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Presentation on Cross Modulation in CDMA Mobile Phone Transceivers

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Part 1
Cross Modulation in CDMA Mobile Phone Transceivers
About the Author

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Rishi Mohindra is the founding President & CEO of Adaptive RF, Inc. Prior to that he was Principal Engineer, RF Systems, in Philips Semiconductors, Business Line Interconnectivity. At Philips he was responsible for the definition of architecture and IC specifications as well as the development, of next generation transceiver chip sets, for WLAN and Wireless Interconnectivity applications. He has earlier specified RF/IF ASICS for CDMA/AMPS/TDMA Mobile Phones, and has also done extensive Systems simulations for both RF ASICs and CDMA/AMPS/TDMA base band modems. He has worked on the System design and definition of PWT, DECT and Pager transceivers and the associated integrated circuits, and has also built various RF transceivers for these applications. His other experience include IEEE 802.4 MAC implementation in software and the design of the digital modem.

He completed his Bachelors in Physics/Electronics in 1985 and Masters in Electronic Engineering in 1990. In 1988 he was Manager R&D with Microtechniques (India), a company for which he was also a consultant from 1984. Among the many products he developed there, a 16-line wireless remote telephone subscriber system had wide spread deployment in India. He joined Philips Semiconductors in 1990, located initially in The Netherlands, and currently in Sunnyvale, USA. He has been granted 4 patents, and applied 15 more.
A basic IS-95 phone design challenge:

**How to reduce phone size and battery drain?**

- Smaller Duplexers ➔ Lower TX-RX isolation
- Lower receiver LNA current ➔ Lower IP3

Cross Modulation Noise EXCEEDS Thermal noise!

Cross Modulation in CDMA Mobile Phone Tranceivers

In a CDMA mobile phone, the transmitter and the receiver are operational simultaneously, and connect to the antenna through a duplexer. Until recently, the duplexers were very large in size and therefore provided sufficient isolation of about 60 dB between the transmitter and receiver. However, with reducing size of the handsets, especially in cellular/PCS dual-band and CDMA/AMPS dual mode designs, the duplexers are also becoming smaller and cheaper, at the expense of isolation between the transmitter and receiver ports. For example, the PCS band duplexers have about 45 dB isolation, while the cellular band duplexers have 45-50 dB isolation. The increased transmitter leakage into the receiver is not generally a problem on its own, but when combined with strong adjacent channel single tone jammers it poses a serious design challenge for the linearity requirement of the receiver low noise front-end RF amplifier (LNA). The time varying envelope of the transmitter leakage signal can cause excessive cross modulation of the strong single tone jammer largely due to the third order nonlinearity of the LNA.
The relevant transmitter and receiver blocks for the cross modulation are depicted above, and the spectrum of the various signals are shown in the next slide. The jammer is present just outside the edge of the channel filters, and therefore a large part of the cross modulation signal power falls within the channel filter pass band. If the IP3 of the LNA is not high enough, the cross modulation signal power within the filter pass band can greatly exceed the total thermal noise power.

The cross modulation phenomenon can also be viewed as a form of a time varying gain compression of the LNA for the smaller jammer signal, by the strong reverse link transmitter leakage signal that uses a non-constant envelope modulation. The time varying gain compression of the LNA is called desensitization of the single tone jammer. It results in AM modulation of the single tone jammer. The cross modulation noise power is the total power in the AM spectrum which is a around the single tone jammer. Keeping the cross modulation power small can result in a large IP3 requirement for the LNA.

This design seminar shows the simulations and measurements done to investigate cross modulation of the single tone jammer at the CDMA LNA input, by the transmitter leakage into the receiver. Based on the simulations, a Cross Modulation Noise model is developed to predict the IP3 requirements of the receiver LNA. The simulation based model is compared with a theoretical one.
1-Tone Desensitization Test for CDMA Mobile Receiver

