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# Flexible Linearity Profile Low Noise Feedforward Amplifiers for Improving Channel Capacity

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***Abstract***

**This paper describes a highly linear Low Noise Amplifier (LNA) exhibiting a flexible linearity profile intended as a way to meet future flexible mobile communications standards. This has the potential of inclusion in Ad-hoc Software Defined Radio (SDR) networks where a frequency band and modulation scheme can be chosen based on the characteristics of the frequency spectrum and user requirements. The linearity profile of the LNA is tailored to cancel distortion generated as a function of the received power profile. This improves the receiver's tolerance to unwanted signals present in the frequency band of interest and reduces the requirement of coding and equalisation to compensate for receiver limitations whilst increasing the available capacity.**

**The flexible linearity profile is achieved by the use of a feedforward amplifier structure which has the capability of large distortion suppression determined by the gain and phase balances within its two loops. To ensure maximum distortion cancellation in the band, adaptive cancellation is used to maximise the cancellation of harmful distortion.**

## INTRODUCTION

The growth of the commercial communications market in recent years has pushed the use of the available radio spectrum to its limit. The number of users a system can support is determined by the channel capacity of the channel in use and the data rate requirements of the users. Channel capacity (C) is defined as the maximum amount of information that can be transmitted through a channel and is a function of the bandwidth (B) of that channel and the signal to noise ratio (S/N) of the received signal:

$$C = B\log_2\left[1+\frac{S}{N}\right] \qquad (1)$$

For a band limited channel, the channel capacity is a function of S/N at the demodulator input, since the receiver will add some noise of its own further reducing the S/N ratio.

Ideally a receiver would not modify the signal in any way. In reality the receiver will alter the signal characteristics through the use of non-linear components. The main constitute of this is limited dynamic range at both the small and large signal handling capabilities. Large signals are distorted by the limiting nature of the circuitry and small signals are buried in the receiver noise floor.

Receiver-added noise consists of any spurious products generated in the limiting nature of receiver circuitry due to large signals, alongside the usual thermal noise and shot noise. If a spurious product is present at the same, or close to the, frequency of a wanted signal then it will degrade the S/N of that signal at the input to the demodulator.

The proposed introduction of wide bandwidth SDRs as a way of producing multistandard terminals capable of receiving current and future standards introduces greater susceptibility to spurious products. The ideal SDR receiver would possess an open front end capable of receiving any service between 400MHz and 6GHz [1]. For practical applications an octave bandwidth has been chosen between 1 and 2GHz. Within this octave band is the existing DCS1800 standard.

To meet the imposed octave bandwidth and dynamic range requirements, Feedforward linearised LNA architectures have been proposed [2], [3]. The bandwidth and dynamic range improvement possible in [2] and [3] are not sufficient to meet the demands of future mobile communications receivers based on SDRs. One solution [4] is the use of an LNA exhibiting a flexible linearity profile. This allows the LNA to exhibit a narrowband high spurious suppression zone tuneable anywhere within the 1GHz band.

## FEEDFORWARD LNA

The feedforward amplifier consists of two loops each containing an amplifier. The first is the error isolation loop based around the Core Amplifier whose function is to produce an error signal at the output of the error combiner. This signal is amplified by the Error Amplifier and subtracted from the output in the error injection loop. This is shown schematically in Figure 1.

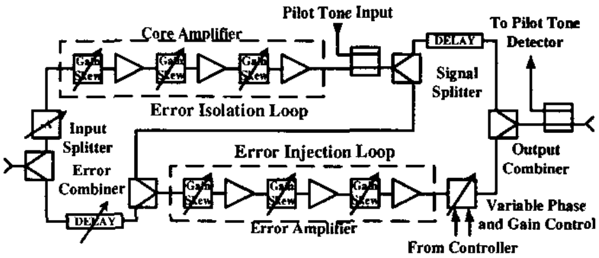


Figure 1: Feedforward LNA Block Diagram

Each of the amplifiers is composed of three minicircuits MMICs amplifiers [5] and two gain skew elements. The function of the gain skew elements is to flatten the gain response of the amplifiers. This extends the bandwidth of the amplifiers at the expense of reduced gain at the lower end of the band. A flat gain response ensures that wideband cancellation can be achieved, since the level of cancellation is a function of the gain and phase errors in the loops. This is shown graphically in Figure 2.

