a desired signal greater than -81 dBm.[12] (See Appendix F for the actual measured data.) Thus, even with perfect estimation, a 20 dB switchable attenuator does nothing to help in this case.

Clearly, a smaller attenuator is needed. Let's try 6 dB. The switching threshold is now S_{th} = –101 dBm + 6 dB = -95 dBm. Consulting the spreadsheet in Appendix F, we see that a 6 dB attenuator reduces the number of locations with harmful interference from 94 to 76, less than 20% improvement. The improvement is small in part because there are many locations with desired signal levels between -95 and –101 dBm that don't benefit from the attenuator. We could try other attenuator values, but the results are disappointing as shown in Table B.1 where we have also included the $C/I < 17$ dB case.

Table B.1 - Attenuator Performance
Yale & Colorado, 220 Total Locations Measured
Assumed noise threshold = -121 dBm

Attenuation, dB	Locations with C/I < 20 dB, C ≥ -101 dBm	Locations with C/I < 17 dB, C≥ -104 dBm
0	94	115
1	86	103
2	81	95
3	78	90
4	74	85
5	76	84
6	76	89
7	79	90
8	83	95
9	83	94
10	82	96
11	84	97
12	86	100
13	89	102
14	91	104
15	91	108
16	93	111
17	94	113
18	94	113
19	94	114
20	94	115

[12] We only consider measured signals above the thermal noise sensitivity (-101 dBm here) because we cannot fault the attenuator for not improving a situation where it would not be applied regardless of the particular attenuation value.

For Yale & Colorado, it appears the optimal attenuator setting is 4 dB, but the optimal attenuation will vary by site and by city, so it is not possible to select one value that is best for all conditions. It is likely, though, that 20 dB is a poor choice globally because Nextel and A-Band cellular signal levels on the street are typically not strong enough that desired signals above -81 dBm would need the attenuator. Also, much of the 3:1 improvement from a large attenuator is superfluous because the IM product is attenuated well below the thermal noise floor where it offers no benefit. For example, Motorola's suggested value of 15 dB offers only a marginal improvement at Colorado & Yale — only three locations see the *C/I* raised above 20 dB.

Thus, there are pitfalls with the switched attenuator even with a perfect estimator because the IM reduction is largely offset by loss in receiver sensitivity, despite the 3:1 theoretical improvement. Another way to state this conclusion is that the attenuator can only be used when the desired signal is relatively strong, but the problem occurs in practice when the desired signal is relatively weak.

Performance With a Practical Estimator. When applied to real-world interference measurements, we've seen that even a *perfect* estimator offers only marginal improvements. A practical estimator cannot do better because it faces several tough problems:

- The samples are noisy, so any estimate is subject to error.
- The channel amplitude is time-varying due to multipath fading.
- Amplitude alone may not be an adequate measure as broadband OOBE may be present from a variety of sources and it may vary from channel to channel. A better measure is *C/I*, but *C/I* is more difficult to measure than amplitude alone.
- In most trunked systems, the only continuously-keyed channel available to measure is the control channel, but the user will be assigned to a traffic channel. Conditions on the traffic channel could be significantly different, making an estimate of the control channel of little value.
- Push-to-talk transmissions are short and may not allow sufficient time to collect samples and make an accurate estimate of the traffic channel.

So, a practical estimator is subject to errors and may do more harm than good. With such small improvements offered by a perfect estimator, there is not much room for the implementation loss of a practical estimator.

Conclusions. On the surface, a switchable attenuator appears to offer significant benefits because of the 3:1 theoretical improvement in dB. Because the attenuator should only appear in the circuit when the desired signal is strong enough to overcome the loss in sensitivity created by the attenuator, a good channel quality estimator is needed. However, even an ideal attenuator with a perfect estimator offers only marginal improvements when applied to a real-world interference environment. Furthermore, the small improvements that are possible are sensitive to the actual attenuation value. The optimal attenuation will vary by city and by cell site. No single attenuation value will be best for all conditions.

Performance can only be worse when a practical estimator is used. The practical estimator must work on a noisy, fading channel and must make an accurate estimate during brief push-to-talk transmissions. To mitigate implementation losses and ensure geographical coverage is not degraded, the designer will probably set the switching threshold high. This high threshold reduces the effectiveness of an already poor-performing feature. In other words, the attenuator can only be used when the desired signal is strong, but the intermodulation problem occurs when the desired signal is weak. The problems associated with a practical estimator make it likely that a switchable attenuator will either be ineffective or do more harm than good.

