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Integrated Cellular Transceivers: Challenging Traditional Test Philosophies

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Abstract

In today's high volume manufacturing of cellular transceivers, cost of test is paramount. With more and more integration of mixed signal and RF components onto the same die, traditional test philosophies are being challenged. Should this highly integrated transceiver be considered as a series of blocks, which need to be tested individually? Would it make more sense to treat the whole die as a radio and test it accordingly? In general, Mixed Signal engineering techniques treat the chip as a series of blocks, and RF engineering techniques treat the chip as a radio. The optimal test flow lies somewhere in between.

This paper will illustrate, with examples, the tradeoffs between treating a system on a chip or SOC as a radio versus a series of functional blocks. Both approaches have their merits and this paper will give an example test list breakdown for each case. Two real world block diagrams of cellular receivers will be used as examples and the test breakdown needed to cover functionality of all the blocks using both philosophies will be discussed. Each approach will be analyzed to determine its effectiveness and efficiency in final test.

To illustrate the differences, two optimized test flows will be presented which contain elements of both approaches and the reasoning behind the tests chosen will be discussed, providing the reader with more insight into writing efficient system tests for radio transceivers. This paper will also highlight the difference between characterization and final test, as well as provide some insight into the differences between mixed signal and RF test.

Introduction to Digital Radio Receivers

As cost pressures continue to rise on the integrated circuit industry, the trend towards higher and higher integration continues. In the RF world, this manifests itself as more and more digital and mixed signal components showing up on traditionally RFICs. The industry goal is to integrate as much onto a single IC as possible.

In the consumer cellular market, it is well established that digital radios can save a lot of battery power as well as conserve precious and finite frequency bandwidth. Let's start by analyzing the contents of a generic digital radio for cellular phone receivers (Figure1).

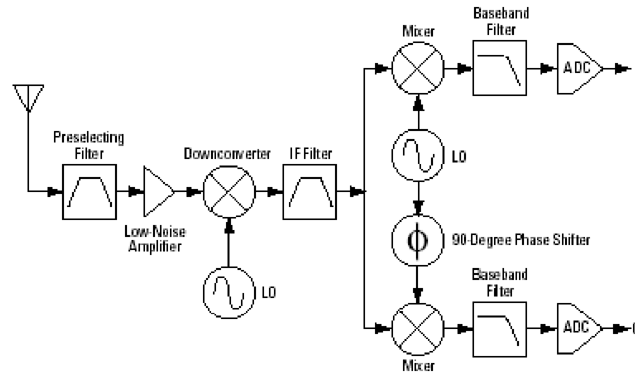


Figure 1: Superhet Digital Radio Block Diagram

The entire spectrum available to the antenna arrives at the Preselecting Filter. This filter limits the spectrum to a few specific frequencies, namely the RX or receiver band of the cell phone. Since this input channel has a very low amplitude, it is then boosted in power by the Low Noise Amplifier or LNA. This signal is then downconverted through the first mixer, and then further filtered to ensure that only one RX channel gets through. What remains is a single RX channel, which needs to be demodulated. This single channel is split into its in-phase and quadrature components by using two additional mixers. The LO's, or local oscillators, for these mixers are offset by a 90 degree phase separation. The baseband signals are then filtered another time and digitized.

In this example, most of the components described are traditional RF system blocks. The only ones that are traditional mixed signal blocks are the baseband filter and the ADCs. In fact, RF engineers typically get the signals directly from the baseband filters and perform their analysis from there.

In the semiconductor test world, things are a bit different. The block diagram changes a bit, which has a huge impact on the test list and test methodology. There is no preselecting filter or baseband analog to digital converters (ADCs). Consider a real world example of a block diagram of a code division multiple access (CDMA) receiver as shown in Figure 2.

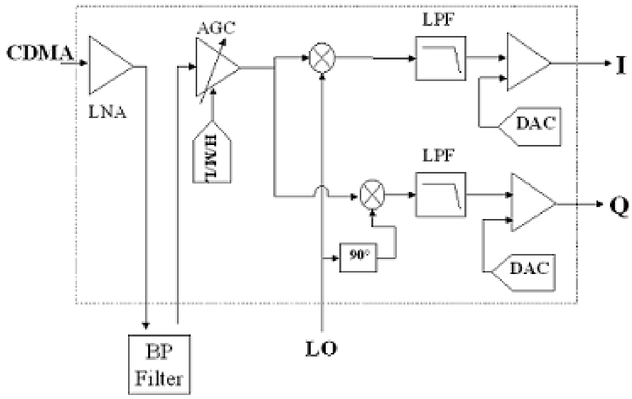


Figure 2: CDMA/AMPS Receiver Block Diagram

The first thing that should be apparent is that this is a slightly different architecture. In fact, this is a zero IF or ZIF design. This means that there is a single LO, and hence, a single down conversion used for the device. In this case, the entire RX input band is incident on the first LNA, and then taken off-chip for further band pass filtering. The signal is then sent through an automatic gain control amplifier or AGC. This AGC amplifies the signal so that it can be detected by the demodulator circuit. Next the signal is directly down converted so that its center frequency is at 0 Hz (hence zero IF.) The 90 degree phase shifter block from the LO causes the incoming signal to be demodulated and broken down into its corresponding I and Q components. Finally the signal is sent through a final low pass filter and buffer before being sent off chip.

