

Silicon Transceiver Family for Low-Power Wireless Communications

Abstract

A family of low-power RF transceivers has been developed for wireless data communications devices operating in the European 433MHz to 869MHz ISM bands or the U.S. 902MHz to 928MHz ISM band. All three IC's have been implemented in a 15GHz silicon bipolar process technology that allows low-power FSK/ASK transceiver operation in commercial wireless products. Typical applications include wireless security systems, wireless meter reading equipment, or virtually any wireless data link application operating up to 1Mb/s. All three devices include an inherent transmit/receive switch, a complete receiver/demodulator, a low-power voltage-controlled oscillator (VCO), and a complete modulator/transmitter. Additionally, the RF2905/2925 include an on-chip PLL frequency synthesizer that can be used to support up to 4-channel operation. For applications requiring more channels, the RF2915 is designed to interface directly to commercially available programmable PLL frequency synthesizers. The RF2905 provides for two-channel transceiver operation, while the RF2925 is optimized for single channel operation in systems using Time Division Duplexing (TDD). The typical DC power consumption of these devices is less than 1uA @ 3.0V in the sleep mode, 8.2mA @ 3.0V in the receive mode, and 23mA @ 3.0V in the transmit mode. At 3.0V operation, the receiver achieves a typical cascaded noise figure of 10dB and the transmitter produces +4dBm (@ 915MHz) typically into a 50Ω load. The chip also provides for modulation flexibility and can be configured as an FSK/FM, or ASK/AM data transceiver. The RF2905/2925 are packaged in a low-cost 48-pin LQFP package. The RF2915 is packaged in a 32-pin LQFP package.

This paper also discusses operation of the device as an unlicensed FSK transceiver in the U.S. 902MHz to 928MHz ISM band with regulatory compliance to FCC Part 15.249. In addition, a variety of application considerations are provided to assist system designers in implementing the device as a one-way transmitter/receiver, or as a full two-way RF transceiver using FSK or OOK AM data modulation.

Product Applications and Technology Selection

Until recently, low-cost wireless data or voice products for a wide range of consumer and industrial applications have predominately utilized lower VHF frequency bands for unlicensed operation of low-power RF

devices. Operation in these frequency bands, such as the U.S. 49.82MHz to 49.90MHz band, has been an obvious choice for designers in these cost sensitive applications due to the abundant supply of low-cost highly integrated components. The success and wide market acceptance of wireless products, such as 49MHz analog cordless telephones, have resulted in the demand for next generation wireless products that achieve higher performance levels at lower cost. Furthermore, the crowded conditions that exist in the traditional VHF frequency bands and the need for additional bandwidth to support advanced products using digital modulation techniques have motivated product designers to develop products that operate in spectrum allocated at UHF, such as the U.S. 902MHz to 928MHz ISM band. To reduce product development cycles in these next generation products three new monolithic RF transceiver products (RF2905/2915/2925) have been introduced by RF Micro Devices that provide product designers with "Antenna-to-Bits and Back" solutions for their wireless applications. Target wireless applications for the RF2905 transceiver family include utility meter reading, security systems, bar code scanners, cordless telephones, and RFID tags just to name a few.

All three transceiver products were designed to achieve high performance levels while minimizing DC power consumption. Integral to the design process was the use of Optimum Technology Matching™ to select the appropriate IC technology to meet the product objective. Optimum Technology Matching™ means that we consider all RFIC technologies at our disposal for new designs to develop the lowest cost solution that meets the technical requirements of a given application. In the case of the RF2905 transceiver family, the primary applications for these devices are in battery powered applications, such as those found in wireless utility meter reading applications where the primary battery may be expected to last for 10 years or more. In the case of the RF2905 transceiver family, a 15GHz silicon bipolar process technology was deemed as an Optimum Technology Match for this application. The silicon bipolar process we selected provides a minimum geometry device that exhibits a 15GHz F_T under 3V and 0.5mA DC operation. Of the GaAs and silicon IC processes we considered, this process allows us to provide a monolithic, low-power, UHF transceiver IC that sells for less than \$4.00 in volume.

Product Descriptions

The RF2905/2915/2925 are quite similar products. All support wireless applications with data rates less than 1MB/s using FSK or ASK digital modulation. The RF2905/2925 also support linear modulation, allowing

their application in systems employing analog FM or AM. All three products, as shown in Figures 1a & 1b, utilize the same single conversion, superheterodyne receiver architecture.