In the IS-95 CDMA 1-tone desensitization test, the Mobile Receiver is subject to a single tone jammer that is 71 dB stronger than the wanted received signal, which is at -101 dBm level. The wanted received signal is just 3 dB higher than the minimum required sensitivity level of -104 dBm. Due to the power control, the mobile’s transmitter power is kept close to it's maximum level i.e. 23 dBm. The time varying desensitization of the LNA creates a weak AM modulation in all of the received signals. The AM modulation is so weak that it does not significantly affect the wanted signal to noise ratio i.e. the S/N of the traffic, sync and the pilot channels after despreading. However, the effect of AM modulation on strong adjacent channel interferers at the LNA input, can be very severe. Under normal circumstances, these strong narrow band AMPS interferers are completely removed by the channel filter before the despreading occurs. With the weak AM modulation however, a small part of the power of these interferers are spread over a 2.5 MHz band, centered around the interfering signal itself. In the 1-tone desensitization test, these interferers are 900 kHz (Cellular band) or 1.25 MHz (PCS band) away from the wanted signal, and a considerable part of the 2.5 MHz band therefore over laps with the received signal band, as sketched above. As the narrow band AMPS interferer is 71 dB stronger than the received signal, there is a significant interference power in the part of the 2.5 MHz band that over laps with the received signal, resulting in considerable reduction in the signal to noise ratio after despreading.
Jammer and Transmitter Leakage

- Both Jammer and TX leakage signals completely removed by RX channel filters, and individually do not degrade Walsh channels S/N after despreading.
- TX leakage of -23 dBm << Nominal RX out-of-band IP3 (about 0 dBm). TX leakage produces very little desensitization of wanted RX signal.
- Only the combination of TX leakage and Jammer produces cross modulation noise that can’t be filtered away, and imposes requirement for high LNA IP3 and Duplexer Isolation.

The transmitter induced LNA desensitization does not significantly effect the IS-95 receiver sensitivity in the absence of jammers, and it also does not effect the IS-95 receiver the dynamic range. However, as stated earlier, it causes a major problem for the 1-tone desensitization test, and thereby forces the use of highly linear LNAs which require very high IP3 at the expense of large current. In comparison, the 2-tone intermodulation tests for the CDMA mobile receiver are not as severe as the desensitization test, because the power level of these 2-tone interferers are much smaller (about 13 dB) compared with the 1-tone jammer in the desensitization test, when the reverse link transmitter is at its maximum level.

The image filter between the LNA and the mixer has about 30 dB rejection at the transmitter frequency, and therefore the mixer is sufficiently protected from cross modulation. The IP3 requirement for this mixer is largely determined by the receive band 2-tone interference.
Analysis of Cross Modulation

Receiver LNA 3rd order nonlinearity:
\[ y(t) = a_1 x(t) + a_3 x^3(t) \quad \text{with} \quad a_3 < 0 \]

Unwanted signals at LNA receiver input:

- 1-tone jammer: \[ s_j(t) = A_j \cos(\omega_j t) \]
- Transmitter Leakage:
  \[ s_T(t) = \text{Real}\left\{F^2(t) + jQ^2(t)e^{j\omega_f t}\right\} \]
  \[ = r(t) \cos(\omega_f t + \Theta(t)) \]

Total Unwanted Signal at LNA input:
\[ x(t) = A_j \cos(\omega_j t) + r(t) \cos(\omega_f t + \Theta(t)) \]

When a modulated and an unmodulated signal are present at the input of a device (e.g. LNA) having 3rd order nonlinearity, then the unmodulated signal gets a part of the modulation from the other signal, at the output of the device.

The LNA nonlinearity and the input signals to the LNA are modeled above.

The bottom equation is substituted in the top equation, and after simplification, the terms are separated based on the frequencies. The term with the frequency \( \omega_1 \) is analysed further as it shows the cross modulation on the jammer. This term is shown in the next slide.
Analysis of Cross Modulation (cont’d)

LNA output signal at jammer frequency:

\[
\left[ \frac{-3a_3}{4} A_j^3 + \frac{3a_3}{2} A_j r^2(t) + a_1 A_j \right] \cos(\omega_j t)
\]

Total Cross Modulation Power:

\[
P_{\text{crossmod}}(t) = \frac{1}{2RA_1^2} \left[ \frac{-3a_3}{2} A_j r^2(t) \right]^2
\]

Average Cross Modulation power:

\[
P_{\text{crossmod}} = 6 + 2(P_{\text{txin}} - P_{\text{IP3}}) + P_j \quad (\text{all in dBm})
\]

In the first equation above, the 1st and the 3rd terms within the brackets are constants, and they only change the power of the unmodulated jammer signal. The 3rd term shows the gain, and the 1st term shows the reduction in gain. The middle term shows the cross modulation component. Only the envelope of the modulated signal produces the cross modulation, while the phase \(\theta(t)\) of the modulated signal does not have any effect. The cross modulation noise power is the power associated with this middle term. Referring it to the LNA input, the time varying equivalent input cross modulation noise power (for the input resistance \(R\)) is given in the next equation. The last equation gives the time averaged total cross modulation power.

