

# Direct-conversion Bluetooth receivers

Direct-conversion receivers have well-known challenges that are difficult to overcome such as dc offset. Due to the large modulation bandwidth, the effect of frequency offsets is negligible on the overall performance of the direct-conversion receiver as implemented in Bluetooth.

By Mark Lane

**D**irect-conversion receivers have been around for a long time and have had an on-again-off-again relationship with radio designers. The idea of direct conversion is best understood by considering the well-known superheterodyne receiver, developed by Armstrong. In the simplest form, the direct-conversion receiver can be considered a superheterodyne receiver where the intermediate frequency (IF) is direct current (dc) or 0 Hz. With an IF of dc, the signal is now centered at dc. The received frequency, which today could be many gigahertz, is converted to dc in one conversion—hence, the name “direct conversion” or the other commonly used name, “Zero IF” (ZIF).

Direct-conversion receivers have well-known challenges that are difficult to overcome. These revolve around “dc offset” cancellation, second-order distortion products (e.g., IP2) and 1/f noise. A number of ancillary problems can effect type approval requirements for such receivers, but generally these problems will limit the functional performance of the receiver. Direct-conversion receivers have significant advantages over a typical superheterodyne receiver.

Wireless devices are everywhere. The cell phone explosion over the last decade is a good example. With high-technology devices becoming more of a commodity item rather than a luxury, the cost of the devices has been driven lower and lower. Cost is by far the most significant parameter for the cell phone manufacturer. With the direct-conversion receiver offering the cell phone manufacturer the lowest component count and cost for the bill of materials, direct-conversion receivers are in a “Renaissance period.” A number of the larger cell phone chipset vendors, such as Analog Devices, RFMD and Qualcomm, have announced direct-conversion receivers for next-generation chipsets.

Bluetooth technology is a protocol for wireless personal-area networks and is based on an ad hoc network structure, using Gaussian frequency shift-keying (GFSK) modulation with a low modulation index (0.24 to 0.32). This introduces unique

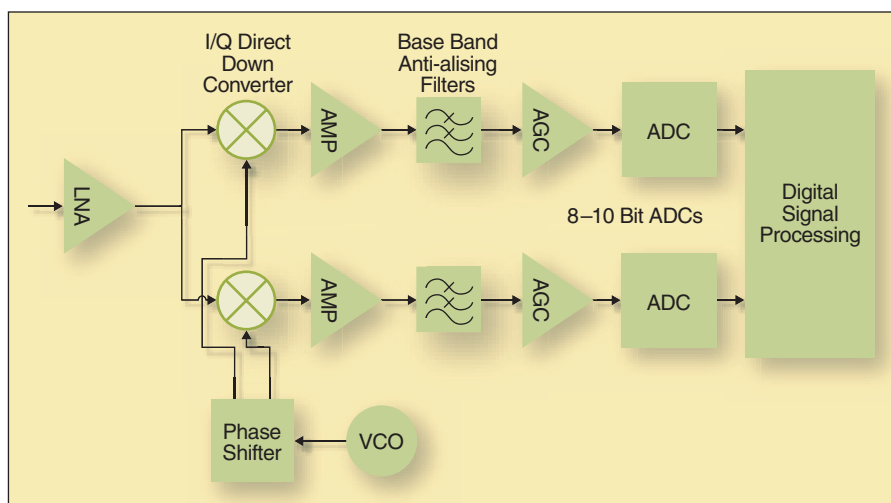


Figure 1. The basic block diagram of a direct conversion as used in a Bluetooth receiver.

challenges for the devices, but the modulation used for Bluetooth technology also suits the use of direct conversion. Bluetooth devices need to be inexpensive, with the total radio bill of materials less than \$10. Therefore, it would seem that a direct-conversion receiver would be good at minimizing the cost of the receiver. However, for this to occur, the well-known challenges of direct conversion need to be overcome.

The basic block diagram of a typical direct-conversion receiver is shown in Figure 1. Although more traditionally used for linear modulation schemes, the direct-conversion receiver is also a convenient receiver for a Bluetooth GFSK received signal.