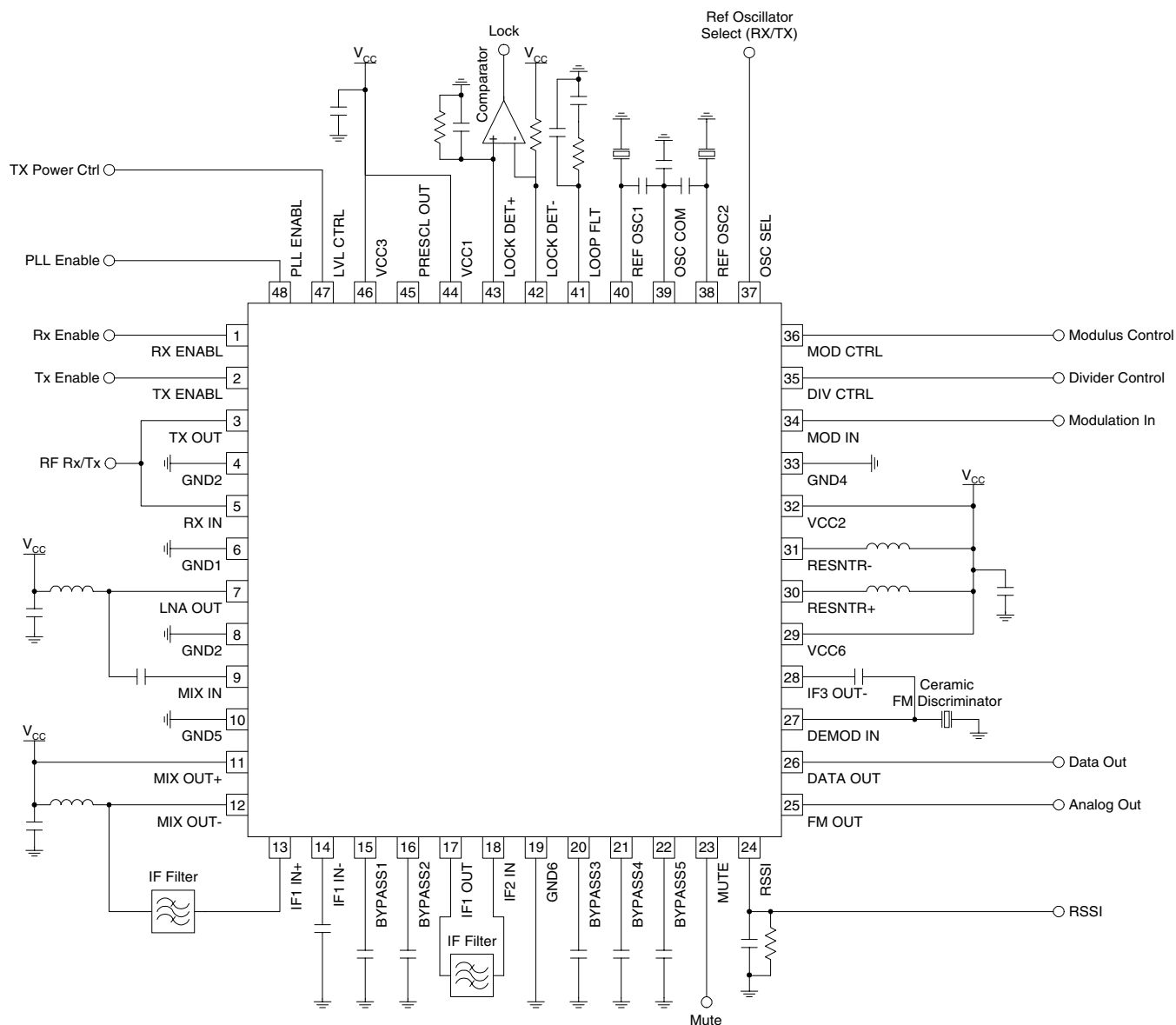


Figure 1a. RF2905/2925 Functional Block Diagram

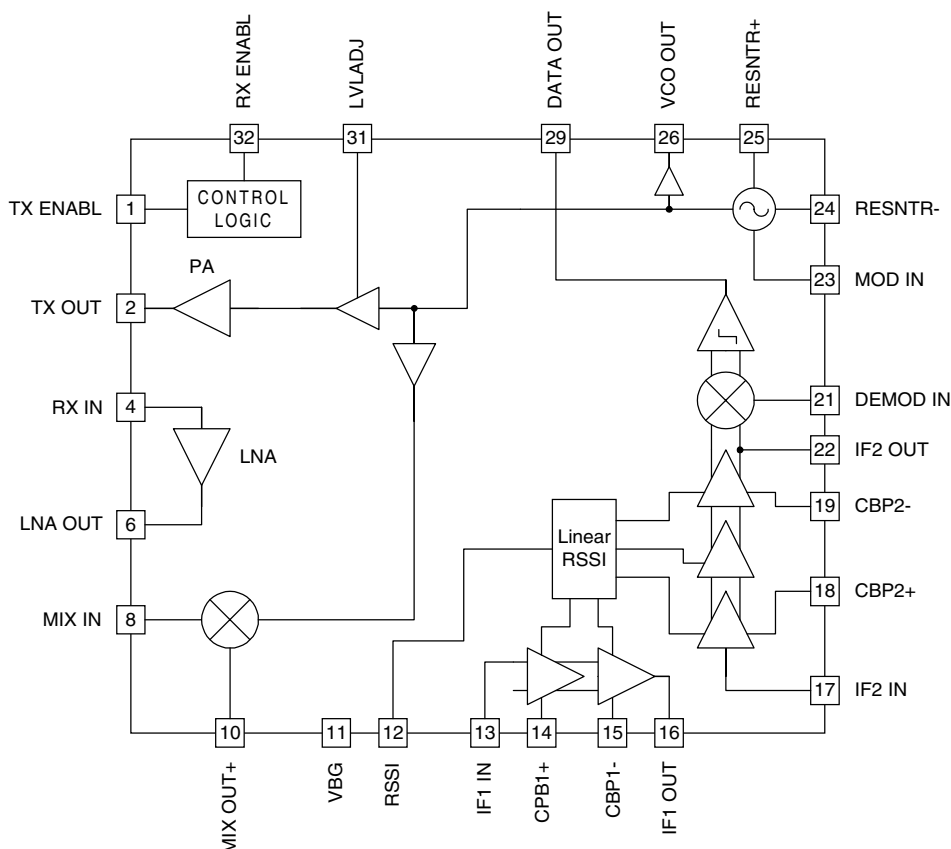


Figure 1b. RF2915 Functional Block Diagram

Frequency Range-All	300-1000MHz
Receiver Sensitivity-All	-97 dBm for 10E-4 BER (FSK)
Tx Power (433/915)-All	+10/+4 dBm @ 3.0V
Modulator FM Deviation-All	500kHz p-p Typical
Rx/Tx Turn-Around Time -RF2905/ 2915/2925	6 mSec/Ext. PLL/150uSec Typ.
DC Power Consumption-Receive- RF2905/2915/2925	8.2/5.5/8.2 mA @ 3.0 V
DC Power Consumption-Transmit- RF2905/2915/2925	23/20/23 mA @ 3.0 V