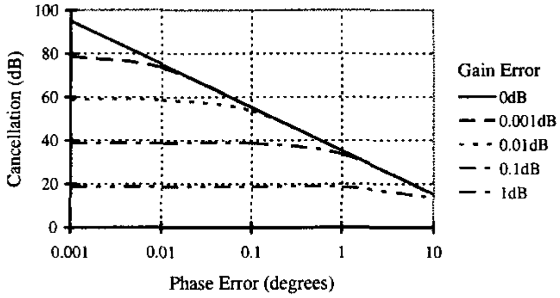
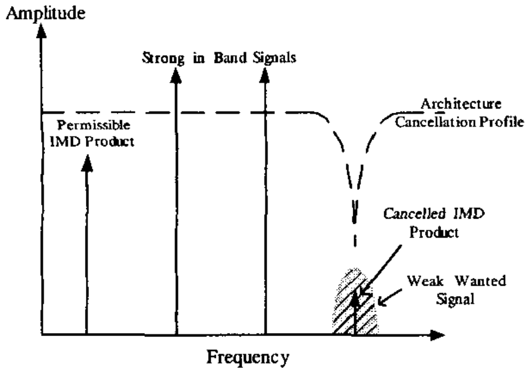


Figure 2: Level of Signal Cancellation

A high level of cancellation requires small gain and phase errors. A cancellation of 50dB requires gain and phase errors no larger than 0.1dB and 0.03°. Which is a very difficult to specify over any reasonable bandwidth.

## ERROR INJECTION LOOP

The error injection loop is responsible for suppressing any spurious products generated by the Core Amplifier. Only the interfering spurious product need to be suppressed so the bandwidth of the suppression zone only need be the bandwidth of the wanted signal. The suppression zone is tuned to the centre frequency of the wanted signal as shown in Figure 3.



Because the suppression bandwidth is comparatively narrow, only covering the wanted signal bandwidth, the level of suppression achievable can be large. This is due to the gain and phase being reasonably constant over narrow bandwidths. The tuning characteristic of the error cancellation loop is shown in Figure 4.

The level of cancellation achievable is typically 60dB over the band. With respect to Figure 2 the gain and phase errors required to achieve 60dB cancellation are very small. The inclusion of gain skew elements within the Error Amplifier help to reduce these errors over the bandwidth of the signal.

To achieve a pragmatic input IP3 specification of XdBm [6] using a realistic Core Amplifiers [4], a distortion cancellation of 50dB is typically required, which is exceeded over the majority of the band.

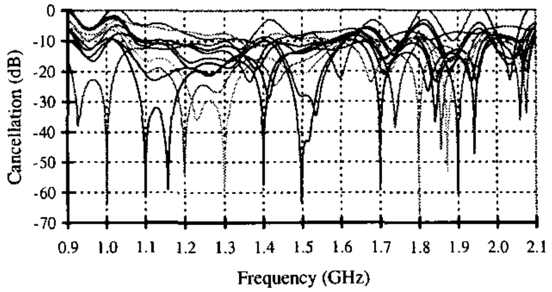


Figure 4: Error Injection Loop Tuning

The cancellation achievable, can often exceeds that displayed in Figure 4, but is not visible due to the 1MHz frequency resolution of the network analyser used to measured Figure 4 with. If one of the suppression zones is zoomed into and a finer frequency resolution used the narrowband cancellation profile is visible as in Figure 5.

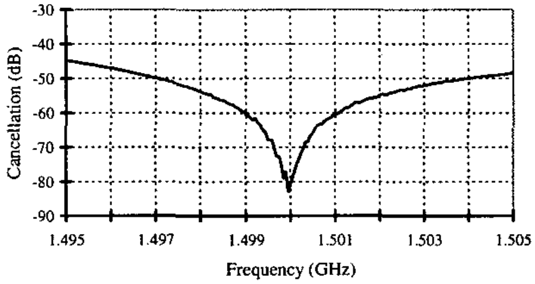


Figure 5: Error Injection Loop Cancellation at 1.5GHz

The narrowband cancellation exceeds the required 50dB. Over the DCS1800 bandwidth, the cancellation is typically 68dB or 50dB cancellation can be achieved over 7MHz. This allows the feedforward LNA to be used with future wideband communications schemes like Orthogonal Frequency Division Multiplexing (OFDM) and Code Division Multiple Access (CDMA).

## ERROR ISOLATION LOOP

The role of the error isolation loop is two fold: The first is to create an error signal which should ideally only contain the distortion products of the Core Amplifier. The second is to reduce the power applied to the Error Amplifier so that it does not generate any distortion products itself.

