APPLICATION NOTE

Effect of RF System Parameters on Receiver (ATA5745/ATA5746) Sensitivity

ATA5745/ATA5746

Introduction

In short-range RF system design, focus is typically placed on transmitter output power and receiver sensitivity to establish a high-quality RF link. However, due to regulatory requirements limiting transmitter output power and the plethora of devices that easily achieve them, often it is the receiver's sensitivity which remains as the key system parameter of interest when designing an RF wireless application.

Given the choice between two receivers priced the same, what's the better choice, a device with a sensitivity of –110dBm (OOK at 2Kb/s with a BER of 10^{-2}) or with a sensitivity of –112dBm (ASK at 9.6Kb/s with a BER of 10^{-3})? One might be inclined to select the device with the best sensitivity number. But, without a theoretical and empirical understanding of the assumptions used to measure sensitivity, a meaningful side-by-side comparison of the devices on sensitivity alone becomes nearly impossible.

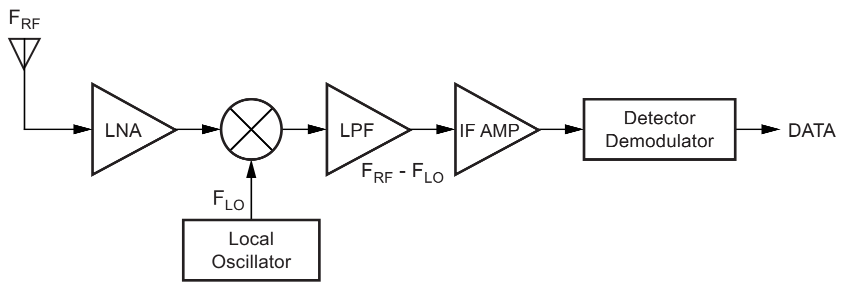
A thorough understanding of what receiver sensitivity means, how it is measured, and how it is affected by other RF system parameters, provides the engineer with a solid foundation upon which to make design decisions that will result in RF system performance that meets or exceeds the design objection.

The purpose of this document is to explain the concept of RF receiver sensitivity as well as associated terms such as BER and jitter. These terms will be combined with other common RF system parameters such as data rate, carrier frequency and modulation format to explore how they interact with and affect the RF receiver performance of Atmel®'s highly integrated UHF ASK/FSK receiver ATA5745.

1. Super Heterodyne Receiver

The most common receiver configuration found today in short-range RF wireless applications is the super heterodyne architecture. The basic principle of operation is the translation of received RF signals to an intermediate frequency band where the weak input signal is amplified before being applied to a detector. This is achieved by mixing a local oscillator signal FLO with the received signal FRF to produce an output consisting of FRF + FLO and FRF – FLO. A lowpass filter typically rejects FRF + FLO and leaves FRF – FLO for further amplification and filtering. The result is a replica of the modulated RF spectrum that appears translated to a lower frequency domain called the intermediate frequency (IF). Finally, the detector/demodulator strips off the IF signal and converts what's left into a digital data stream for processing. A block diagram depicting this general principle is shown in Figure 1-1.

Figure 1-1. Super Heterodyne Receiver Block Diagram



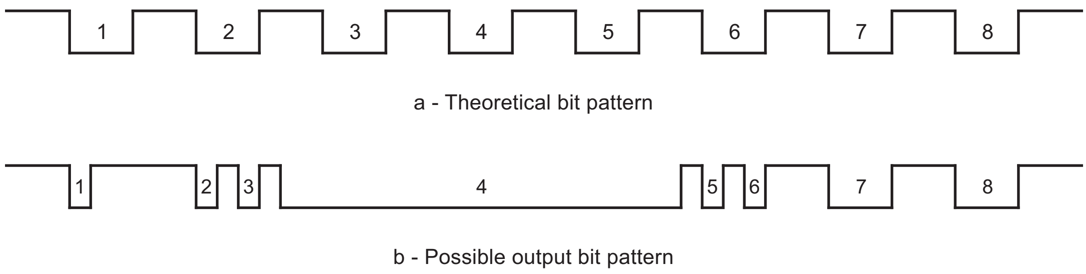
2. Receiver Sensitivity Terminology

In simple terms, receiver sensitivity is defined as the minimum amount of signal power required at the input of a receiver that results in an accurately demodulated signal "MOST of the time". The criterion that defines "MOST of the time" is bit error rate. Input signal power is expressed in dBm while bit errors are expressed as a rate, usually 10^{-3} or 1 error per every 1000 bits.

