# IEEE P802.15
# Wireless Personal Area Networks

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| Re: | |
| Abstract | This study recommends an optimum balance of resolution and dynamic range in for ADC circuits in an OFDM-based UWB system. |
| Purpose | Discussion, plus contribution to a possible OFDM-based UWB IEEE PHY standard. |
| Notice |  |
| Release |  |

# Choosing Resolution and Dynamic Range in an OFDM UWB System

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## Foreword

*For the past year, via email and phone calls, I've had the privilege to coach Bart Stein with his special research project at Columbia Grammar and Preparatory School (www.cgps.org) in New York City. A remarkable 16-year-old, and now a junior at Columbia Prep., Bart chose UWB as his area of investigation.*

*Dave Leeper, Intel Corporation (david.g.leeper@intel.com)*

## 1. Introduction

Resolution and dynamic range are two key settings for an analog-to-digital converter (ADC) in an MB-OFDM-based UWB system. Poor choices for these parameters can lead to distortion from clipping of signal peaks and/or excessive quantizing noise. These distortions will produce constellation phase errors that reduce operating margin. The purpose of this study is to discover optimal combinations of resolution and dynamic range that lead to minimum constellation phase error.

## 2. Resolution & Dynamic Range

ADCs convert the continuous values of an analog waveform to sampled digital values. Because the digital values have finite precision, they necessarily introduce quantization noise into the process. In addition, OFDM signals can occasionally exhibit large peak values that lie outside the dynamic range of the ADC, causing the ADC to hard-limit or "clip" the digital representation of the signal.

Both clipping and quantization noise will decrease system operating margin in a way that is difficult to predict analytically because the effects are non-linear and because they are compounded by the Fast-Fourier-Transform processing in the OFDM demodulation process. This study relies on *simulation* to find optimal combinations of resolution & dynamic range that result in minimum phase error in the MB-OFDM (QPSK) constellation.

ADCs are a significant part of a transceiver's overall power budget, and an ADC's power consumption rises rapidly with increasing resolution. As a rule of thumb, the power consumption in a traditional ADC design doubles with each additional bit of resolution, so that

$$\boldsymbol{P} \text{ is proportional to } \mathbf{2}^{\boldsymbol{N}},$$

where $N$ = the number of bits resolution provided by the ADC. Increasing N reduces quantization noise, but beyond some value, increasing $N$ will yield little improvement in transceiver performance.

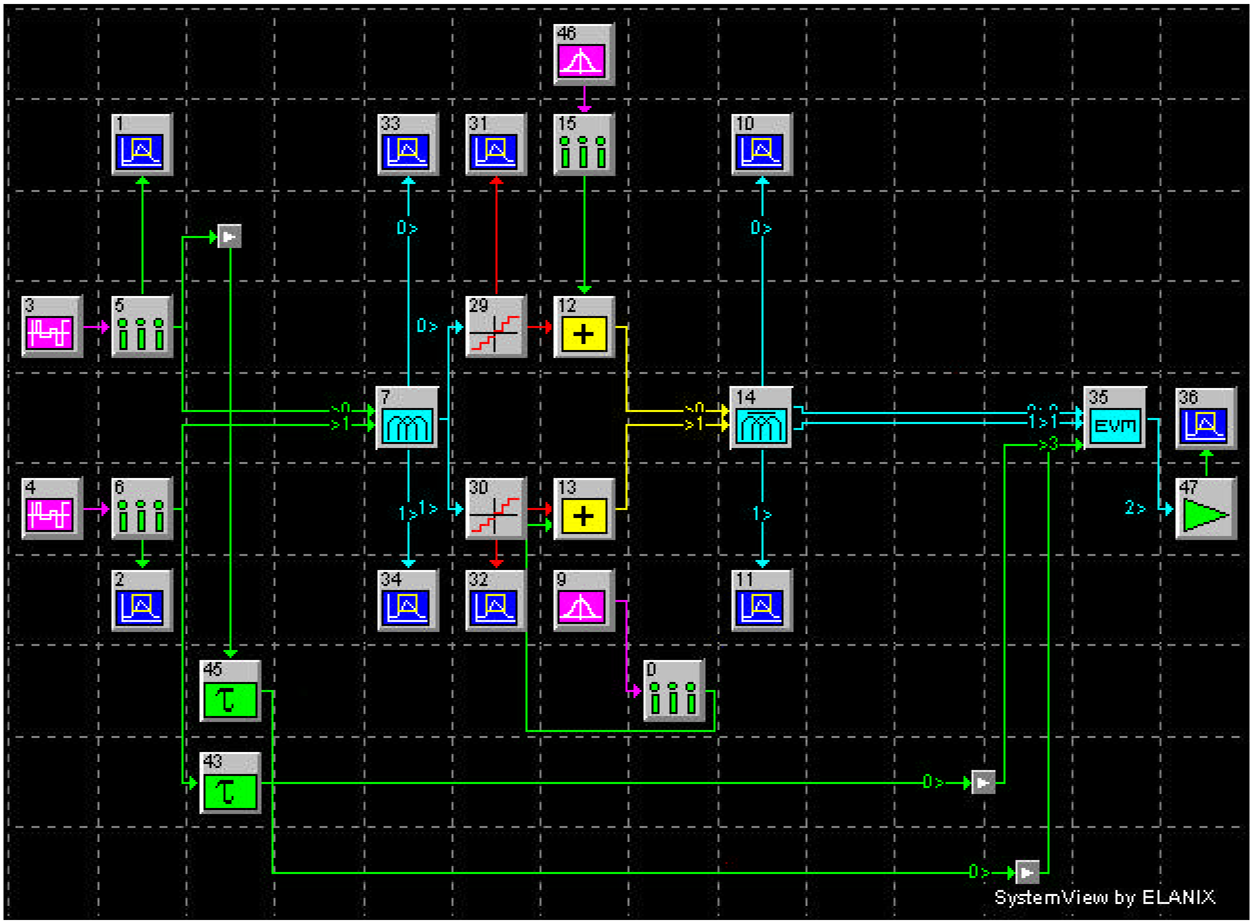
Similarly, increasing the dynamic range, *R*, of the ADC will improve performance, but large dynamic ranges may be difficult to achieve in small battery-powered devices, and beyond some point there is little improvement in performance.

