TESTING METHODS AND ERROR BUDGET ANALYSIS OF A SOFTWARE DEFINED RADIO

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ABSTRACT

Ideally a Software Defined Radio (SDR) is designed to accept a multitude of waveforms at any carrier frequency. This paper will discuss the importance of PHY layer measurements made in both the digital and analog domains including the additive effects impairments can have on BER. The paper will consider interoperability of a SDR with respect to three different modulation formats; OFDM, CDMA, and QAM. The importance of BER budgeting and a multitude of critical measurements including EVM, CCDF, ACP, spectrum mask, constellation displays, noise figure, phase noise will be discussed.

1. INTRODUCTION

There are many definitions for software-defined radios (SDR), but one basic but suitable one is: "A radio in which all or some of the PHY layer function are realized in software." The baseband section of the radio, or digital IF, may be implemented with FPGAs, ASICs, or DSP for signal processing which can be reconfigured for different waveforms. The software takes on its own identity, and can be transported or deployed to different hardware platforms. Additionally an SDR can inter-communicate, regardless of the hardware platform. This allows different organizations to be able to communicate with each other. SDRs may be easily upgraded with new waveforms without having to return them to the manufacturer for long periods of time to get upgrades.

2. SDR CONSIDERATIONS

Customers desire a dynamic radio for dynamic requirements such as changing data rates, a wide array of environmental conditions, and higher reliability. Because of the dynamic usage required, the RF engineer must design and test a radio that can meet these diverse requirements and has additional of "head-room" to account for future requirements. One unique capability of a modern SDR is the ability to conform to these different requirements. For example a ground solider using basic voice communication many miles from his installation or a special operative that requires real-time streaming video for a mission. Additionally there are many existing radio waveforms that exist today that will continue to stay operational even as new radios and technology is introduced. This poses a challenge to the radio design engineer who must incorporate all of the "older" formats and add additional ones for the increase in data transmission requirements. It is also a reasonable assumption that to some extent SDR's will be "upgradable" when new formats are introduced. Will the radio perform equally well for all the other entities it communicates with? Unfortunately the answer is no! This further requires engineers to implement a dynamic forecast at the onset of design and have a good understanding of how the radio performs at different points in the PHY layer of the radio.

The cognitive radio will represent a significant leap in the field of radio design. The premise of a cognitive radio is that one day a radio will be able to sense "white space" in the RF spectrum and then configure itself to use that frequency for communication. Cognitive radio is very dependent on fast processing and the further development of software PHY layer architecture. To realize this technology it is obvious that the receiver will require a wide bandwidth and/or a flexible front end to move operating frequency. This would require a wideband IF with a high sampling ADC and/or a variable oscillator. Understandably this introduces new issues for the RF engineer which we will touch on in this paper. An enabling technology for frequency agility in an SDR is the NCO (numerically controlled oscillator) used as component of a digital up-convertor or down-converter implemented on FPGA. The paper will touch on some design consideration when implanting a "cognitive" front-end.

With software defined radio architecture myriad unique challenges are presented, many of which emanate from the change in signal formats. Signal amplitudes once represented by an analog voltage or potential between two points, are now a series of digital word sample points on a signal bus of many different voltage potentials. Often the signal is represented on time sampled dual I–Q signal busses complicating test matters further.

Diagnosing digital issues thus requires a different test interface to different hardware. Probing I–Q busses with many test connections becomes essential. Probing is often complicated when using FPGAs, as many of the desired test points may not be readily accessible outside of the chip.

To add to all these challenges, cross format analysis is often a crucial troubleshooting need. Since most SDR designs ultimately get converted back to analog signals, it is frequently necessary to compare the analog signal with the digital signal that initially created it. This requires cross

format analysis capability to compare modulation parameters between a digital signal and an analog signal.
Comparative analysis can extend well beyond baseband I–Q measurements, ranging through IF and RF frequencies. Fortunately Agilent offers one software package that can connect to all parts of the radio to probe at DSP, Digital or Analog IQ, or IF or RF.