A few new components are visible in this block diagram as well. Notice there are two DAC's at the I and Q buffers. In ZIF architectures, converting a signal from RF to baseband will inevitably have a DC component. If the component is too high, the signal needed will not be detectable. These two DAC's will compensate for the DC component and make sure the signal stays around 0V. Also notice that the AGC block needs some sort of control to manage the level of amplification for the receiver. These kinds of DAC blocks are quite common for mixed signal test engineers, but may be new for RF test engineers.

This device is a CDMA/AMPS receiver, which also supports PCS. Table 1 includes some of the basic specifications for these standards.

	RX Frequency	*Channel spacing*	*Modulation*
PCS	1.9 GHz	1.25 MHz	QPSK
CDMA	820 MHz	1.25 MHz	QPSK
AMPS	820 MHz	30 kHz	FM

Table 1: PCS, CDMA, AMPS Summary

Figure 3 shows another example of a real world cellular receiver. It is also a ZIF receiver, but this one is designed to work in the GSM or global system for mobile communications band.

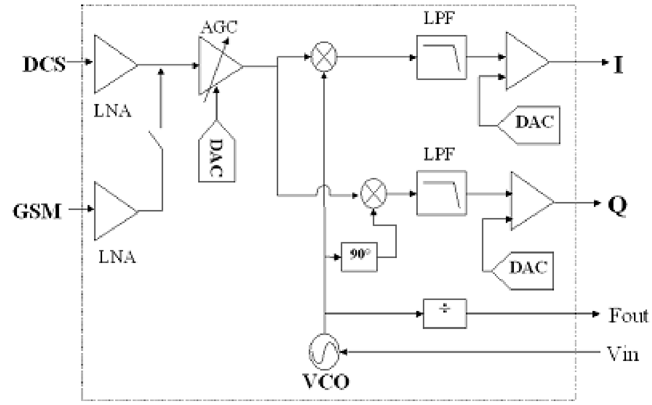


Figure 3: GSM/DCS Receiver Block Diagram

From a block diagram point of view, this is very similar to the CDMA chip. It is also a ZIF receiver, except that it works at two different bands. This is why it has two LNA's before the AGC. Each LNA is tuned for either the DCS or GSM frequency band. Also, it is not necessary to have off chip filtering as GSM adjacent channel filtering is less rigorous. Note that this chip has a voltage controlled oscillator or VCO integrated right onto the chip. This adds more complexity to the chip test list. This device is described as a DCS, GSM850, GSM and PCS compatible receiver. It is also specified as being EDGE ready. Table 2 summarizes what this means from a high level point of view.

	RX Frequency	*Channel Spacing*	*Modulation*
DCS	1805-1880 MHz	200 kHz	GMSK
GSM850	869-894 MHz	200 kHz	GMSK
GSM	925-960 MHz	200 kHz	GMSK
PCS	1930-1990 MHz	200 kHz	GMSK
EDGE	Any Above	200 kHz	8PSK

Table 2: DCS/GSM/PCS/EDGE Summary

Mixed Signal vs. RF Test Engineering

As integration increases, it is becoming more and more necessary for RF engineers to learn mixed signal test and for mixed signal engineers to learn RF techniques. The main difference between RF engineers and mixed signal engineers is that RF engineers do a frequency conversion before their digitizing. RF engineers also play more tricks with incident and reflective waves by using reflectometers. For this discussion though, the device under test or DUT acts as the frequency translator, and the digitizing is done using traditional mixed signal techniques. Therefore, all RF blocks will be treated as cascaded RF elements, and the mixed signal blocks will be tested with mixed signal techniques. For consistency, keep in mind that dBm for a 50 ohm system is defined as:

$$dBm = 10\log[((vout)^2/50)/1mW]$$

This is an absolute measurement of signal level compared to 1mW. All baseband power and gain measurements need to be converted to this unit for consistency with other radio specifications.

Production vs. Characterization

Traditionally, test engineers start with a very complete test program, and then simply remove some of the tests when production starts. As the product matures, additional tests are removed until a final test flow is achieved. This process can take years to achieve a final test flow. Looking at the different modes of operation, there is a strong temptation to test all permutations of types of modulation, frequencies, and channels. There is also a great deal of pressure from the designers to add additional tests to the test flow for their "pet" module.