For any given dynamic range *R*, there is an optimal *N*, and for any given *N*, there is an optimal *R*. In the sections that follow, the tradeoff between these parameters is examined, and combinations are presented that produce minimum phase error in an MB-OFDM QPSK constellation.

## 3. Simulation Model

The functioning of the experimental system used to examine dynamic range and resolution for a MB-OFDM UWB system was wholly centered on the utilization of specialized application software known as *SystemView*. *SystemView*, by Elanix, is advanced software used to simulate and theoretically examine communication systems. The program possesses a deep library of "tokens" that are representative of different communication components. These tokens are entirely scalable and adaptable, and can be combined together in order to recreate the hardware of a communication system.

The first step in the experimental setup of this study was to recreate a MB-OFDM UWB system utilizing *SystemView*. This was done by using the deep library of communication "tokens" in *SystemView*. The tokens were scaled comparable to the parameters of initial deployment MB-OFDM UWB systems. Figure 3 illustrates the setup of the MB-OFDM UWB system in *SystemView*.




Tokens 3 and 4 are the source tokens that feed consumer data to the system. For the purpose of this study, tokens 3 and 4 were feeding PN (pseudo number) sequences locked to a defined seed. This is necessary in order to assure that testing of multiple dynamic ranges and resolution numbers were all performed under the same conditions. Tokens 3 and 4 were feeding data at a rate of 400 Mbps, approximately the target for OFDM UWB systems when they are initially deployed.

Tokens 5 and 6 are sampler tokens that simply pluck samples from the data inputs 3 and 4. Token 5 outputs in-phase samples to token 7, while token 6 outputs quadrature samples to token 7. Token 7 is an OFDM modulator and modulates a signal with the input data coming from tokens 5 and 6. The OFDM modulator sends signals 300 nanoseconds in length, and has a cyclic prefix of 60 nanoseconds. These, again, are parameters on par with initial deployment OFDM UWB systems.

Tokens 29 and 30 are the focus of this experiment. These tokens are the quantizer tokens where both the resolution and dynamic range of the system is set. The OFDM modulator feeds both quantizer tokens, feeding token 29 with an in-phase signal, and token 30 with a quadrature signal. The quantizer token then performs the process of ADC (analog to digital conversion) based upon the user-defined resolution setting, and outputs quantized signals at a limited amplitude (the dynamic range). Tokens 9-15 and token 46 are void for this experiment because they exist as a medium by which Gaussian Noise can be added to the transmitting signal, which was not done in this study. So, the transmitted signal is transmitted directly to token 14, which serves as an OFDM demodulator. The OFDM demodulator simply demodulates the signal and outputs the recovered in-phase and quadrature signals, ideally representing the input data. The outputs of token 14 are inputted to token 35, another crucial part of this experiment.