Currently there are many people testing their SDR with the golden radios. This is where one radio is used as a benchmark to test other radios. This is a justifiable solution in Aerospace and Defense where proprietary standards prevent purchase of a standardized test solution. Although this method is effective with pass/fail testing it does not provide the vendor with key quantitative parametric data. This makes it impossible to predict compatibility with other units or vendors without retesting. This is especially needed with SDR. The interoperability requirements of most of the newer SDR's will require more than just a BER measurement from a golden radio. It is very important to characterize different points in your radio and many cases there are other measurements that will need to be made to properly troubleshoot your device.

3. BER AND EVM

In any digital communications link there are bit senders and bit receivers that are physically separated. One very important measure of the Quality of Service (QoS) of the network link provider is the ratio of bits sent correctly to bits in error. This ratio is called the Bit Error Rate or BER.

Different levels of service quality are required depending on the type of network data being transported between locations. Voice traffic will tolerate much higher error rates than data traffic. Digitized voice can tolerate bit errors as high as 1 bit per thousand bits sent or 10-3 BER. Computer data demands bit error rates of 1 per million to 1 per trillion or BER's of 10-6 to 10-12 depending on content. For example, internet surfing does not demand the same quality of service as bank fund transfers [1].

As received signal strength increases, the error rate will fall to a very low level or error floor. This error floor is called the "Residual" bit error rate or "Residual BER". It is the 'normal' operating performance of the data link. It is largely determined by the performance limitations inherent in the transmitter and receiver. As received power is increased, ultimately the receiver will reach an overload point where the error rate increases quickly. The errors resulting from the imperfect implementation of the PHY layer is the focus of this paper.

BER can be tested in handful of ways. A common method used to verify a radios performance during the design process is to perform a loopback residual BER test. Loop-back testing can be effective for quick testing however many loop-back tests remove impairments that are part of a SDR system, which can inadvertently lead to false measurement results. For example, a digital modulator to demodulator loop-back test might be error free. Next, an IF loop-back test is performed and presents excessive errors, possibly indicating a problem within the IF. However, to assume so could be a false conclusion, as impairments may have summed up to be excessive. Another method is to use a bit error ratio tester (BERTs) input data into the transmitter and compare the data emerging out of the receiver to find the ratio of errors to correctly sent bits. BER may also be measured in simulation using tools such as Agilent ADS. One of the benefits of using ADS for SDR development is that it has the flexibility to co-simulate with different environments. For example it may co-simulate with other tools such as MATLAB, or C code, or an HDL simulator such as ModelSim. This is useful for the development and test of SDRs since this provides for a complete system simulation that includes both digital and analog domains. The ADS software can be used with data acquisition hardware such as a logic analyzer, scope, and spectrum analyzer for BER testing. Similarly, tools such as the Agilent ESG and PSG can generate test signals of any format (digital IQ, digital IF, analog IQ, and RF). Flexible signal generation provides the ability to isolate and test functional blocks of the radio with independent test signals.

A common example of a higher level measurement used to help identify and isolate signal quality problems that contribute to BER is EVM. Most often EVM is used as a transmitter measurement, however it can also be used to evaluate IF and IQ signals in the receiver.

The concept of Error Vector Magnitude also known as RCE (relative constellation error) is quite simple. If you model the transmitted signal as the sum of two complex signals -- a perfect signal, and an error signal, then you can develop a metric which is the magnitude of the error signal. Essentially a vector from the ideal signal to the transmitted signal is the error vector. The magnitude of this vector is the error vector magnitude, or EVM. If the measured signal were perfect, then the length of the error vector would be zero. EVM is very helpful in determining what elements in your SDR are causing BER. For example a W shape in a EVM vs. time plot would give a RF design engineer a clue that there may be some unnecessary FM on the transmitted signal.

Can we say that EVM is directly related to BER? Strictly speaking the answer would be no. It is possible to get some EVM and no BER. However, they are symbiotic. EVM is useful in identifying errors that contribute to BER. Generally a higher EVM predicts a higher BER. For some types of errors the correlation will be high. Such is the case for non-deterministic errors such as noise. In these cases EVM is sometimes used to closely predict BER. However, for other types of errors the correlation will be looser.