Test engineers should strongly resist the temptation to put all these tests into the production test flow. Keep in mind that each device should be characterized before going into production, and characterization should be as complete as possible. For production, however, the main goal is to determine that the DUT is good and that it is functional. It is not necessary to characterize every device that ships from the test floor. However, understanding the need to minimize risk, there is a very easy way to get the best of both worlds.

One approach could be to minimize the test flow at the beginning of the ramp up, and characterize every Nth device (see Figure 4) putting all results into a datalog.

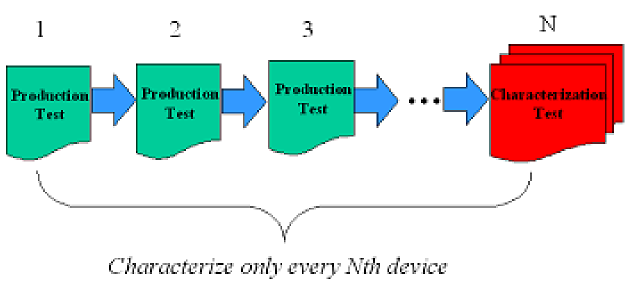


Figure 4: Alternative Production Flow

This approach can get the best of both worlds. It allows a much faster production test time, and still allows visibility into overall device performance. This approach also has the benefit of keeping track of production corners and also keeping costs low. Defining P as production test time, and C as characterization test time, overall test time will be:

$$Teff = \{P*(N-1)+C\}/N.$$

For example if N=50, P=2.0 seconds and C = 60.0 seconds, Teff = 3.16 seconds. As the product matures, simply increase N to further improve throughput. If N = 200, Teff becomes 2.29 seconds.

This paper assumes that the characterization test flow is pretty obvious to derive (although time consuming to code.) Based on this production flow approach, it becomes extremely important to reduce the production tests needed to show that the DUT is working and meets specifications. The best way to do this is start by analyzing each block of the DUT.

SOC Test Generation Block by Block Approach

A good approach to developing a test list for these devices is to understand the kinds of measurements needed for each of the blocks of the radio. Once all blocks are understood, the tests are then cascaded together to come up with a complete test list, which covers all of the individual blocks.

Amplifiers

When testing amplifiers, the primary measurements of interest are:

- Gain
- Noise Figure
- Impedance Match
- Saturation/Compression
- Flatness across Channel
- Intermodulation Distortion

To describe any amplifier's performance, gain and saturation, will show the block's amplification and dynamic range. The flatness across the channel will make sure that the gain is constant across the channel frequency range. Since each block in any radio design will add noise to the signal, noise figure will determine exactly how much noise is added. For DUT test, impedance match of internally connected amplifiers is probably not necessary or even possible to measure. It is assumed that if there were a problem with the impedance match of an internal node, it would certainly show up on one of the other measurements (gain, flatness, or noise figure).

The previous measurements show a variety of linear effects. It is also crucial to measure non-linear effects on the incident signals. Figure 5 shows the most popular non-linear measurement, intermodulation distortion. The idea is that when two signals are applied to the DUT, more than these two signals appear at the output. F1 and F2 are applied very close to each other in the frequency band. It turns out that two intermodulation products will appear very close to the F1, and F2 signals at 2*F1-F2 and 2*F2-F1.

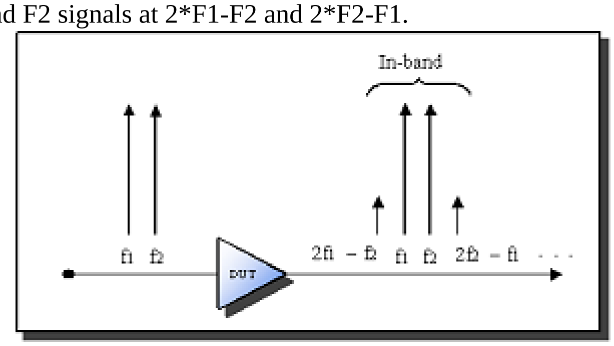


Figure 5: In Band Intermodulation Products

An interesting property of these signals is that the fundamentals (f1 and f2) will increase 1 dB at the output for every 1 dB increase at the input. The intermodulation products have a 3 to 1 growth. This means that if the fundamentals are increased by 1 dB on the input, the intermodulation products will grow by 3 dB. We can plot these two lines on an input vs output chart. Finding where these two lines intersect is called the third order intercept or TOI, shown in Figure 6.