Only a part of the above cross modulation noise power falls into the pass band of CDMA receiver channel filters. Simulations, which are described later, show that for the Cellular band, the cross modulation noise power into the pass band of CDMA receiver channel filters is 6 dB less than the one-sided power i.e. 9 dB less than that given by bottom equation.
The top level Cross Modulation simulation setup using the HP ADS Communication System Designer is shown above. The attenuated mobile transmitter signal is combined with a 1-tone jammer and fed into a LNA. The LNA is modeled by a gain block having a third order non-linearity. A 1.25 MHz wide band pass raised cosine filter at the output of the LNA selects the total receive band noise due to cross modulation. The cross modulation noise is measured by a power meter that operates on the time domain samples of the signal envelope at the filter output. This method is most accurate as it does not involve power measurements from a spectrum (directly at the LNA output) that usually suffers from spectral leakage effects. However, the simulation runs slower because of the impulse response time of the band pass filter. For a quick simulation, the LNA output spectrum can be directly observed. The effects of spectral leakage are considerably reduced by using a Hanning time window.
ADS Simulation

- A TX-RX full duplex spacing of 45 MHz not required in simulation.
- Just 4-6 MHz spacing is sufficient. Ensure that spectral leakage (due to simulation) of TX is much less than the cross modulation noise in the RX channel.
- Sampling rate of 32 samples/chip used for a 6 MHz TX-RX spacing.
- Use extended IS-95 FIR filter impulse response to lower out-of-band noise floor.

The simulation is done in the IQ modulation domain, and a pseudo-carrier frequency does not have to be assigned in ADS when multiple RF sources are used together, provided the sampling rate is large enough to encompass the large frequency separation. The 1-tone jammer is kept about 6 MHz away from the reverse link transmitter, and is therefore considered a relatively very wide band modulated signal requiring considerable over sampling. From the simulation requirements, a Cellular full duplex spacing of 45 MHz is not required between the reverse link transmitter and the one-tone jammer. With a 6 MHz spacing, the spectral leakage of the reverse link transmitter is much lower than the cross modulation noise in the receive band.
The IS-95 reverse link mobile transmitter is shown above. In the numeric domain, an impulse source clocks two PN (pseudo random noise) sequence generators that are based on IS-95. Each chip output of the PN source has 2 samples. It is down sampled to 1 sample/chip and then upsampled to 4 samples per chip with zero insertion in order to be compatible with the following stage IS-95 FIR filters. IS-95 defines the impulse response of these filters with 4 samples/chip, assuming the I and Q data inputs are an impulse stream. After the FIR filter, the Q channel is delayed by Tchip/2 i.e. by 2 samples, for offset QPSK modulation. The I and Q signals are converted to time domain and QAM modulated on to a carrier at frequency “ftx” MHz.

The out-of-band noise floor is flat and very high for the IS-95 transmitter. In order reduce the out-of-band noise floor and to reduce spectral leakage, especially into the RX channel for cross modulation simulation, the impulse response of the IS-95 FIR filters must be extended. This is done by cascading a raised cosine filter either in base band or at RF, after increasing the sampling rate. The band width of the raised cosine filter must be carefully set so that it is not too narrow to degrade the IS-95 RHO factor and the MSE (mean square error of IS-95 filter coefficients), and at the same time fit the TX spectral template. Too wide a band width produces a step in the spectrum skirt (out-of-band region has a step in the noise floor).
A model for gated RF power measurement is shown above. The output of an envelope detector is squared and integrated over the gated time (between Tsave and Tstop). The “CHOP” block selects the gated region of the signal. Only one power measurement sample must be read at the output port.
The simulated spectrum at the output of the LNA is shown in the figure above. The cross modulation noise spectrum at the output of the RX band pass channel filter is in the region marked by the rectangle.