4. WAVEFORM STRUCTURE REVIEW

This paper will assume that the reader has a solid foundation of single carrier modulation, and will not specifically review its architecture. It is also expected that the reader have a familiarity of code division multiple access (CDMA) and orthogonal frequency-division multiplexing (OFDM) consequently the paper will give a very high-level review on these types of signals.

CDMA is well known for it's ability to transmit multiple channels using the spread spectrum technique. Each data channel is multiplied by a unique code, called an orthogonal code (Walsh Codes). Orthogonal codes are also known as Walsh Codes. After each data channel is multiplied by its assigned orthogonal code, the data channels are combined using simple linear summation. The output of the linear summation, therefore, contains multiple data channels belonging to one user. Since this user is one of many who will share the same frequency spectrum, an additional code is required to separate this user's transmission from other users. This additional code is a Spread Spectrum code, otherwise knows as a PN code. Following multiplication by the PN code, the signal is filtered and modulated onto an RF carrier.

OFDM uses a multicarrier scheme to achieve transmission efficiencies (data rate per Hz of bandwidth) similar to traditional, single-carrier schemes (QPSK, QAM, etc.), but with better immunity to common channel impairments. It does so by clocking many carriers simultaneously, but at proportionately slower symbol rates compared to single carrier modulation (SCM) schemes. In OFDM a symbol is no longer one-dimensional in time, but is a block of time. Individual time points are essentially meaningless in terms of relating them to the data payload; they can only be interpreted when taken in groups and FFT'ed. In the frequency domain it may be difficult to see but there are in fact multiple carriers, 52 in WLAN, with a null in the center. Consequently with OFDM the bandwidth becomes a function of the number of carriers and the frequency spacing rather than the just the symbol rate and filter as in the case for SCM. Adjacent channel energy is not distortion in OFDM, but rather the composite roll-off of all of the carriers, which have almost no baseband filtering, and thus appear as SinX/X in the frequency domain [2].

Ideally having one radio to communicate with different entities is very desirable. Additionally it is very advantageous to harness the positive attributes that different waveforms provide. This obviously another advantage of implementing SDR.

For Single Carrier Modulation we are very familiar with how to implement it and have very easy leverage tools for creation and implementation. Additionally because of it's basic nature it can be very flexible for design and troubleshooting for a specific communication systems. Because of the coding property of CDMA it innately offers a security benefit when transferring data. Because you can allocate users to specific code it also enables the waveform to carry many different users. Furthermore CDMA offers a benefit of requiring fewer base stations and lower power than other common cellular communications networks. OFDM is robust in the presence of single-frequency interferers and noise, because (unlike SCM) the loss of an individual carrier (or several) is not fatal to the entire transmission. The lost bits can be recovered through error correction algorithms. Also, because of the slower symbol rate, a given length of impulse noise may obscure fewer symbols. OFDM is also tolerant of multipath; the spectral notches or dropouts common to multipath only affect a limited number of carriers. Those remaining will often contain the error correction data needed to regenerate the entire bitstream. In addition, the OFDM signal structure inherently lends itself to strong equalization schemes, which can further reduce the effects of multipath.

5. IMPAIRMENTS

These waveforms enjoy different positive traits because of the difference in inherent characteristics. Unfortunately these characteristics also share differences in the ability to maintain QoS while subjected to different impairments. Implementing filters in FPGAs has many advantages. These filters can be reconfigured to meet the needs of an adaptable SDR. However, as with any design, there are tradeoffs in cost and performance. High quality digital filters require more filter taps, meaning a greater number of multiplications and additions. Multiplication especially are costly and increase word length. This in turn can cause overflows or require truncation which reduces dynamic range. Latency and timing of the FPGA design are concerns that severely impact design and/or signal quality. A good DSP engineer will be able to maximize the efficiency of his or her design by using best practices in there design, however tradeoffs affecting signal quality, cost, and speed/bandwidth must always be made. As a result, it is important to consider the impacts of the digital impairments along with analog impairments in the system error budget.

One desirable attribute of a SDR is frequency configurability and agility, for several reasons: First the radio may need to transmit at different frequencies to communicate with different existing radios. Second, choosing the frequency to transmit and receive at may be necessary on the battle field to avoid interference. Third, military radio waveforms are often hopped rapidly to avoid detection and for countermeasures. A fourth reason is that frequency agility is necessary capability to enable cognitive radio technology.