There is very little in the way of ambiguity when it comes to measuring signal power applied to the input of a receiver. RF signal generators are capable of providing accurate output powers into a standard 50Ω load.

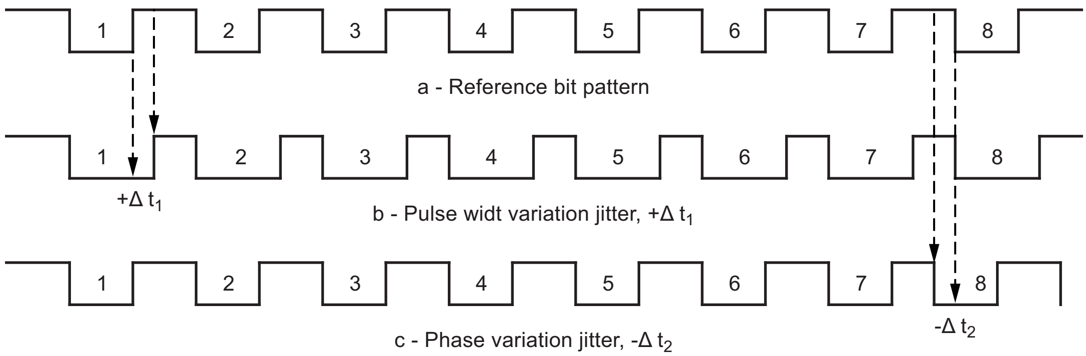
However, when it comes to defining a bit error, there is much more to consider. One can define a bit error in several different ways. One simple way to measure a bit error rate would be to count the total actual number of demodulated pulses over a given interval of time and compare them by the total theoretical number of demodulated pulses over the same interval. This approach isn't acceptable because it does not detect changes in pulse width, a phenomenon that may occur as the RF signal grows weaker. For example, Figure 2-1a shows a theoretical 8-bit modulation stream. Figure 2-1b shows a possible demodulated bit stream at the output of a receiver. Clearly, the output of the receiver shown in Figure 2-1b would not be considered acceptable, but according to the bit error criteria defined above, it would not have any bit errors because both Figure 2-1a and Figure 2-1b possess the same number of pulses during the defined interval.

Figure 2-1. Bit Pattern



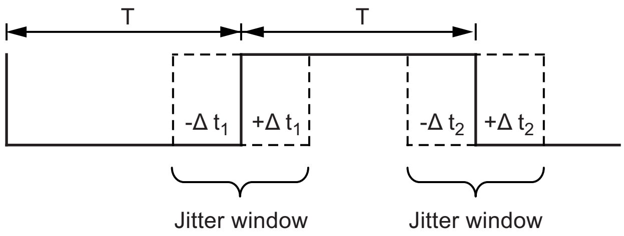
To reconcile this disparity, the concept of "jitter" must be introduced and applied to the bit error criteria. For the case of demodulated data from an RF receiver, jitter is the unwanted variation of phase or pulse width in the demodulated signal. Some examples of jitter are shown in Figure 2-2. Figure 2-2a shows the reference bit pattern and Figure 2-2b and Figure 2-2c show pulse width and phase jitter, respectively.

Figure 2-2. Examples of Jitter



A common approach for defining a bit error is to create a time limit, ±Δt, that is a percentage of the edge to edge bit period, T. Using this approach, a bit error would be any bit edge transition that occurs outside of the time limit window ±Δt. An example of the bit error rate jitter window is shown in Figure 2-3. In this case, jitter of ±25% is depicted. For the balance of this document, the default assumption for BER will be 10^{-3} with a ±25% jitter window.

