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TUTORIAL 5436

Getting Started with a Radio Design

By: Martin Stoehr, Principal Member of the Technical Staff, Applications
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Abstract: The process of designing a radio system can be complex and often involves many project tradeoffs. With a little insight, balancing these various characteristics can make the job of designing a radio system easier. This tutorial explores these tradeoffs and provides details to consider for various radio applications. With a focus on the industrial, scientific, medical (ISM) bands, the subjects of frequency selection, one-way versus two-way systems, modulation techniques, cost, antenna options, power-supply influences, effects on range, and protocol selection are explored.

A similar version of this article appeared on *Electronic Design*, December 21, 2012.

Click here for an overview of the wireless components used in a typical radio transceiver.

Selecting the Right Frequency

Why would a designer want to operate in the 868MHz/915MHz band rather than the 433.92MHz part of the spectrum? In other words, how do you choose which frequency to use? The answer is affected by two primary considerations: either the application has a traditional and/or predefined band in which it operates, or the designer must balance the tradeoffs of each parameter in the design to make the best band selection (**Figure 1**).

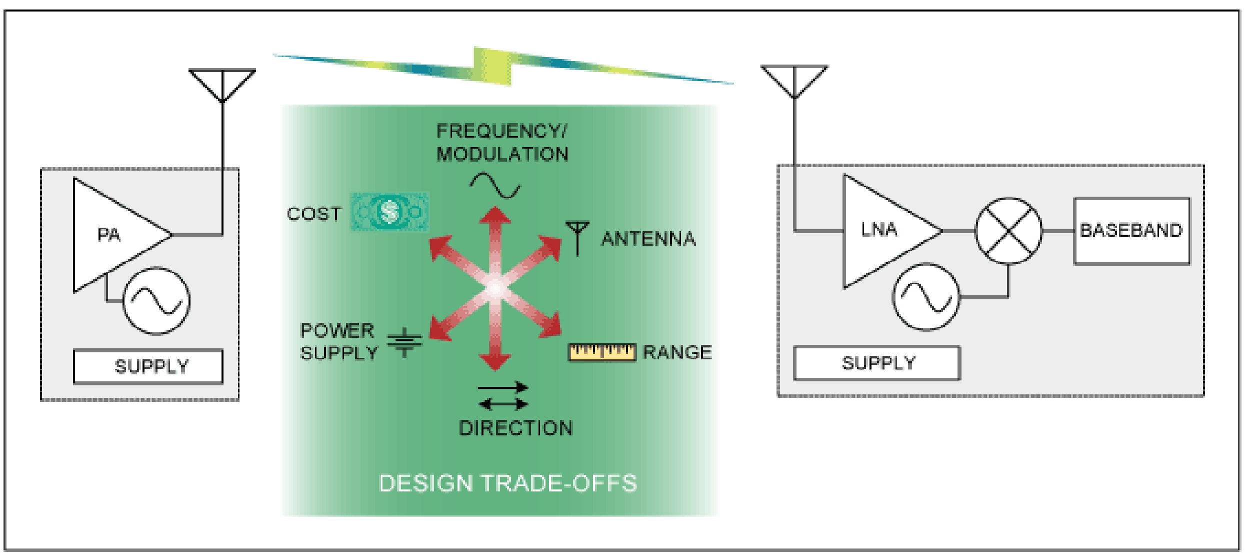

Figure 1. Common radio design trade-offs.

Commonly the most important parameter of a new design is meeting a targeted range for the system. The answer to "which band is a better choice" would be simplified if the application had an unrestricted antenna size and placement, if the distance between radios were clear from obstructions, and if the unit were wired to line voltage supplies. If however, the application is a consumer product that must have an unexposed antenna, if its signal must penetrate walls in a home, and its system needs to run for several years off of a coin cell battery, these tradeoffs become more important.

In general, the lower-frequency bands provide better range capabilities and are less dependent on line-of-sight (LOS) communication, but in practice the other impacts tend to dominate the ultimate range obtained by the system. Parameters such as the antenna size and radiation pattern, true operating environment (fewer obstructions versus worst-case planning), and the noise impact from the application surroundings tend to have the greatest influence on the actual range of the system.

