Keywords: Short-range radio, ISM Band Radio, 260-470MHz ISM Band, UHF Transmitter, FCC Part 15.231, RKE, TPM, Wireless Home Security, Wireless Remote Control, Wireless Radio Transmission, RF Field Strength, 315 MHz ISM Band, 433 MHz ISM Band, 900 MHz ISM Band

APPLICATION NOTE 3815

Radiated Power and Field Strength from UHF ISM Transmitters

Mar 01, 2007

Abstract: Short-range radios that operate at the Industrial, Scientific, and Medical (ISM) frequencies from 260MHz to 470MHz are widely used for remote keyless entry (RKE), home security, and remote control. A critical performance measurement for the radio transmitter is the power that it radiates from the antenna. This power must be high enough to make the link between the transmitter and receiver reliable, yet it must not be so high that it exceeds the radiation limits established in Part 15.231 of the FCC Regulations. This application note discusses the relationship between FCC field-strength requirements in the 260MHz to 470MHz frequency range and the radiated power and typical quantities measured on a test receiver. Tables will illustrate the values that a designer can expect to obtain in field tests.

Introduction

Very often the antennas in the transmitters for applications in the 260MHz to 470MHz Industrial, Scientific, and Medical (ISM) frequency band are so small that they radiate only a small fraction of the power available from the transmitter's power amplifier. This makes measuring the radiated power a very important task. This measurement is complicated because the radiation limits in Part 15.231 of the FCC Regulations are expressed as field strength (volts/meter) at a distance of 3 meters from the transmitter. In addition, the receive antenna, its placement, and the units used on the measuring receiver all affect the measurement of radiated power.

This application note will explain both the relationship between radiated power to field strength and the units used in the measurement receiver. Tables will illustrate the relationship between FCC field-strength requirements in the 260MHz to 470MHz frequency range and the radiated power. The typical quantities measured on a test receiver will be shown. By understanding this relationship and knowing some conversion factors, the user can determine whether measurements made at a test receiver indicate that the transmitter is close to its radiated power goal.

The Relationship Between Field Strength and Radiated Power

Power transmitted from an antenna spreads out in a sphere. If the antenna is directional, the variation of its power with direction is given by its gain, G(Θ, Φ). At any point on the surface of a sphere with radius, R, the power *density* (PD) in watts/square meter is given by Equation 1.

$$PD = P_T G_T / 4\pi R^2 \qquad \text{Eq 1}$$

This expression is simply the power radiated by the transmitter, divided by the surface area of a sphere with radius, R. The gain symbol, G_T, has no angular variation. This is because most of the antennas used in the 260MHz to 470MHz ISM frequency band are very small compared to the operating wavelength and, therefore, have patterns that do not vary sharply with direction. The gain is often quite small because the antennas are very inefficient radiators. For this reason, P_T and G_T are kept together and taken to mean the

Effective Isotropic Radiated Power (EIRP) of the transmitter and antenna combination. Consequently, EIRP is the power that would be radiated from an ideal omnidirectional, i.e., isotropic, antenna.

The power density at a distance, R, from the transmitter can also be expressed as the square of the field strength, E, of the radiated signal at R, divided by the impedance of free space, designated in Equation 2 as η_0. The value of η_0 is 120πΩ, or about 377Ω.

$$PD = E^2 / \eta_0 \qquad \text{Eq 2}$$

Combining these two equations results in a simple conversion of the EIRP, which is $P_T G_T$ to field strength, E, in volts/meter.

$$E = \frac{\sqrt{30 P_T G_T}}{R} \qquad \text{Eq 3}$$

Alternately, Equation 3 can be rearranged to express EIRP in terms of the field strength.

$$P_T G_T = E^2 R^2 / 30 \qquad \text{Eq 4}$$

At the 3-meter distance of the FCC requirements, the relationship is even simpler.

$$P_T G_T = 0.3E^2 \qquad \text{Eq 5}$$

As an example, the FCC limit on average field strength at 315MHz is about 6mV/meter. Using Equation 5, the limit on average radiated power is 10.8µW, or -19.7dBm.

The conversion from field strength to EIRP is further complicated because some documents express field strength in a logarithmic, or dB, format. In the example above, the field strength of 6mV/meter could also be expressed as 15.6dBmV/meter or 75.6dBµV/meter.