Table 1. Performance Summary for the RF2905 Transceiver Family

Table 1 also provides a performance summary for key parameters associated with each device. Receiver interfaces are designed to be directly compatible with low-cost 10.7MHz ceramic filters. On the transmit side, carrier modulation is imparted by either direct modulation of the VCO using the on-chip modulation varactors

in FM/FSK applications, or through modulation of the carrier amplitude using a linear output power control pin in AM/ASK applications. The devices also include an inherent 50Ω T/R switch that greatly simplifies their antenna interface. The receiver input and transmitter outputs can be connected directly together (with DC

block) and provide a 50Ω interface without external matching components in the transmit and receive operating modes. The RF2905/2925 provide an on-chip PLL to lock the VCO to one of the reference crystal oscillators. The RF2915 is designed to interface the on-chip VCO to an external PLL frequency synthesizer. Selection of the transceiver appropriate for a given

application begins with consideration of the number of RF channels required by the system. Tables 2a & 2b provide a selection guide for the transceivers based on the number of channels required in transceiver or simplex (Rx or Tx only) applications.

Product Part #	# of RF Channels in European 433MHz ISM band	# of RF Channels in European 869MHz ISM band**	# of RF Channels in U.S. 915MHz ISM band
RF2925	1	1	1
RF2905	1	1	2
RF2915	10	10	171

Table 2a. RF Channels* Supported in Two-Way Transceiver Operation

Product Part #	# of RF Channels in European 433MHz ISM band	# of RF Channels in European 869MHz ISM band**	# of RF Channels in U.S. 915MHz ISM band
RF2925	1	1	1
RF2905	2	2	4
RF2915	10	10	171

Table 2b. RF Channels Supported in One-Way Simplex Operation

* 150kHz Channel Bandwidth

** Operation in bandwidth allocated for wideband use in non-specific applications within the 868-870MHz Frequency band

While only single-channel transceiver operation is supported in the 433MHz to 869MHz European ISM bands using the RF2905/2925, the RF2915 provides ten (10) 150kHz channels in 433MHz European ISM band when used in conjunction with an external PLL frequency synthesizer. As shown in Table 2b, the RF2905 can be used to provide a four-channel receiver or transmitter in the U.S. 915MHz ISM band for simplex applications. Four channel operation is accomplished with the RF2905 by independent control of the two reference oscillators (OSCSLT) and the prescaler modulus control input (MODCTL). Using the RF2905, a two-channel receiver or transmitter in the 433MHz to 869MHz bands is also supported without the need for an external PLL. For applications requiring more channels, the RF2915 should be used to interface to an external PLL frequency synthesizer. The RF2915 includes all the functionality of the RF2905 minus the on-chip PLL.

By design, all three transceivers are intended to operate half-duplex. Therefore, an additional consideration in selection of the transceiver product is the Rx/Tx turn-around time. The RF2905 provides independent control (ON/OFF) of the on-chip crystal reference oscillators to provide multiple channels, but minimum Tx/Rx (or Rx/Tx) turn-around times are typically on the order of milliseconds due to the start-up time required by the crystal reference oscillators. In general, applications requiring turn-around times less than 1msec, such as those found in systems using TDD, should utilize the RF2915 or RF2925. Using the RF2925, both on-chip reference oscillators remain on in both transmit and receive modes and the device is capable of providing turn-around times less than 150μsec. The RF2915 relies on an external reference oscillator circuit, thus the device is applicable to both TDD and FDMA system applications.

28.8Kb/s FSK Receiver Application Considerations

In order to minimize susceptibility to receiver desensitization in the low power single-conversion receiver, RF-IF conversion gain should be limited to that required to set the receiver noise figure. The RF2905 typically provides 16dB of RF-IF voltage gain in the LNA/mixer, achieving a 10dB cascaded noise figure. Additional rejection of interference within the 902MHz to 928MHz band is provided by dual 10.7MHz ceramic IF filters that were selected to establish a 150kHz channel. The 150kHz channel bandwidth is much wider than the 28.8Kb/s data bandwidth and sacrifices some receiver sensitivity in this application. The additional bandwidth allows for center frequency errors in the transmitter and receiver associated with low-cost crystals. The 10.7MHz IF was selected because of the availability of low-cost ceramic filters in a variety of bandwidths up to 280kHz. The user is free to select other IF's and/or filters that are compatible with the 25MHz, -3dB bandwidth provided by the 100dB limiting IF. A balanced multiplier is provided as an FSK demodulator. An external 10.7MHz ceramic discriminator provides the quadrature phase component for the multiplier. Other quadrature networks, such as a discrete LC tank can also be used with the chip.

The IF also provides over 80dB of received signal strength indication (RSSI). The RSSI works with the IF amplifiers to provide a DC output voltage proportional to the strength of the RF input signal. A graph of the RSSI response is shown in Figure 3.

The graph shows a typical range of 0.5V to 2.5V over

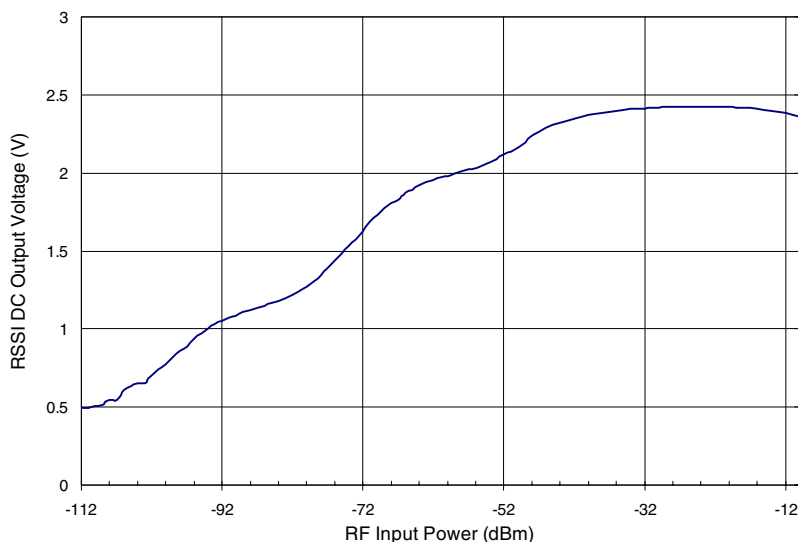
RF input power range of 80dB. The RSSI output could also be used as the demodulator in a simple AM on-off keyed (OOK) system. An external data slicer would be necessary to convert the analog RSSI output to a logic level in this type of system.