An NCO can be used for rapid frequency agility or may be simply be used as the method to allow flexible control of output frequency. But NCOs also require tradeoffs in FPGA resources and performance that will affect signal quality. Typically an NCO design is implemented using a LUT (Look Up Table) that is essentially a list of sinusoidal values that can be referenced and indexed by an accumulator. The size and bitwidth of the LUT largely determines the quality of the signal the NCO can produce. The size of the LUT largely determines the resolution of the NCO. Additionally because the NCO is mixed with a LO it is common to have multiplied word lengths. This phenomenon can create issues in spur free dynamic range and usage of FPGA resources for dithering and correction.

For cost reasons, analog in-phase and quadrature (I/Q) modulators and demodulators are often used in transceivers — especially for wide bandwidth signals. Being analog, these I/Q modulators and demodulators usually have imperfections that result in an imperfect match between the two baseband analog signals, I and Q, which represent the complex carrier. IQ gain mismatch can cause the IQ constellation to go from a square (uniform) shape to a rectangular shape leading to a higher BER. Quadrature skew occurs when the two oscillators are not offset by exactly 90°. This will generally cause a phase arch of the symbol points and again lead to errors in the radio. These impairments can lead to problems in the channel estimation OFDM system such as WLAN quadrature skew can cause issues with the channel estimation sequence which corrupts the equalizer leading to spreading of the constellation.

Random noise can create a fuzzy distribution of the sample points and usually dominated by amplifiers and/or channel loss. Noise figure (NF) of the system can be taken into account to assure that the radio is does not have this issue.

Phase noise is generally dominated by the any oscillators in the system and usually arch or spread the constellation diagram. In OFDM however phase noise results in each subcarrier interfering with several other subcarriers — especially those in close proximity. There are two reasons for this. First, close-in phase noise that results in the constellation rotation for the data carriers also results in rotation of the pilot carriers. In fact, carrier phase error rotates all subcarriers by the same amount, regardless of the subcarrier frequency. Phase-tracking algorithms use the pilot symbols to detect this common rotation and compensate all of the carriers accordingly. This error is often referred to as common pilot, or common phase error (CPE). Phase noise that is not considered to be close in results in inter-carrier interference. Instead of constellations with visible rotation, phase noise in an OFDM signal generally results in fuzzy constellation displays, similar to what would be expected if noise is added to the signal.

For the rest of this paper we primarily will focus on the effects phase noise, and S/N (and/or NF) on the system. It should also be noted however that another rather large contributor is the AM/PM distortion of the PA. Additionally, the channel also creates more dynamic problems than just loss. There are other secondary contributors to the error floor to be aware of, such as group delay, distortion, or inter symbol interference (ISI), however for many signal formats modern digital equalizers are very effective at mitigating the effects of group delay.

6. SYSTEM BUDGETING

As was addressed earlier, we have a different set of waveforms that are going to be demodulated in the radio. These waveforms have resiliency to some impairments and are more venerable to others. For SDR's it becomes apparent that it is vital that an engineer must be mindful of how each waveform is affected by particular impairments.

The measurements used to confirm residual BER prediction budgets allow the engineer or technician to separate modulator, transmitter, receiver, and demodulator issues.

Many vendors now provide products with capacity upgrade paths by increasing the complexity of the radio's modulation. Sequential installation systems make the interoperability of subsequent installations essential for success. Residual BER budgets help ensure interoperability between different receivers or transmitters. Equally important, a residual BER budget is essential for assuring units will not dribble errors when deployed years after the base station is installed. Residual BER prediction also gives manufacturers the ability to upgrade a modem with confidence that the currently-installed RF will support it.

Residual BER budgets are also an essential element for controlling cost of the sources and power amplifier —two of the most expensive pieces in any radio link. The most important technical contribution of residual BER prediction is that it mathematically relates key analog metrics used to specify components to digital bit errors used to evaluate systems. This bridges the gap between the network provider's quality of service metric and the radio engineer's analog component metrics [1].