Appendix C - Denver Public Safety Frequencies

Table C.1 - Denver Public Safety Frequencies (Voice Channels Only)		
Channel	**Downlink (MHz)**	**Uplink (MHz)**
Public Safety 1	854.9875	809.9875
Public Safety 2	855.4875	810.4875
Public Safety 3	855.9875	810.9875
Public Safety 4	856.4875	811.4875
Public Safety 5	857.2375	812.2375
Public Safety 6	857.7375	812.7375
Public Safety 7	858.4875	813.4875
Public Safety 8	859.2375	814.2375
Public Safety 9	859.7375	814.7375
Public Safety 10	860.4875	815.4875
Public Safety 11	855.2375	810.2375
Public Safety 12	855.7375	810.7375
Public Safety 13	856.2375	811.2375
Public Safety 14	856.7375	811.7375
Public Safety 15	857.4875	812.4875
Public Safety 16	858.2375	813.2375
Public Safety 17	858.7375	813.7375
Public Safety 18	859.4875	814.4875
Public Safety 19	860.2375	815.2375
Public Safety 20	860.7375	815.7375
Public Safety 21	866.1875	821.1875
Public Safety 22	866.5875	821.5875
Public Safety 23	867.1250	822.1250
Public Safety 24	867.6500	822.6500

Appendix D - Public Safety Frequencies, 855-861 MHz
(Per FCC Part 90.617)

Table D.1 - Interleaved Public Safety Frequencies (70 Total)		
854.9625	857.2625	859.2625
854.9875	857.4375	859.4375
855.2125	857.4625	859.4625
855.2375	857.4875	859.4875
855.4625	857.7125	859.7125
855.4875	857.7375	859.7375
855.7125	857.7625	859.7625
855.7375	857.9375	859.9375
855.9625	857.9625	859.9625
855.9875	857.9875	859.9875
856.2125	858.2125	860.2125
856.2375	858.2375	860.2375
856.2625	858.2625	860.2625
856.4375	858.4375	860.4375
856.4625	858.4625	860.4625
856.4875	858.4875	860.4875
856.7125	858.7125	860.7125
856.7375	858.7375	860.7375
856.7625	858.7625	860.7625
856.9375	858.9375	860.9375
856.9625	858.9625	860.9625
856.9875	858.9875	860.9875
857.2125	859.2125	
857.2375	859.2375	

Appendix E - Nextel Denver Licensed Frequencies, 851-861 MHz
(As of November, 2002)

Table E.1 - Nextel Denver SMR Downlink Frequencies (851-861 MHz)				
851.0125	852.9875	854.8125	857.3375	859.3875
851.0875	853.0625	855.1125	857.3875	859.5375
851.1625	853.1375	855.2875	857.5375	859.5625
851.1875	853.1625	855.4125	857.5625	859.5875
851.2375	853.1875	855.4375	857.5875	859.6125
851.2625	853.2375	855.6125	857.6125	859.6375
851.4125	853.2625	855.6375	857.6375	859.6875
851.4625	853.3125	855.6875	857.6875	859.7875
851.6875	853.3375	855.9125	857.8375	859.9125
851.7125	853.4375	855.9375	858.0125	860.0125
851.7625	853.4875	856.0125	858.0375	860.0375
851.7875	853.5375	856.0375	858.0625	860.0625
851.8875	853.5625	856.0625	858.0875	860.0875
851.9125	853.6125	856.0875	858.1125	860.1125
851.9625	853.6375	856.1125	858.1375	860.1375
852.0125	853.6875	856.1375	858.1875	860.1625
852.0375	853.7375	856.1625	858.3375	860.1875
852.0625	853.8125	856.1875	858.3875	860.3375
852.1375	853.9125	856.3375	858.5375	860.3875
852.1625	853.9375	856.3875	858.5625	860.5375
852.1875	853.9625	856.5375	858.5875	860.5625
852.3375	854.0625	856.5625	858.6125	860.5875
852.3625	854.1625	856.5875	858.6375	860.6125
852.3625	854.1875	856.6125	858.6875	860.6375
852.4125	854.2375	856.6375	858.7875	860.6875
852.4875	854.2625	856.6875	858.9125	860.7875
852.5625	854.2875	856.7875	859.0125	
852.5875	854.3875	857.0125	859.0375	
852.6625	854.5375	857.0375	859.0625	
852.6875	854.5625	857.0625	859.0875	
852.8125	854.6125	857.0875	859.1125	
852.8375	854.6375	857.1125	859.1375	
852.9125	854.6625	857.1375	859.1625	
852.9375	854.7125	857.1625	859.1875	
852.9625	854.7375	857.1875	859.3375	

Appendix F - Measured Interference Data & Attenuator Analysis
Intersection of Yale & Colorado, Denver, CO

The attached spreadsheet contains measurements of Denver's control channel (854.9875 MHz) and several Nextel and AT&T Wireless (the A-Band carrier) frequencies at the Yale & Colorado cell sites. Measurements are linear averages over approximately 100 feet with at least 50 subsamples per measurement. Units are dBm. Receiver intermodulation levels in the public safety receiver are not measured directly, but are predicted from the strongest interferer using performance curves created from laboratory measurements of several M/A-COM portable and mobile radio receivers. Additional information on the data collection and analysis is found in Denver's June 10, 2003 report [9].