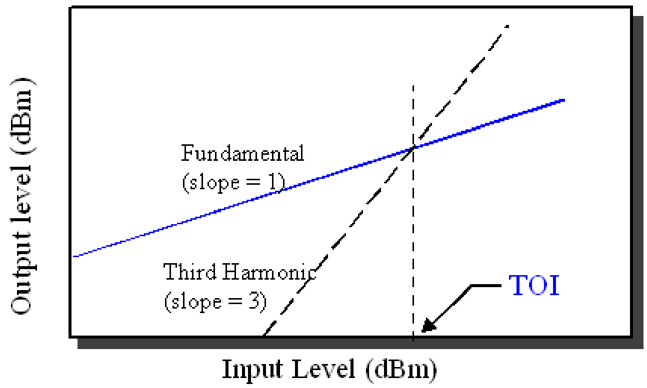


Figure 6: Third Order Intercept

Mixers

In the ZIF radio block diagram, the next block of interest is the mixer. In measuring mixers, the primary interest is in:

- Gain
- Noise Figure
- Impedance Match
- RF to IF Isolation
- LO to IF Isolation
- LO to RF Isolation

The good news for the test engineer is that some of these concepts are easy to cascade. Gain and noise figure for an amplifier coupled with a mixer, can be combined into one measurement. In other words, for both of these blocks combined, one measurement can be made to qualify both blocks. Once again, impedance match of an internal node is not so crucial to measure in production as any impedance match problems will show up in gain or noise figure.

The other measurements are graphically depicted in Figure 7. The signal incident on the mixer is called the RF signal at port 1. The LO is the local oscillator signal which is incident at port 2. The IF or intermediate frequency is known as the output port, which is visible at port 3.

RF to IF isolation is shown in blue and it is simply the amount of unwanted RF signal which "bleeds through" to the IF port. LO to IF isolation is shown in gray, and LO to RF isolation is shown in pink.

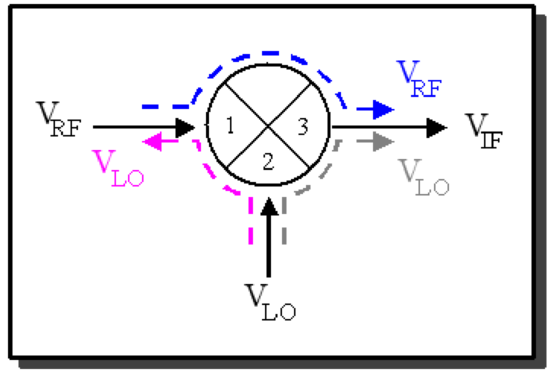


Figure 7: Mixer Isolation Paths

Mixer operation is simple as it is designed to take an input RF signal and translate that up and down in the frequency domain by the equation: FIF = FLO-FRF, and FIF=FRF-FLO. In radio design, either the lower or upper IF bandwidth is filtered out (see Figure 8).

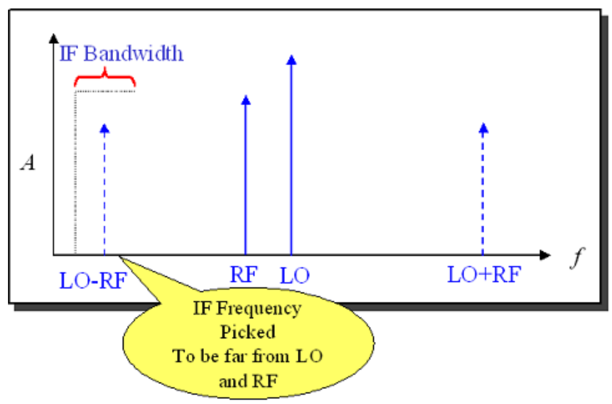


Figure 8: Mixer Output Products

DUT verification for test engineers is simplified greatly because most RF receivers are designed such that the LO-RF and LO+RF are always much greater than the channel bandwidth. This means that there is no need to test for this bleed through effect.

Other intermodulation products can, however, be generated due to other frequencies and interactions, which can indeed show up in the operating band of the radio. A SINAD (signal to noise + distortion) test can be used to check the entire operating bandwidth for these intermodulation products.

Demodulators

The next block in the ZIF radio design is the demodulator (see Figure 9). For the ZIF design, the demodulation occurs by taking an LO frequency, and shifting it by 90 degrees. This signal is then applied to two different mixers. The resultant demodulation becomes highly dependent on extremely accurate phase separation between the two mixers, and how accurately the gain of the I and Q paths are matched. These characteristics are described by:

- Phase Mismatch

- Amplitude Mismatch

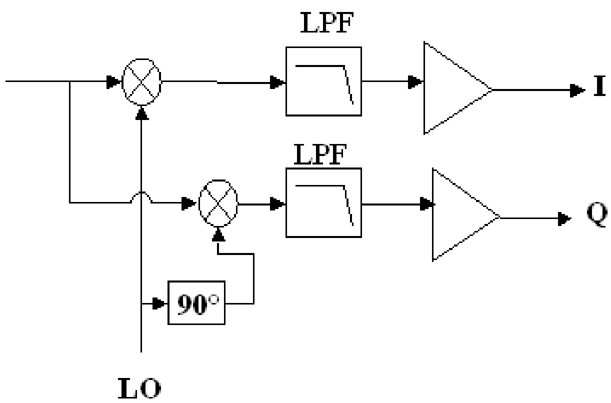
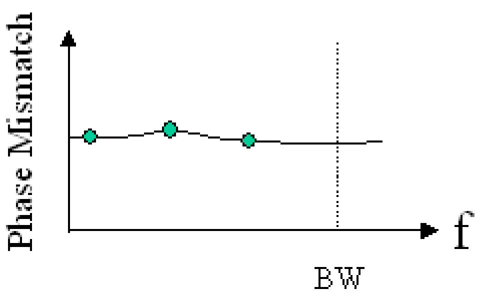


Figure 9: ZIF Demodulator

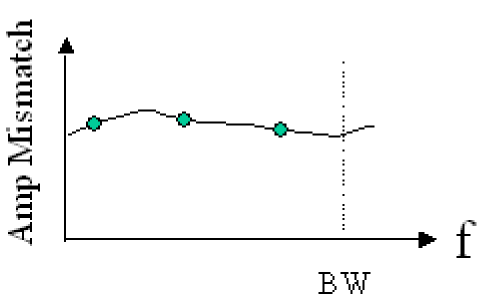
The theory behind how this works is based on the idea that information can be sent over the RF link by instantaneously varying the amplitude and phase of the signal. For thorough testing of the device, phase mismatch of the demodulator across the entire operating band of the channel must be measured. In practice, a few points are measured and linearity is assumed between the points (see Figure 10).



$$\varphi_i - \varphi_q$$

Figure 10: Phase Mismatch Plot

Also, the gain of the I and Q signals must be identical. This is measured by sending in a single tone and checking the amplitude difference between the I and Q outputs. Figure 11 shows the graphical representation and the equation used to make this measurement.



$$20\text{Log}(I/Q)$$

Figure 11: Amplitude Mismatch Plot

Baseband Filters

The next major functional block common to both ZIF receivers is the baseband anti-aliasing filter. For the baseband anti-aliasing filter the measurements of interest are:

- Amplitude Ripple Per Channel
- Phase Response Per Channel
- 3dB Rolloff
- Cumulated ISI

Amplitude ripple is measured by looking over the entire operating channel and finding variation in the pass band. This can be measured at the same time as amplitude mismatch is made. The same idea applies to Phase response per channel.

Additionally, a major filter figure of merit is the frequency point at which the amplitude drops by 3 dB. This can also be a time consuming search. One approach might be to make several data point measurements and then do an interpolation to find exactly where the 3 dB point occurs. This 3 dB point is known as the operating bandwidth of the device.

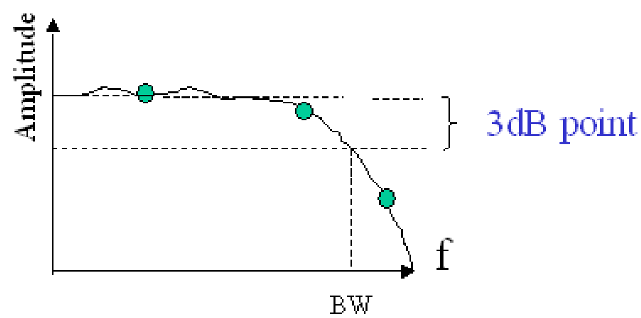


Figure 12: Amplitude Ripple and 3 dB Rolloff

Even ideal filters will affect the incident signals in some way. Figure 13 shows the impulse response on a standard LPF filter. If the signal is spread too far in the time domain, inter symbol interference is created. This can cause signal degradation.

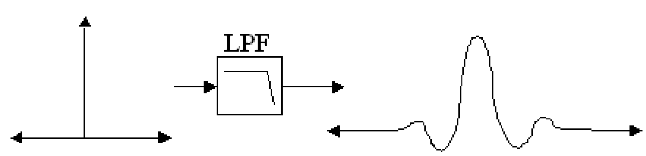


Figure 13: LPF Impulse Response

Beyond the 3 dB cutoff frequency, the ISI is the ultimate goal of any baseband filter measurement. The test engineer wishes to ensure that the baseband filter will not cause inter symbol interference. If ISI is too high, the device will not be able to demodulate the signal properly.