The output of the FSK demodulator is DC coupled internally to the data slicer. An on-chip 1.6MHz RC filter is provided at the demodulator output to filter the undesired 2xIF product. The data slicer is a one bit analog-to-digital converter that uses the balanced output from the demodulator to make a bit decision and provide a rail-to-rail output. This balanced data slicer has a speed advantage over a conventional adaptive data slicer where a large capacitor is used to provide DC reference for the bit decision. Since the balanced data slicer does not have to charge a large capacitor, the RF2905 requires a much shorter preamble and exhibits a response time that is nearly instantaneous when compared to an adaptive RC data slicer. For best operation of the balanced on-chip data slicer, FM deviation needs to exceed the center frequency error anticipated between the transmitter and receiver. In general, the FM deviation should be set as wide as possible to avoid duty cycle distortion in the data output when the received signal is not centered on the FM discriminator.

FSK Tx Modulator/PLL Considerations

On-chip varactors are used to impart FSK/FM modulation directly to the VCO. This direct modulation eliminates the need for frequency upconversion and greatly simplifies the filtering requirements required to comply with FCC Part 15.249. In order to directly modulate the

Figure 3. RSSI Output Voltage vs. RF Input Power



VCO, the PLL bandwidth should also be set much lower than the data bandwidth to avoid distortion of the transmitted FSK signal. As a competing consideration, the PLL bandwidth (in conjunction with the start-up time of the crystal reference oscillators) also effects the Rx/Tx turn-around time (Rx/Tx switching time) of the transceiver. Therefore, a trade-off exists in selecting the appropriate PLL bandwidth that allows the VCO to be directly modulated at the data rate while achieving the desired Rx/Tx turn-around time.

As the primary consideration, the modulation rate needs to be much higher than the PLL bandwidth to prevent the PLL from tracking out the modulation. In application, long strings of "1's" or "0's" can also be tracked out by the PLL and can produce bit errors. Therefore, the lowest frequency data input to the modulator should always be greater than the PLL bandwidth. For these reasons, Manchester encoding is recommended when using the FSK modulator. When Manchester encoding is used, two symbols are required to transmit a single bit of information. Using Manchester encoding, a binary one is represented by a positive half-bit period pulse followed by a negative half-bit period pulse. A binary zero is represented by a negative half-bit period pulse followed by a positive half-bit period pulse. Since a Manchester encoded data stream has zero DC value on a bit-by-bit basis, long strings of "1's" or "0's" will not be distorted by the PLL. The PLL bandwidth is set externally to the device using a passive second-order loop filter that uses two capacitors and a resistor in a shunt configuration (see Figure 4). Experimentally, we have determined that the PLL bandwidth should be a least five to ten times lower than the minimum data rate input to the modulator. In our 28.8Kb/s example, the 1kHz PLL bandwidth main-

tains data symbol integrity and provides a 6msec Rx/Tx turn-around time. The peak frequency deviation provided by the modulator varies with the amplitude of the modulation input. Figure 5 provides a graph of the FM deviation characteristics of the open loop VCO as a function of the modulation input (MODIN). Once a PLL bandwidth consistent with the data rate has been established, the PLL lock time can be predicted using second-order PLL loop equations. Figure 6 provides a plot of the RF2905 PLL lock time as a function of the PLL loop bandwidth. To determine the Rx/Tx turn-around time of the transceiver, the start-up time of the crystal reference oscillator should be added to the PLL lock times in Figure 6. The start-up time of the crystal reference oscillators can also be influenced by the choice of external circuitry and the PLL configuration.

The Rx/Tx turn-around time includes both the start-up time of the crystal oscillator and the PLL lock time. For all practical purposes, the start-up time of the crystal oscillator sets a lower bound on the Rx/Tx turn-around time that can be achieved in operation. In other words, if the PLL takes zero seconds to lock, the Rx/Tx turn-around time is the time it takes the crystal reference oscillator to start. The RF2905 includes a dual-modulus/dual-divide prescaler that provides 64/65 and 128/129 divisors. Thus, for operation in the 915MHz ISM band, either 7MHz or 14MHz crystals can be used in the reference oscillator circuitry. Since the start-up time of an oscillator is inversely proportional to the bandwidth of the crystal, a 14MHz crystal oscillator will start twice as fast as a 7MHz crystal oscillator (assuming a constant crystal "Q"). Therefore, by using a 14MHz crystal and the 64/65 prescaler, the start-up time of the crystal oscillator can be cut in half over that achieved by the 7MHz crystal oscillator circuit. Experimentally,