## Bluetooth technology

This new protocol has been developed over the last five years and has many potential uses. However, arguably the two biggest uses for this technology are for wireless interconnect and hands-free operation in cell phones and cable replacements in the computer industry. Bluetooth technology is an interesting protocol with unique features that make using a direct-conversion receiver possible. Before delving into the direct-

conversion receiver requirements, consideration must be given to the modulation used for Bluetooth technology, because this does make the job easier.

## The modulation

Bluetooth technology, with a 1 Mbps raw data rate, uses GFSK modulation with a low modulation index, ranging from 0.24 to 0.3 and a BT of 0.5. Those of you familiar with Gaussian minimum shift keying (GMSK) will immediately realize that the low modulation index reduces the frequency modulation (FM) detection options. At baseband, this means the signal is not guaranteed to cross through 0 V in each symbol. Therefore, the detection options at baseband are limited to a frequency to voltage converter, such as an FM discriminator.

The spectrum of a maximum-length DH1 packet, sending pseudo random bit sequence (PRBS) data centered at 2.4 GHz, is shown in Figure 2. One thing to note about the spectrum in Figure 2 is that the power of the signal is concentrated around 2.4 GHz. The power spectral density (PSD) is greatest at 2.4 GHz.

Let's examine the effect of interference on the type of modulation shown in Figure 2.

## Interference

Any spurious signals in the receiver, other than the desired received signal, can be classified as interference. The source of interference could be external (environmental) to the receiver or from sources within the receiver. The Federal Communications Commission (FCC) and other regulatory bodies try to control environmental interference sources through licensing equipment and in specialized cases, equipment operators.

## FM and FSK systems

FM is inherently a non-linear process where a signal voltage is converted to a frequency deviation. The “time” representation of the signal is simple.

$$S(t) = A_c \cos(w_c t + m \cdot \sin(w_m t)) \quad (\text{Eq. 1})$$

$A_c$  is the amplitude of the carrier signal

$w_c$  is the angular frequency of the carrier signal

$t$  is time

$m$  is the modulation index

$w_m$  is the angular frequency of the modulating frequency

The factor that is particularly interesting is the modulation index ( $m$ ). This is defined below.

$$m = k_m \cdot A_m / w_m \quad (\text{Eq. 2})$$

$A_m$  is the amplitude of the modulating signal.  $k_m$  is the voltage to frequency scaling factor.

In typical analog FM system,  $k_m$  represents the gain of the modulation path into a VCO. However  $k_m$  and  $A_m$  define a parameter that is relevant to all FM systems called the deviation. Hence, the modulation index can be further defined as;

$$m = w_d / w_m \quad (\text{Eq. 3})$$

$w_d$  is the deviation of the carrier signal due to the modulating signal  $w_m$ .

Although the three equations above were derived assuming a tone-modulating signal as in analog FM systems, these equations equally apply to FSK data systems. The only significant difference is that the modulating signal is a series of bits at a maximum data rate—in the case of Bluetooth, this is 1 MHz. The datastreams modulate the carrier in a manner where a logic 1 in the datastream causes a positive frequency deviation and a logic 0 causes a negative frequency deviation. Hence, in FSK data systems, the maximum modulating frequency is one-half of the data rate (e.g., 500 kHz in Bluetooth products).

## Signal/noise ratio (S/N)

The signal/noise (S/N) of the signal at the output of the FM demodulator is defined as follows. (Note: Rather than go into too much detail on deriving this formula, the formula has been stated and referenced for the discerning reader.<sup>[1]</sup>)

$$S/N_d = 3 \cdot m^2 \cdot S_x \cdot (S_r / n \cdot f_x) \quad (\text{Eq. 4})$$

$S_x$  defines the statistic nature of the modulating signal. In the case of data systems, the likelihood of a logic 1 or 0 is equal and so this parameter is usually 0.5.