In the one-tone desensitization test of an IS-95 mobile phone, an unmodulated -30 dBm (Pjam) carrier tone at an offset of 900 kHz (Cellular) or 1.25 MHz (PCS) interferes with the received CDMA signal at -101 dBm (Prx). Because of the CDMA transmitter open and closed loop power control, the handset is forced to transmit the maximum power when the received signal is close to the sensitivity level of -104 dBm. With a typical 45 dB isolation (Ltx) in the duplexer, the transmitter leakage into the receiver LNA is -22 dBm. The unmodulated interferer at the LNA input is about -33 dBm considering a 3 dB insertion loss (Lrx) in the duplexer received path.

Due to the 3rd order nonlinearity of the LNA, the jammer get cross modulated by the transmitter leakage. A part of this cross modulation power falls in the receive channel. If the LNA ip3 or the duplexer isolation is not large enough, the cross modulation power in the receive channel can significantly exceed the total thermal noise power.
Simulated Model for Cross Modulation Noise

Total cross modulation noise within the 1.25 MHz receive band

**Cellular band:**

\[
P_{\text{noise}} = -3 + 2(P_{\text{tx}} - P_{\text{IIIP3}} - L_{\text{tx}}) + P_{\text{jam}} - L_{\text{rx}} \quad \text{(units dBm and dB)}
\]

**PCS band:**

\[
noise = -5.6 + 2(P_{\text{tx}} - P_{\text{IIIP3}} - L_{\text{tx}}) + P_{\text{jam}} - L_{\text{rx}} \quad \text{(units of dBm and dB)}
\]

**Equivalent noise figure of a 0 dB gain amplifier:**

\[
F = 10\log \left( \frac{P_{\text{noise}} + 174 - 10\log(1230000)}{10} \right) \quad \text{dB}
\]

Based on the simulation results, a model has been derived, showing the relationship among the LNA IP3, transmitter leakage power, the 1-tone jammer power, and the total receive in-band cross modulation noise power. The first and second equations above depict the models.

The receiver in-band cross modulation noise power in the PCS band is about 2.6 dB less than in the cellular band for the same transmitter and interferer levels, because the PCS 1-tone interferer is further away from the receive band, compared with the cellular 1-tone interferer.

In the equations above,

- \(P_{\text{noise}} = \) Cross Modulation noise power in 1.23 MHz receiver pass band.
- \(P_{\text{tx}} = \) transmitter power at antenna (23 dBm Cellular, 15 dBm PCS), at \(f_{\text{TX}}\).
- \(L_{\text{tx}} = \) duplexer attenuation at \(f_{\text{TX}}\), from antenna to Receiver LNA.
- \(P_{\text{IIIP3}} = \) input 2-tone IP3 of receiver LNA.
- \(P_{\text{jam}} = \) 1-tone jammer power (-30 dBm) at antenna, at 900 kHz (cellular) or 1.25 MHz (PCS) offset from receive frequency \(f_{\text{RX}}\).
- \(L_{\text{rx}} = \) duplexer insertion loss (antenna to LNA) around \(f_{\text{RX}}\).

If the cross modulation noise power is modeled as an equivalent noise power of a 0 dB gain amplifier, then the last equation models the noise figure of such an amplifier.
Cross Modulation Noise vs Duplexer Isolation

- Cross modulation is only AM noise
- 3 dB less S/N degradation relative to AWGN of same power

The variation of Pnoise versus the duplexer isolation Ltx, is plotted above.

Comparison of Cross Modulation noise with additive White thermal noise

A simulation was done to compare the effects of white noise and cross modulation noise on the pilot and traffic signal to noise ratio after de-spreading. It was found that the cross modulation power had to be about 3 dB higher than the thermal white noise power in order to produce the same signal to noise ratio after de-spreading. This could be attributed to the fact that there is no phase noise associated with cross modulation. Cross modulation is only an amplitude modulation effect. Secondly, the in-band cross modulation noise only occupies about half of the 1.23 MHz span, and after despreading some of its power may go outside the relevant band. This 3 dB correction has not been incorporated into the equations and graphs.
Simulated Model for Cross Modulation Noise

A variation of the equivalent Cross Modulation noise figure versus the duplexer isolation $L_{tx}$, is plotted above for the Cellular band. Presently duplexers have about 50 dB TX-RX isolation shown by the green shaded region.