In addition to the original measurements and IM predictions, the spreadsheet includes an analysis of the improvement offered by a switchable attenuator. The following assumptions are built into the formulas used in the spreadsheet:

- The attenuator appears in the receiver prior to any active or non-linear device.
- The thermal noise floor of the receiver is specified by the user (-121 dBm in our case).
- The minimum *C/I* is specified by the user (either 20 or 17 dB in our case).
- Required *C/I* = required *C/N*.
- For an attenuator value of *A* dB, receiver sensitivity is increased by *A* dB and the IM product is reduced by 3*A* dB.
- The estimator is perfect.
- The attenuator is only used if the desired signal exceeds the thermal noise floor plus the required *C/I* plus the attenuator value. E.g., if the required *C/I* is 20 dB and attenuator is 6 dB, the attenuator only appears in the circuit if the original signal exceeds –121 + 20 + 6 = -95 dBm.
- If the predicted intermodulation product is reduced below the thermal noise floor, then the product's amplitude is set to the thermal noise floor. In the other words, *C/N* would govern in this case, not *C/I*.

The spreadsheet computes the *C/I* in every case, but only counts those that fall below the required *C/I and* have a signal level above the minimum required level in a thermal noise environment (e.g., -101 dBm for thermal noise floor of -121 dBm and required *C/I* of 20 dB).

City and County of Denver 800 MHz Interference Measurements
Site: Yale & Colorado
Pericle Communications Company
Spring, 2003

Attenuator Performance Inputs and Result			
Thermal Noise Floor:	-121	dBm	Bad Locations:
Minimum C/(I+N):	20	dB	76
Minimum Signal Level:	-101	dBm	
Attenuation:	**6**	dB	
Switching Threshold:	-95	dBm	

								C/I Performance Without Attenuator				C/I Performance With Attenuator			
Latitude	**Longitude**	**Denver CCH 854.9875**	**Nextel 852.4125**	**Nextel 863.4125**	**Nextel 865.4375**	**AT&T 870.2100**	**AT&T 870.6000**	**Max.**	**IM**	**C/I**	**C/I < 20 dB & C > -101 dBm**	**DEN CCH**	**IM**	**C/I**	**C/I < 20 dB & C > -101 dBm**
39.6671	-104.9363	-99	-47	-65	-53	-63	-84	-47	-114	15	1	-99	-114	15	1
39.6668	-104.9363	-101	-56	-65	-53	-70	-86	-53	-120	19	0	-101	-120	19	0
39.6665	-104.9363	-101	-58	-65	-53	-75	-88	-53	-120	19	0	-101	-120	19	0
39.6662	-104.9363	-90	-57	-65	-53	-72	-88	-53	-120	30	0	-96	-121	25	0
39.6660	-104.9362	-99	-61	-65	-53	-73	-88	-53	-120	21	0	-99	-120	21	0
39.6658	-104.9362	-102	-56	-65	-53	-74	-90	-53	-120	18	0	-102	-120	18	0
39.6657	-104.9363	-102	-61	-65	-53	-78	-90	-53	-120	18	0	-102	-120	18	0