As accurate allocation of BER system budgets become more imperative to SDR engineer it is beyond the extent of this paper. The author highly encourages the reader to review this topic in more detail. Agilent provides an application note (1397-1) that gives the reader more insight to the importance and prediction of BER budgets as well as measurements technique and applications.

In many cases we do some post "correction" to the signal. A great example is WiMAX or an OFDM signal. As we discussed, an OFDM signal can easily be effected by phase noise. However, as in fixed WiMAX (and other

OFDM formats), there is a significant amount of correction implemented in the phase tracking algorithms that are employed. This can actually render them less susceptible than even other types of communication waveforms[2].

In the VSA software you can include pilot tracking and equalizer training that will greatly improve the overall performance. This can obviously be implemented in your system to improve your performance. The drawback is that you will need to put in cost for development and also in your devices computational power.

Creating a system budget by close evaluation of the system is important step to making decisions about required system architecture and performance levels. For SDRs, however this process can become quite complex since the number of variables and factors increases with the number of waveforms that must be supported. In our examples we have chosen settings to yeild a high level of impairments for simplicity of simulation. Our BER measurements will obviously be much higher than in a typical radio. Fortunately it is also possible to verify and test system errors empirically using simulation tools before hardware is built.

7. DESIGN AND TESTING

To demonstrate how one can evaluate waveform impairments on different waveforms for a software defined radio a simulation was built using Advanced Design System (ADS). Part of the radio can then be realized in hardware with a Xilinx demo board. Three signals were selected for the test-bed of the SDR; Single Carrier QAM, W-CDMA, and WiMAX. Using simulation the impairment levels of different circuit elements can be easily varied to see the effects on EVM and BER. For the purposes of this paper we will examine the effects of just a few impairments on the system. However using simulation a variety of system impairments could be evaluated including the combined effects that multiple impairments will have on the system.

A benefit to using these software tools is that the same tools used to examine signal quality on real hardware are also used to measure signals in software simulation. This brings consistency to the design and test process and allows direct correlation of measured results in simulation and in hardware. In this example the Agilent VSA software is added as an icon to the ADS simulation and can perform vector signal analysis on signals in simulation. This VSA software is the same software that is uses in Agilent's vector signal analyzers, scopes, and logic analyzers. An additional advantage is provided through the linkages between Agilent simulation tools and Agilent instruments. Using "Connected Solutions" between simulation and measurement instruments allows designers to run simulations with hardware in the loop. Using a common measurement tool to evaluate signal quality throughout the radio provides a means to measure and directly compare performance throughout the radio. Bottle necks can then be quickly identified.

In this example we used the ADS software to measure the quality of a WiMAX signal throughout the radio. These measurements were made in software. However, the same measurements could all me made with hardware.

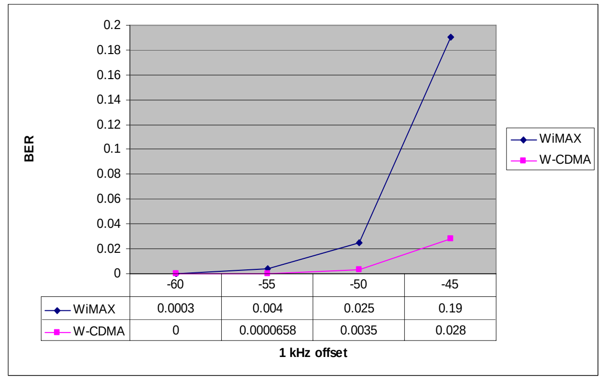

Figure 1.

In figure 1 we can see that, as expected, both signals are degrading when phase noise is increased. We can also see very evidently that the WiMAX signal is degraded much more than the CDMA signal. Although data rates are not exactly the same for both signals it is a reasonable expectation that this may be the case in your SDR as well! This is an example of why you need to budget for different waveforms.