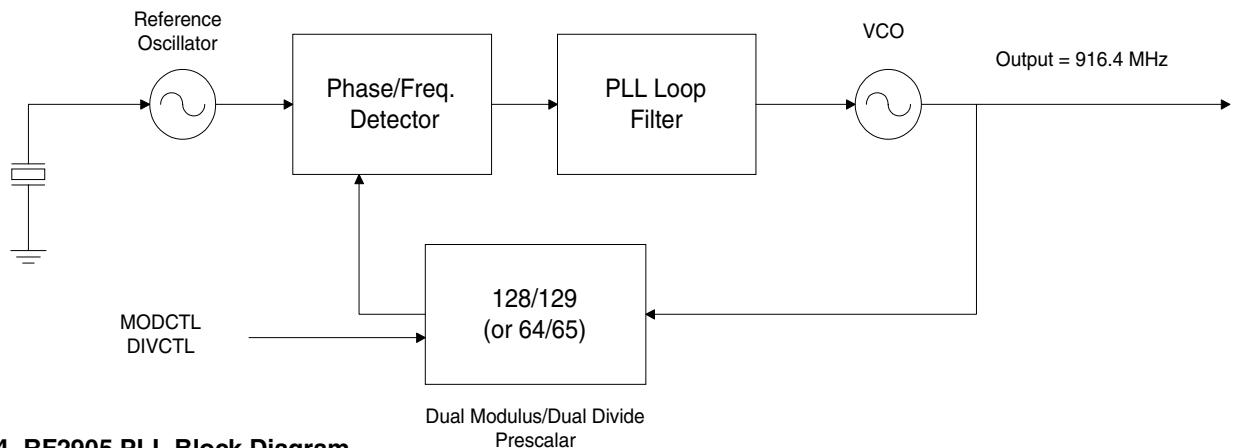


Figure 4. RF2905 PLL Block Diagram

Figure 5. Deviation from Carrier vs. Modulation Input Voltage
(Vcc=3V, LVL ADJ=3V)

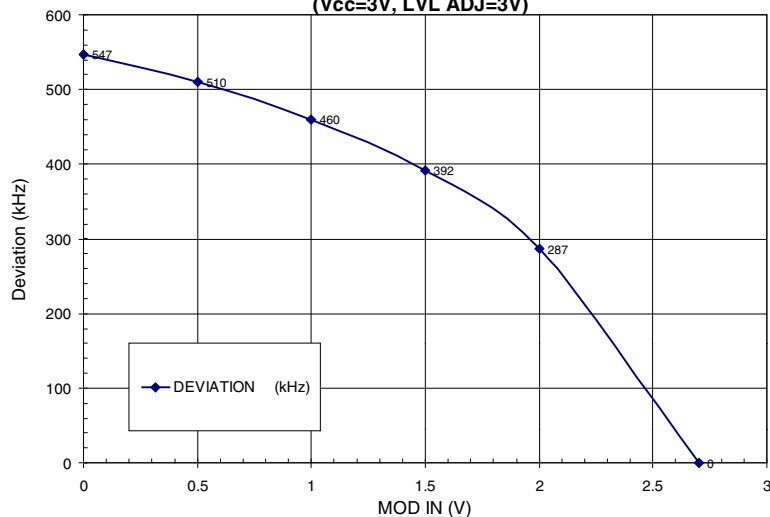
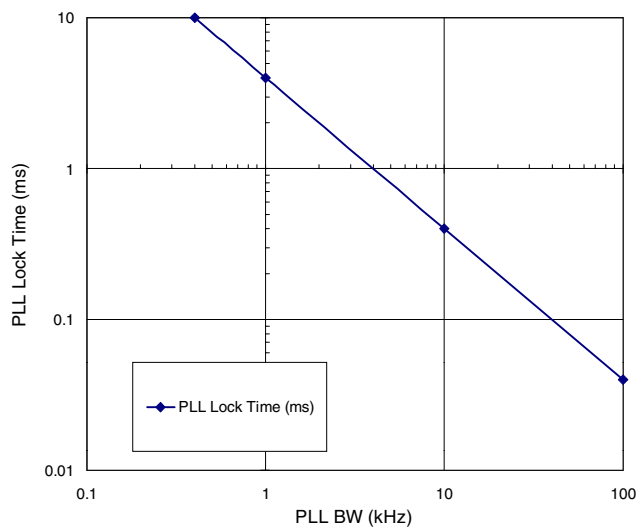


Figure 6. PLL Lock Time vs. PLL BW



oscillator start-up times of 1 msec have been recorded using 14MHz crystals. To achieve an Rx/Tx turn-around time of 1msec would require the PLL bandwidth to be greater than 10kHz and the use of 14MHz reference crystal oscillators. As mentioned previously, if a turn-around time less than 1 msec is required, then the RF2925 should be considered for the application.

Transceiver Range Considerations

A sample receiver sensitivity calculation for a system using the RF2905/2915/2925 is shown below. In Equation 1 below, the noise figure applied is the measured SSB noise figure of the device. The IF detection bandwidth (BW) of 150kHz established by the 10.7MHz

ceramic filters provided on the evaluation PCB, and the required IF predetection signal-to-noise ratio is chosen to be 12dB to provide a BER of 10^{-4} for FSK demodulation. Since no RF image filter is provided on the evaluation PCB, a 3dB degradation due to the image noise is also taken into account.

Equation 1.

$$\text{Sensitivity} = -174\text{dBm} + \text{Image Noise} + \text{NF} + 10\log \text{BW}^{**} + \text{SNR}(\text{dBm})$$

$$\text{Sensitivity} = -174\text{dBm} + 3\text{dB} + 10\text{dB} + 10\log(150\text{K})\text{dB} + 12\text{dB}(\text{dBm})$$

$$\text{Sensitivity} = -97.2\text{dBm}$$

**BW= Noise equivalent predetection bandwidth

Transmit power is restricted for unlicensed devices operating under FCC Part 15.249 to a field strength of 50mV/meter at a distance of three (3) meters. Assuming a unity gain isotropic antenna, this corresponds to a transmitter output power level of 0.75mW or -1.25dBm. The RF2905/2915/2925 provide a healthy +4dBm max. at 3.0V to provide additional margin for applications that utilize more lossy antennas. As shown in Figure 7, DC current consumption of the device is also reduced at lower output power settings.