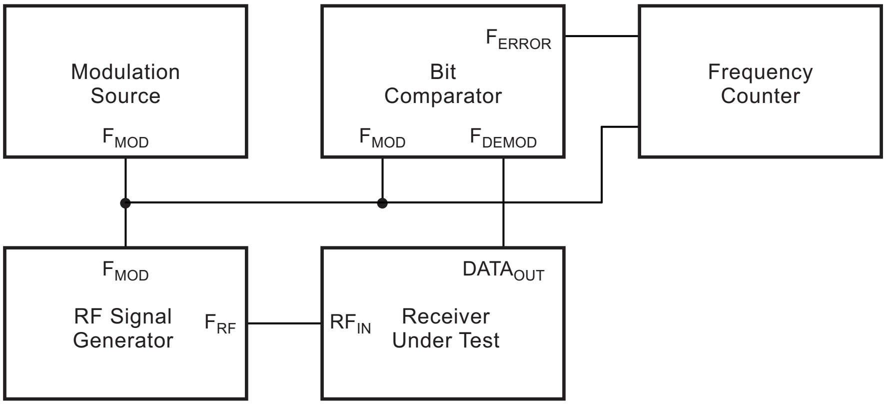
Figure 2-3. Reference Signal with Jitter Windows Defining a Bit Error



3. Sensitivity Measurements

Several instruments are needed to perform sensitivity measurements; an RF signal generator, a modulation source, a bit comparator, and a frequency counter. All are common instruments in a modestly equipped RF lab, with the possible exception of the bit comparator. Please refer to Figure 3-1 for a configuration drawing showing the interconnection of these instruments.

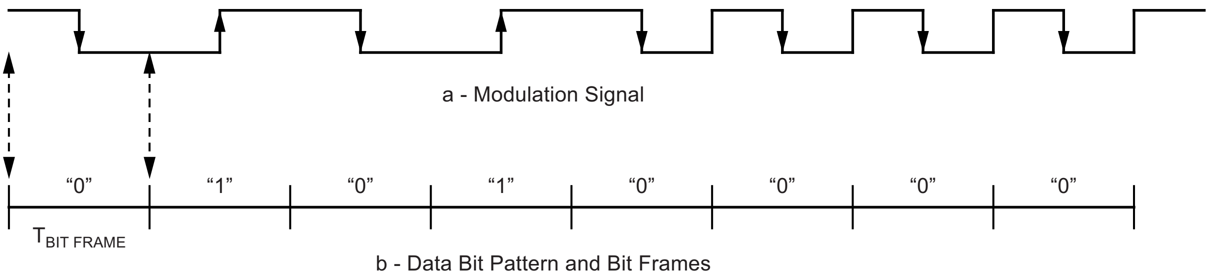
Figure 3-1. Sensitivity Measurement Set-up



The bit comparator used to gather sensitivity data contained in this document is a custom design and is not commercially available. In simple terms, it generates a pulse, F_{ERROR}, whenever the demodulated signal, F_{DEMOD}, exceeds the jitter window (set to ±25% as default) with respect to the reference signal, F_{MOD}. See previous section titled Receiver Sensitivity Terminology for more details and definitions of jitter and jitter window. The Bit Error Rate is calculated by dividing the bit comparator's error signal, F_{ERROR}, by the reference signal, F_{MOD}. Additionally, the bit comparator has provisions to enable the adjustment of the jitter window from ±10% to ±55%. The modulation source consisted of a square wave signal whose duty cycle was maintained at 50% and whose frequency was varied. A commonly accepted data bit encoding standard for low-cost and low data rate RF systems that conforms to this signal definition is Manchester. In many applications, Manchester yields optimum receiver performance by virtue of the characteristic average DC level of 50% that is present on the demodulated signal.