Token 35 serves as an Error Vector Magnitude (EVM) component that determines the average phase error of the system. Since average phase error is the key statistic being examined in this study, the EVM is clearly a crucial component. The EVM is able to calculate the average phase error of the system by comparing in-phase and quadrature samples representing the received phasors, to in-phase and quadrature samples representing the ideal phasors. This difference, initially in radians, but converted to degrees through token 47, represents the average phase error of the system.

All of the dark blue tokens present in the system are analysis tokens. They serve to provide statistical and graphical analysis based upon what they are being inputted with. Analysis tokens 1 and 2 provide graphical and statistical information on the pre-modulation signal. Analysis tokens 33 and 34 provide graphical and statistical information on the post-modulation but pre-quantization signal. Analysis tokens 31 and 32 provide graphical and statistical information on the post-modulation post-quantization signal. Analysis tokens 10 and 11 provide graphical and statistical information on the post-demodulation signal. Finally, analysis token 36 provides graphical and statistical information on the Error Vector Magnitude of the signal.

Many of the analysis tokens exist only for educational purposes, and are not relevant to the purpose of this study. However, tokens 33 and 36 provide critical analysis to this study. Token 33 is where undistorted input signal to the quantizer can be observed, as shown in figure 4.

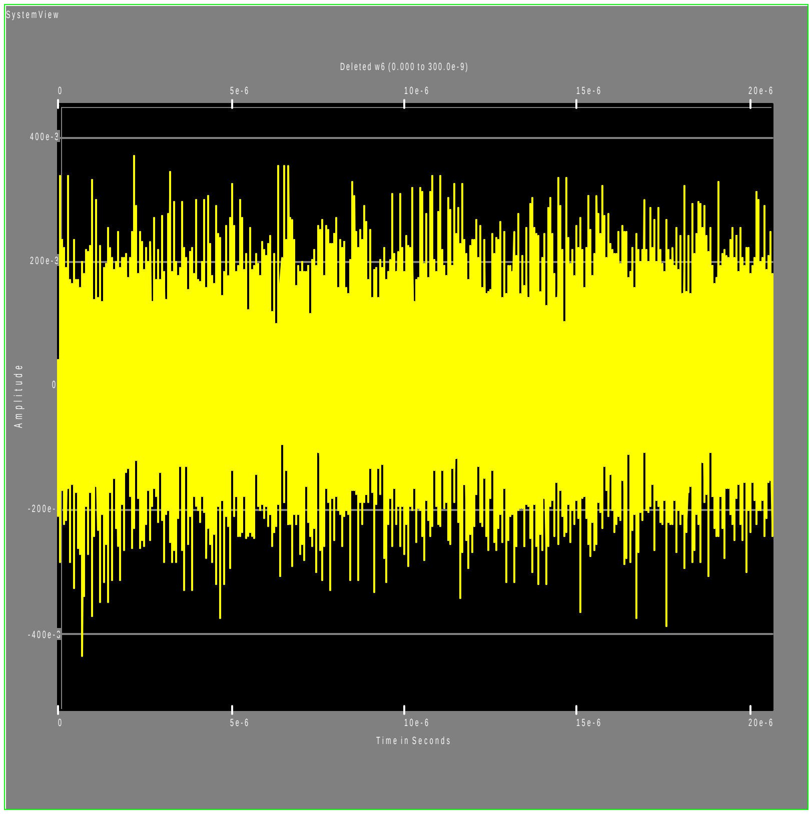
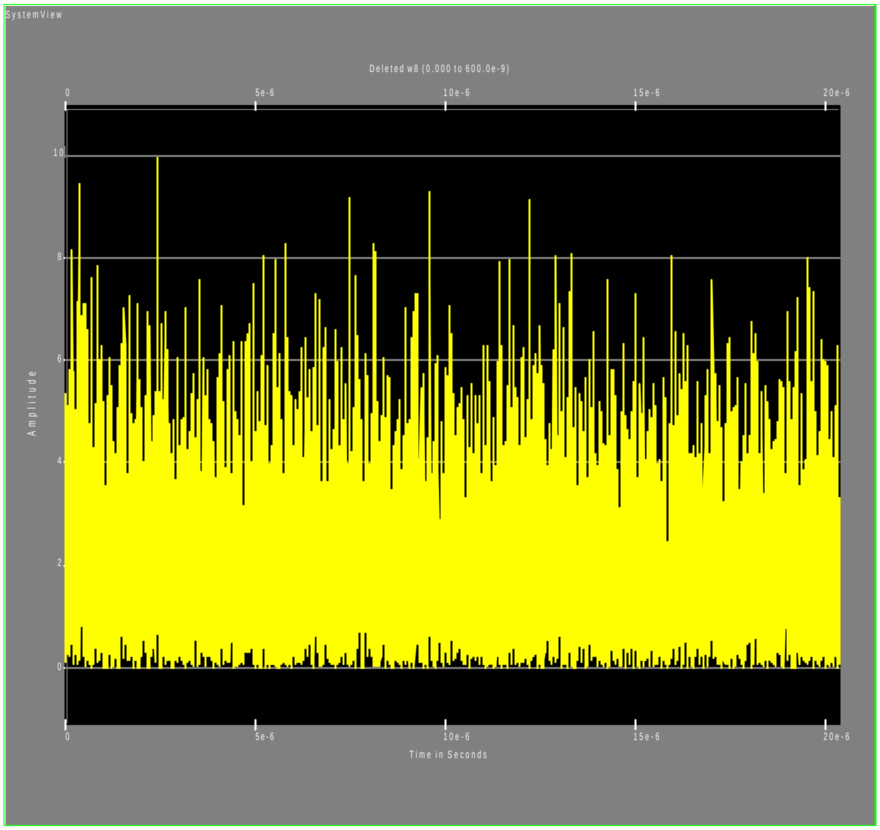



