DESIGN CONSIDERATIONS FOR THE FRONT END OF FREQUENCY AGILE SDR RECEIVERS

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ABSTRACT

The analysis of spectrum occupancy measurements in a broad range of frequencies [1] has showed that design of direct downconversion receivers providing conversion from RF to baseband poses a challenge. This challenge stems from maintaining linearity in receivers in light of potentially unpredictable levels of interference. While inband interference is generally considered in the evaluating the performance of conventional receivers, wideband receivers must also take into account the effects of outband interference. Yet the development of wideband front end receivers is a key to achieving frequency agility and realizing the ultimate goal of ideal software definable radio (SDR) receivers. This paper considers design requirements to minimize the impact of multiple narrowband interferers and compares strategies to combat the strong interferer problem.

1. INTRODUCTION

Spectrum measurements in the busiest metropolitan area (New York city at the time of Republican convention in August 2004 [1]) have shown considerable presence of high intensity spectral components in the broad range of frequencies. Figures 1 and 2 below illustrate that point. Although spread-spectrum techniques are inherently resistant to narrow-band interference (NBI) in communication systems power enough spectral components of interference might pose a serious problem to providing reliable communication for many wireless systems having broadband front end. These powerful interfering signals may push low noise amplifiers into a nonlinear region creating very severe nonlinear distortion.

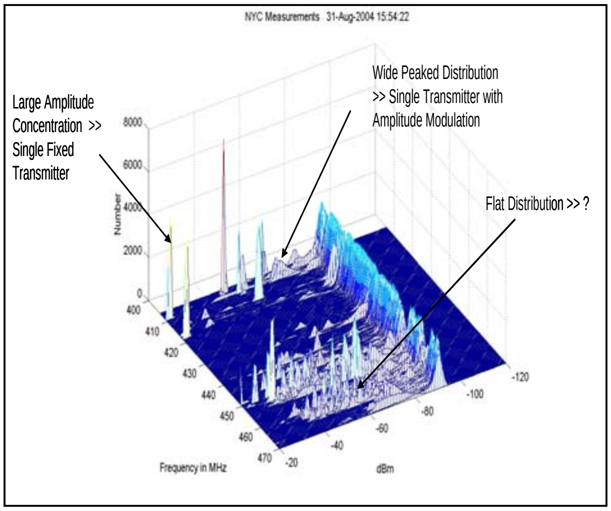


Figure 1. Amplitude histogram of PCS band (courtesy of [1]).

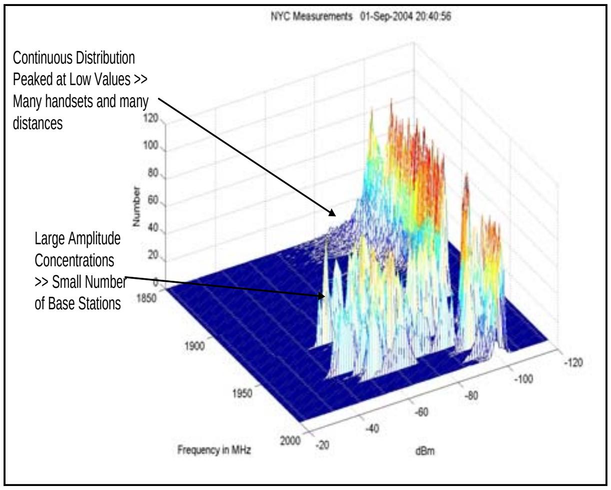


Figure 2. Amplitude histogram of public safety band (courtesy of [1]).

2. CONSIDERATIONS FOR WIDEBAND RECEIVER FRONT END DESIGN.

In all receivers, parameters such as spurious free dynamic range (SFDR) are of great concern because they determine the linearity with which signals can be processed. When a receiver is sufficiently nonlinear, strong interference from an adjacent channel can produce harmonics and intermodulation products, overpowering and effectively “locking out” a weak signal of interest (generally through 3rd order intermodulation product(s)). This is often referred to as the “near-far” problem.

By and large, wireless equipment manufacturers have (perhaps rightfully) focused on solving the “near-far” design challenge. The challenge can be framed as one of designing receivers that are more capable of receiving weak signals located at frequencies closer to stronger signals. By its very objective, it presumes that the weak and strong signals are from the same type of service (e.g., the PCS band) or from a service that is immediately adjacent in frequency. This has generally constrained the challenge in such a way that the designer can use relatively narrowband front end circuits as well as design communication services in such a way as to allow base stations to “command” a receiver to increase or decrease transmitted power to the minimum level necessary for successful communications.