A pictorial representation of Manchester data bit encoding is supplied in Figure 3-2a and Figure 3-2b. The bit frame period, $T_{BIT\ FRAME}$, is defined as the reciprocal of the data rate. A data bit "0" appears as a falling edge during $T_{BIT\ FRAME}$ while a data bit "1" appears as a rising edge during $T_{BIT\ FRAME}$. A key observation to note is that the data bit pattern affects the frequency of the modulation signal. When alternating data bit polarities are used, e.g., "0101", the resultant modulation signal frequency is half the data rate. However, when consecutive "1"s or consecutive "0"s used, the modulation signal frequency is equal to the data rate. In this document, it was assumed that consecutive data bits of the same polarity were used to generate the modulation signal. This means that a data rate of 1kB/s will require a modulation source of 1kHz.

Figure 3-2. Pictorial Representation of Manchester Data Bit Encoding



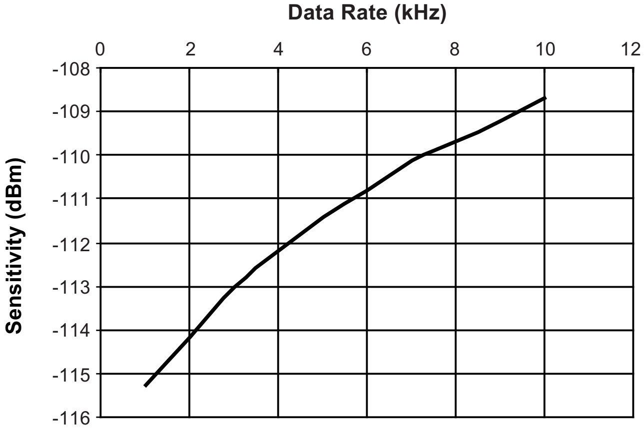
The ATA5746 (315MHz) reference design was used in this document to gather the typical data and to show relationships between measured sensitivity as a function of various RF system parameters. Sensitivity data for each graph was obtained from a sample population of ten boards. The data points shown are based on an average of this population. The trend lines interpolate behavior between data points and utilize a TBD (e.g., linear, 1st order, log, etc.) to create best fit. Caution should be exercised before assuming that the results observed on the Atmel receiver can be extended to receivers from other suppliers without first verifying the results.

4. Sensitivity as a Function of Data Rate

This section quantifies the effect of data rate on measured sensitivity. Default settings are Manchester encoding, BER of 10^{-3}, and a jitter window of ±25%. Data was measured at 315MHz using data rates of 1, 2.5, 5, and 10Kb/s with ASK modulation.

Receiver sensitivity is a function of the transmission data rate. Consistent with theory, as data rate goes down, receiver sensitivity goes up. Theoretically, doubling the data rate reduces sensitivity by 3dB. Figure 4-1 generally reflects this relationship, especially when comparing sensitivities at 10kHz (–108.5dBm) and 5kHz (–111.5dBm).

Figure 4-1. Sensitivity as a Function of Data Rate (ASK)



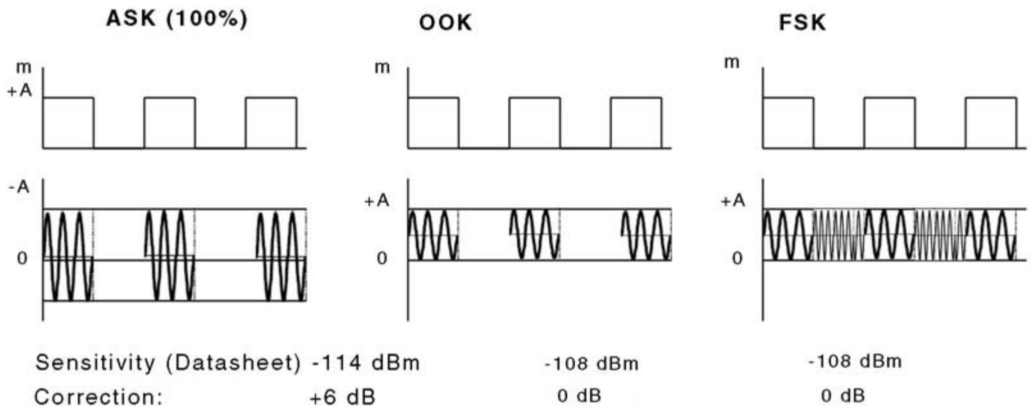
Since the data rate has a substantial effect on the RF receiver's sensitivity, careful consideration of this system parameter is warranted, especially when designing RF systems for long-range applications. It is no coincidence that automotive remote start applications commonly use a transmission data rate of less than 1kHz.