With respect to path loss equations for estimation of indoor transceiver range, a convenient point of reference is the one-over-r-squared free space path loss equation (Equation 2).

$$Pr = PtGtGr (\lambda / 4\pi)^2 (1 / d^2) \quad \text{Eq. 2}$$

For indoor RF propagation, experience has shown one should expect higher path loss than that predicted by the free path loss equation. Published models for estimation of path loss in buildings modify the exponent of the distance term in Equation 2 (2 for free space) to

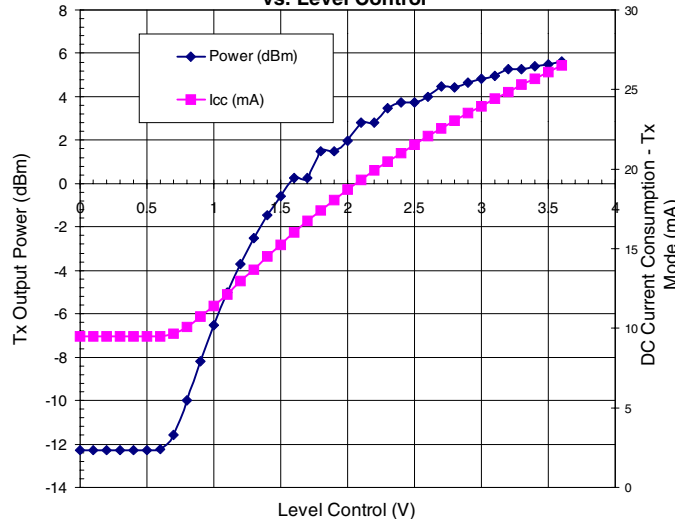
three or more and often include a fixed offset term. Actual RF propagation in buildings will depend on a wide variety of factors, but for estimation purposes one might assume the distance exponent is in the range of 3 to 4 in many scenarios. Solving Equation 2 (assuming unity gain antennas and a distance exponent of three or four) results in a range prediction of 450feet and 132feet in the 902MHz to 928MHz frequency band, respectively. The free-space path loss equation predicts a range of nearly one mile. Obviously, the range of the device will depend on the environment in which the device is operated and on a variety of considerations that are beyond the scope of this example.

915 MHz Transceiver Test Results

In order to further validate the transceiver design, field testing of a two-way 916MHz radio link using the RF2905 hardware was undertaken to characterize the range of the device in a commercial office building. For obvious reasons, the RFMD Corporate Headquarters building was selected for performance of the in-building range testing. The RFMD Corporate Headquarters, as shown in Figure 8, is an "L" shaped building that is constructed using interior/exterior steel stud walls and a brick exterior. Interior to the building, along the center-line, are steel-frame office cubicles containing steel office furniture. Based on the building construction, one would expect an RF signal might be challenged in attempting to propagate throughout the building.

To accomplish the testing, an RF2905 transmitter was set-up in the far corner of the Engineering Lab (see Figure 8) and operated at an output power level of 0.75mW into 50Ω. The 916.4MHz carrier was modulated at 28.8Kb/s with an occupied signal bandwidth of 110kHz. The transmitted output was observed on a

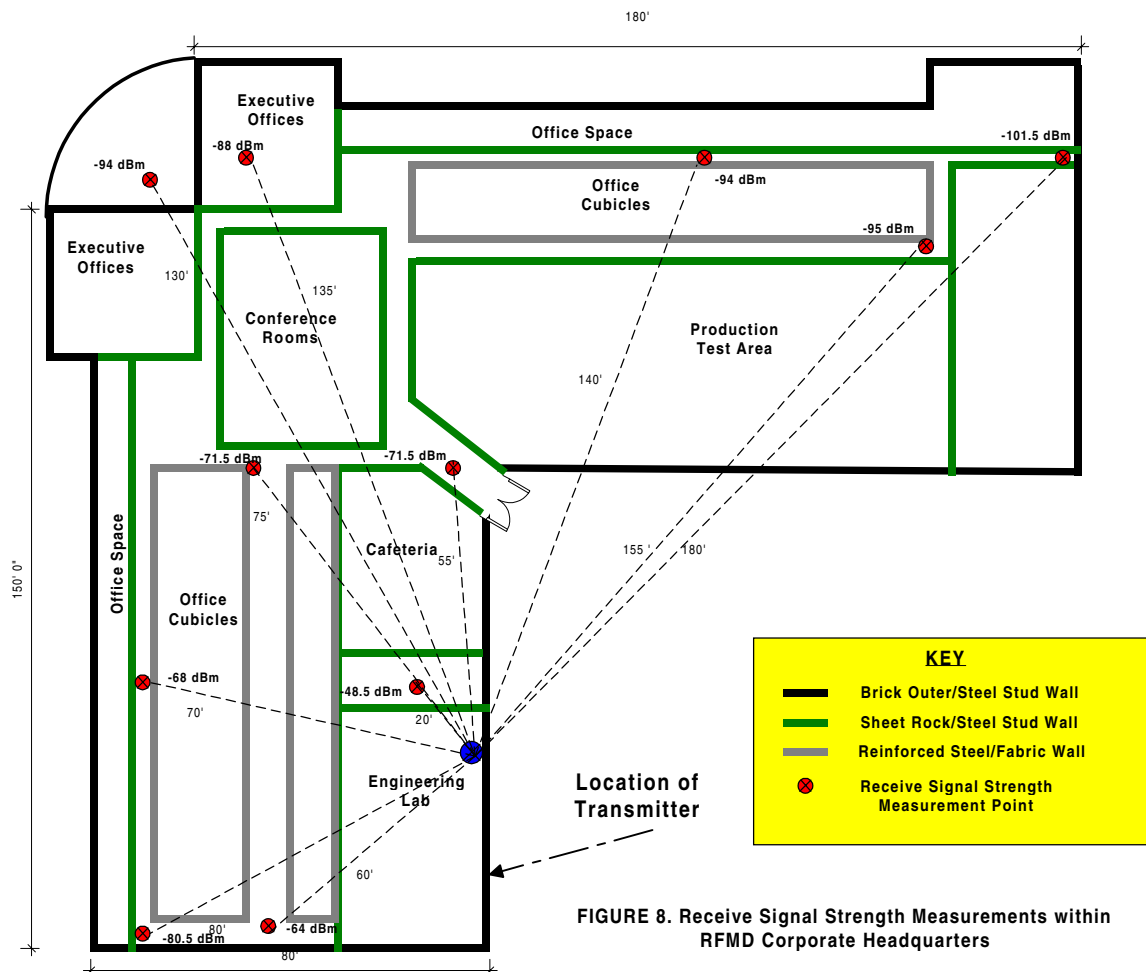
Figure 7. TX Output Power and DC Power Consumption vs. Level Control