What about output power in these bands? How does that limit aspects like range or harmonics? The transmitter power can help compensate for other deficiencies in the system. However, this must be balanced by the restrictions imposed by regulating authorities. It is very common to push the limits of the transmitter to make up for losses and inefficiencies in the antenna and matching system.

To further explore path loss in RKE systems, refer to application note 3945, "Path Loss in Remote Keyless Entry Systems." To help estimate and plan the range of a system (link budget), refer to application note 5142, "Radio Link-Budget Calculations for ISM-RF Products," and its related Link Budget Spreadsheet.

One-Way and Two-Way Systems

There still exists a broad range of applications that only require a one-way communication system. For example, actions like unlocking a car door or opening the window blinds in a house do not require any form of wireless feedback. Because of this, there will always be a need for simple, cost-effective, one-way wireless communication.

Although a single-direction form of communication will likely always find a market, the need for monitoring, feedback, status display, and other user interactions is increasing. Thus the one-way system may trend to a full transceiver arrangement. For example, in a remote keyless entry system, the user may want to make sure their vehicle is locked; or in the case of adjusting the window blinds in a house, the user may want to know what the air temperature is at the window. These are both examples of a simple one-way technology which could migrate to a two-way application.

Modulation

There are many styles of modulation from which to select in the ISM bands. Designers tend to gravitate toward ASK in the low bands (< 470MHz portion of the IEEE® UHF band) due to its ease of use and because the hardware tends to be less expensive. Alternatively, FSK got a start in the low band with tire-pressure-monitoring system (TPMS) applications; it was found to be less prone to the detrimental effects of the application environment (a rotating tire in a wheel well tends to cause amplitude modulation (AM)). Any form of AM uses a linear demodulation method, so a good deal of noise gets through the system, while an FM system has better signal-to-noise ratio (SNR) with wider modulation (200kHz on a standard FM channel). However, FM loses carrier lock quickly beyond a certain sensitivity threshold (waterfall).

FSK is used more prominently in the high band (> 470MHz portion of the IEEE UHF band) because of the need to meet tighter regulatory specifications. Running a frequency-base form of modulation allows the transmitter to operate as a CW signal, which cuts back on the kicking effects suffered from turning a PA on and off (ASK or OOK). Upper frequency bands (> 1GHz, commonly L-, S-, and C-Bands as defined by IEEE) tend to use more sophisticated methods of modulation, mostly due to the overcrowding at those frequencies. This in turn necessitates better co-channel interference rejection.

Cost

Another driving force in ISM radio system design is the need for inexpensive yet reliable operation. Most of Maxim's portfolio of ISM radios available provides small integrated devices with few peripheral components and relatively small footprints. Available transmitters tend to be very simple—low pin-count circuits that require only rudimentary interfacing for the data to be transmitted, plus some minor impedance matching components and common decoupling capacitors. Likewise, the receivers tend to keep the bill of material (BOM) component counts low, while still allowing enough flexibility for the system designer to make adjustments to meet the needs of a particular application. Printed circuit board (PCB) costs are reduced with small footprint ICs, small BOMs, and no special requirements for more than two-layer stack-ups. Beyond the board and peripheral component cost, the only other external components needed are an antenna and a battery (for non-line-voltage systems).

Antenna

An antenna's physical properties, such as type, size, shape, and orientation, can have a great impact on the design and effectiveness of a system. Since form factor can be a major constraint in any ISM application, these properties may dictate what frequency band is chosen and ultimately, which radio is used.

Antennas take many forms, from simple 1/4λ monopoles and 1/2λ dipoles, to loop, F, and others. They can also be categorized as E-field or M-field, depending on which form of current model they utilize. Antenna design can be an art form unto itself. The first step in selecting an antenna is to determine the largest dimensional length permitted within constraints of the application and whether to use a "trace" or a physically attached antenna. **Table 1** provides relevant antenna geometries based on the band of interest:

