

A COMPARISON BETWEEN OOK/ASK AND FSK MODULATION TECHNIQUES FOR RADIO LINKS

DARRELL L. ASH
MURATA ELECTRONICS NORTH AMERICA, INC., CARROLLTON, TEXAS

INTRODUCTION

Short range unlicensed radio links, with typical ranges of 1 to 100 meters, are becoming more and more popular. Millions of these radios are used today in such applications as automotive keyless entry, tire pressure monitoring, gate openers, wireless security systems, data links, remote meter reading and too many other applications to enumerate. With the number of short range devices (SRD's) increasing daily, the potential for interference by competing nearby SRD's or other wireless services has increased dramatically over the last few years. It is becoming more and more important for SRD's to be capable of reusing the same spectrum shared by other SRD's. To share the same spectrum, radio receivers must ignore co-channel interfering signals that are weaker than the desired signal. Such a receiver exhibits what is commonly referred to as the "capture effect". The term "capture effect" is commonly associated with FM or FSK receivers and not with OOK/ASK by the industry in general. The industry also believes that FSK receivers are more sensitive than OOK receivers. This paper will show that, when properly implemented, OOK can actually outperform FSK in both the areas of sensitivity and co-channel interference tolerance.

OOK/FSK CONSIDERATIONS

Before making the decision whether to use OOK or FSK for an application, several factors, other than sensitivity and co-channel interference, should be carefully considered. A good example is the bandwidth required to transmit data with OOK modulation versus that required with FSK modulation. In the case of FSK, using the minimum criteria for good noise performance, the bandwidth needed is 1.5 times that required for OOK [1]. This is a very important consideration in the new limited bandwidth ETSI SRD bands at 868 MHz.

The simplicity of the OOK transmitter is without equal. Either the stabilized oscillator in the transmitter or a buffer amplifier on its output is simply turned on and off in synchronization with the data to be transmitted. One very important result of using this type of modulation is at least a 50% reduction in battery current drain when compared to that consumed by an FSK transmitter. The FSK transmitter must be on 100% of the time that data is being transferred.

The implementation of the FSK transmitter requires accurate control of both the center frequency and the frequency deviation. As a result, the preferred implementation requires a frequency synthesizer and a bulk crystal for stability. Many of the SRD applications, such as tire pressure monitoring, involve rapid temperature cycling over temperature extremes (-40 to +85 degrees C) as well as severe shock and vibration. Bulk crystals are inherently fragile. They also usually require compensation in the oscillator circuit to operate over large temperature excursions. On the other hand, an OOK transmitter can be implemented using a SAW resonator and a simple oscillator circuit. The SAW resonator is easily capable of handling the temperature, shock and vibration extremes of such applications.

The implementation of the FSK receiver also requires accurate frequency control so a frequency synthesizer and bulk crystal must be used. In addition, the demodulation of the transmitted FSK signal requires another accurate frequency reference for the discriminator or phase locked loop. This is not the case with an OOK receiver.

OOK VERSUS FSK SENSITIVITY

Optimum sensitivity for either an OOK or an FSK receiver is obtained using a coherent or synchronous demodulator. This can be implemented using a phase locked loop (PLL) demodulator for either OOK or FSK. The tune voltage for the VCO (locked to the RF carrier) in the PLL can be used as the demodulated FSK data. OOK is demodulated by inserting the output of the VCO as one input to a multiplier and the RF carrier as the other input. The output of the multiplier is 2X the input frequency and the DC term which is the desired OOK data. A pseudo-synchronous OOK demodulator, with little or no degradation over a true synchronous demodulator, can be implemented simply by applying the incoming RF signal to both input ports of a multiplier. Referring to Figure 1, this is the technique used in RFM's ASH receiver for demodulating signals from the noise level to 20 dB above the noise level. This type of OOK demodulator is much simpler to implement than the PLL approach.