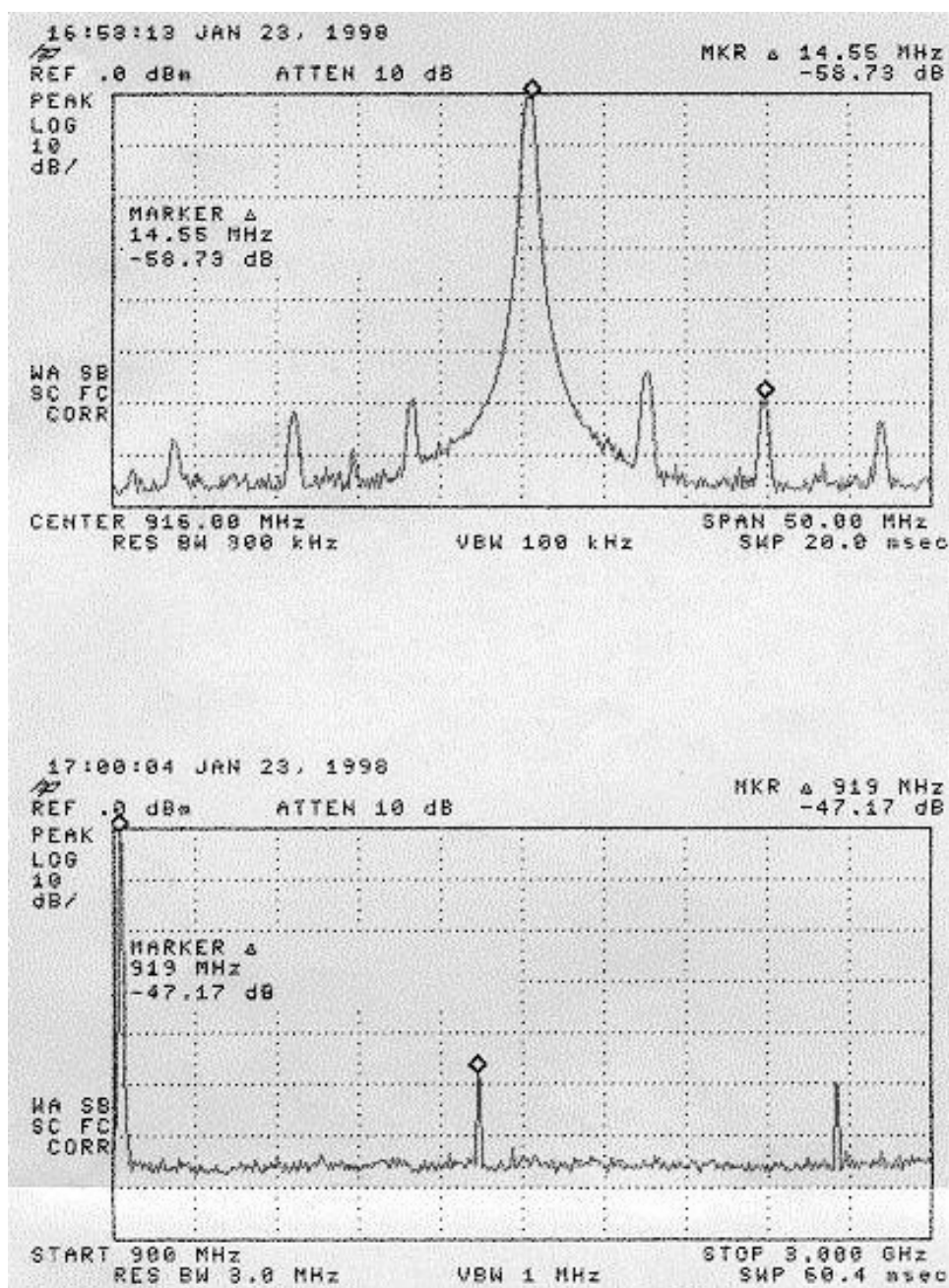


spectrum analyzer and is shown in Figure 9a (close in) and Figure 9b (broadband). In order to achieve compliance to FCC Part 15.249, the spurious emissions from the device must fall below the levels shown in Figure 10. As shown in Figure 9a, the highest spurious emissions from the device outside the ISM band are offset from the carrier by twice the reference frequency. The level of this reference spur is -58.7dBm. This compares to the out-of-band limit of -49.3dBm for FCC compliance in this frequency range. FCC Part 15.249 also limits harmonics of the transmitted output to 500microvolts/meter, or -41.25dBm. As shown in Figure 9b, the second and third harmonics of the transmitter output are also well below this level.

The receiver was operated from a 3.6V lithium battery located at various locations throughout the building. One-quarter wavelength monopole antennas were used on both the transmitter and receiver. A digital voltmeter was used to measure the RSSI output voltage from the receiver. The measured DC RSSI output was then compared against measured RSSI output versus RF input power (ref. Figure 3) to determine the signal

strength at the point of measurement. Since the RSSI detector is a broadband power detector, the data output was monitored throughout the field test to ensure the signal being detected was the one that was transmitted. A typical output from the receiver data slicer for the 28.8Kb/s Manchester encoded data signal used in the test is shown in Figure 11. Figure 11 also displays a sample of the transmitted random data. Using a low-side LO on the receive side results in data inversion from the transmitter to the receiver. The measured signal power at various points throughout the building are as shown in Figure 8. A signal level consistent with a bit error rate of less than 10^{-4} was maintained throughout the building, except in the furthest corner. In this location, the data signal was still quite discernible, but had fallen below the target signal quality. As a point of comparison, the measured data was plotted against the path loss equation for distance exponents of 2, 3 and 4 in Figure 12. Although the data applicability is limited, it is clear that the path loss exceeds a $40\log(R)$ prediction at the extremes of the building.