Table 1. Antenna Geometries

f (MHz)	λ (m)	λ/4 (cm)	λ/4 on FR4 (cm)	Aperture Size (cm^2)	Reactive Near Field (cm)	Far Field (m)
260	1.153	28.83	16.72	1058	18.35	2.31
300	0.9993	24.98	14.49	795	15.90	2.00
315	0.9517	23.79	13.80	721	15.15	1.90
330	0.9085	22.71	13.17	657	14.46	1.82
434	0.6907	17.27	10.02	380	10.99	1.38
435	0.6892	17.23	9.99	378	10.97	1.38
470	0.6379	15.95	9.25	324	10.15	1.28
[868]	0.3454	8.63	5.01	95	5.50	0.691
902	0.3324	8.31	4.82	88	5.29	0.665
915	0.3276	8.19	4.75	85	5.21	0.655
928	0.3231	8.08	4.68	83	5.14	0.646

Trace antennas on FR4 "shrink" by 0.58 due to the board dielectric, reactive near field is calculated as $\lambda/2\pi$, far field is 2λ, and aperture is for a lossless isotropic antenna $\lambda^2/4\pi$.

Based on Table 1, it should be apparent that smaller antennas can be used efficiently in the higher frequency bands. However, there is an upper limit to this process: as the physical size of the antenna shrinks, so too does the aperture. A smaller aperture results in less energy being transferred from the antenna to the environment and vice versa.

Some basic tips to keep in mind when selecting an antenna design:

- The dielectric material of a board will shorten the effective length of a trace antenna.
- Loop antennas generate a magnetic field while other "aerial" antennas generate an electric field.
- Magnetic antennas (loops) are less susceptible to the near-field environment (such as a user's hand on a remote control).
- The antenna's ground plane (counterpoise) distance and orientation can greatly impact the radiation pattern.

For a deeper discussion of ISM antennas, refer to application note 3401, "Matching Maxim's 300MHz to 450MHz Transmitters to Small Loop Antennas," application note 3621, "Small Loop Antennas: Part 1 - Simulations and Applied Theory," and application note 4302, "Small Antennas for 300MHz to 450MHz Transmitters."

Power Supply

The methods and sources of powering the radio system can be as numerous as the applications in which they are designed. Common supplies include AC line voltage, car batteries (12V) and 5V automotive buses, lithium batteries (3V), multicell alkaline batteries (1.5V), rechargeable cells (1.2V), energy-harvested sources, and more. In most cases, the transmitter is run from one source and the receiver from another (such as lithium cell in the TX, and 5V automotive bus for the RX). With these configurations, the most common power-supply tradeoff is battery life in a transmitter (or transceiver) versus the output power of the PA. When focusing on batteries, it is recommended to use both highly efficient transmitter and receiver circuits, along with a well-disciplined protocol. Battery life must be considered in all aspects of the system, such as startup time of the radio circuit, microcontroller usage, on/off duty cycle, PA efficiency, usable voltage levels, receiver "listen" power, and the sleep current of all circuits.

Maxim's ISM radios are some of the most efficient, lowest current drain parts on the market. **Table 2** provides a summary of the ISM transmitters' current drain:

Table 2. ISM Transmitter Current Drain

Part	Mod	315MHz TX Current (mA)	434MHz TX Current (mA)	915MHz TX Current (mA)	Sleep Current (µA)
MAX1472	ASK	9.1	9.6	—	0.005
MAX1479	ASK	6.7*	7.3*	—	0.0002
	FSK	10.5*	11.4*	—	
MAX7032		< 12.5*	< 6.7	—	< 0.8
MAX7044	ASK	7.7†	8.0†	—	0.04
MAX7049	ASK	16*	16*	16*, 27‡	< 0.35
	FSK	21*	21*	21*, 41‡	
MAX7057	ASK	8.1*	8.5*	—	< 1.0
	FSK	12.2*	12.4*	—	
MAX7058	ASK	8.0*	8.3* (390MHz)	—	< 1.0
MAX7060	ASK	12.5*	14.2*	—	< 0.05
	FSK	19*	25*	—	

3.0V supply levels, 50% duty cycle for ASK, * at +10dBm, † at +13dBm, ‡ at +15dBm.