Finally, the FCC radiation limits change with frequency over the 260MHz to 470MHz band. This change means that, at every frequency, one needs to calculate the field strength per the FCC requirement formula, then convert from one measurement unit to the other. In Part 15.231 the FCC sets the field-strength limit at 3750µV/meter at 260MHz, and allows a linear increase to 12500µV/meter at 470MHz.

Table 1 combines Equation 1 through Equation 5 with the FCC formula for average field-strength limits. The data in Table 1 thus provide a quick conversion at 5MHz frequency intervals for the multiple ways of characterizing the radiation strength. The gain of the transmitting antenna is assumed to be 0dB.

Table 1. EIRP vs. FCC Part 15.231 Average Field-Strength Limits

Frequency MHz	Field Strength µV/meter	Field Strength dBµV/meter	EIRP mW	EIRP dBm
260	3750	71.5	0.004	-23.7
265	3958	72.0	0.005	-23.3
270	4167	72.4	0.005	-22.8
275	4375	72.8	0.006	-22.4
280	4583	73.2	0.006	-22.0
285	4792	73.6	0.007	-21.6
290	5000	74.0	0.007	-21.1

295	5208	74.3	0.008	-20.9
300	5417	74.7	0.009	-20.6
305	5625	75.0	0.009	-20.2
310	5833	75.3	0.010	-19.9
315	6042	75.6	0.011	-19.6
320	6250	75.9	0.012	-19.3
325	6458	76.2	0.013	-19.0
330	6667	76.5	0.013	-18.8
335	6875	76.7	0.014	-18.5
340	7083	77.0	0.015	-18.2
345	7292	77.3	0.016	-18.0
350	7500	77.5	0.017	-17.7
355	7708	77.7	0.018	-17.5
360	7917	78.0	0.019	-17.3
365	8125	78.2	0.020	-17.0
370	8333	78.4	0.021	-16.8
375	8542	78.6	0.022	-16.6
380	8750	78.8	0.023	-16.4
385	8958	79.0	0.024	-16.2
390	9167	79.2	0.025	-16.0
395	9375	79.4	0.026	-15.8
400	9583	79.6	0.028	-15.6
405	9792	79.8	0.029	-15.4
410	10000	80.0	0.030	-15.2
415	10208	80.2	0.031	-15.0
420	10417	80.4	0.033	-14.9
425	10625	80.5	0.034	-14.7
430	10833	80.7	0.035	-14.5
435	11042	80.9	0.037	-14.4
440	11250	81.0	0.038	-14.2
445	11458	81.2	0.039	-14.0

450	11667	81.3	0.041	-13.9
455	11875	81.5	0.042	-13.7
460	12083	81.6	0.044	-13.6
465	12292	81.8	0.045	-13.4
470	12500	81.9	0.047	-13.3

The Relationship Between Measured Receiver Power and Radiated Power

If one restricts the units of measurement to received power and radiated power, then the relationship between received to transmitted power is well known. It is the basis for space-loss calculations in communication systems.

Starting with the power density at a distance, R (Equation 1), the power received by an antenna at this distance is simply the power density multiplied by the *effective area* of the receive antenna. The effective area of an antenna is defined by Equation 6.

$$A_{eff} = G\lambda^2 / 4\pi \qquad \text{Eq 6}$$

The quantity, λ, is the wavelength of the transmission. Multiplying the density in Equation 1 by the effective area of the receive antenna leads to the familiar free-space-loss equation.

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \qquad \text{Eq 7}$$

Equation 7 says that if the receive antenna gain is near unity (which is the case for a small antenna like a quarter-wave stub), the power loss at 3 meters for a transmission at about 300MHz (corresponding to a 1-meter wavelength) is approximately $(1/12\pi)^2$, or 31.5dB for a receiving antenna with unity gain. Although this value will probably vary from 25dB to 35dB, depending on the gain of the receiving antenna, this is a good first check of the transmitter, antennas, and test setup. If, for example, one expects an RKE transmitter circuit board to radiate -20dBm of power, then one should see somewhat less than -50dBm of power on a spectrum analyzer connected to a receive antenna with approximately unity gain, placed 3 meters away.

The Relationship Between Measured Receiver Voltage and Radiated Power

In many measurements intended to demonstrate compliance with FCC regulations, the receiver measures the RF voltage at the measurement antenna rather than the power. This happens because the FCC wants field-strength measurements, not EIRP. Because the units of field strength are volts/meter (or mV/meter or µV/meter), converting a voltage measurement to volts/meter through a calibration constant is intuitively easier.