5. Sensitivity as a Function of Modulation

This section quantifies the effect of modulation on measured sensitivity. Default settings are Manchester encoding, BER of 10^{-3}, and a jitter window of ±25%. Data was measured at 315MHz using data rates of 1, 2.5, 5, and 10Kb/s with both ASK and FSK modulation.

Amplitude Shift Keying (ASK) and Frequency Shift Keying (FSK) are two different forms of modulation that represent digital data as variations in amplitude and frequency changes of a carrier wave. On-Off Keying (OOK) is a special form of ASK where no carrier is present in a transmission of a “zero”. By definition, OOK sensitivity is 6 dB lower than ASK sensitivity due to the lower peak value of transmitted power. Figure 5-1 illustrates the different modulation types.

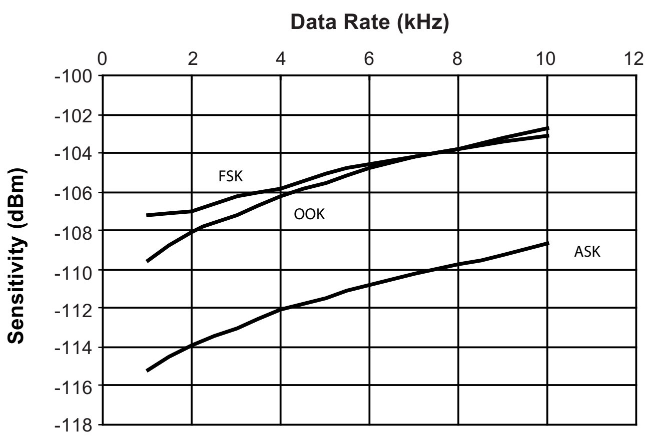
Figure 5-1. Modulation Comparison



RF devices in the marketplace almost always describe modulation types as either ASK or FSK. However, ASK as described in Figure 5-1 is rarely implemented. In reality, OOK modulation is most often used when describing an ASK modulation scheme.

Figure 5-2 shows the measured sensitivity using ASK and FSK modulation. OOK sensitivity was calculated by applying a 6dB correction from the measured ASK sensitivity. The measurements illustrate that ASK modulated signals yield approximately 7dB better sensitivity than FSK modulated signals at similar data rates. However, OOK (the most commonly used form of ASK), offers very little improvement in sensitivity compared to FSK modulated signals.

Figure 5-2. Sensitivity as a Function of Modulation and Data Rate



6. Sensitivity as a Function of BER

This section quantifies the effect of BER on measured sensitivity. Default settings are Manchester encoding at 1kB/s, and ±25% jitter. Sensitivity was measured on the same Atmel receiver using the various bit-error rates commonly used in competitive RF receivers: 10^{-3} (Atmel), 2×10^{-3} (competitor A), 3×10^{-3} (competitor B), 10^{-2} (competitor C).

Since the following measurements are gathered using a constant 1kB/s data rate, it may make more sense to look at bit-error rate as the number of errors allowed per 1000 bit frames. Table 6-1 shows how each branded receivers' sensitivity parameter relates to the number of errors allowed per 1000 bit frames.