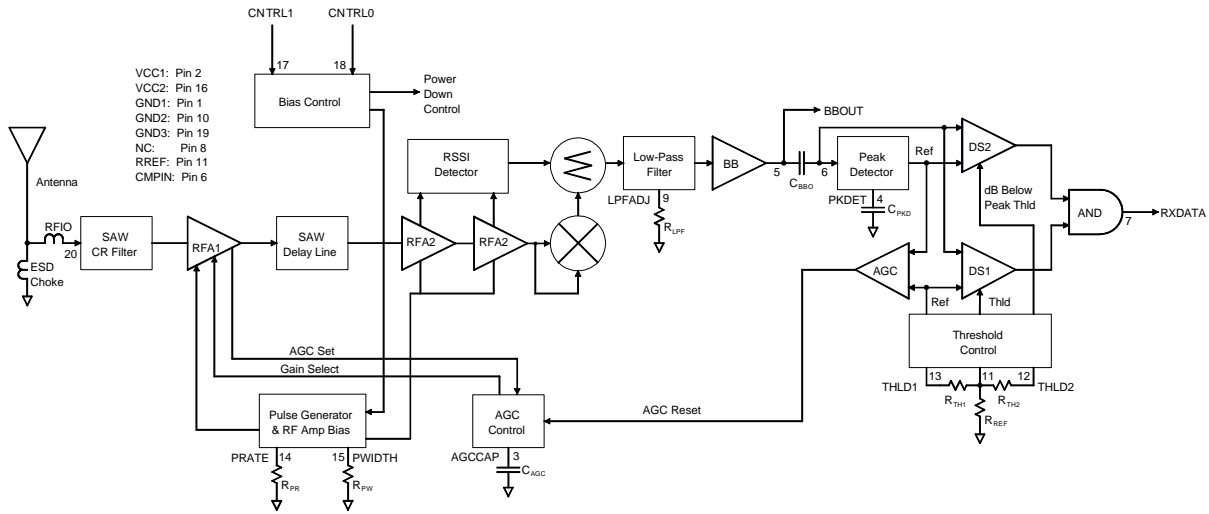


Figure 1
2nd Generation ASH Receiver Block Diagram

The best way to compare the sensitivity or range of OOK and FSK radio receivers is to look at the bit error rate of the receiver versus the signal to noise ratio of the incoming signal. The approach taken in this paper to make this comparison was developed by Peebles in his book *Digital Communication Systems* [2].

The energy over one data bit interval is:

$$E = A^2 T_b / 2 \quad (1)$$

where A is the amplitude of the signal and T_b is the time for one bit. The average energy per bit divided by twice the channel noise density N_0 is:

$$\epsilon = A^2 T_b / 4 N_0 \quad (2)$$

Thus, for coherent OOK and coherent FSK, the probability of bit errors P_e is:

$$P_e = (1/2) \text{erfc}[(\epsilon/2)^{1/2}] \quad (3)$$

where $\text{erfc}[\]$ is the well known complimentary error function as outlined by Peebles in Appendix F of his book.

The probability of bit errors for non-coherent FSK is:

$$P_e = (1/2) \exp(-\epsilon/2) \quad (4)$$

Equations 3 and 4 are plotted in Figure 2.

Referring to Figure 2, the non-coherent FSK example is approximately 1 dB poorer than coherent OOK and FSK. The majority of the FSK receivers used by the industry are non-coherent, using a frequency discriminator with a low frequency resonator as the frequency reference. From these plots, we find that the coherent OOK receiver, as exemplified by the receiver of Figure 1, exhibits a lower probability of error versus signal to noise ratio than the majority of the FSK receivers implemented. The

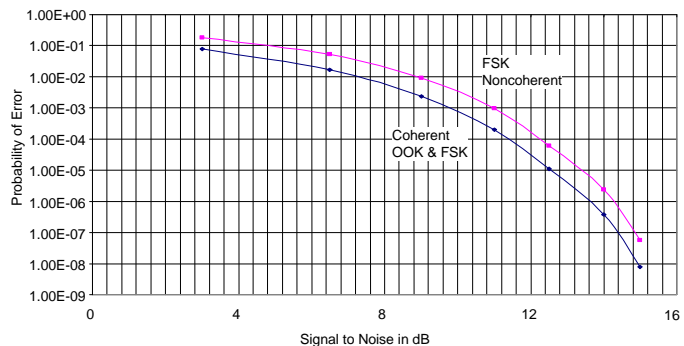


Figure 2
Error Probability Versus Signal to Noise Ratio

probability of error versus signal to noise ratio for the coherent OOK receiver is identical to that for the coherent FSK receiver. Thus, we conclude there is no sensitivity or range advantage to implementing the more complicated FSK radio link rather than a simple OOK radio link.