Receive antennas manufactured primarily for measuring electromagnetic compliance have a calibration constant in units of 1/(meters). (We will discuss the meaning and derivation of this calibration constant below.) It is, thus, important that we show how the voltage measurement relates to the EIRP. When the receiver picks up the power from the antenna, the power becomes a voltage across a load resistor, Z_0, which is usually 50Ω. Relating the receive voltage to the receive power by Equation 8,

$$V_R^2 = P_R Z_0 \qquad \text{Eq 8}$$

and substituting this into Equation 7, yields an expression (Equation 9) for the received voltage in terms of the EIRP.

$$V_R = \frac{\lambda}{4\pi R} \sqrt{P_T G_T Z_0 G_R} \qquad \text{Eq 9}$$

The Relationship Between Measured Receiver Voltage and Field Strength

Relating the received power, and ultimately the received voltage, to field strength can be done by using the approach shown in Equations 6 and 7. The power density is multiplied by the effective area of the receive antenna. The only difference in Equation 10 is that the power density is now expressed in terms of the field strength, E, as in Equation 2.

$$P_R = (E^2 / \eta_0) A_{eff} = (E^2 / \eta_0) G_R \lambda^2 / 4\pi \qquad \text{Eq 10}$$

Remembering that P_R is related to the received voltage by Equation 8 leads to Equation 11, which links V_R to E.

$$V_R^2 = Z_0 (E^2 / \eta_0) G_R \lambda^2 / 4\pi = \frac{Z_0 G_R}{4\pi\eta_0} E^2 \lambda^2 \qquad \text{Eq 11}$$

Taking the square root of both sides shows that the received voltage is just a coefficient times the field strength. Given that most receivers have $Z_0 = 50\Omega$ and that $\eta 0 = 120\pi\Omega$, the equation reduces to the simple result in Equation 12.

$$V_R = \lambda E \sqrt{\frac{Z_0 G_R}{4\pi\eta_0}} = \frac{\lambda E \sqrt{G_R}}{9.73} \qquad \text{Eq 12}$$

The coefficient linking the field strength, E, to the receive voltage, V_R, is usually given as the ratio of E to V_R. This is because V_R is the measured quantity and E is the quantity that is compared to the FCC requirements. Manufacturers of antennas used for field-strength measurements list this coefficient, called the Antenna Factor (AF), in their data sheets as a function of frequency.

In terms of the variables in Equation 12, the antenna factor is given below.

$$AF = E / V_R = \frac{9.73}{\lambda \sqrt{G_R}} \qquad \text{Eq 13}$$

The units in Equation 13 are either in $(\text{meters})^{-1}$ or in a dB ratio given by 20 $\log_{10}$ [volts/meter)/volts]. The antenna gain is expressed in terms of the power gain, so a 6dB antenna gain is a factor of 4, and a 10dB antenna gain is a factor of 10, etc. If the wavelength is 1 meter (300MHz frequency) and the antenna gain is 6dB, then the AF in Equation 13 is 4.87 $(\text{meters})^{-1}$, which would be 13.6dB $(\text{meters})^{-1}$.

One of the most commonly used receiving antennas for field-strength measurements is a Log-Periodic Antenna (LPA) with a gain that is independent of frequency over its intended measurement range. This means that its AF increases linearly with frequency. A typical LPA, the TDK RF Solutions Model PLP-3003, has an AF of 14.2dB at 300MHz, or 5.1 meters^{-1}. Its AF vs. frequency is shown in **Figure 1**. Following Equation 13, the gain of this antenna is 5.6dB at 300MHz.