*For AWGN comparison, reduce noise figure by about 3 dB*
Receiver LNA Specifications

Philips Semiconductors BiCMOS Process

**TABLE 1** Comparison of LNA IP3 requirement based on cross modulation model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cellular</th>
<th>PCS</th>
<th>(proposed)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ptx dBm (based on IS-95 standard)</td>
<td>23</td>
<td>23</td>
<td>15</td>
<td>dBm</td>
</tr>
<tr>
<td>Ltx dB</td>
<td>55</td>
<td>54</td>
<td>48</td>
<td>dB</td>
</tr>
<tr>
<td>Pjam dBm (based on IS-95 standard)</td>
<td>-30</td>
<td>-30</td>
<td>-30</td>
<td>dBm</td>
</tr>
<tr>
<td>Lnx dB</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>dB</td>
</tr>
<tr>
<td><strong>LNA specifications for 1-tone IS-95 test (Cross Modulation):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNA Input IP3 (in TX band)</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>dBm</td>
</tr>
<tr>
<td>LNA Noise Figure</td>
<td>2.6</td>
<td></td>
<td>3.1</td>
<td>dB</td>
</tr>
<tr>
<td>LNA Gain</td>
<td>16.5</td>
<td>17</td>
<td>17</td>
<td>dB</td>
</tr>
<tr>
<td>Equivalent Cross Modulation Noise Figure</td>
<td>2.3</td>
<td>2.1</td>
<td>2.1</td>
<td>dB</td>
</tr>
<tr>
<td>(equivalent AWGN effect on despreading)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNA current</td>
<td></td>
<td>13.3</td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td><strong>LNA specifications for 2-tone IS-95 test (highest gain mode):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNA Input IP3 (in RX band)</td>
<td>15.5</td>
<td></td>
<td>15.5</td>
<td>dBm</td>
</tr>
<tr>
<td>LNA gain</td>
<td>16.5</td>
<td>16</td>
<td>16</td>
<td>dB</td>
</tr>
<tr>
<td>LNA noise figure</td>
<td>1.7</td>
<td>2.0</td>
<td>2.0</td>
<td>dB</td>
</tr>
<tr>
<td>LNA current</td>
<td>4.9</td>
<td>5.9</td>
<td>mA</td>
<td></td>
</tr>
</tbody>
</table>

LNA Specification

The cross modulation noise power significantly contributes to the overall receiver noise figure if the LNA IP3 is insufficient. A dual band LNA in the Philips Semiconductor’s QUBIC-3 BiCMOS process, with the specifications listed in TABLE 1 above, can meet the IS-95 mobile test requirements. In this table, the equivalent noise figure for the cross modulation has been computed by including the additional 3 dB benefit that is gained when compared with white noise. It can be seen that for the cross modulation case, the required IP3 for the LNA, or the isolation for the duplexer, is very high compared with the 2-tone test case.

Due to the very high IP3 requirement of the LNA in the PCS band, there is a proposal to change the IS-95 specifications according to which the reverse link transmitter power should be reduced from 23 dBm to 15 dBm, for the one-tone desensitization test. If implemented, it would amount to a major relaxation of the LNA input IP3 or the duplexer isolation, in the PCS band.
Theoretical results and simulations on gain compression and desensitization of the LNA are presented. Based on this, a linearization technique of the LNA is proposed, backed with simulations. Using this linearization technique it may be possible to considerably reduce the high IP3 requirement for the LNA, or the high duplexer TX-RX isolation requirement, for cross modulation noise that results from the combination of TX leakage and Jammers at the LNA input. The advantage of this technique is that it may be possible to do the linearization completely within the receiver LNA block itself.
Desensitization Analysis

First a look at Gain Compression:

\[
c(t) = \frac{GAIN_{\text{large signal}(t)}}{GAIN_{\text{small signal}}} \quad \text{(definition of Gain Compression)}
\]

\[
= 1 - \frac{P_T(t)}{2P_{IP3}} \quad \text{(For an ideal memory less 3rd order nonlinearity)}
\]