Table 6-1. Errors Allowed per/1000 Frames

Branded Receiver	BER	Errors Allowed per 1000 Bit Frames
Atmel	10^{-3}	1
Competitor A	2×10^{-3}	2
Competitor B	3×10^{-3}	3
Competitor C	10^{-2}	10

A higher bit-error rate, or the more errors allowed per 1000 frames, will yield more favorable sensitivity measurements. As expected, Figure 6-1 shows that measurements conducted using a BER rate of 10^{-2} gives way to the best sensitivity measurement of –116.6dBm. Stating this in a different way, Atmel receiver sensitivity specified as –115.3dBm at BER = 10^{-3}, is the same as specifying it as –116.6 at BER = 10^{-2}.

Figure 6-1. Sensitivity as a Function of BER (315MHz; ASK; 1kHz)

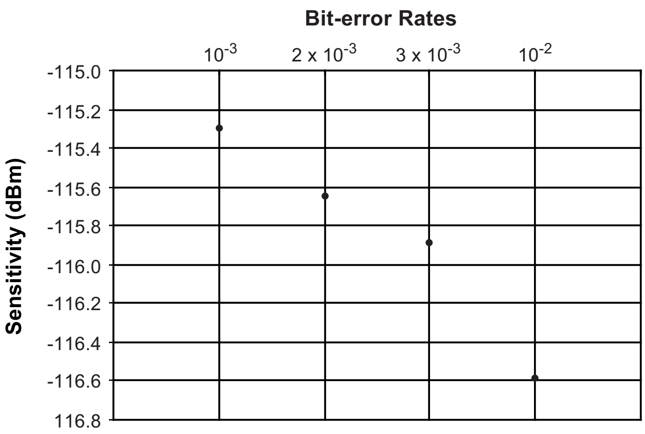
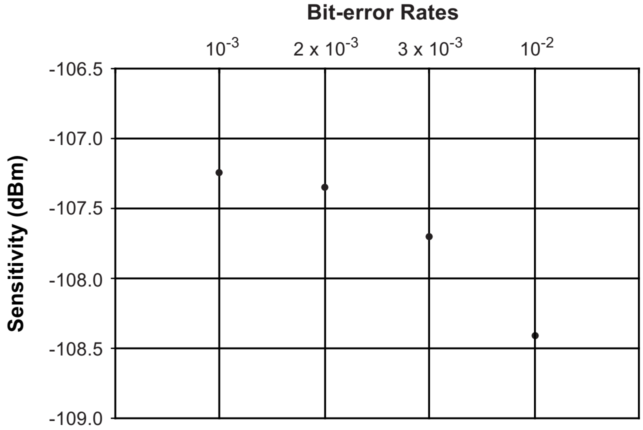


Figure 6-2 shows that this trend is consistent with sensitivity measurements made when the receiver is modulating a FSK signal.

Figure 6-2. Sensitivity as a Function of BER (315MHz; FSK; 1kHz)



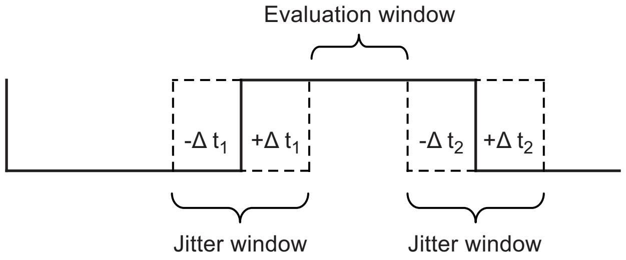
These figures show that the bit-error rate plays a key role in how sensitivity measurements should be interpreted. For example, a competitive receiver promoted with a sensitivity of –116dBm at BER = 10^{-2} would perform worse than an Atmel device with a specified sensitivity of –115dBm at BER = 10^{-3} due to the different BER parameter associated with the sensitivity. It is important to know that a sensitivity parameter without a BER is meaningless. When comparing receiver sensitivities, one should always consider the corresponding BER.