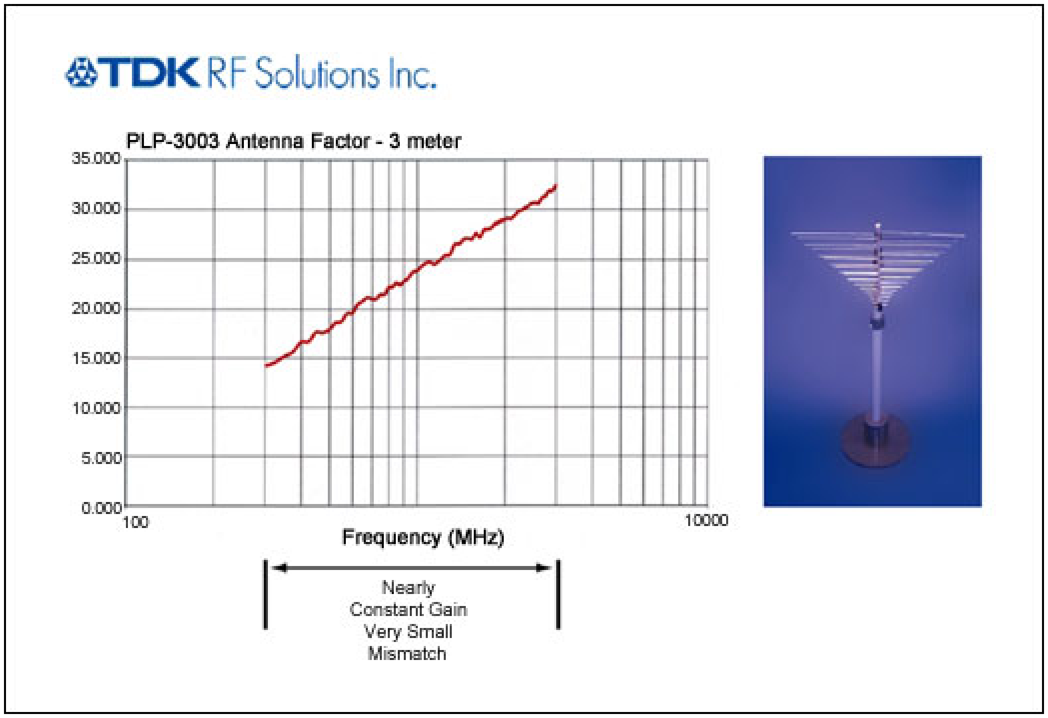

Figure 1. Antenna Factor (AF) vs. frequency of a typical measurement antenna.

If we apply the information from Equation 13 and Figure 1 to the FCC average field-strength limit of 5417μV/meter at 300MHz, we would expect to see 1056μV measured at a 50Ω input receiver. Expressing this in dB, the 74.7dBμV/m field strength in the FCC limits would appear as 60.5dBμV in the receiver, which corresponds to -46.5dBm of power across a 50Ω load. This result is consistent with the earlier power-loss estimate. (See above where we determine that a -20dBm EIRP signal at the source would be received at about -50dBm in a receiver.)

Voltage and Power at the Measurement Receiver

Table 2 shows the voltage that would be measured with an antenna and a 50Ω receiver in compliance with the FCC field-strength limits. The AF used in Table 2 comes from the specifications for the Log Periodic antenna in Figure 1. **Table 3** shows the power that would be measured with the same equipment. Table 3 uses the effective radiated power from a transmitter and antenna that corresponds to the field-strength limits, then applies the space loss and receive antenna gain to determine the power across a 50Ω load. The results in both tables are mutually consistent. Consequently, these tables give designers and users of short-range UHF transmitters a set of reference numbers to help determine whether they are meeting the FCC requirements and are radiating the needed power.

Practical Measurement Considerations

The tables in this application note give approximate values for measured power and voltage as a function of specifications such as field strength and EIRP. These values will vary when different measurement antennas are used. There are also several correction factors that one needs to make in the course of a measurement. Cable losses and mismatch losses must be taken into account, and they are frequency dependent. The measurement environment, especially the reflection from the ground or floor, can make a significant difference (as much as 6dB) in the measured receiver voltage. The ground reflection needs to be calibrated by using another reference antenna, usually a dipole. The polarization of the radiating antenna needs to matched as best as possible with the polarization of the measurement antenna. The directional pattern of the radiating device needs to be considered, even if the radiating antenna is electrically small (under 1/6 of a wavelength), because the package, test mount, and coaxial cable ground shields can introduce directional variation.

The field-strength numbers in these tables refer to the limits on the *average* power permitted by the FCC. Radiating a peak power level up to 20dB more than the average power limits is permitted, provided that the duration of the transmissions and the duty cycle obey some restrictions. Consequently, one needs to consider power levels that are significantly higher than those found in these tables. Because the measured values follow the field-strength limits dB for dB, adjusting the expected measurement level to ensure proper device function is not difficult. If, for instance, a product has a duty-cycle profile that permits a peak field strength at 315MHz that is 10dB higher than the FCC average field strength, then the peak field strength can now be 19.1µV/meter, or 85.6dBµV/meter. A glance at Table 2 and Table 3 indicates that the expected measured voltage and power should be in the 71dBµV and -36dBm range.