In general, for a memory less higher order nonlinearity:

\[
c(t) = 1 + k_1 \frac{P_T(t)}{P_{IP3}} + k_2 \left( \frac{P_T(t)}{P_{IP3}} \right)^2 + \ldots and \ldots.
\]

Gain Compression of LNA

The above equations show the gain compression of a large signal that has a time varying instantaneous power \( P_T(t) \) at the LNA input. \( P_{IP3} \) is the LNA input IP3. In the expressions for gain compression \( c(t) \) which is time varying, memory effects and phase distortions have not been considered.
Desensitization $d(t)$ is the fractional change in gain of a small signal when a large signal appears. Mathematically,

$$d(t) = \frac{s_J(t)}{P_T(t)} \left| \frac{P_T(t)}{P_J} \right| = 0$$

$s_J(t)$ is the small signal jammer, with power $P_J$.

$P_T(t)$ is the power of the large signal.

The Jammer $s_J(t)$ gets desensitized by the strong TX leakage power $P_T(t)$.

 Condition: $P_J \ll P_T \ll P_{IP3}$

$d(t)$ varies in sync with $P_T(t)$ AM modulation of Jammer $s_J(t)$.

**Desensitization**

When a smaller jammer signal $s_J(t)$ is present along with the time varying larger TX leakage signal that has an instantaneous power $P_T(t)$ at the LNA input, the smaller signal undergoes a time varying gain change (desensitization) that is about double that of the large signal.

The time varying desensitization of the smaller signal is basically AM modulation, and it is another definition of cross modulation. Using this definition, it is easier to see how the LNA can be linearized for minimizing cross modulation.
Simulation results for gain compresion of a large signal, and simultaneous desensitization of a single tone small signal, are shown above, for a 3rd order nonlinearity. The x-axis is the large signal input level relative to the input IP3, in dB. The y-axis shows the change in gain for the large and the small signals, in dB.
Linearization by Gain Modulation

Remove AM modulation by making \( d(t) = \text{constant} \).
Modulate LNA gain as \( a_1(t) \).
Total LNA gain for jammer is \( a_1(t)d(t) \).
Equating \( a_1(t)d(t) = 1 \), the equation for \( a_1(t) \) is:

\[
a_1(t) = a_1\left[ 1 + \frac{P_T(t)}{P_{IIP3}} \right]
\]

(i.e. gain changes with signal power)

Investigate envelope gain “E” versus Cross Mod noise power

\[
a_1(t) = a_1\left[ 1 + \frac{P_T(t)}{P_{IIP3}} \right] E=1 \text{ for cancellation of AM}
\]

The time varying desensitization of the single tone jammer produces spectral spread of its power, resulting in significant increase in the receiver channel cross mod noise. To greatly reduce cross modulation, the total gain of the jammer should be made time independent. This can be done by linearly varying the LNA gain by the instantaneous power \( P_T(t) \) according to the equation above.

By doing this linear gain modulation, \( a_1(t)d(t) = 1 \) for the optimum case when \( E=1 \) and there is negligible AM modulation of the jammer, and so there is very little spectral spreading.
Gain Modulation of LNA

The proposed block diagram for the LNA linearization is shown above. In this figure, the constant $E$ represents the gain of the envelope power detector, combined with the proportionality constant of the gain control of the LNA. Ideally, the value of the envelope gain $E$ should be one.
Models for the envelope power detector are depicted above. In a real implementation in silicon, it may be required to have an external control to calibrate E. Also, the instantaneous power $P_T(t)$ that is used for the gain modulation, could be directly generated in the base band modem, with an appropriate delay. Also, it is not necessary that $P_J \ll P_T$ for the linearization to be effective. Even when the two powers are equal, the linearization works well. Another problem with implementation is the detection of $P_T(t)$ at the LNA output where the external filter may offer changing load in the transmit band. It may be required to buffer the output stage or have a current tap at an appropriate point in the LNA, for the detection of $P_T(t)$. 
Implementation of the LNA gain modulation in HP ADS is shown above.

At the extreme left is the LNA which models the nonlinearity, using various possible models in HP ADS. In the present simulation, only the IP3 has been included for the nonlinearity.