VCOs

For the examples used in this paper, the VCO block is only present in GSM ZIF receiver. For VCO characterization, major interests are:

- VCO Output Power
- VCO Frequency Range
- Voltage vs. Frequency Response
- Phase Noise

The output power and frequency range are straightforward RF measurements. In order to test voltage vs. frequency response, the VCO must be locked with a PLL circuit. First the VCO is locked at the lower end of the band, and the output frequency, and input voltage are measured. Next, the VCO is locked at the upper end of the band and another frequency and voltage measurement is made. The slope is then recorded as: (V1-V2)/(F1-F2).

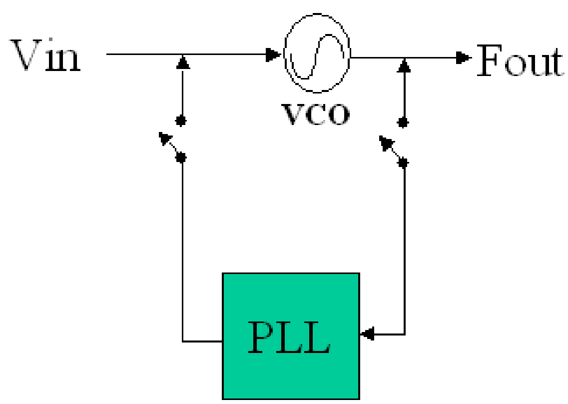


Figure 14

To measure phase noise, lock the VCO, and compare the maximum output with the power over a narrow bandwidth at a specific offset frequency. The purpose of this measurement is to ensure that any received signal will stay within band. This number is usually recorded with the measurement bandwidth normalized as in dBc/Hz (see Figure 15).

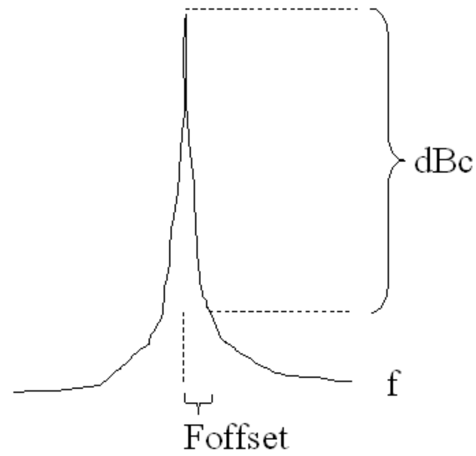


Figure 15: Phase Noise Measurement

Overall DUT System Test List

As stated before, many of the tests that the RF blocks have in common can be cascaded. By cascading all relevant tests, an overall radio test list can be generated. Beginning with the GSM radio receiver, Table 3 provides a rather comprehensive production test list.

GSM Receiver	Number of Meas
Non-Linearity Tests	
TOI Two Tone test (DCS/GSM)	2
Noise Figure (DCS/GSM)	2
Automatic Gain Control Linearity	
Min/Max AGC settings (Saturation)	2
Gain/Balance Tests	
Receiver Gain (DCS/GSM)	2
Phase Mismatch Tests	3
Amplitude Mismatch Tests (Flatness)	3
SINAD Measurements	3
Baseband Filter Response	
Amplitude Ripple (I and Q)	6
DC Offset Correction DAC Tests	
INL/DNL	2
AGC Digital to Analog Conv Tests	
INL/DNL	1
RX VCO Tests	
Vmeas	2
Fmeas for RF	2
Power Out Meas for RF	2
Calculate VCO slope and Phase noise	0
Total Measurements	32

Table 3: GSM Comprehensive Test List

The list starts with the non-linear tests. The non-linearity tests include TOI, and Noise Figure. In the case of the GSM receiver, there will need to be two measurements for each of these tests. One measurement will be for the DCS LNA path, and the other for the GSM LNA path. Table 2 shows the frequency bands of interest for GSM/DCS radios. As the final test list gets generated, it is a good idea to use as many corner cases of this frequency band as possible. For instance, the NF measurement could be made at 869 MHz, and 1805 MHz. The TOI's could then be measured at 960 MHz and 1990 MHz. This provides coverage at various frequency points in the operating band.

The next section, AGC linearity, will require two measurements. One measurement is for minimum sensitivity, and the other for maximum input power. This test will make sure that the DUT is not in compression over the specified dynamic range. This test could be done in the middle of the GSM band, or 914 MHz. Remember, that as the test list is being generated, make sure that the test frequencies show a representative list of the operating bands of the device.

The gain/balance tests will be the most involved. Recall that in order for the demodulator to work properly, proper phase and amplitude match across the operating channel must be ensured. For this reason, three phase and amplitude measurements must be made, and three corresponding SINAD measurements must be made at high, med and low band. The good news is that this can generally be done in six baseband captures (three captures of both I and Q), but all three quantities must be calculated and datalogged. Overall gain must also be checked for both the GSM and DCS LNA's.