OOK VERSUS FSK CO-CHANNEL INTERFERENCE

As mentioned earlier, the term “capture effect” is commonly associated with the ability of a receiver to ignore co-channel interfering signals that are weaker than the desired signal. Analog FM receivers are far superior to analog AM receivers when exposed to co-channel interference. Capture in an analog FM receiver is measured by a quantity called the “capture ratio”. For practical purposes this is the ratio in dB of wanted to unwanted signal that will cause a 30 dB suppression of the unwanted signal at the detector output. Typical values for good quality receivers lie between 1 and 2 dB [3]. Analog AM receivers do not exhibit this behavior.

The performance of digital FM and AM radio receivers, FSK and OOK, is much different than that of analog radio receivers. Let us consider the plots of Figure 2 in this context. The curve describing the probability of error versus signal to noise ratio (SNR) for coherent OOK and FSK shows clearly that the probability of error decreases by approximately an order of magnitude when the SNR is increased from 12 dB to 13 dB. Thus, for a change in SNR of only 1 dB, the probability of error is decreased by a factor of 10. The decrease is a factor of 100 for a 2 dB change in SNR from 12 dB to 14 dB. This is similar to the “capture effect” of the analog FM radio, but it applies to both OOK and FSK digital radios.

Now let us compare the measured co-channel interference performance of the referenced Murata OOK receiver to a commonly available single chip FSK receiver. The data taken is plotted in Figure 3. The OOK receiver was characterized with both CW and FSK interference. Using either CW or FSK interfering signals gave the same results with the OOK receiver. The FSK receiver was tested with CW interference only, since tests with FSK and OOK interference gave approximately the same results as CW. The “Y” axis of Figure 3 is the difference in dB between the desired signal level and the level of the interfering signal that could be handled without loss of the desired data. The “X” axis is the level of the desired signal in dBm. Of course, the goal is that the receiver be able to function with the interfering signal as close to the desired signal level as possible. The desired signal level range of most interest includes -90 to -40 dBm. These are the signal levels most commonly encountered in actual radio links. Levels above -40 dBm are only encountered when the transmitter is less than a meter from the receiver.

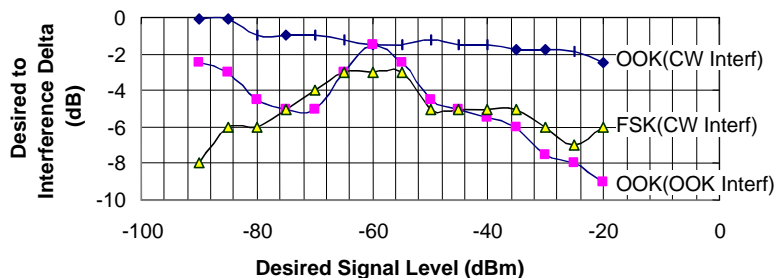


Figure 3
Capture Effect for OOK and FSK

Referring to Figure 3, note that the best performance for the OOK receiver was obtained with CW or FSK interference. At the desired signal levels of -85 and -90 dBm, the interfering signal was just a few tenths of a dB from the desired level. The worst case was -2.5 dB at a desired level of -20 dBm. This is excellent performance and indicates that such an OOK receiver would work extremely well in the presence of FSK co-channel interference. The performance of the OOK receiver with OOK interference was also very good. At -90 dBm the interference was 2.5 dB below the desired level. The worst case was at a desired level of -20 dBm where the difference was 9 dB. The best performance was at a desired level of 60 dBm where the difference was 1.5 dB. In comparison, the FSK receiver performance at -90 dBm showed an 8 dB difference with the best performance at -60 dBm at a difference of 3 dB.