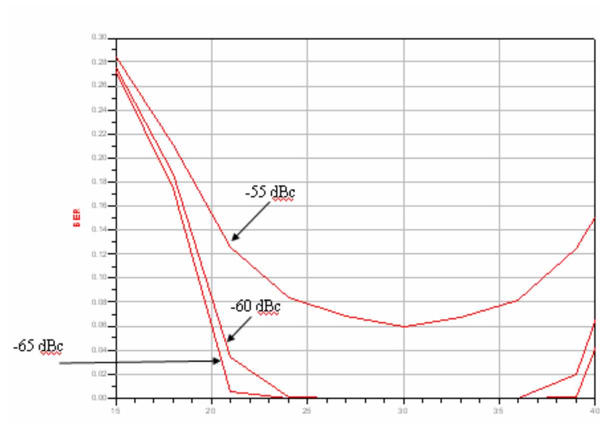

Figure 2

If figure 2 we have changed the LO's PN performance, input a WiMAX signal, then swept the output power from the transmitter, and then plotted the corresponding BER for each LO (red trace) at the radio's output Where we have denoted the different phase noise values you can see a relatively sharp transition in the plot. This type of plot can be very helpful for our budgeting and required output power. It seems from this plot that a -55 dBc value may not reach our residual BER floor and therefore not be acceptable. When comparing the -60 from the -65 dBc results we see that a difference of 5 dB of output power essentially yields the same BER. Understanding this level of performance aids in defining component requirements and can help set range and expected system performance. Now it is possible to cross correlate the WiMAX signal the CDMA and Single carrier signals for the SDR and view BER performance in relationship to differing phase noise. This valuable data can then be used in the development of the error budget to cut hardware costs, minimize redesign effort, and cut troubleshooting time.

8. MEASUREMENTS

As was talked about earlier it is very important to get real metrics on the radio. Golden radio testing is very undesirable for an SDR that demands interoperability. Hence it is important to get the correct measurements to identify potential issues and ensure proper design. There are different measurement techniques and measurement apparatuses for testing a radio. For phase noise you can use the direct measurement technique or a phase detector. The direct method generally is made with a spectrum analyzer, where the limitation of the measurement is the phase noise performance of the spectrum analyzer. Although high performance spectrum analyzers have continually improved phase noise performance the phase detector is still the most accurate and also gives you more measurement range. In the case of noise figure you can also use a spectrum analyzer which uses the noise source and calculates noise figure using the Y-factor method. For a more accurate measurement the cold source is desired. It gives the lowest amount of measurement uncertainty and requires a specialized network analyzer or special measurement equipment. Many spectrum analyzers now have the ability to do vector signal analysis. The ability to make power measurements and demodulate signals is advantageous. Distortion measurements such as adjacent channel power measurements (ACP) and spectral emission mask measurements are helpful in determining out of channel power leakage and identification of unwanted emissions. The complimentary cumulative distribution function (CCDF) is very effective measurement for setting the signal power specifications for mixers, filters, amplifiers, and other components. CCDF is statistically constructed peak-to-average power ratio measurement and has become very popular with many new noise-like waveforms. Many custom demodulation measurement applications are available for most commercial formats. The Agilent 89601A VSA software can demodulate more than 50 formats and do a variety of other measurements. The software can connect to a spectrum/signal analyzer, an oscilloscope or a logic analyzer. This is very helpful for a SDR design engineer due to the ability to probe FPGA and test to RF antenna with the same software. Agilent also has many example programs for engineers leverage to create their own custom demodulation application using MATLAB software.

9. CONCLUSIONS

Multiple waveforms present different challenges and testing requirements. We have reviewed just a small set of differences between waveform characteristics. The list will obviously extend much further with a myriad of waveforms that are already required. These interoperability challenges as well as the possible need for an upgradeable radio are obvious reasons for implementation of a more comprehensive level system budget. Using the ADS software it is possible to design a SDR and simulate performance as well acquire live data as implementation of the radio transpires. Additionally, when testing SDR's it becomes more important to consistently test multiple "domains" (digital, IQ, RF) as well as in simulation, and this is done more efficiently with one piece of software (89601A). The software uses the same algorithm and the same user interface to give the user consistency of the measurement as well as drive down costs.

10. REFERENCES

[1] Agilent Application Note AN 1397-1, "Lower Cost and Improving Interoperability by Predicting Residual BER: Theory, Measurements, and Applications," *lit no. 5988-6082, July 17 2002*

[2] B. Cutler, "Effects of Physical Layer Impairments on OFDM Systems," *RF Design*, May 2002, pp. 36-44,