Inherently the FSK transmitters will drain more current because the signal is "always on" during a transmission (because the data is encoded in the frequency of the signal). In contrast, an ASK transmitter turns the PA on and off, so during the "off" cycle the system is not using as much current. The importance of current drain becomes more apparent when compared to the batteries that will provide the current. Each manufacturer provides information on their battery dimensions, capacities, and usage models. Common battery information is shown in **Table 3**.

Table 3. Common Battery Specifications

Battery	Technology	Nom Voltage (V)	Capacity (mAh)	Ø/Thick (mm)	Weight (g)
A27	Alkaline	12*	22	8.0/28	4.4
394	Silver Oxide	1.55	63	9.4/3.5	1.1
A312	Zinc - Air	1.4	160	7.9/0.5	3.6
CR2032	Lithium	3.0	225	20/3.2	2.9
CR2450	Lithium	3.0	620	24.5/5.0	6.8
CR3032	Lithium	3.0	500	30/3.2	6.8
CR2	Lithium	3.0	850	15.6/27.0	11
AAA	Alkaline	1.5	1000	10/44	11
AAA	NiCd	1.2	250+	10/44	9.5
AAA	NiMH	1.2	550+	10.5/44	13
9V	Alkaline	9†	550	25.5 x 16.5 x 46	46
AA	Alkaline	1.5	2500	14/50	23
AA	NiCd	1.2	600+	14/50	22.7
AA	NiMH	1.2	1500+	14.5/50	26
CGR18650	Li-Ion	3.6	2250	18.6/65	45
C	Alkaline	1.5	7+ Ah	25/49	70
D	Alkaline	1.5	16+ Ah	34/60	141
Automotive	Lead - Acid	12‡	40+ Ah	Various	Various

*button stack (12-cell), †6-cell, ‡6-cell

In addition to measuring the current draw of the circuitry, another impact on battery life is the self-discharge rate. For the types of batteries used in ISM applications, this rate is strongly linked to the technology used (**Table 4**).

Technology	Anode	Cathode	Electrolyte	Self-Discharge (%/month)
Lithium	Li	MnO_2	$LiClO_4$	< 0.08
Alkaline	Zn	MnO_2	KOH	< 0.17
Silver Oxide	Zn	Ag_2O	NaOH/KOH	< 0.17
Li-ion	$LiCoO_2$	LiC_6	Li Salt (var)	2–3
Lead - Acid	PbO_2	PbO_2	H_2SO_4	~ 6
Zinc - Air	Zn	O_2	Zn	~ 8 (exposed)
NiCd	NiOOH	Cd	KOH	15–20
NiMH	NiOOH	(var)	KOH	~ 30

Table 4. Battery Self-Discharge Rate

Lithium (Li+) batteries are the most popular for small consumer devices, due to their compact size and long life (low self-discharge). Other influences on battery selection are the peak discharge rate and the storage and usage temperature. Even though these batteries can provide stable voltages for a majority of their lifetime, each technology suffers from a form of voltage fade caused by a gradual increase of the series resistance within the cell (internal resistance (IR)). This fade is often used to specify the minimum operating voltage of a radio. However, when lithium batteries reach 90% of their nominal voltage, the remaining useful current begins to reach its limit as well.

For example, when a CR2032 battery has been used for 200mAh, the internal resistance typically doubles from the nominal value of about 15Ω to about 30Ω, while the voltage drops from 3.0V to 2.8V. There is commonly a knee around 225mAh where the IR of the battery reaches approximately 50Ω and the supply level drops to about 2.3V. By the time the capacity is drained off to 240mAh, the internal resistance can be over 120Ω, and the voltage has usually dropped below 1.8V. Thus the voltage drop is a less critical aspect of the battery life than the complete loss of current capacity.

Range

The predicted range of system is highly dependent on many factors, particularly operating frequency, transmitter output power, antenna efficiencies, and the receiver sensitivity. Obstacles, motion, and even atmospheric conditions can greatly influence the operating distance, but these are variables outside the control of a system designer. Thus, planning for worst-case environments usually limits the design options to TX power, antenna selection, and RX sensitivity.