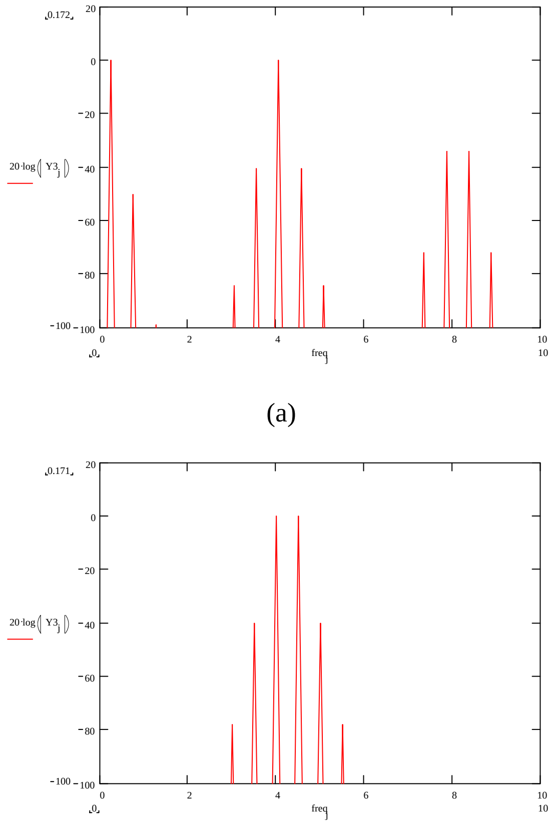
In frequency agile receivers, however, the front end circuitry must respond to a wide range of frequencies. This forces the designer to take a fresh look at the issue of distortion and intermodulation since the source of the distortion can occur at any frequency within the receiver’s passband, even one that is far removed from the signal of interest. Consider, for example, the case of a PCS receiver being used in proximity to an amateur radio antenna transmitting 1 kW of power at 28 MHz. In a conventional radio the interference would be far outside the passband and therefore generally could be ignored from consideration. However, in a frequency agile receiver any signal that has the potential of driving an amplifier into nonlinearity must be considered and analyzed.

In a conventional narrowband receiver, third order intermodulation products are generally recognized to be of greatest concern. This is because in the usual case ($f_1 \approx f_2$) the products $2f_1 \pm f_2$ and $2f_2 \pm f_1$ are located close in frequency to f_1 and f_2. Yet in the wideband case where f_1 and f_2 are widely separated, the closest intermodulation products may turn out to be 2nd order. Worse yet, if the front end in question is driven into strong distortion, it may lock out everything except the strongest input signal entirely.

Table 1 compares two scenarios that might generate intermodulation products that are close in frequency to the signal of interest. Note that when the interfering signal is close in frequency to the desired signal third order products are closest, but when the interfering signal is far removed from the desired signal, 2nd order products (or others) might occur at frequencies of concern. Further, in the special case where the interfering signal is very low in frequency compared to the desired signal, higher order intermodulation products ($f_{desired} \pm m \cdot f_{\mathrm{interfere}}$) that are normally ignored may have to be considered.

Desired Signal Frequency	Interfering Signal Frequency	Order and Frequency of Intermods
f	1.1 f	(3rd order) 0.9 f, 1.2 f
f	0.1 f	(2nd order) 0.9 f, 1.1 f

Table 1. Comparison of closest intermodulation frequencies for two closely spaced tones and two widely spaced tones.



(a)

(b)

Figure 3. Simulated intermodulation spectra for (a) widely separated signals (4 GHz and 250 MHz) and (b) closely spaced signals (4 GHz and 4.5 GHz). Identical amplifier models and amplitude levels were used for these simulations.

Figure 3 further illustrates the result of intermodulation between a desired signal and a relatively low frequency interferer. With identical non-linear amplifier models and input amplitudes, (a) shows the presence of multiple, high order intermodulation products while (b) shows the relative dominance of third order products

The problem of relatively low frequency interference is still further challenging since, as can be observed in the range equation (Friis transmission formula),

$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{(4\pi \cdot r)^2}$$

the relative dropoff of received power for a given transmitted power and distance is more gradual at low frequencies than at high frequencies (due to the larger λ). For example, an FRS walkie-talkie (operating at roughly 460 MHz in the U.S.) will have roughly 14.7 dB of received power advantage over an 802.11 signal (roughly 2.5 GHz) at 1 km distance from the transmitter (assuming equal transmitted power).

3. APPROACHES FOR COMBATTING DISTORTION IN WIDEBAND FRONT ENDS.

From the preceding discussion, it is clear that frequency agile, software defined radios (SDR) require a front end that can accommodate a wide range of signal amplitudes and frequencies without significantly compromising linearity. Unfortunately, this seems to be inconsistent with the objective of reducing the supply voltage used to power the input low noise amplifier (LNA), which tends to severely limit the achievable IP3 for the amplifier.