Referring to Figure 3, the co-channel performance of the OOK receiver is superior to the FSK receiver with CW or FSK interference at all desired signal levels. With OOK interference, the OOK receiver is overall better than or equivalent to the FSK receiver over the desired signal range of -90 to -40 dBm. Note that at -90 dBm the OOK has an advantage of 5.5 dB and at -60 dBm the OOK advantage is 1.5 dB.

Optimization of the OOK Receiver for Co-Channel Interference

The capture performance of the OOK receiver in Figure 3 could not be obtained using a superregenerative receiver or a superheterodyne receiver with an envelope detector. The architecture of the demodulator circuit is very important when addressing co-channel interference. Referring to Figure 1, the Murata receiver tested includes a logarithmic detector with a pseudo-synchronous detector as the final stage of the overall detector. This provides an overall detector response that is square law for low signal levels and transitions into a log response for higher signal levels. Figure 4 is a plot of the overall detector response with RF input level in dBm as the "X" axis and detected output voltage on the "Y" axis. The linearity of the response in this semi-log plot illustrates how closely it approximates a logarithmic detector. The combination of the square law and logarithmic responses provides excellent threshold sensitivity and more than 70 dB of detector dynamic range. This detector response combined with 30 dB of AGC range in RFA1, yields more than 100 dB of receiver dynamic range. The onset of saturation in the output stage of RFA1 is detected and generates an AGC Set signal to the AGC Control function which subsequently reduces the gain of RFA1 by 30 dB in one step. The AGC is reset by comparing the output of the peak detector to a fixed threshold reference for Data Slicer 1 (DS1) [4].

Referring to Figure 4, if the desired signal level is higher than the co-channel interference, the OOK modulation of the desired signal results in an output voltage change from the detector that is dependent upon the difference between the two signals. As shown in Figure 1, the output of the detector circuit, BBOUT, is capacitively coupled to the input of the data slicers. Thus, the DC offset created by the interfering signal is ignored if the interference is CW or FSK. This results in a noise-free data output if the peak to peak level of BBOUT has not been reduced below the threshold level of the slicer circuitry. As a result, the plot in Figure 3 of CW interference in the OOK receiver shows excellent performance.

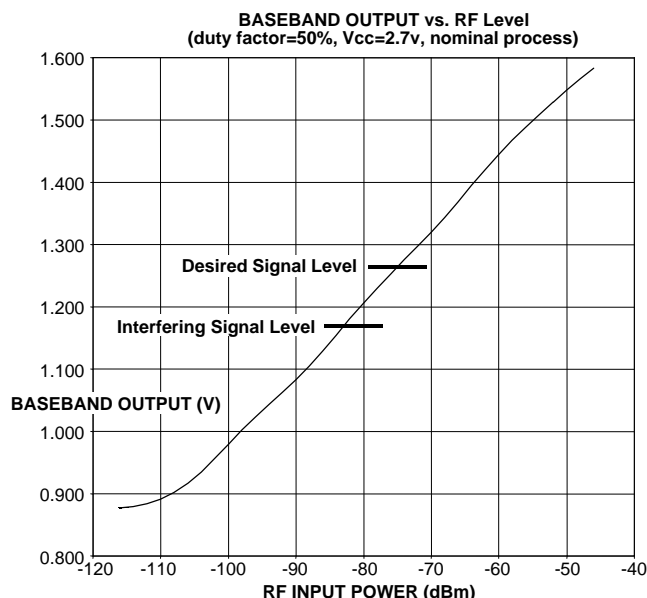
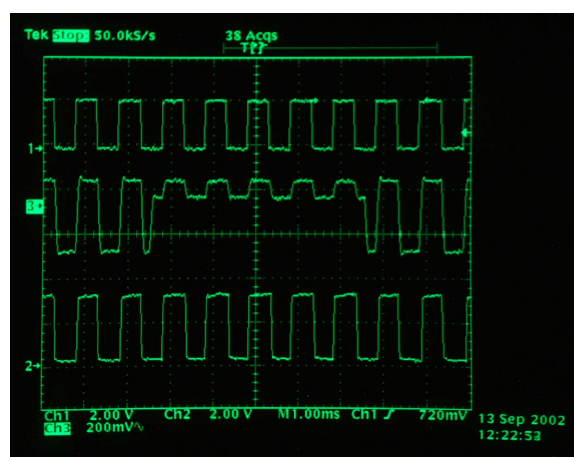