Unlike the error injection loop, the error isolation loop has to suppress all of the input signals present in the band; interfering and wanted. If a narrowband cancellation profile is used, then signals outside the suppression zone are not suppressed. These will experience cancellation in the output combiner, and generate distortion products in the error amplifier.

The level of wanted signal cancellation in the output combiner is a function of the cancellation of the individual loops as shown in Figure 6. This cancellation causes a reduction in the LNA gain, and the intercept point performance.

Practically, the Core Amplifier employing gain skew elements can achieve gain and phase errors of 1dB and 1° respectively across the 1GHz band. With regard to Figure 2 the suppression of the error isolation loop would be approximately 20dB.

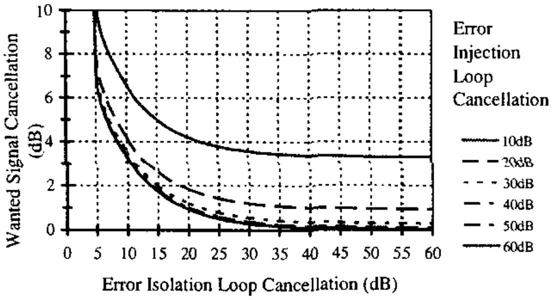


Figure 6: Main Signal Cancellation.

The error isolation loop is capable of slightly greater than 20dB cancellation over the whole octave band between 1 and 2GHz. The wideband cancellation profile of the error isolation loop is shown in Figure 7.

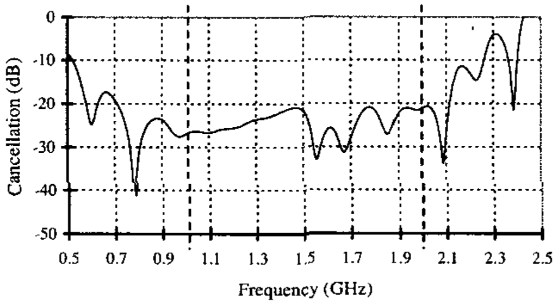


Figure 7: Error Isolation Loop Cancellation.

Under these conditions the wanted signal experiences a 1dB gain reduction in the output combiner and hence a 0.5dB reduction in intercept point performance. This is viewed as a tolerable reduction in LNA performance for wideband operation.

## ADAPTIVE CANCELLATION

The error isolation loop is tuned for 20dB wideband cancellation and does not need any further control, since the gain and phase errors are relatively large at 1dB and 1° respectively.

The gain and phase balance tolerances in the error injection loop are a lot smaller due to the high level of cancellation required. As a result a closed loop control scheme must be employed to tune the loop for maximum cancellation.

Adaptive cancellation relies on detecting the level of cancellation in the loop and manipulating the variable gain and phase elements to maximise this cancellation. A microprocessor running an algorithm, monitors the output of an analogue to digital converter (ADC) and drives digital to analogue converters (DAC) which controls the gain and phase elements. The output of the ADC is proportional to the level of cancellation in the loop.

Cancellation detection schemes are divided into two groups, those utilising pilot tones and those not. The pilot tone techniques generally introduce extra complexity, but have the advantage that by manipulation of the pilot tone parameters the centre frequency and bandwidth of the suppression zone can be controlled.

## SPREAD SPECTRUM PILOT TONE

Conventional pilot tone schemes based on continuous wave (CW) pilot tones operate either in a different channel to the wanted signal, or are only enabled when the wanted signal is not being received. This is to avoid the pilot tone from interfering with the wanted signal, but has the disadvantage that the amplifier characteristics may change during reception of the wanted signal and the amplifier characteristics are not constant over different channels.

To maximise the spurious suppression at the frequency of the wanted signal it is necessary for the pilot tone to operate on the same frequency as the wanted signal all of the time. To prevent interfering with the wanted signal, it is necessary for the pilot tone to have lower power than the wanted signal so as to maintain the S/N ratio demands of the demodulator. As an example, DCS1800 requires an S/N ratio of 10dB at the demodulator input. Hence the pilot tone power within the 200kHz demodulator bandwidth must be 10dB lower than the wanted signal at the output of the LNA.

To enable detection of the pilot tone, direct sequence spread spectrum (DSSS) is applied so that when the pilot tone is detected the wanted signal is rejected allowing the pilot tone power to be easily measured.

Detection the pilot tone is first accomplished by converting it down to baseband and then correlated with the baseband P/N sequence. The signal at output of the correlator is low pass filtered at 10Hz to reduce the effect of the wanted signal and the resulting DC voltage measured with the ADC. A schematic of the pilot tone generator and detector is shown in Figure 8.