Figures 9a & 9b. Observed Transmitter Output Waveforms

Conclusion

A family of transceiver IC's have been developed that offer robust transceiver performance in wireless radio applications in the European and U.S. ISM bands. The IC's can be configured for FM/FSK or AM/ASK data modulation. Product differentiation with regard to the number of RF channels and the Rx/Tx turn-around time are provided in the RF2905 family to support a wide range of battery-powered applications. The viability of using the device as a wireless data transceiver

has also been demonstrated in a large commercial office building. The IC's are manufactured on 8-inch silicon wafer ICs, and are currently available in volume for under \$4.00.

Figure 10. Maximum Spurious Emission Levels for Compliance to FCC Part 15.209,15.249 902-928 MHz

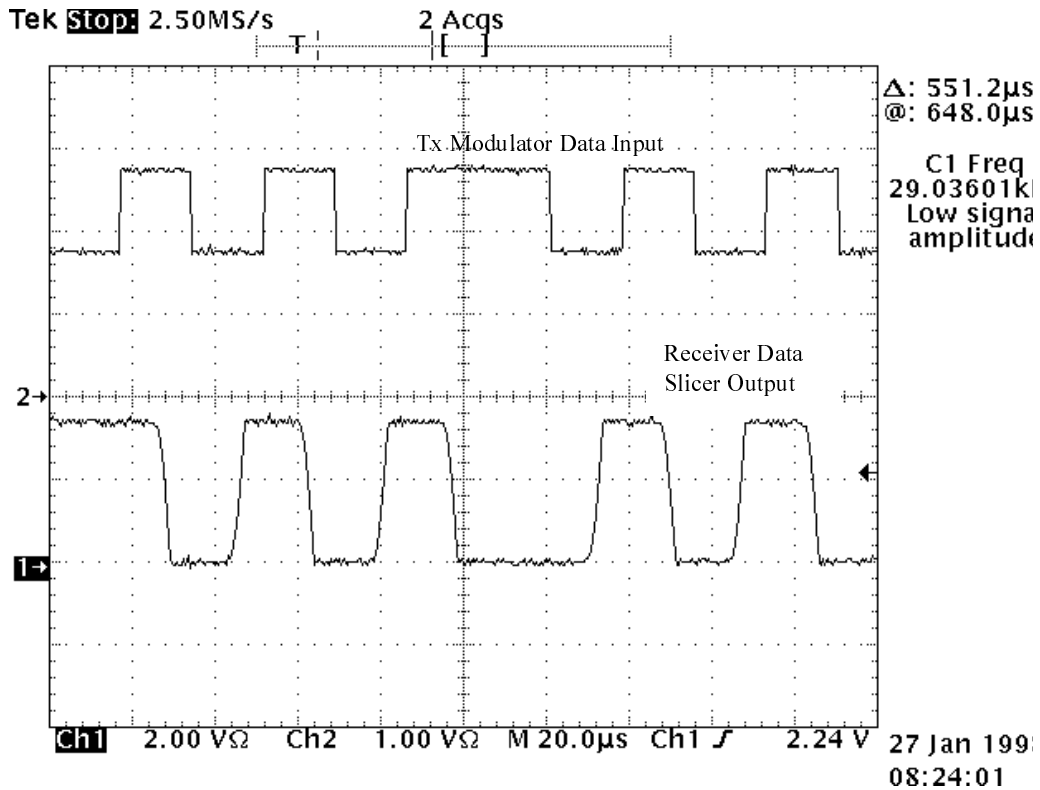
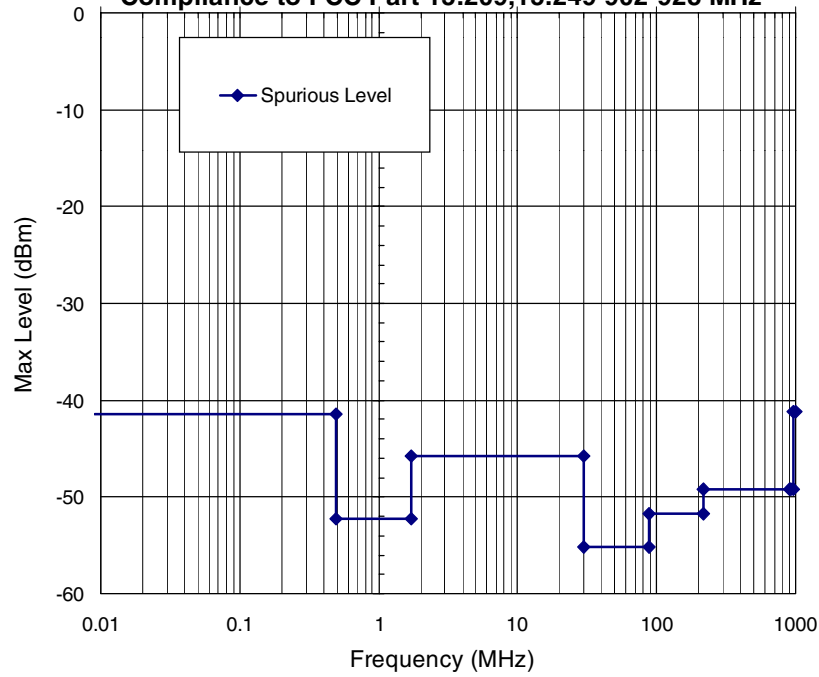


Figure 11. Typical Tx Modulator Input/ Receiver Data Slicer Output

Figure 12. Measured Rx Signal Power As Compared to Free Space Path Loss Estimates