39.6655	-104.9363	-94	-60	-65	-53	-65	-90	-53	-120	26	0	-100	-121	21	0
39.6654	-104.9364	-80	-54	-65	-53	-65	-89	-53	-120	40	0	-86	-121	35	0
39.6654	-104.9365	-79	-43	-65	-53	-61	-84	-43	-110	32	0	-85	-121	36	0
39.6654	-104.9367	-78	-44	-64	-53	-64	-85	-44	-111	33	0	-84	-121	37	0
39.6654	-104.9371	-79	-55	-65	-53	-65	-85	-53	-120	41	0	-85	-121	36	0
39.6654	-104.9374	-81	-57	-65	-53	-74	-88	-53	-120	40	0	-87	-121	35	0
39.6654	-104.9379	-84	-62	-65	-53	-76	-90	-53	-120	36	0	-90	-121	31	0
39.6654	-104.9383	-84	-69	-65	-53	-75	-90	-53	-120	36	0	-90	-121	31	0
39.6654	-104.9387	-83	-67	-65	-53	-73	-89	-53	-120	37	0	-89	-121	32	0
39.6654	-104.9392	-84	-69	-65	-53	-65	-84	-53	-120	37	0	-90	-121	32	0
39.6654	-104.9395	-89	-58	-65	-44	-58	-79	-44	-111	22	0	-95	-121	26	0
39.6655	-104.9400	-94	-63	-65	-51	-63	-83	-51	-118	23	0	-100	-121	21	0
39.6655	-104.9403	-88	-69	-65	-50	-60	-80	-50	-117	29	0	-94	-121	27	0
39.6655	-104.9405	-92	-67	-64	-48	-50	-69	-48	-115	23	0	-98	-121	23	0
39.6656	-104.9405	-90	-67	-63	-43	-49	-72	-43	-110	20	1	-96	-121	25	0
39.6657	-104.9406	-96	-67	-65	-40	-53	-72	-40	-107	11	1	-96	-107	11	1
39.6659	-104.9406	-98	-67	-63	-40	-52	-68	-40	-107	9	1	-98	-107	9	1
39.6663	-104.9406	-101	-66	-63	-43	-45	-68	-43	-110	9	0	-101	-110	9	0
39.6667	-104.9406	-97	-64	-64	-33	-41	-67	-33	-100	3	1	-97	-100	3	1
39.6670	-104.9406	-97	-64	-63	-27	-38	-67	-27	-85	-12	1	-97	-85	-12	1
39.6672	-104.9406	-97	-62	-63	-27	-39	-62	-27	-85	-12	1	-97	-85	-12	1
39.6673	-104.9406	-97	-62	-59	-29	-39	-61	-29	-91	-6	1	-97	-91	-6	1
39.6673	-104.9406	-100	-64	-57	-30	-38	-61	-30	-92	-8	1	-100	-92	-8	1
39.6673	-104.9406	-107	-60	-56	-28	-37	-60	-28	-87	-20	0	-107	-87	-20	0
39.6673	-104.9406	-107	-61	-56	-27	-36	-60	-27	-86	-21	0	-107	-86	-21	0
39.6673	-104.9406	-107	-61	-56	-27	-36	-60	-27	-87	-20	0	-107	-87	-20	0
39.6673	-104.9406	-100	-61	-57	-30	-38	-60	-30	-92	-7	1	-100	-92	-7	1
39.6674	-104.9407	-91	-63	-59	-32	-38	-64	-32	-97	6	1	-97	-115	18	1
39.6676	-104.9407	-93	-63	-62	-24	-40	-62	-24	-77	-17	1	-99	-95	-5	1
39.6679	-104.9407	-98	-66	-56	-27	-45	-58	-27	-85	-13	1	-98	-85	-13	1
39.6683	-104.9407	-99	-63	-56	-29	-36	-61	-29	-89	-10	1	-99	-89	-10	1
39.6687	-104.9407	-94	-65	-53	-38	-48	-47	-38	-105	11	1	-100	-121	21	0
39.6690	-104.9407	-102	-67	-45	-43	-55	-45	-43	-110	8	0	-102	-110	8	0
39.6694	-104.9407	-96	-71	-43	-46	-52	-33	-33	-99	3	1	-96	-99	3	1
39.6696	-104.9407	-92	-69	-42	-44	-55	-29	-29	-90	-2	1	-98	-108	10	1
39.6697	-104.9407	-94	-66	-38	-42	-57	-30	-30	-93	-2	1	-100	-111	10	1
39.6698	-104.9407	-96	-73	-40	-46	-56	-30	-30	-94	-2	1	-96	-94	-2	1
39.6698	-104.9406	-96	-72	-38	-49	-52	-31	-31	-94	-1	1	-96	-94	-1	1