**Figure 4: Input Signal to Quantizer after Elimination of 300 Nanosecond Delay**

Token 36 is the critical focus of this study. It provides analysis of the output of the EVM token, which records average phase error. The output of token 36 is essentially an error waveform from which numerical values can be extracted. The average value of the waveform appearing at token 36 represents the phase error caused by quantization and clipping. As an example, figure 5 shows the waveform resulting from a quantizer with dynamic range of +/- 3.5 s, and a resolution of 5 bits, where "s" is the RMS value of the input signal.




.**Figure 5: An Error Waveform Whose Mean Value Represents Average Phase Error**

Another way to observe the phase errors present in a system is to examine a constellation diagram that shows the accuracy with which signals hit their intended phases. The constellation diagram of an ideal transmission is shown in figure 6.

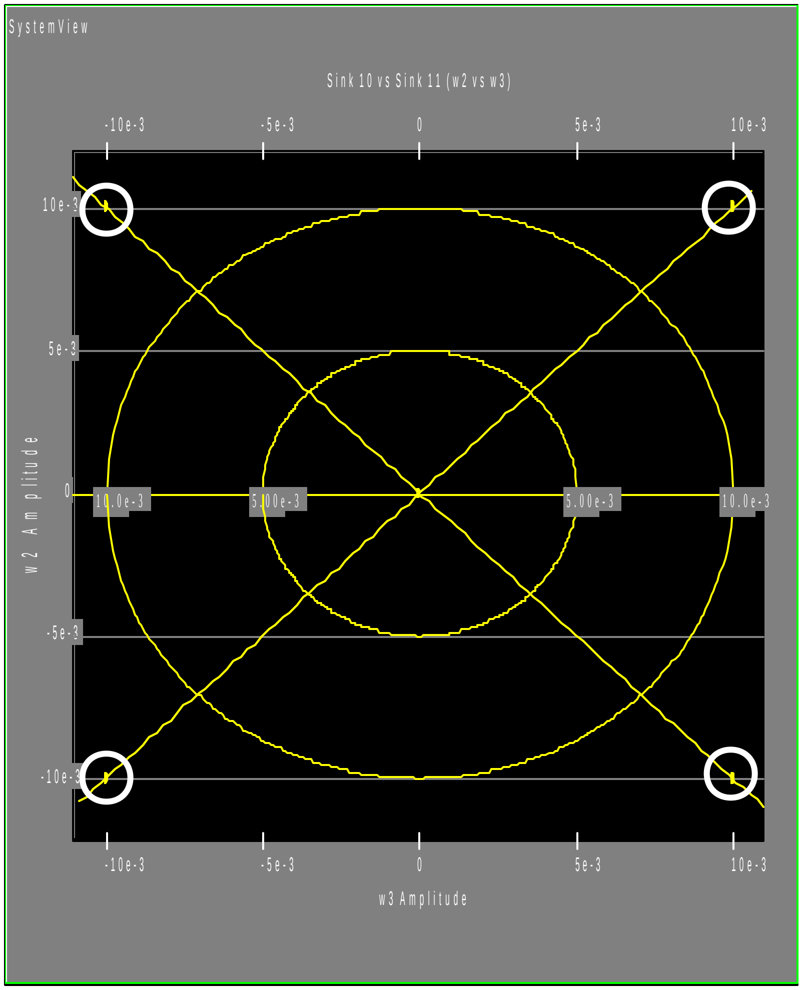



**Figure 6**

The four points in white circles illustrate that every signal transmitted in the system hit its intended phase perfectly. Figures 7, 8, and 9 illustrate constellation diagrams for different combinations of dynamic range and resolution tested in this study.