For the filter response, both the I and the Q channels must be checked and at least three measurements must be made for each in order to find exactly where the 3 dB rolloff occurs. This makes a total of 6 measurements.

Since the GSM receiver has two DC offset correction DAC's, two traditionally mixed signal tests of INL and DNL will be needed in order to ensure that all bits are working properly. INL stands for integral non-linearity while DNL stands for differential non-linearity. These tests are well defined and can be found in any mixed signal test text. In order to perform these tests, the part must have some sort of test circuit to breakout the DAC output voltage. For the AGC circuit, one additional INL/DNL test will be needed.

Recall that this GSM receiver also has a VCO. This implies that two measurements of both frequency and voltage need to be made in order to calculate the VCO frequency response slope. The VCO's output power and phase noise will also be needed, for a total of six different VCO measurements.

Using the technique of block by block analysis, a production test list has now been generated that checks the major functionality of each block. Each block has been activated and its major effects measured. The total number of measurements needed for this GSM receiver is 32.

For the CDMA receiver, the main difference is that it has an embedded LNA that must be tested. It does not have a VCO so those tests can be omitted. The test summary can be seen in Table 4.

CDMA Receiver	Number of Meas
Non-Linearity Tests	
TOI Two Tone test (LNA/RX Chain)	2
Noise Figure (LNA/RX Chain)	2
Automatic Gain Control Linearity	
Min/Max AGC settings (Saturation)	2
Gain/Balance Tests	
Receiver Gain	1
Phase Mismatch Tests	3
Amplitude Mismatch Tests (Flatness)	3
SINAD Measurements	3
Baseband Filter Response	
Amplitude Ripple (I and Q)	6
DC Offset Correction DAC Tests	
INL/DNL	2
AGC Digital to Analog Conv Tests	
INL/DNL	1
Total Measurements	25

Table 4: CDMA Receiver Comprehensive Test List

For the non-linearity tests, the performance of the first LNA by itself will be needed and then the overall performance of the rest of the receive chain should be measured. This works out to be 2 NF measurements and 2 TOI measurements.

For the gain/balance tests, only the receiver gain of the chain from the output of the SAW filter will be needed, but the rest of the list will be identical to the GSM test list.

Of course the CDMA receiver has no VCO on board, so these tests will not be needed. However, the same techniques as before should be employed to ensure that all major frequencies in the 820 MHz band and the 1900 MHz band are represented in the test list.

Once again, the entire DUT has been tested and each block has been represented in the final test list. The end result is 25 measurements needed to test this CDMA receiver.

SOC Test Breakdown A Radio Approach

In the previous example, signals used on the DUT were limited to CW's or discrete carrier waves at the input and output of the device. In the real world, this is never the case. Once the DUT is installed in a phone, it is only given complex signals with coherent messages. Modulated signals are measured with EVM.

EVM or error vector magnitude is a measure of modulation quality. It is a measurement which quantifies how several radio blocks act and interact. If a modulated signal is applied to the receiver and a plot is made of the I and Q plane, the result is what is referred to as constellation plots. Figures 16 and 17 are constellation plots for GSM and EDGE modulation respectively. GSM is a constant amplitude modulation and appears as a circle with discrete points. Edge is much more complex and appears as a series of dots on the I-Q plane. EVM is the magnitude of error that the measured signal has as compared to the ideal constellation plot. Since this is a dynamic measurement, it contains both amplitude and time components.

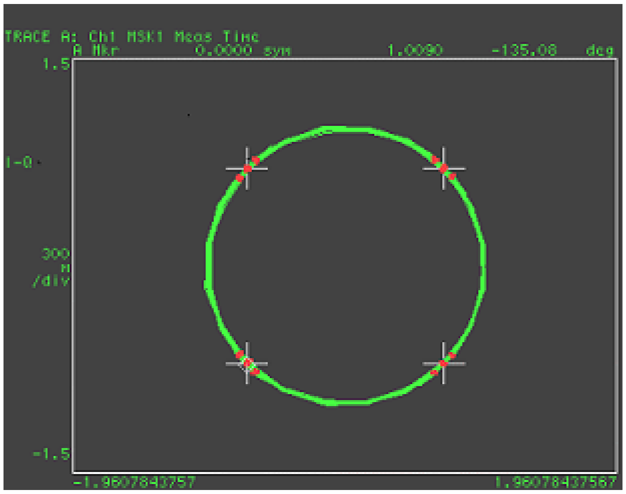


Figure 16: GSM Constellation Plot

By using EVM, the DUT is no longer being treated as a series of blocks. Now the DUT is being treated as a system. The benefit here is that one test can replace several other discrete tone tests.