7. Sensitivity as a Function of Jitter Window

This section quantifies the effect of jitter window on measured sensitivity. Default settings are Manchester encoding at 1kB/s, and BER of 10^{-3}. Data will be measured at 315MHz and 433.92MHz using jitter windows of ±10%, ±25%, ±40% for ASK modulation. The jitter window is used to address changes in pulse width as the received RF signal grows weaker. Generally, a ±25% jitter window is used for sensitivity measurements. In this section the relationship between measured sensitivity and jitter window size will be analyzed.

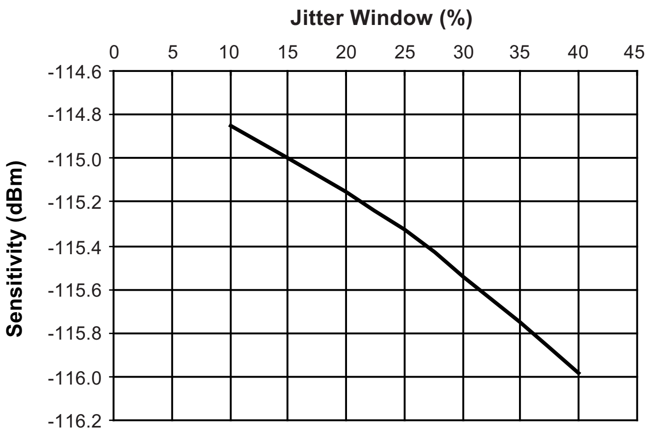
As the jitter windows increases, the evaluation window decreases. For example, a ±25% jitter window will yield a 50% evaluation window, and increasing the jitter window to ±40% will result in a 20% evaluation window. Figure 7-1 illustrates this relationship.

Figure 7-1. Reference Signal with Jitter Windows and Evaluation Window



As the received RF signal grows weaker, changes in pulse widths become greater and more inconsistent. As the jitter window size increases, the evaluation window is narrowed and becomes less susceptible to this phenomenon. Figure 7-2 shows that received sensitivity improves as the jitter window is increased.

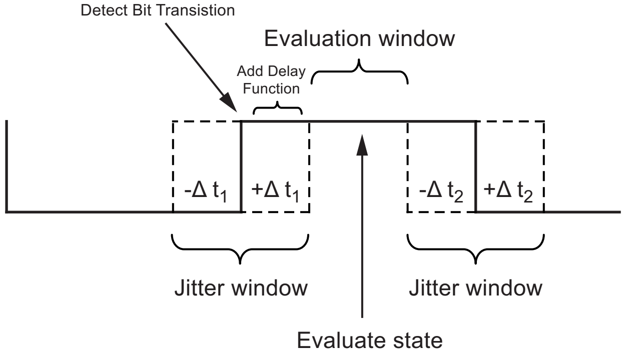
Figure 7-2. Sensitivity as a Function of Jitter Window Size



Knowing that a wider jitter window will result in better receiver sensitivity has implications on the design of the baseband software. It is important to note that poorly designed baseband decoding can significantly degrade RF system performance.

To address this, an idea worth considering would be the application of a delay after a bit transition detection. This principal is illustrated in Figure 7-3.

Figure 7-3. Decode Routine Using Delay Function

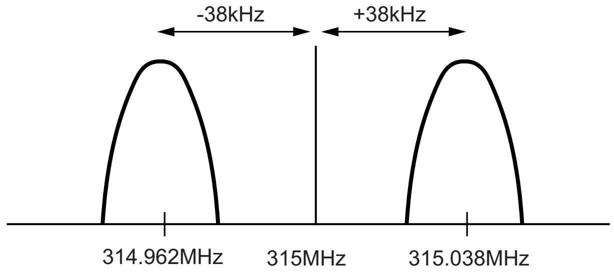


8. Sensitivity as a Function of Frequency Deviation (FSK)

This section quantifies the effect of frequency deviation on sensitivity. Default setting is ±38kHz as stated in the datasheet. Sensitivity was measured using frequency deviations swept from ±15kHz to ±120kHz for FSK modulation.