$m$  is modulation index

$S_r$  is the received signal power into the FM demodulator

$N$  is noise power spectral density into the FM demodulator

$f_x$  is the noise bandwidth of the receiver into the FM modulator

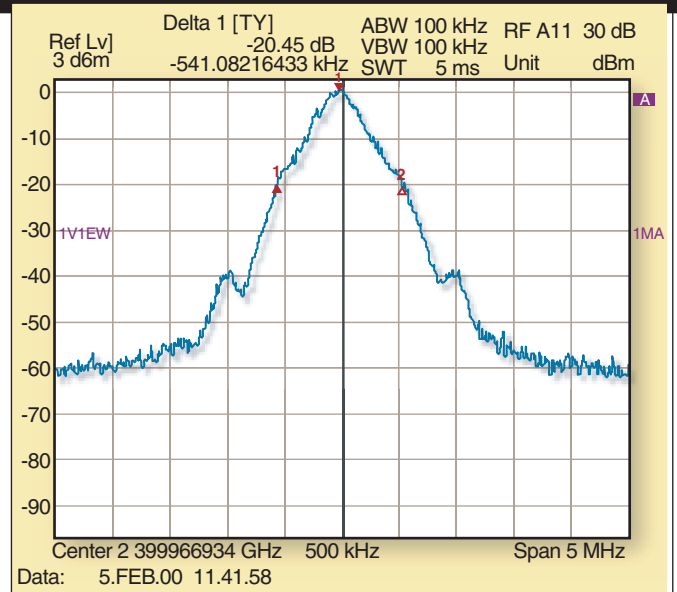


Figure 2. The spectrum of maximum-length DH1 packet, sending PRBS data in the payload, at 2.4 GHz.

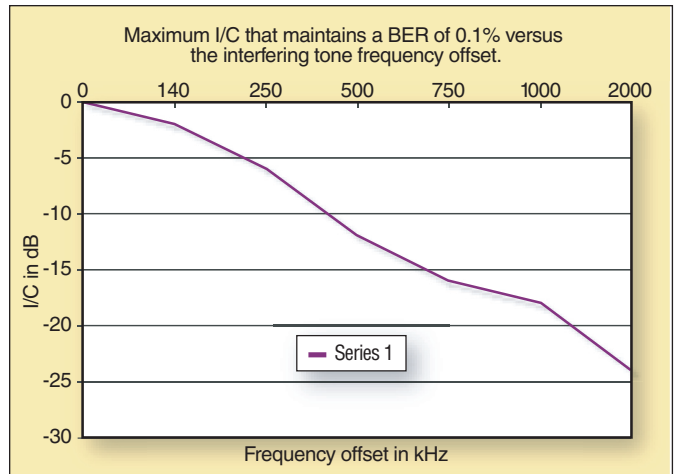


Figure 3. The single-sided I/C performance of the FM demodulator with no channel filter. Note the Gaussian shape to the response and the similarity to the shape of the spectrum in Figure 2.

$S/N_d$  is easily calculated from the requirements in Bluetooth technology. The receiver sensitivity measurement requires the BER to be less than 0.1% or correct 99.9% of the time. Because this article is to focus on the direct-conversion issues, it is left for the interested reader to calculate  $S/N_d$ . However, the interesting thing to note is that  $S/N_d$  is proportional to  $m^2$ .

The sensitivity of a GFSK data system ultimately depends on the data sent. If the Bluetooth data sequence is a string of ‘1111000011110000...’, the modulation index can be calculated. As can be seen from this data, the sequence repeats every eight bits, which means the modulating frequency is the data rate/8 or 125 kHz (the rate for Bluetooth data is 1 Mbps). The deviation is fixed, and most Bluetooth devices use 160 kHz, which means the modulation index is 1.28. For a data string ‘101010...’, the maximum modulating frequency, the modulation index is now 0.32. It is evident from Equation 4 that  $S/N_d$  is proportionate to the modulation index square, which changes with the data. This example illustrates that the signal-to-noise ratio of the received signal has a non-linear relationship to the frequency of the received signal and is largest when the frequency is the lowest.

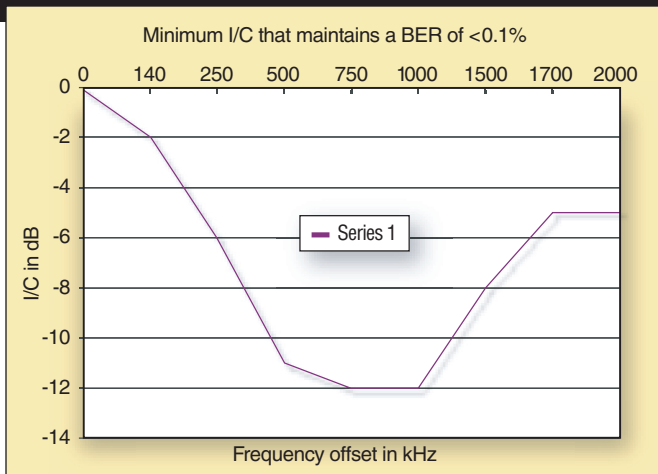


Figure 4. The effect of the channel filter on the interference response of the receiver.