Figure 4
RF Input Level Versus Detected Output



(top) Data Input to Signal Generator (middle) BBOUT
(bottom) OOK Receiver Data Output

Figure 5
Oscilloscope Plot

Now let us consider the performance with OOK interference in the OOK receiver. The scope photograph of Figure 5 illustrates the performance of the receiver under this condition. The time response at the top of the display is the data applied to the modulation input of the desired signal generator. The center trace is the signal at BBOUT of the receiver in Figure 1. Note the pedestal that five of the pulses sit upon. This pedestal is caused by the co-channel OOK interfering signal. The bottom trace is the slicer output showing removal of the interfering signal pedestal. This is accomplished in the receiver of Figure 1 by taking advantage of DS2 whose reference is the peak of the data pulse. The slicer threshold level below the peak of the data pulse is set by external resistor, R_{TH2} . The other slicer, DS1, is also used to guarantee that pulses close to the sensitivity limit of the receiver will be passed. This slicer has a fixed threshold level set by external resistor, R_{TH1} . Thus, when the input data pulse exceeds this threshold level, DS1 goes high on its output. Referring to Figure 6, the outputs of the two slicers are applied to the input of an AND gate. Both inputs must be high to obtain a high output from the AND gate. Since the interfering signal appears during the time the data pulses are low, the output of DS1 will include the interfering pulses, but DS2 outputs only the desired data. As a result, the interfering pulses do not appear at the output of the AND gate which is the receiver

PRACTICAL EXAMPLE: OOK VERSUS FSK FOR TIRE PRESSURE MONITORING

An SRD application that is presently receiving a great deal of attention is automotive tire pressure and temperature monitoring. Data is periodically transmitted from the tires to a central receiver in the car. The transmitters in the tires are in a very harsh environment. The tires can get very hot after high speed driving over long distances. The tires experience severe shock and vibration when traversing rough roadways. Transmitters in the tires also experience high centrifugal forces. As mentioned earlier, this is a very difficult environment for a transmitter using a bulk crystal for the frequency reference. The reliability of such a transmitter in this environment would be highly questionable, whereas a simple SAW based OOK transmitter in this application is very reliable.

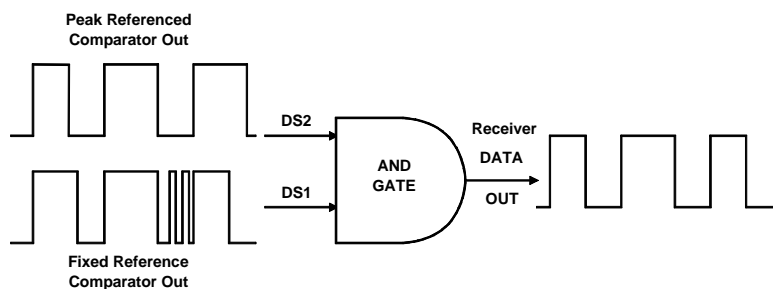
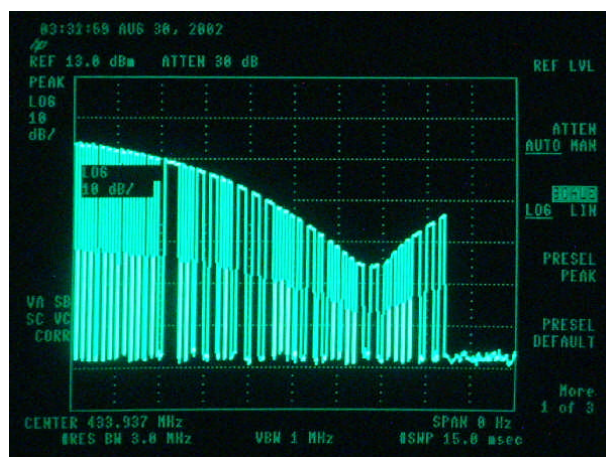


Figure 6
Data Slicer Combination

One problem encountered in this application that has led some in the industry to look more seriously at FSK rather than OOK is commonly referred to as flutter. Simply defined, flutter is the variation in the level of the transmitted signal as the tire rotates. The signal is usually minimum when the transmitter is close to the ground and maximum when the transmitter reaches the highest point above the ground. This can be closely simulated in the laboratory by superimposing a sinusoidal variation in amplitude upon the transmitted RF carrier. The limiting IF amplifier in an FSK receiver can help smooth out the amplitude variation if the minimum signal level observed is of sufficient amplitude for good limiting.