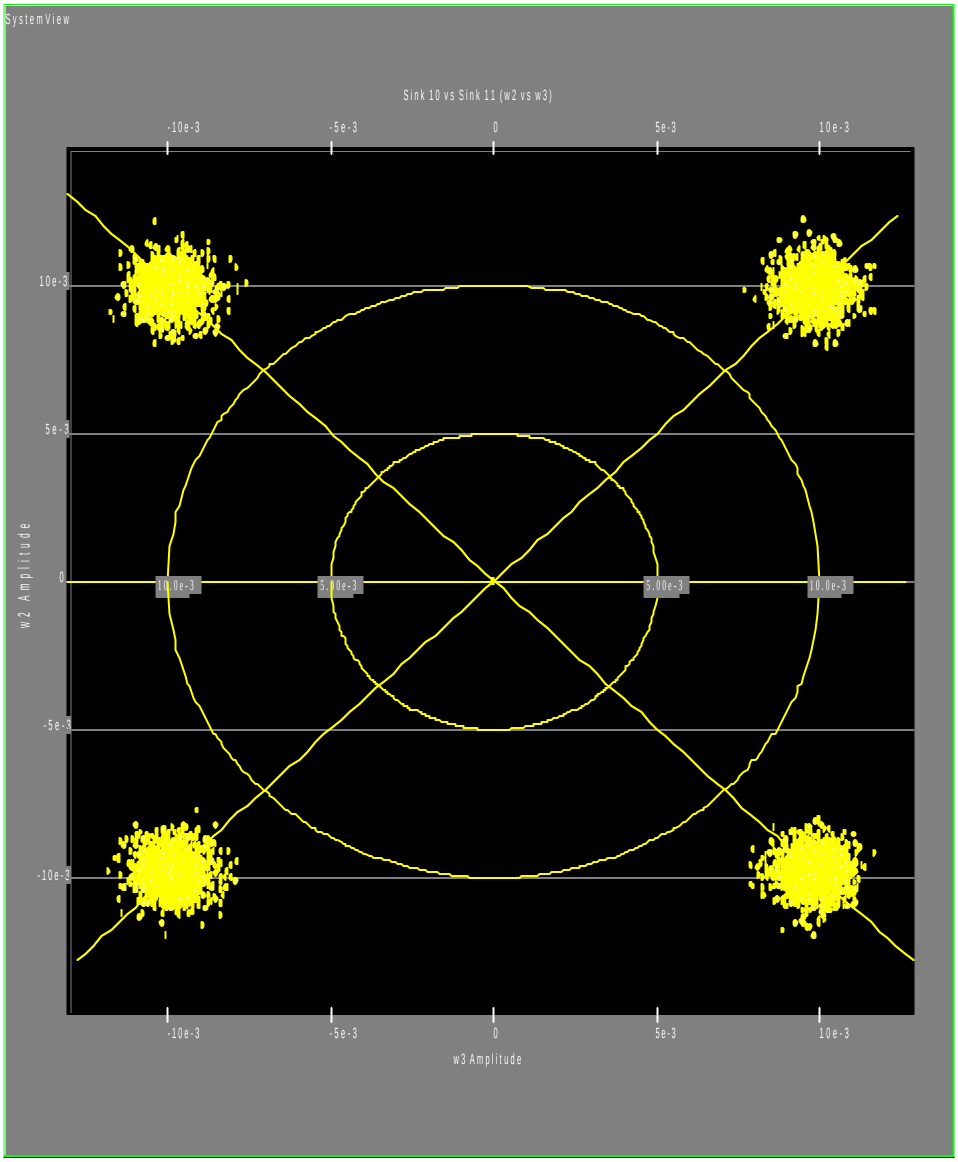



**Figure 7: Dynamic Range of 2.5 s, Resolution of 7 bits**

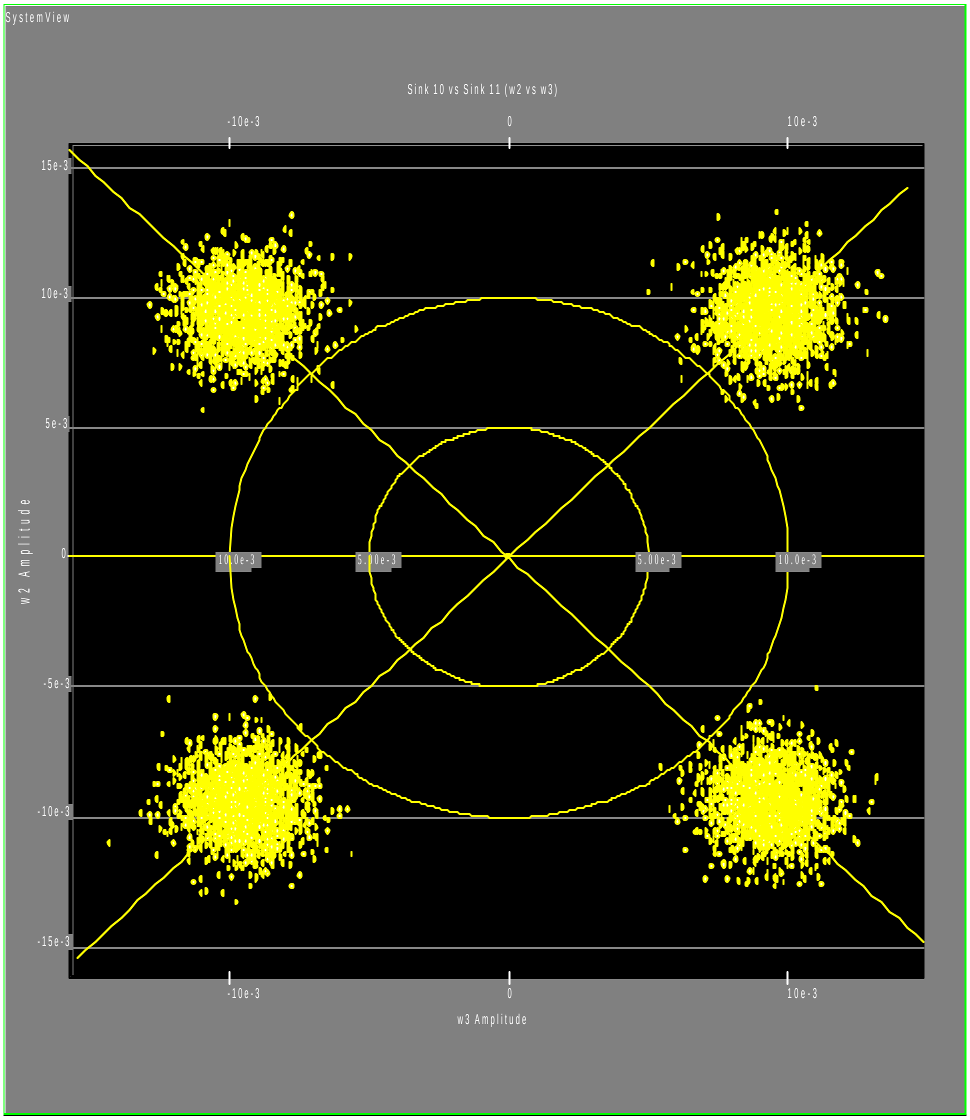



**Figure 8: Dynamic Range of 2 s, Resolution of 5 bits**

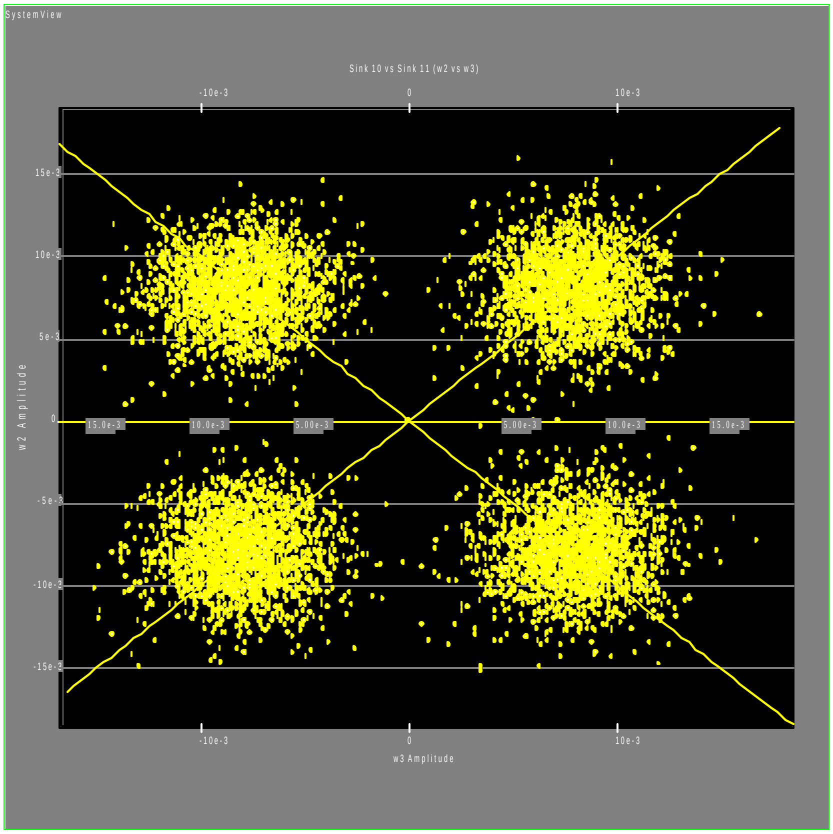



**Figure 9: Dynamic Range of 1.5 s, Resolution of 3 bits**

Figure 7, 8, and 9 show the "blooming" of a phase constellation diagram. When a constellation diagram "blooms", it represents an increase in average phase error. Figures 7, 8, and 9 illustrate an increase in average phase error as