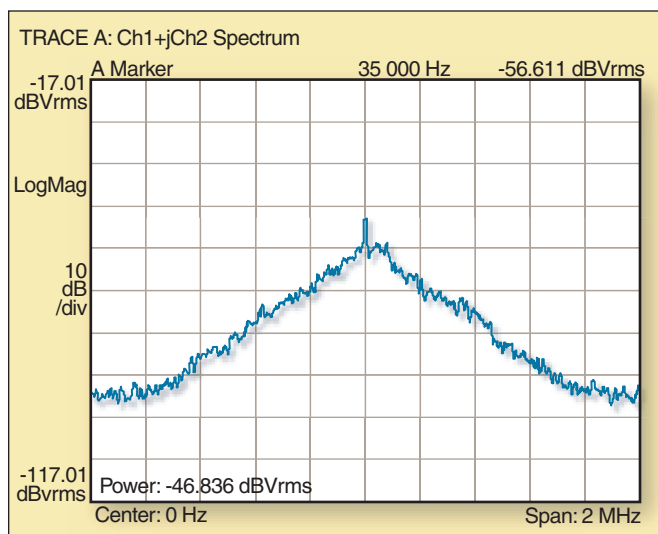


Figure 5. An actual Bluetooth signal at the based band output of a direct-conversion receiver, showing the GFSK signal and the dc offset. (Note: Due to a slight frequency offset in the receiver, the dc offset is not in the middle of the GFSK signal.)

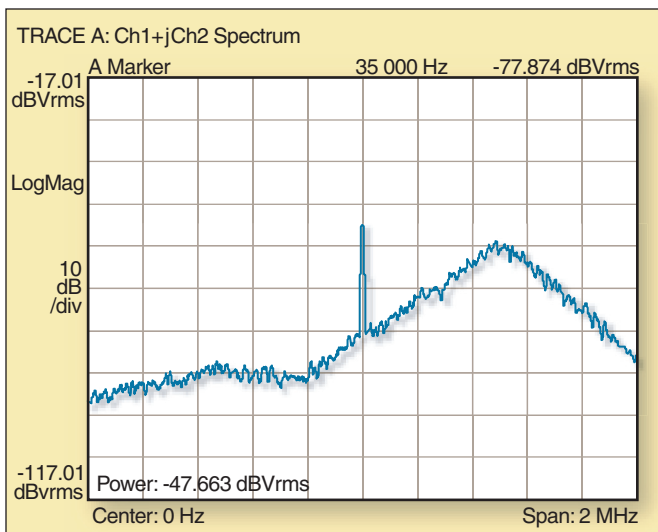


Figure 6. The same GFSK signal shifted in frequency by 500 kHz so the dc offset in the receiver is clear to see.

The frequency domain representation requires undertaking an FFT of the time-domain signal, (Equation 1). Analytically, this is complicated because it involves solving Bessel functions that result in an infinite number of sidebands. However, the higher-order sidebands quickly have insignificant power and so can be ignored. Carson's rule is used predominantly to determine the overall useful bandwidth of the FM system. As GFSK is a data system, the modulating signal is not as well-defined as in the older analog FM systems. The data used to modulate the carrier is assumed to be PRBS. This is generally a good assumption, as most digital modulation systems try to randomize the data as much as possible.

### The carrier to interference (C/I) profile for GFSK

Not surprising is the relationship between carrier to interference (C/I) vs. frequency across the modulation bandwidth. To determine this, a simulation was developed using Agilent's Advanced Design System (ADS) that measured the maximum interference level as a function of frequency the receiver could withstand and still maintain a bit error rate (BER) of 0.1%. If this result is graphed as interference to carrier (I/C) vs. frequency, the plot follows the same PSD as the spectrum in Figure 2. However, because the graph is the inverse of the C/I, the number in decibels becomes negative.