Once all these effects are measured and accommodated, then one can use the tables presented here to determine whether the transmitter is performing as designed.

Table 2. Measured Receiver Voltage as a Function of FCC Field-Strength Limits

Frequency MHz	Field Strength µV/meter	Field Strength dBµV/meter	Meas. Antenna Gain	Meas. Antenna Gain, dB	Meas. Antenna Factor, 1/meter	Meas. Antenna Factor, dB(1/m)	Meas. Recv. Voltage, µV	Meas. Recv. Voltage, dBµV
260	3750	71.5	3.6	5.6	4.4	13.0	844	58.5
265	3958	72.0	3.6	5.6	4.5	13.1	874	58.8
270	4167	72.4	3.6	5.6	4.6	13.3	903	59.1
275	4375	72.8	3.6	5.6	4.7	13.4	931	59.4
280	4583	73.2	3.6	5.6	4.8	13.6	958	59.6
285	4792	73.6	3.6	5.6	4.9	13.8	984	5939
290	5000	74.0	3.6	5.6	5.0	13.9	1009	60.1
295	5208	74.3	3.6	5.6	5.0	14.1	1033	60.3
300	5417	74.7	3.6	5.6	5.1	14.2	1056	60.5
305	5625	75.0	3.6	5.6	5.2	14.3	1079	60.7
310	5833	75.3	3.6	5.6	5.3	14.5	1101	60.8
315	6042	75.6	3.6	5.6	5.4	14.6	1122	61.0
320	6250	75.9	3.6	5.6	5.5	14.8	1143	61.2
325	6458	76.2	3.6	5.6	5.6	14.9	1163	61.3
330	6667	76.5	3.6	5.6	5.6	15.0	1182	61.5
335	6875	7637	3.6	5.6	5.7	15.2	1201	61.6
340	7083	77.0	3.6	5.6	5.8	15.3	1219	61.7
345	7292	77.3	3.6	5.6	5.9	15.4	1236	61.8
350	7500	77.5	3.6	5.6	6.0	15.5	1254	62.0
355	7708	77.7	3.6	5.6	6.1	15.7	1270	62.1

360	7917	78.0	3.6	5.6	6.2	15.8	1286	62.2
365	8125	78.2	3.6	5.6	6.2	15.9	1302	62.3
370	8333	78.4	3.6	5.6	6.3	16.0	1318	62.4
375	8542	78.6	3.6	5.6	6.4	16.1	1333	62.5
380	8750	78.8	3.6	5.6	6.5	16.3	1347	62.6
385	8958	79.0	3.6	5.6	6.6	16.4	1361	62.7
390	9167	79.2	3.6	5.6	6.7	16.5	1378	62.8
395	9375	79.4	3.6	5.6	6.8	16.6	1388	62.9
400	9583	79.6	3.6	5.6	6.8	16.7	1402	62.9
405	9792	79.8	3.6	5.6	6.9	16.8	1414	63.0
410	10000	80.0	3.6	5.6	7.0	16.9	1427	63.1
415	10208	80.2	3.6	5.6	7.1	17.0	1439	63.2
420	10417	80.4	3.6	5.6	7.2	17.1	1451	63.2
425	10625	80.5	3.6	5.6	7.3	17.2	1463	63.3
430	10833	80.7	3.6	5.6	7.4	17.3	1474	63.4
435	11042	80.9	3.6	5.6	7.4	17.4	1485	63.4
440	11250	81.0	3.6	5.6	7.5	17.5	1496	63.5
445	11458	81.2	3.6	5.6	7.6	17.6	1506	63.6
450	11667	81.3	3.6	5.6	7.7	17.7	1517	63.6
455	11875	81.5	3.6	5.6	7.8	17.8	1527	63.7
460	12083	81.6	3.6	5.6	7.9	17.9	1537	63.7
465	12292	81.8	3.6	5.6	7.9	18.0	1546	63.8
470	12500	81.9	3.6	5.6	8.0	18.1	1556	63.8