A properly implemented OOK receiver will continue to output good data even with signal levels dropping as low as the sensitivity level of the receiver. An example will be presented here that represents a worst case condition. The highest flutter rate will be experienced with a small diameter tire running at the highest expected speed. A 24 inch (61 cm) tire is an example of a very small diameter tire. In Europe, it is possible the speed could be as high as 160 miles per hour (257.5 km per hour). In this example, such a tire would require 26.77 ms for one complete revolution. Thus, the variation in signal level can be simulated by using 37 Hz sinusoidal amplitude modulation of the RF carrier. The most popular data rate being used is 9600 bits per second. An HP8657B signal generator was used to generate the signal. The generator was modulated on its pulse input (OOK) by the desired 9600 b/s data and was modulated on its AM input by a 37 Hz sine wave. The amplitude of the 37 Hz sinusoid was increased until the modulation depth was 30 dB to simulate severe flutter. Of course, 30 dB is much worse than the flutter expected to be encountered in the field. Typical flutter is expected to be 10 to 15 dB, but the desire was to show how the OOK receiver would function with a depth of 30 dB.

A spectrum analyzer was set up to measure the depth of the flutter. Thus, the analyzer was set up for zero span to make the horizontal axis display time rather than frequency. Figure 7 is a photograph of the screen of the spectrum analyzer displaying the signal with flutter applied. The vertical axis is the power level in dBm. During the set up, the peak level of the signal generator was set quite high, -3 dBm, to allow noise free viewing of the 30 dB variation in signal level produced by the flutter source. Then the signal generator output was reduced to -70 dBm peak and applied to the OOK receiver input. The receiver was an Murata RX5500 designed for operation at 433.92 MHz.

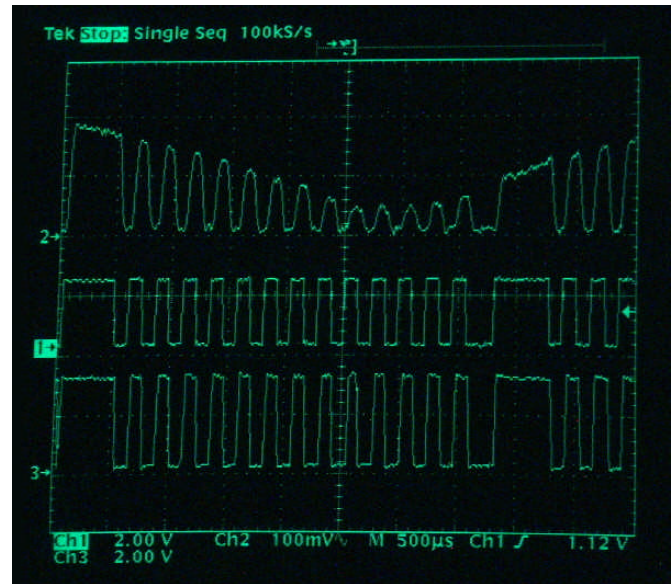


Signal with 9.6 kb/s OOK Modulation and 37 Hz Flutter

Figure 7
Spectrum Analyzer Plot

Figure 8 is a photograph of the screen of an oscilloscope showing the BBOUT signal, see Figure 1, on the top trace, the data input to the signal generator on the middle trace, and the data output of the receiver on the bottom trace. Note the sinusoidal amplitude variation, representing flutter, on the signal at BBOUT. Note the data output from the data slicers on the bottom trace is a good reproduction of the original data even at the lowest signal level. With the peak output of the signal generator at -70 dBm and the flutter variation at 30 dB, the lowest signal level at the bottom of the sinusoid is -100 dBm. Thus, the performance of the OOK receiver in the presence of extreme flutter was excellent.