								C/I Performance Without Attenuator				C/I Performance With Attenuator			
Latitude	Longitude	Denver CCH 854.9875	Nextel 852.4125	Nextel 863.4125	Nextel 865.4375	AT&T 870.2100	AT&T 870.6000	Max.	IM	C/I	C/I < 20 dB & C > -101 dBm	DEN CCH	IM	C/I	C/I < 20 dB & C > -101 dBm
39.6698	-104.9406	-95	-80	-40	-48	-53	-31	-31	-95	0	1	-95	-95	0	1
39.6698	-104.9407	-94	-79	-39	-46	-54	-30	-30	-93	-1	1	-100	-111	11	1
39.6698	-104.9407	-95	-79	-38	-49	-54	-31	-31	-95	-1	1	-95	-95	-1	1
39.6698	-104.9407	-96	-79	-41	-51	-55	-32	-32	-96	1	1	-96	-96	1	1
39.6698	-104.9407	-97	-70	-40	-44	-59	-32	-32	-97	0	1	-97	-97	0	1
39.6699	-104.9407	-94	-69	-37	-45	-63	-46	-37	-104	10	1	-100	-121	21	0
39.6702	-104.9407	-100	-69	-35	-46	-64	-50	-35	-102	2	1	-100	-102	2	1
39.6705	-104.9407	-92	-74	-41	-51	-63	-49	-41	-108	15	1	-98	-121	23	0
39.6709	-104.9406	-97	-74	-39	-53	-68	-52	-39	-106	9	1	-97	-106	9	1
39.6712	-104.9406	-101	-76	-41	-53	-73	-53	-41	-108	7	1	-101	-108	7	1
39.6715	-104.9406	-103	-75	-43	-53	-69	-57	-43	-110	7	0	-103	-110	7	0
39.6718	-104.9406	-103	-76	-38	-53	-73	-61	-38	-105	2	0	-103	-105	2	0
39.6719	-104.9404	-103	-81	-49	-53	-73	-54	-49	-116	13	0	-103	-116	13	0
39.6719	-104.9401	-103	-76	-42	-53	-80	-56	-42	-109	5	0	-103	-109	5	0
39.6719	-104.9398	-104	-73	-36	-53	-73	-56	-36	-103	-1	0	-104	-103	-1	0
39.6719	-104.9396	-103	-73	-37	-53	-72	-55	-37	-104	1	0	-103	-104	1	0
39.6719	-104.9393	-97	-78	-52	-53	-76	-59	-52	-119	22	0	-97	-119	22	0
39.6719	-104.9389	-91	-71	-52	-53	-84	-68	-52	-119	28	0	-97	-121	24	0
39.6719	-104.9386	-93	-59	-39	-53	-84	-66	-39	-106	13	1	-99	-121	22	0
39.6721	-104.9385	-100	-60	-35	-53	-84	-65	-35	-101	1	1	-100	-101	1	1
39.6724	-104.9385	-102	-59	-36	-53	-84	-68	-36	-103	2	0	-102	-103	2	0
39.6727	-104.9385	-101	-61	-42	-53	-86	-70	-42	-109	8	0	-101	-109	8	0
39.6730	-104.9385	-99	-70	-50	-53	-86	-72	-50	-117	18	1	-99	-117	18	1
39.6732	-104.9385	-93	-62	-52	-53	-86	-73	-52	-119	26	0	-99	-121	22	0
39.6733	-104.9386	-82	-68	-53	-53	-87	-72	-53	-120	38	0	-88	-121	33	0
39.6734	-104.9388	-84	-75	-58	-53	-89	-73	-53	-120	36	0	-90	-121	31	0
39.6734	-104.9391	-87	-77	-60	-53	-87	-72	-53	-120	33	0	-93	-121	28	0
39.6733	-104.9394	-88	-81	-58	-53	-80	-64	-53	-120	32	0	-94	-121	27	0
39.6733	-104.9396	-86	-82	-52	-53	-82	-64	-52	-119	33	0	-92	-121	29	0
39.6732	-104.9396	-97	-81	-52	-53	-82	-65	-52	-119	22	0	-97	-119	22	0
39.6733	-104.9395	-94	-83	-57	-53	-78	-62	-53	-120	26	0	-100	-121	21	0
39.6733	-104.9393	-86	-81	-57	-53	-84	-68	-53	-120	35	0	-92	-121	30	0
39.6733	-104.9390	-82	-79	-60	-53	-88	-73	-53	-120	38	0	-88	-121	33	0
39.6733	-104.9387	-81	-74	-59	-53	-87	-72	-53	-120	39	0	-87	-121	34	0
39.6733	-104.9386	-82	-66	-52	-53	-86	-72	-52	-119	36	0	-88	-121	33	0
39.6733	-104.9383	-80	-67	-48	-53	-86	-71	-48	-115	35	0	-86	-121	35	0
39.6733	-104.9379	-79	-81	-61	-53	-89	-76	-53	-120	41	0	-85	-121	36	0
39.6733	-104.9374	-79	-81	-59	-53	-88	-73	-53	-120	41	0	-85	-121	36	0
39.6734	-104.9371	-79	-83	-62	-53	-90	-75	-53	-120	42	0	-85	-121	37	0
39.6733	-104.9369	-92	-79	-63	-53	-89	-70	-53	-120	28	0	-98	-121	23	0
39.6731	-104.9368	-102	-78	-63	-53	-87	-71	-53	-120	18	0	-102	-120	18	0
39.6727	-104.9369	-103	-77	-61	-53	-87	-73	-53	-120	17	0	-103	-120	17	0
39.6723	-104.9369	-102	-72	-57	-53	-86	-70	-53	-120	18	0	-102	-120	18	0
39.6720	-104.9369	-94	-71	-56	-53	-85	-67	-53	-120	26	0	-100	-121	21	0
39.6719	-104.9370	-82	-71	-54	-53	-85	-66	-53	-120	38	0	-88	-121	33	0
39.6719	-104.9373	-83	-76	-54	-53	-84	-65	-53	-120	38	0	-89	-121	33	0
39.6719	-104.9376	-83	-75	-52	-53	-84	-65	-52	-119	36	0	-89	-121	32	0
39.6719	-104.9381	-86	-70	-45	-53	-83	-63	-45	-112	26	0	-92	-121	29	0
39.6719	-104.9385	-89	-62	-43	-53	-84	-66	-43	-110	21	0	-95	-121	26	0
39.6719	-104.9389	-91	-70	-53	-53	-83	-66	-53	-120	29	0	-97	-121	24	0
39.6719	-104.9392	-95	-75	-50	-53	-76	-60	-50	-117	22	0	-95	-117	22	0
39.6719	-104.9394	-97	-72	-38	-53	-71	-54	-38	-105	8	1	-97	-105	8	1