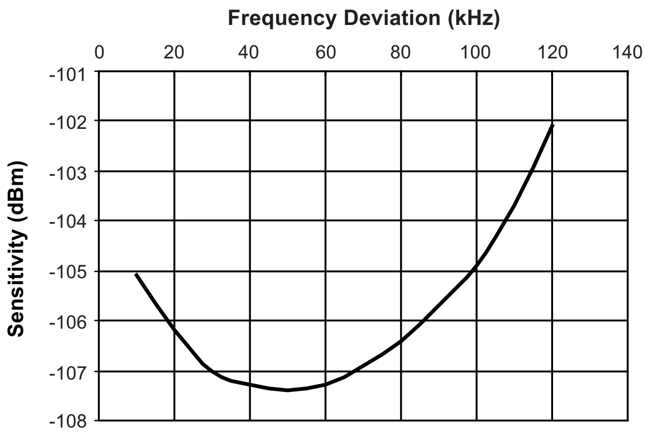
Frequency deviation is the distance between the two frequencies as show in Figure 8-1.

Figure 8-1. Frequency Deviation



The ATA5746 datasheet states that the demodulator is optimized to receive a FSK signal with frequency deviations from ±18kHz to ±50kHz with a default setting of ±38kHz. Figure 8-2 illustrates that performance starts to fall off at frequency deviations above and below this optimal setting.

Figure 8-2. Sensitivity as a Function of Frequency Deviation



8.1 Conclusion

Sensitivity measurements show that data rate has the largest effect on sensitivity. Data rates ranging from 1kHz to 10kHz yielded differences in sensitivity up to 7dB. The next most significant parameter is jitter window size. As the jitter windows size increases, the evaluation window narrows and the receiver's performance improves drastically. The frequency deviation in an FSK-modulated signal is an important parameter to consider when developing an RF system. In this case, the ATA5746 receiver recommends a ±38kHz deviation. Testing shows that signals with frequency deviations straying from the recommended value negatively impacts the receiver's performance. Sensitivity as a function of BER is important to consider given that manufacturers use different bit error rates when specifying a receiver's sensitivity. It is important to compare "apples to apples" when selecting a receiver. Unless the sensitivity figure of receivers under consideration is compared using the same BER criteria, the resulting decision will be flawed. Finally, comparisons in modulations schemes shows that ASK-modulated signals yield much better sensitivity than FSK-modulated signals. However, these results don't hold too much currency considering "true" ASK is rarely used in the real world. In reality, OOK is most often used when describing an ASK RF system. Measurements showed that OOK-modulated signals yielded very similar sensitivity results when compared to FSK-modulated signals.

RF receiver sensitivity is affected by a number of system parameters. It is important to recognize that sensitivity measurements need to be evaluated with the knowledge of the entire RF system. Data rate, modulation schemes, BER, jitter window, and frequency deviation all contribute to a receiver's performance.

The ATA5746 receiver was used for all measurements discussed in this application note. However, the same principles apply to all receivers including Atmel's entire of line of receivers shown in Table 8-1.

Table 8-1. Atmel Receivers

Atmel Receivers	Market	Frequency
ATA5745	Automotive	433MHz
ATA5746	Automotive	315MHz
ATA5723	Automotive	315MHz
ATA5724	Automotive	433MHz
ATA5728	Automotive	868MHz
ATA8201	Industrial	315MHz
ATA8202	Industrial	433MHz
ATA8203	Industrial	315MHz
ATA8204	Industrial	433MHz
ATA8205	Industrial	868MHz

For more information on Atmel's RF automotive devices visit:
http://www.atmel.com/products/caraccess/default.asp

For more information on Atmel's industrial RF devices visit:
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9. Revision History

Please note that the following page numbers referred to in this section refer to the specific revision mentioned, not to this document.

Revision No.	History
9174B-AUTO-05/15	• Put document in the latest template

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