The key to making the OOK receiver work with flutter is the value of the coupling capacitor connecting BBOUT to the slicer input. If this capacitor is too large, the overall BBOUT waveform, shown on the top trace of Figure 8, centers itself around the quiescent input voltage at the slicer input. This produces a slicer output that drops data at the low points of the superimposed sinusoidal modulation. The value of the capacitor must be reduced to the point that the data input to the slicer remains centered around the quiescent DC voltage at that point. This guarantees the proper output from the slicer under flutter conditions. The value of the capacitor that was used with the Murata receiver was .0047 μ F. The exact capacitor value is not critical. For example, the capacitor used in this experiment had a tolerance of $\pm 20\%$.



(top) BBOUT (middle) Data Input to Signal Generator (bottom)
OOK Receiver Data Output

Figure 8
Oscilloscope Plot

CONCLUSION

The following points have been made in this paper:

1. OOK transmitters are simpler than FSK;
2. OOK transmitter current is 50% lower than FSK;
3. SAW based OOK transmitters are more robust when exposed to extreme temperatures, vibration and shock;
4. FSK transmission requires 1.5 times the bandwidth compared to OOK;
5. OOK receivers are simpler than FSK;
6. OOK receiver sensitivity is equal to or better than FSK;
7. Properly implemented, OOK receiver performance in the presence of co-channel interference is generally better than FSK;
8. Properly implemented, OOK receiver performance with amplitude flutter is equal to or better than FSK.

In the past, OOK radio links have commonly been associated with the poor performance of superregenerative receivers and poorly implemented superheterodyne receivers. The simplicity of OOK has been the main drive for its application in millions of SRD's in the past. It has been shown in this paper that properly implemented OOK links can outperform or equal FSK links in all areas of concern while maintaining simplicity. An example of the simplicity of a properly implemented OOK receiver is the Murata receiver whose performance was outlined in this paper. Figure 9 is a schematic diagram of the Murata receiver showing the external components necessary to achieve the performance illustrated in this paper.

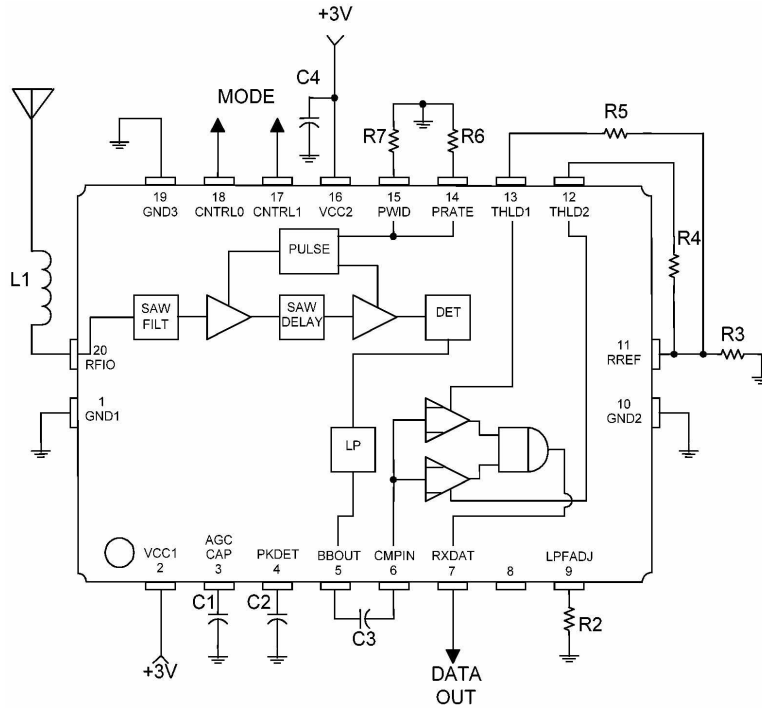


Figure 9
Murata OOK Receiver Schematic

ACKNOWLEDGEMENT

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