								C/I Performance Without Attenuator				C/I Performance With Attenuator			
Latitude	Longitude	Denver CCH 854.9875	Nextel 852.4125	Nextel 863.4125	Nextel 865.4375	AT&T 870.2100	AT&T 870.6000	Max.	IM	C/I	C/I < 20 dB & C > -101 dBm	DEN CCH	IM	C/I	C/I < 20 dB & C > -101 dBm
39.6718	-104.9395	-101	-72	-36	-53	-68	-53	-36	-103	2	1	-101	-103	2	1
39.6717	-104.9395	-101	-72	-39	-53	-70	-51	-39	-106	5	0	-101	-106	5	0
39.6715	-104.9395	-102	-75	-35	-53	-67	-46	-35	-102	0	0	-102	-102	0	0
39.6714	-104.9395	-95	-71	-35	-53	-66	-45	-35	-101	6	1	-95	-101	6	1
39.6712	-104.9395	-91	-64	-41	-53	-65	-44	-41	-108	18	1	-97	-121	24	0
39.6710	-104.9395	-88	-65	-36	-53	-66	-39	-36	-103	15	1	-94	-121	27	0
39.6708	-104.9395	-88	-64	-43	-53	-66	-42	-42	-109	21	0	-94	-121	27	0
39.6706	-104.9395	-85	-68	-38	-53	-68	-43	-38	-105	19	1	-91	-121	30	0
39.6705	-104.9395	-89	-67	-29	-53	-66	-38	-29	-89	0	1	-95	-107	12	1
39.6703	-104.9395	-92	-62	-28	-53	-67	-43	-28	-87	-5	1	-98	-105	7	1
39.6701	-104.9395	-88	-62	-28	-53	-65	-43	-28	-88	1	1	-94	-106	13	1
39.6699	-104.9395	-90	-62	-27	-53	-64	-43	-27	-85	-5	1	-96	-103	7	1
39.6697	-104.9395	-90	-62	-26	-53	-64	-45	-26	-82	-8	1	-96	-100	4	1
39.6695	-104.9395	-89	-63	-28	-53	-64	-46	-28	-87	-1	1	-95	-105	11	1
39.6693	-104.9394	-93	-58	-40	-53	-64	-52	-40	-107	14	1	-99	-121	22	0
39.6692	-104.9394	-98	-58	-44	-53	-64	-57	-44	-111	13	1	-98	-111	13	1
39.6691	-104.9393	-98	-58	-44	-53	-61	-57	-44	-111	13	1	-98	-111	13	1
39.6689	-104.9393	-106	-54	-55	-53	-62	-69	-53	-120	14	0	-106	-120	14	0
39.6686	-104.9393	-103	-49	-53	-53	-59	-72	-49	-116	13	0	-103	-116	13	0
39.6685	-104.9394	-88	-44	-56	-50	-52	-71	-44	-111	23	0	-94	-121	27	0
39.6683	-104.9394	-94	-45	-57	-49	-43	-70	-43	-110	16	1	-100	-121	21	0
39.6681	-104.9393	-97	-46	-59	-50	-44	-68	-44	-111	14	1	-97	-111	14	1
39.6679	-104.9394	-95	-45	-60	-49	-47	-66	-45	-112	17	1	-101	-121	20	0
39.6677	-104.9394	-100	-44	-61	-49	-49	-64	-44	-111	11	1	-100	-111	11	1
39.6675	-104.9394	-100	-46	-63	-52	-52	-76	-46	-113	14	1	-100	-113	14	1
39.6674	-104.9395	-90	-47	-65	-51	-50	-71	-47	-114	24	0	-96	-121	25	0
39.6673	-104.9395	-94	-55	-65	-49	-59	-67	-49	-116	22	0	-100	-121	21	0
39.6671	-104.9395	-94	-53	-64	-47	-56	-80	-47	-114	19	1	-100	-121	21	0
39.6669	-104.9395	-94	-51	-65	-43	-50	-79	-43	-110	16	1	-100	-121	21	0
39.6668	-104.9395	-90	-55	-64	-44	-43	-78	-43	-110	21	0	-96	-121	25	0
39.6666	-104.9396	-98	-55	-65	-47	-43	-77	-43	-110	12	1	-98	-110	12	1
39.6664	-104.9396	-99	-52	-62	-49	-45	-75	-45	-112	14	1	-99	-112	14	1
39.6663	-104.9396	-97	-55	-64	-50	-46	-75	-46	-113	17	1	-97	-113	17	1
39.6661	-104.9396	-103	-56	-64	-47	-58	-75	-47	-114	10	0	-103	-114	10	0
39.6659	-104.9396	-101	-59	-64	-46	-52	-77	-46	-113	12	0	-101	-113	12	0
39.6657	-104.9396	-97	-58	-64	-46	-57	-76	-46	-113	16	1	-97	-113	16	1
39.6676	-104.9345	-94	-54	-65	-53	-72	-89	-53	-120	26	0	-100	-121	21	0
39.6676	-104.9347	-85	-51	-65	-53	-73	-89	-51	-118	33	0	-91	-121	30	0
39.6676	-104.9351	-86	-48	-65	-53	-73	-90	-48	-115	30	0	-92	-121	29	0
39.6675	-104.9356	-88	-51	-65	-53	-66	-90	-51	-118	31	0	-94	-121	27	0
39.6675	-104.9362	-91	-36	-65	-53	-64	-87	-36	-103	12	1	-97	-121	24	0
39.6676	-104.9367	-97	-37	-63	-53	-65	-80	-37	-104	7	1	-97	-104	7	1
39.6679	-104.9373	-98	-38	-62	-53	-62	-81	-38	-105	7	1	-98	-105	7	1
39.6681	-104.9378	-84	-27	-61	-53	-57	-81	-27	-86	2	1	-90	-104	14	1
39.6682	-104.9384	-85	-28	-62	-51	-55	-81	-28	-88	3	1	-91	-106	15	1
39.6683	-104.9388	-87	-37	-64	-51	-57	-79	-37	-104	16	1	-93	-121	28	0
39.6683	-104.9391	-84	-45	-58	-50	-52	-74	-45	-112	29	0	-90	-121	31	0
39.6683	-104.9392	-85	-48	-54	-50	-51	-67	-48	-115	30	0	-91	-121	30	0
39.6682	-104.9392	-83	-44	-53	-49	-51	-70	-44	-111	29	0	-89	-121	32	0
39.6682	-104.9393	-90	-45	-58	-50	-51	-73	-45	-112	22	0	-96	-121	26	0
39.6682	-104.9397	-95	-52	-63	-46	-42	-66	-42	-109	14	1	-101	-121	20	0
39.6682	-104.9402	-101	-60	-61	-43	-42	-59	-42	-109	8	0	-101	-109	8	0