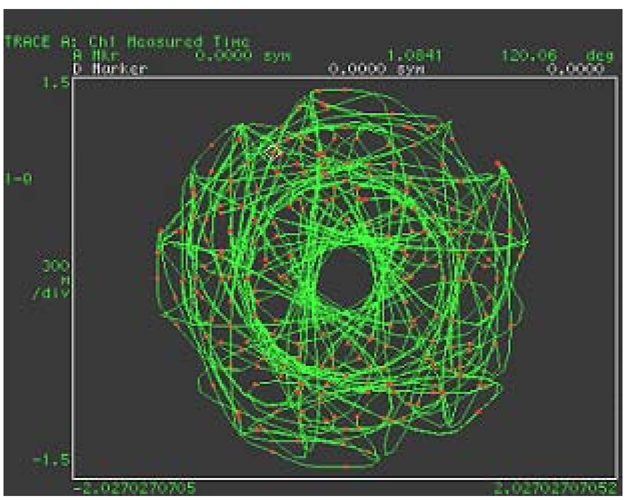


Figure 17: EDGE Constellation Plot

In order for a demodulator to pass a complex demodulation test, the phase and amplitude balance have to be correct across the entire operating band. Also, there has to be very little inter symbol interference (see Figure 13). What this means is that by using EVM to test the demodulator, all of the amplitude/phase imbalance tests, and all of the filter tests can be replaced with a single EVM measurement. This will greatly reduce the test list. Of course, for the EVM measurement to be accurate, very good test instrumentation linearity is required, and extremely robust demodulation algorithm must be available.

CDMA modulation uses QPSK or quadrature phase shift keying modulation. Figure 18 shows QPSK modulation with various filter slopes. This is intended to demonstrate the effect of defective filters on the EVM constellation plot.

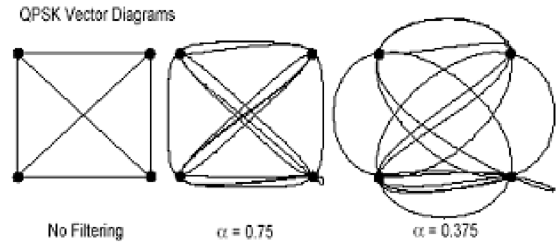


Figure 18: CDMA's QPSK Modulation With Various Filter Slopes

Tables 5 and 6 show the new abbreviated test list that would be needed to provide good coverage of these two receivers using EVM. Note that the GSM test list was reduced from 32 elements to 18 elements. The CDMA test list went from 25 to 11 measurements. Keep in mind that this did not reduce test coverage at all. In fact, EVM provides the entire phase and amplitude response across the entire operating band and not just three discrete points. It could easily be argued that test coverage is significantly improved.

GSM Receiver	**Number of Meas**
Non-Linearity Tests	
TOI Two Tone test (DCS/GSM)	2
Noise Figure (DCS/GSM)	2
Automatic Gain Control Linearity	
Min/Max AGC settings (Saturation)	2
Gain/Balance Tests	
Receiver Gain (DCS/GSM)	2
EVM (EDGE)	1
Baseband Filter Response	
Amplitude Ripple (I and Q)	0
DC Offset Correction DAC Tests	
INL/DNL	2
AGC Digital to Analog Conv Tests	
INL/DNL	1
RX VCO Tests	
Vmeas	2
Fmeas for RF	2
Power Out Meas for RF	2
Calculate VCO slope and Phase noise	0
Total Measurements	18

Table 5: GSM Test List with EVM

CDMA Receiver	Number of Meas
Non-Linearity Tests	
TOI Two Tone test (LNA/RX Chain)	2
Noise Figure (LNA/RX Chain)	2
Automatic Gain Control Linearity	
Min/Max AGC settings (Saturation)	2
Gain/Balance Tests	
Receiver Gain	1
EVM (CDMA) QPSK	1
Baseband Filter Response	
Amplitude Ripple (I and Q)	0
DC Offset Correction DAC Tests	
INL/DNL	2
AGC Digital to Analog Conv Tests	
INL/DNL	1
Total Measurements	11

Table 6 CDMA Test List with EVM

Conclusions

This test list breakdown has been done based off of information found in the public domain. It is by no means exhaustive. This is just a representation of one specific GSM receiver and one specific CDMA receiver. Of course, there will be many other details in the final test list not included here.

It is very common for production test lists to contain many redundant tests that do not improve system test coverage. This paper is meant to demonstrate the kind of thinking needed in order to come up with a comprehensive test list that makes sense instead of "shot-gunning." Keep in mind differences between characterization and production. The best of both worlds can be achieved without significantly driving up cost of test.

Minimizing the number of tests will always be the greatest throughput advantage. Take advantage of how the radio blocks work and interact to get as much impact as possible from each test. Keep in mind that the ability to perform EVM measurements on cellular receivers will greatly enhance coverage and drive down cost of test. The ability to perform these tests at final will ultimately determine cost of test.

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