Table 3. Measured Receiver Power as a Function of EIRP

Frequency MHz	Field Strength µV/meter	EIRP mW	EIRP dBm	Meas. Antenna Gain	Meas. Antenna Gain, dB	Meas. Recv. Power, µW	Meas. Recv. Power, dBm
260	3750	0.004	-23.7	3.6	5.6	0.014	-48.5
265	3958	0.005	-23.3	3.6	5.6	0.015	-48.2
270	4167	0.005	-22.8	3.6	5.6	0.016	-47.9
275	4375	0.006	-22.4	3.6	5.6	0.017	-47.6

280	4583	0.006	-22.0	3.6	5.6	0.018	-47.4
285	4792	0.007	-21.6	3.6	5.6	0.019	-47.1
290	5000	0.007	-21.2	3.6	5.6	0.020	-46.9
295	5208	0.008	-20.9	3.6	5.6	0.021	-46.7
300	5417	0.009	-20.6	3.6	5.6	0.022	-46.5
305	5625	0.009	-20.2	3.6	5.6	0.023	-46.3
310	5833	0.010	-19.9	3.6	5.6	0.025	-46.2
315	6042	0.011	-19.6	3.6	5.6	0.025	-46.0
320	6250	0.012	-19.3	3.6	5.6	0.026	-45.8
325	6458	0.013	-19.0	3.6	5.6	0.027	-45.7
330	6667	0.013	-18.8	3.6	5.6	0.028	-45.5
335	6875	0.014	-18.5	3.6	5.6	0.029	-45.4
340	7083	0.015	-18.2	3.6	5.6	0.030	-45.3
345	7292	0.016	-18.0	3.6	5.6	0.031	-45.1
350	7500	0.017	-17.7	3.6	5.6	0.031	-45.0
355	7708	0.018	-17.5	3.6	5.6	0.032	-44.9
360	7917	0.019	-17.3	3.6	5.6	0.033	-44.8
365	8125	0.020	-17.0	3.6	5.6	0.034	-44.7
370	8333	0.021	-16.8	3.6	5.6	0.035	-44.6
375	8542	0.022	-16.6	3.6	5.6	0.035	-44.5
380	8750	0.023	-16.4	3.6	5.6	0.036	-44.4
385	8958	0.024	-16.2	3.6	5.6	0.037	-44.3
390	9167	0.025	-16.0	3.6	5.6	0.038	-44.2
395	9375	0.026	-15.8	3.6	5.6	0.039	-44.1
400	9583	0.028	-15.6	3.6	5.6	0.039	-44.1
405	9792	0.029	-15.4	3.6	5.6	0.040	-44.0
410	10000	0.030	-15.2	3.6	5.6	0.041	-43.9
415	10208	0.031	-15.0	3.6	5.6	0.041	-43.8
420	10417	0.033	-14.9	3.6	5.6	0.042	-43.8
425	10625	0.034	-14.7	3.6	5.6	0.043	-43.7
430	10833	0.035	-14.5	3.6	5.6	0.043	-43.6

435	11042	0.037	-14.4	3.6	5.6	0.044	-43.6
440	11250	0.038	-14.2	3.6	5.6	0.045	-43.5
445	11458	0.039	-14.0	3.6	5.6	0.045	-43.4
450	11667	0.041	-13.9	3.6	5.6	0.046	-43.4
455	11875	0.042	-13.7	3.6	5.6	0.047	-43.3
460	12083	0.044	-13.6	3.6	5.6	0.047	-43.3
465	12292	0.045	-13.4	3.6	5.6	0.048	-43.2
470	12500	0.047	-13.3	3.6	5.6	0.048	-43.2

The article was published in the November 2006 issue of *High Frequency Magazine*.

Related Parts		
MAX1472	300MHz-to-450MHz Low-Power, Crystal-Based ASK Transmitter	Free Samples
MAX1479	300MHz to 450MHz Low-Power, Crystal-Based +10dBm ASK/FSK Transmitter	Free Samples
MAX7030	Low-Cost, 315MHz and 433.92MHz ASK Transceiver with Fractional-N PLL	Free Samples
MAX7031	Low-Cost, 308MHz, 315MHz, and 433.92MHz FSK Transceiver with Fractional-N PLL	Free Samples
MAX7032	Low-Cost, Crystal-Based, Programmable, ASK/FSK Transceiver with Fractional-N PLL	Free Samples
MAX7044	300MHz to 450MHz High-Efficiency, Crystal-Based +13dBm ASK Transmitter	Free Samples