Latitude	Longitude	Denver CCH 854.9875	Nextel 852.4125	Nextel 863.4125	Nextel 865.4375	AT&T 870.2100	AT&T 870.6000	C/I Performance Without Attenuator: Max.	IM	C/I	C/I < 20 dB & C > -101 dBm	C/I Performance With Attenuator: DEN CCH	IM	C/I	C/I < 20 dB & C > -101 dBm
39.6683	-104.9406	-102	-60	-58	-37	-38	-61	-37	-104	2	0	-102	-104	2	0
39.6681	-104.9409	-101	-63	-60	-26	-46	-66	-26	-82	-20	0	-101	-82	-20	0
39.6679	-104.9409	-99	-64	-58	-25	-51	-67	-25	-80	-19	1	-99	-80	-19	1
39.6677	-104.9409	-95	-65	-59	-24	-49	-67	-24	-76	-19	1	-95	-76	-19	1
39.6676	-104.9409	-96	-66	-63	-25	-49	-69	-25	-79	-17	1	-96	-79	-17	1
39.6676	-104.9411	-96	-65	-65	-31	-57	-71	-31	-96	0	1	-96	-96	0	1
39.6676	-104.9413	-95	-69	-65	-41	-52	-72	-41	-108	13	1	-95	-108	13	1
39.6677	-104.9414	-98	-73	-65	-37	-51	-66	-37	-104	5	1	-98	-104	5	1
39.6679	-104.9414	-102	-71	-65	-27	-50	-68	-27	-87	-15	0	-102	-87	-15	0
39.6681	-104.9414	-105	-68	-65	-31	-49	-73	-31	-95	-10	0	-105	-95	-10	0
39.6682	-104.9414	-102	-75	-64	-41	-49	-69	-41	-108	6	0	-102	-108	6	0
39.6684	-104.9414	-99	-74	-63	-40	-57	-67	-40	-107	8	1	-99	-107	8	1
39.6684	-104.9414	-99	-71	-63	-34	-57	-65	-34	-101	2	1	-99	-101	2	1
39.6685	-104.9415	-93	-72	-61	-32	-56	-64	-32	-96	3	1	-99	-114	15	1
39.6685	-104.9416	-88	-70	-63	-31	-56	-67	-31	-95	7	1	-94	-113	19	1
39.6685	-104.9417	-92	-72	-60	-28	-56	-61	-28	-88	-4	1	-98	-106	8	1
39.6686	-104.9418	-98	-76	-61	-35	-60	-57	-35	-102	5	1	-98	-102	5	1
39.6687	-104.9418	-98	-75	-61	-38	-63	-52	-38	-105	8	1	-98	-105	8	1
39.6689	-104.9418	-99	-77	-61	-41	-66	-58	-41	-108	9	1	-99	-108	9	1
39.6691	-104.9418	-99	-81	-57	-47	-65	-57	-47	-114	16	1	-99	-114	16	1
39.6692	-104.9418	-93	-79	-54	-45	-65	-53	-45	-112	19	1	-99	-121	22	0
39.6693	-104.9417	-90	-74	-52	-45	-67	-51	-45	-112	22	0	-96	-121	25	0
39.6693	-104.9417	-88	-77	-51	-44	-68	-53	-44	-111	23	0	-94	-121	27	0
-0.0167	-0.0167	-89	-77	-56	-44	-64	-51	-44	-111	22	0	-95	-121	26	0
39.6686	-104.9419	-90	-77	-64	-35	-60	-63	-35	-102	13	1	-96	-120	25	0
39.6685	-104.9421	-99	-79	-63	-34	-61	-55	-34	-100	1	1	-99	-100	1	1
39.6684	-104.9422	-98	-78	-63	-31	-64	-56	-31	-96	-2	1	-98	-96	-2	1
39.6682	-104.9423	-101	-78	-63	-36	-61	-56	-36	-103	1	0	-101	-103	1	0
39.6680	-104.9423	-102	-85	-62	-48	-67	-61	-48	-115	12	0	-102	-115	12	0
39.6679	-104.9423	-104	-80	-63	-48	-70	-67	-48	-115	12	0	-104	-115	12	0
39.6677	-104.9423	-99	-74	-65	-45	-68	-66	-45	-112	13	1	-99	-112	13	1
39.6676	-104.9423	-89	-72	-65	-44	-68	-67	-44	-111	21	0	-95	-121	26	0
39.6676	-104.9422	-80	-68	-65	-39	-67	-76	-39	-106	25	0	-86	-121	35	0
39.6675	-104.9419	-84	-70	-65	-40	-64	-79	-40	-107	23	0	-90	-121	31	0
39.6674	-104.9418	-99	-73	-65	-41	-63	-79	-41	-108	9	1	-99	-108	9	1
39.6672	-104.9418	-103	-75	-65	-40	-62	-77	-40	-107	4	0	-103	-107	4	0
39.6669	-104.9418	-103	-78	-65	-42	-52	-77	-42	-109	6	0	-103	-109	6	0
39.6666	-104.9418	-105	-77	-65	-44	-59	-67	-44	-111	6	0	-105	-111	6	0
39.6662	-104.9418	-106	-82	-65	-47	-64	-68	-47	-114	8	0	-106	-114	8	0
39.6659	-104.9418	-102	-83	-65	-49	-69	-71	-49	-116	15	0	-102	-116	15	0
39.6657	-104.9418	-101	-81	-65	-50	-66	-74	-50	-117	16	0	-101	-117	16	0
39.6656	-104.9418	-89	-78	-65	-49	-67	-73	-49	-116	27	0	-95	-121	27	0
39.6655	-104.9417	-81	-76	-65	-52	-75	-85	-52	-119	38	0	-87	-121	34	0
39.6655	-104.9413	-80	-73	-65	-52	-74	-85	-52	-119	38	0	-86	-121	35	0
39.6656	-104.9410	-81	-67	-65	-44	-63	-82	-44	-111	31	0	-87	-121	34	0
39.6656	-104.9409	-80	-63	-65	-48	-56	-69	-48	-115	35	0	-86	-121	35	0
39.6656	-104.9409	-80	-62	-64	-53	-53	-66	-53	-120	40	0	-86	-121	35	0
39.6656	-104.9409	-81	-67	-64	-40	-60	-75	-40	-107	27	0	-87	-121	35	0
39.6654	-104.9408	-100	-64	-65	-43	-63	-79	-43	-110	10	1	-100	-110	10	1
39.6650	-104.9408	-99	-67	-64	-45	-62	-77	-45	-112	13	1	-99	-112	13	1
39.6646	-104.9408	-98	-67	-65	-50	-57	-71	-50	-117	20	1	-98	-117	20	1
39.6642	-104.9408	-96	-70	-65	-52	-69	-74	-52	-119	22	0	-96	-119	22	0