the dynamic range tightens and the resolution becomes coarser. Limiting the "bloom" of a constellation diagram is equivalent to limiting the average phase error.

## 4. Simulation Results

The following table (figure 10) contains the principal output of this study. It shows the average phase error returned for multiple combinations of dynamic range and resolution, while highlighting optimum numbers in red. Figure 11 graphically illustrates figure 10.

**Average Phase Error (Degrees) vs Resolution and Dynamic Range**

| | N = Number of ADC Bits | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Dynamic Range** | **3** | **4** | **5** | **6** | **7** | **8** | **…** | **24** |
| **1.5** s | 9.14 | 7.35 | 6.71 | 6.45 | 6.35 | 6.29 | | 6.24 |
| **2.0** s | 7.05 | 4.72 | 3.77 | 3.53 | 3.40 | 3.36 | | 3.31 |
| **2.5** s | 6.50 | 3.55 | 2.28 | 1.80 | 1.61 | 1.55 | | 1.51 |
| **3.0** s | 7.07 | 3.50 | 1.83 | 1.10 | 0.73 | 0.58 | | 0.45 |
| **3.5** s | 7.99 | 3.91 | 1.96 | 1.01 | 0.53 | 0.31 | | 0.01 |
| **4.0** s | 9.13 | 4.55 | 2.24 | 1.11 | 0.55 | 0.28 | | 0.00 |