Figure 3 shows the single-sided response of the I/C curve from the center of the modulated signal out to an offset of 2 MHz. Interpreting the results of Figure 3 is interesting.

- The signal has a low susceptibility to interference in the middle of the channel.

- The signal has a high susceptibility to interference at the band edges. At 500 kHz from the center of the channel the susceptibility has deteriorated by 12 dB.

In actual fact, the channel filter will influence the response of Figure 3. This will be observed as an increasing I/C curve at offsets greater than the channel filters cut frequency (see Figure 4). However, in Bluetooth products, all receivers have at least a 1 MHz equivalent noise bandwidth so these filters provide little attenuation for signals less than 500 kHz from the channel center.

Figure 3 is also supported by a theory discussed in (1). This theory states that the output of the frequency detector can be represented by the equation:

$$X_o(t) = k(a_i/a_c) \cdot w_i \cos(w_i t) \quad (\text{Eq. 5})$$

$X_o(t)$  interference output from the frequency detector

$a_i$  is the interference amplitude

$a_c$  is the carrier amplitude

$w_i$  is the interference angular frequency

Equation 5 only applies as long as  $a_c$  is greater than  $a_i$ . In other words, Equation 5 only applies as long as the FM demodulator is "captured" by the wanted signal and not the interference.

As  $w_i$  tends to 0, so  $X_o(t)$  tends to zero. For an interference at 0 Hz (i.e., dc), the effect of the interference is negligible. Generally, FSK systems operate better under this type of interference than any linear modulation system. Note Figure 3 shows that when the interference is at 0 Hz, the I/C ratio can tend to 1 (i.e., 0 dB).

### DC offsets

DC offsets are a major problem in a direct-conversion receiver. There are many ways in which they can be produced in the receiver, but the end result is an interfering signal at dc (Figure 5). Due to frequency offsets between the sending and receiving end, dc offsets generated in the receiver may not be at the center of the received signal's PSD. The maximum offset from the center is a function of the maximum frequency offset between sending and

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receiving ends allowed by the Bluetooth specification; in Bluetooth products, this is  $\pm 75$  kHz.

In Figure 3, a  $\pm 75$  kHz offset results in a small change in the maximum I/C ratio that keeps the BER  $\leq 0.1\%$ . Due to the large modulation bandwidth, the effect of frequency offsets is negligible on the overall performance of the direct-conversion receiver. To illustrate the effect of the dc offset and the center frequency of the GFSK signal, compare Figure 5 with Figure 6. The same dc offset exists in the receiver in both cases, but in Figure 6, the GFSK center frequency has been shifted by 500 kHz and the dc offset is more noticeable. This further illustrates the point that the dc offset is a lot more “damaging” to the signal where the PSD is less.

## Conclusion

Although dc offsets are a major challenge for direct-conversion receivers, consideration must be given to the effect of this type of interference on the modulation. Due to the low-modulation index GFSK signal used in Bluetooth products, the PSD is greatest at the center of the signal, which at the output of a direct-conversion receiver is dc. Hence, the signal is relatively immune to dc offsets, especially compared to interference at frequency offsets of 500 kHz. Although the dc offset is calibrated out of the receiver to minimize any effect it may have on the receiver performance, the accuracy of the calibration determines the complexity. In the case of Bluetooth and GFSK modulation, a highly accurate calibration is not required. **RFID**

## Bibliography

1. “Digital and Analog Communication Systems,” K. Sam Shanmugam, John Wiley and Sons 1979, pgs 366-367.

## ABOUT THE AUTHOR

Mark Lane has 15 years of experience in the wireless industry and more than four years of experience with Bluetooth RF systems development. Lane holds three patents with another three pending. He is currently a senior manager of engineering at RF Micro Devices. Originally from New Zealand, Mark has a 1<sup>st</sup> Class Honors degree from Auckland University and has worked in product development in Landmobile (Trunked MPT1327 networks), GSM and Bluetooth technology. He can be reached at [mlane@rfmd.com](mailto:mlane@rfmd.com).

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