								C/I Performance Without Attenuator				C/I Performance With Attenuator			
Latitude	**Longitude**	**Denver CCH 854.9875**	**Nextel 852.4125**	**Nextel 863.4125**	**Nextel 865.4375**	**AT&T 870.2100**	**AT&T 870.6000**	**Max.**	**IM**	**C/I**	**C/I < 20 dB & C > -101 dBm**	**DEN CCH**	**IM**	**C/I**	**C/I < 20 dB & C > -101 dBm**
39.6637	-104.9407	-102	-69	-65	-51	-73	-80	-51	-118	16	0	-102	-118	16	0
39.6631	-104.9408	-100	-74	-65	-51	-77	-86	-51	-118	18	1	-100	-118	18	1
39.6626	-104.9408	-100	-76	-65	-53	-74	-89	-53	-120	20	0	-100	-120	20	0
39.6622	-104.9408	-102	-75	-65	-53	-72	-86	-53	-120	18	0	-102	-120	18	0
39.6617	-104.9408	-102	-75	-65	-53	-73	-87	-53	-120	18	0	-102	-120	18	0
39.6613	-104.9408	-106	-80	-65	-53	-73	-85	-53	-120	14	0	-106	-120	14	0
39.6725	-104.9407	-102	-81	-44	-53	-77	-61	-44	-111	9	0	-102	-111	9	0
39.6729	-104.9407	-106	-81	-43	-53	-82	-65	-43	-110	4	0	-106	-110	4	0
39.6732	-104.9407	-98	-83	-42	-53	-81	-65	-42	-109	11	1	-98	-109	11	1
39.6734	-104.9407	-98	-85	-51	-53	-80	-66	-51	-118	20	1	-98	-118	20	1
39.6738	-104.9407	-106	-86	-54	-53	-78	-72	-53	-120	14	0	-106	-120	14	0
39.6741	-104.9407	-104	-85	-54	-53	-79	-72	-53	-120	16	0	-104	-120	16	0
39.6745	-104.9407	-102	-83	-56	-53	-78	-69	-53	-120	18	0	-102	-120	18	0
39.6749	-104.9407	-96	-84	-53	-53	-85	-77	-53	-120	24	0	-96	-120	24	0
39.6753	-104.9407	-102	-86	-49	-53	-87	-80	-49	-116	14	0	-102	-116	14	0
39.6757	-104.9407	-103	-87	-55	-53	-80	-78	-53	-120	17	0	-103	-120	17	0
39.6761	-104.9407	-99	-85	-56	-53	-80	-80	-53	-120	21	0	-99	-120	21	0
39.6765	-104.9407	-90	-87	-56	-53	-89	-83	-53	-120	30	0	-96	-121	25	0
39.6768	-104.9407	-100	-87	-57	-53	-90	-86	-53	-120	20	1	-100	-120	20	1
										Total	94			Total	76