s = RMS voltage of ADC input signal

**Figure 10**

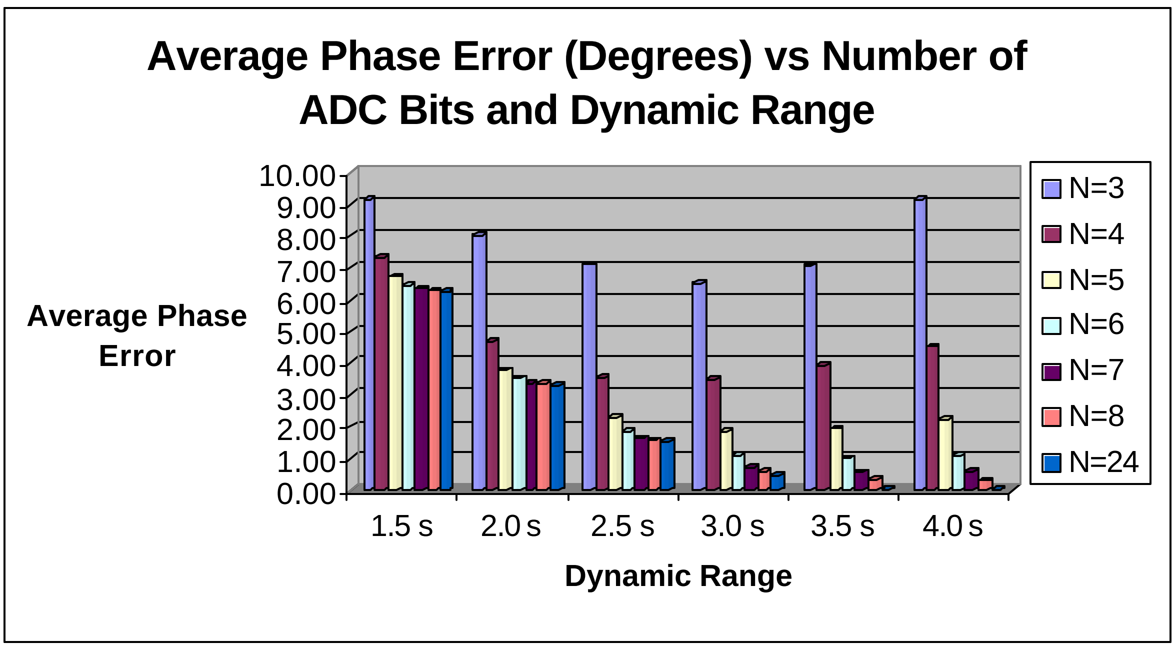



**Figure 11**

The highlighted values are the lowest average phase error for the given resolution selection. Resolutions of 7 bits, 8 bits, and 24 bits probably represent unrealistic power levels, but they were included in this study as experimental controls. The same can be said for the dynamic range of 4.0 s, which again requires a greater power input than MB-OFDM UWB systems may be able to provide. Resolution numbers of 5 and 6 became the area of focus because they provided low average phase error, and do not present unmanageable power levels. Within these resolution selections, the dynamic ranges of 2.5 s, 3.0 s, and 3.5 s became the area of focus, because average phase error was low, and again they did not present unmanageable power levels. In order to make a selection, the highlighted values of the resolution numbers of 5 and 6 bits were compared. The optimum average phase error for a resolution of 6 bits was only .82 degrees lower than the optimum average phase error for a resolution of 5 bits. This .82 degree reduction came at the expense of a .5 s increase in dynamic range as well the power increases associated with a higher resolution number. The power requirement increases significantly outweighed the marginal increases in average phase error performance. Thus, the optimum selections of resolution and dynamic range concluded to be N=5 bits and 3 s. The parabola illustrating the minimum, optimum value for a resolution selection of N=5 bits is illustrated below in figure 12.

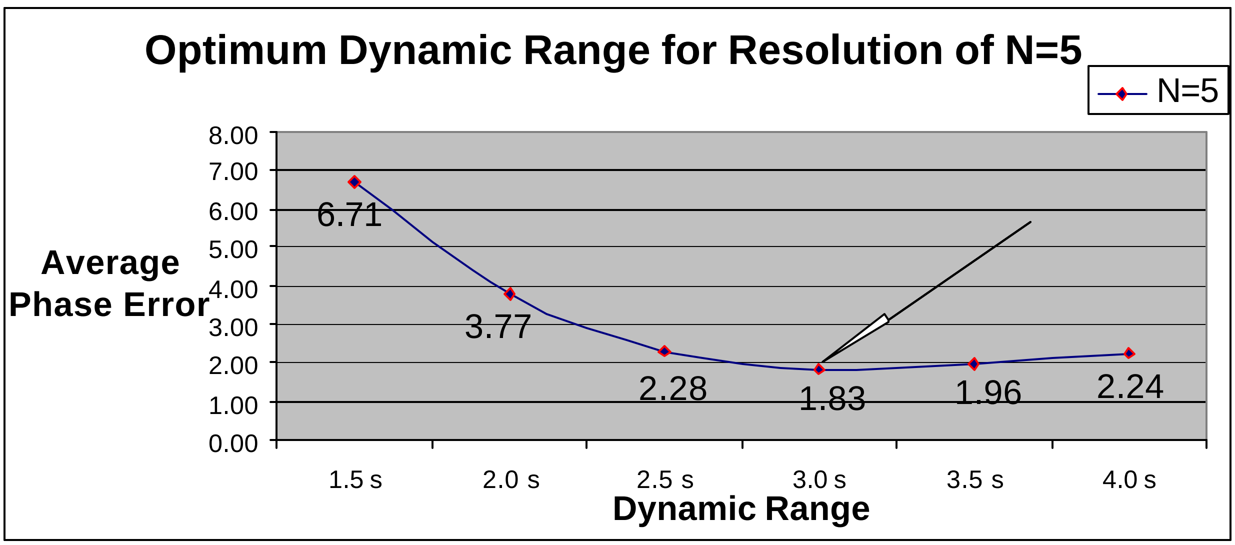



**Figure 12 with Arrow Pointing To Optimum Value**

## 5. Conclusions

The purpose of this study was to uncover the selection of dynamic range and resolution that provides the optimum balance of power consumption and minimum constellation phase error in a MB-OFDM UWB system. A simulation model was built utilizing specialized application software known as *SystemView* by Elanix. 42 different combinations of dynamic range and resolution were tested, some as experimental controls. After close analysis of data, it was concluded that a dynamic range of 3 s, and a resolution of 5 bits appears to yield the optimum balance of power consumption and minimum constellation phase error.