Any solution to this front end dynamic range problem must physically limit the total power being driven into the LNA while at the same time maximizing the level of the desired signal in order to maximize signal to noise ratio while not driving the amplifier into distortion. With this is mind, let us consider several potential methods for achieving wideband amplification while maximizing linearity performance.

Multiplexed Narrowband Amplifiers.

This approach uses a technique that has been used by the audio community. In essence the total required frequency spectrum is divided into narrower “bands” and each band is handled by a separate amplifier. The cluster of amplifiers is coupled together through a multiplexer (analogous to a diplexer and similar to a crossover network in audio).

This approach has the advantage that none of the individual amplifiers is required to operate over a wideband of frequencies and therefore are less prone to the unique dynamic range problems associated with wideband amplifiers.

The primary disadvantage of this approach is that construction of a wideband multiplexer poses a unique challenge at frequencies of interest. Furthermore, achieving a well-behaved amplitude and phase response (without multiple “peaks” and “valleys”) is difficult and deviation from ideal performance may tend to adversely affect the detection of wideband protocols such as CDMA and 802.11,

Tunable Narrow Bandwidth Amplifiers.

In this approach, a passive LC network (usually that used to match the input of the LNA to the antenna) is tuned so that the response is optimized to pass the desired input frequency while attenuating or outrightly rejecting other frequencies.

This approach requires minimal modification of the structure of the internal LNA itself and is therefore relatively easy to design. However, the LNA and its required matching are still affected by Fano’s limit so that tunability may be limited.

Feedforward and Feedback Frequency Selection.

This approach tuning by preselecting the input to an LNA with feedforward or feedback cancellation being used to reject undesired frequency bands.

The advantage of these approaches is that they can potentially be implemented over a wide range of frequencies provided that the core LNA operates over the frequencies of interest. The feedback has a potential disadvantage in that stability is of utmost concern, particularly at the frequencies of interest.

Adaptive Interference Cancellation.

An alternate strategy is rather than cancel all signals within one or more undesired frequency bands, to cancel out the strongest few signals that are the primary dynamic range “hogs”.

There are several methods to achieve this. The first one can be solved by adaptive filtering [2 - 4]. For example, authors in [2] suggested using the modified multiuser approximate conditional mean (ACM) filter to suppress NBI. That filter was augmented by additionally employing a multiuser decision-directed Kalman (MDK) filter to reduce required computational power. While the MDK filter retains the same performance as the ACM filter, it requires much less computation. The whole idea was based on the use of nonlinear functions in the ACM and the MDK filters to develop nonlinear adaptive least mean square (LMS) filters. However, the level of complexity of that solution was still beyond of implementation requirements for the portable wireless applications. The same can be said about [3], and [4]. In [3] it was shown that neural network-based decision feedback scheme in combination with an eigenvector network can closely approximate a Bayesian receiver with significant advantages, such as improved bit-error ratio (BER) performance, adaptive operation, and single-user detection in multiuser environment. Simon Haykin in [4] gave a very good description feedforward and recurrent neural networks and their applications to communication systems. The inherent complexity and high processing power requirements are still inhibiting the application of these methods in practice. Another potential way to minimize narrow band interference is through using same selective filters before LNA. It solves one problem but creates a huge another one. Namely, the system frequency agility might suffer beyond of necessity to use some highly undesirable analog components in that type of filters.

The second method of rejecting NBI is based on the introduction of sliding window the central frequency of which corresponds to the central frequency of the signal of interest. If that frequency is not known, the window can periodically slide through the entire band of interest. The window based approach limits interference only to the NBI components that happened to be inside of narrow window bandwidth of which is defined by the bandwidth of desirable signals.

4. CONCLUSIONS.

In this paper we introduced the challenge associated with developing wideband front end amplifiers for frequency agile SDR receivers. As elaborated above, such front end amplifiers are a design challenge, not only because a wideband frequency response must be achieved with a well-behaved amplitude and phase characteristic, but also because increasing the bandwidth of an amplifier makes it inherently more susceptible to distortion from outband interferers.

We presented empirical data associated with the level of interference that a transceiver may likely encounter. We also considered several approaches to limiting level of interference seen at the input of the low noise amplifier in order to control the level of distortion that results. Of these, tunable input LNAs and adaptive feedback LNAs appear to show the greatest promise for alleviating to susceptibility to distortion.

Since it is easily demonstrated that the front end of the receiver ultimately limits its overall performance. Solving the dynamic range challenge in wideband receivers will prove to be a key milestone in the development of frequency agile SDR.

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