Since the simple gain modulation for linearization is only an AM modulation, it is done on the magnitude of the RF signal in the simulation. At the output of the LNA, the signal is split into two paths. The top path extracts the magnitude and phase of the envelope after down converting to base band I and Q. The lower path detects the time varying signal power $P_T(t)$, and constructs a base band signal $\left[1 + \frac{P_T(t)}{P_{OIP3}}\right]$, which is then multiplied with the magnitude information of the top path. This AM modulated magnitude is combined with the original phase information back into I and Q (polar to rectangular conversion). The I and Q signals are then converted back to RF using a QAM modulator.
In the simulation above, the cross modulation noise power in the receive channel is measured as a function of the envelope gain factor E. The simulation setup is almost identical to the earlier cross modulation setup, except that here the linearization of the LNA is performed inside the block tagged “Nonlinear LNA.” This block is shown in detail in the previous slide. When E = 0, there is no linearization at all, and the “Nonlinear LNA” block simply behaves as a nonlinear gain. When E = 1, the linearization is optimum, and the cross modulation noise is minimal.
For the LNA linearization investigation, a simulation was done using HP ADS to see the effect of the envelope gain E, on the cross modulation noise power in the receive band. The result is shown above. The LNA input IP3 was taken as 2 dBm, the transmitter power leakage into the LNA was taken as -23 dBm, and the single tone jammer power was -33 dBm. According to the earlier derived cross modulation noise model for Cellular band, the cross modulation noise power should be -86.3 dBm in the receive band without linearization i.e. for E = 0. In the above figure it can be seen that the cross modulation power varies between -86.3 dBm (for E = 0) and -113 dBm (for E = 1). The simulator noise floor gave -116 dBm cross modulation noise power with no LNA nonlinearity.
The simulated spectrum for the LNA cross modulation with \((E = 1)\) and without \((E = 0)\) linearization, is shown above. It can be visually seen from this spectrum how significantly linearization reduces the cross modulation noise power. Simulations were also done to investigate exponential gain modulation from the envelope (gain in dB linearly varying with envelope voltage), but the results were comparatively inferior.

**Effect on Received CDMA Signal**

The desensitization due to cross modulation also occurs on the wanted signal which is extremely small in comparison with the transmitter leakage power. It slightly degrades the orthogonality of the Walsh channels and degrades the despread S/N more severely for Traffic channels that are at relatively weaker levels compared with other channels on the same carrier. The orthogonality is degraded slightly because the mean gain change interval (due to desensitization) is much less than the 64-chip symbol interval over which the orthogonality is established. With the additional gain modulation for linearization, the orthogonality of the received Walsh channels actually improves (even though it may be very small), as it removes to a large extent the time varying desensitization. This occurs independently of the presence of jammers.
References

- IS-95 Dual band triple mode LNA+Mixer specifications by Rishi Mohindra (Philips Semiconductors internal document), August 1998.
- Agilent ADS documentation.
ADS Project and Exercise

**ADS project: crossmod_prj**

**Design files:**

1) CROSSMOD
   Simulates LNA cross modulation noise and spectrum
2) CROSSMOD_LINEARIZE
   Linearizes the LNA and measures cross modulation noise and spectrum. Measures Cross Mod noise versus envelope gain E.

Cross Modulation simulation:
Simulate the design CROSSMOD, and observe the input and output LNA signal spectrum. The output spectrum has a very large cross modulation noise. It is -86 dBm as measured by the power meter after the receive channel filter. The ip3 of the LNA is TOI = 2 dBm, the TX leakage is -23 dBm, and the jammer level is -33 dBm. The results are already saved in the file CROSSMOD.dds that can be opened through the results display window.

Linearization simulation:
The linearization simulation is done in the design CROSSMOD_linearize. It is similar to the previous simulation except that the LNA has been now included in a linearization block. An important parameter to adjust is the envelope gain E. When E = 0, the linearization is completely switched off, and the LNA output signal spectrum is identical to the CROSSMOD design simulation. When E = 1, the linearization is optimal i.e. the cross mod noise is minimal. It can be visually seen in the output signal spectrum and accurately measured by the receive channel power meter which reads about -108 dBm. The results can also be seen in the display file named CROSSMOD_linearize.dds.

If the parameter sweep block is enabled, the cross mod noise can be plotted as a function of E which is swept from 0 to 1.5. The minimum cross mod noise occurs at E = 1. The results are also available in the display file named CROSSMOD_Esweep.
End of Design Seminar...