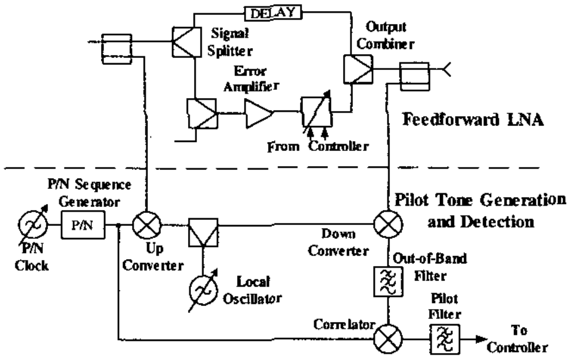


Figure 8: Pilot Tone Schematic

When used with the DCS1800 specification and a practical LNA [4] the pilot tone is spread over the channel bandwidth of 200kHz. Under cancellation, the pilot tone power should be -97dBm in the channel bandwidth at the output of the LNA so as not to interfere.

Detection of the pilot tone relies on it being at least equal to, if not greater in signal power than the spread wanted signal at the output of the correlator. Figure 9 shows the pilot tone and wanted signal in the RF domain at 1.5GHz. For visual convenience the resolution bandwidth of the spectrum analyser is 10kHz. The noise power of the pilot tone in 200kHz bandwidth is 13dB higher, thus maintaining the 10dB S/N. The wanted signal is wideband frequency modulated (FM).

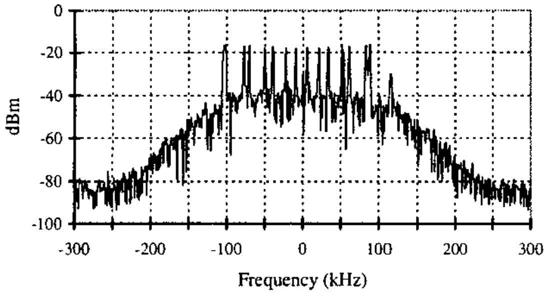


Figure 9: Wanted signal and Pilot tone

When the pilot tone is decorrelated and low pass filtered at 10Hz the pilot to wanted ratio is 45dB as shown in Figure 10. This is a processing gain of 55dB overall. The spectrum analyser resolution bandwidth is again 10kHz.

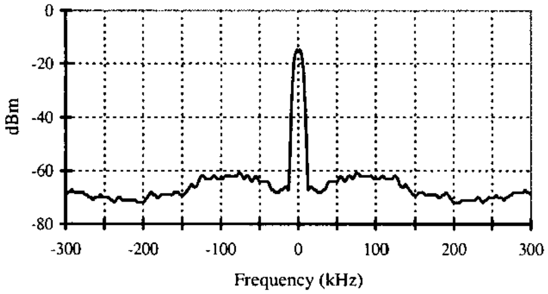


Figure 10: Correlator Output

A processing gain of 55dB allows the wanted signal to be increased by 55dB until the wanted signal power is equal to that of the pilot tone at the output of the correlator. This means that 50dB cancellation can be achieved at wanted signal powers up to –47dBm. Since the intermodulation distortion (IMD) generated by two –13dBm tones without cancellation applied is -56dBm, cancellation is not required for wanted signal powers greater than –61dBm.

## CONCLUSION

The channel capacity of a communications system is a function of the S/N, not only of the channel but the receiver circuitry up to the input of the demodulator. In a wideband open frontend receiver suffering from limited dynamic range the noise floor will be swamped by spurious distortion products which could interfere with a received wanted signal.

To facilitate wideband operation of an LNA between 1 and 2GHz, whilst still providing sufficient intercept point performance, a flexible feedforward structure is utilised. The optimum cancellation profiles of the two loops are a wideband moderate cancellation in the error isolation loop and a tuneable high suppression zone in the error injection loop. Sufficient cancellation, 50dB, can be achieved to allow the reception of a DCS1800 service in the band of interest.

To facilitate tuning of the error injection loop adaptive cancellation is utilised. Cancellation detection is accomplished by the use of a spread spectrum pilot tone. Due to the processing gain achieved in the detection process it is continuously operated whilst still maintain the 10dB S/N of the DCS1800 demodulator.

A fixed pilot tone power will enable 50dB spurious cancellation to be achieved at wanted signal powers between –102dBm and –47dBm, but is not necessary for wanted signal power greater than –61dBm.

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