Transmitter output power can have the biggest impact on the range of the system. Often, higher-than-permitted power is used from the PA to make up for poor antenna efficiencies, due to smaller than 1/4-wave geometries, especially in the low bands where antenna efficiencies can be less than 10% (key fob sizes). It is particularly important to stay within any regulatory requirements of the targeted region of operation. More power may be permitted if the duty cycle of the transmitter is varied according to the governing bodies.

When selecting a PA based on output power, remember:

- A higher output power requires higher supply current.
- The higher frequency bands require higher operating current (commonly due to PLL current).
- Higher output power may impact regulatory limits such as maximum radiated power, occupied bandwidth, and

harmonic power.

Table 5 summarizes Maxim's ISM transmitters' capabilities.

Table 5. ISM Transmitter Capabilities

Part	Bands (MHz)	Typical TX Power (dBm)
MAX1472	300 to 450	10
MAX1479	300 to 450	10
MAX7032	300 to 450	10
MAX7044	300 to 450	13
MAX7049	288 to 945	15 (adjustable)
MAX7057	300 to 450	10
MAX7058	315/390 (300 to 450)	10
MAX7060	280 to 450	10, 14*

All power specs are driving a 50Ω load and include the matching/harmonic filter loss.

*With 5V supply.

On the receiver side of the system, the sensitivity is the overwhelming governor of obtainable range. Similar to the transmit side, a receiver that can pick out a signal with 3dB less power may be able to compensate for a bad antenna or a poor link environment.

When selecting for a receiver's sensitivity, remember:

- Generally receivers have better sensitivity for ASK modulation.
- Receivers typically exhibit better sensitivity for lower frequencies.
- The data rate has a noticeable impact on sensitivity with much better numbers for low speeds.

Table 6 summarizes Maxim's ISM receivers' sensitivity specifications.

Table 6. ISM Receiver Sensitivity Specifications			
Part	Mod	315MHz RX Sensitivity (dBm)	434MHz RX Sensitivity (dBm)
MAX1470	ASK	-115	-110
MAX1471	ASK	-116	-115
	FSK	-109	-108
MAX1473	ASK	-118	-116
MAX7032	ASK	-114	-113
	FSK	-110	-107
MAX7033	ASK	-118	-116
MAX7034	ASK	-114	-113
MAX7036	ASK	-109	-107
MAX7042	FSK	-107	-106

All sensitivities listed as "average power." "Average carrier power" would be 3dB lower and "peak power" would be 3dB higher.

Protocols

Selecting a protocol for your application can be the final step of the system design or the starting point, depending on the application. Protocols govern how the radios will exchange information and include parameters such as telephony (analog audio) requirements, data/bit structure, encoding methods, handshaking exchange processes, and network disciplines for sharing the airwaves. There are many standard protocols to choose from and just as many proprietary forms of communication. Usually the design parameter that has the greatest impact on the protocol selection is whether a one-way or two-way system is being used. Two-way systems tend to be more complicated, due to a need to negotiate the airwaves and prevent collisions between different radio nodes.

Common Applications

Various applications tend to group into specific communication direction, frequencies, and modulation techniques due to their common requirements or limitations. **Table 7** summarizes typical usage models based on the application and provides guidance for frequencies and modulation methods commonly found in each application:

Table 7. Common Applications					
Application		Direct	Frequency	Modulation	Notes
	Remote keyless entry (RKE)	1-way	315MHz, 434MHz	ASK	After-market systems and high-end luxury automobiles are moving toward two-way communication to provide feedback to the user in addition to the RKE function.

Automotive	Passive keyless entry (PKE)	2-way	125kHz, 13.56MHz	ASK	—
	Tire-pressure monitoring system (TPMS)	1-way	315MHz, 434MHz	FSK	—
	Garage-door opener (GDO)	1-way	315MHz, 390MHz	ASK	The U.S. Military uses 390MHz in certain locations; as such 315MHz is used to cover those areas
	Electronic toll collection (ETC) and automatic vehicle identification (AVI)	1-way	—	—	—
	Wireless OBDII	1-way	315MHz, 434MHz	ASK	Monitor maintenance conditions, driving habits, etc.
Automatic meter reading (AMR)	Water meter	1-way	470MHz, 868MHz, 915MHz	FSK	AMR is a growing field of automation for large utilities and the meter-manufacturing industry. It is a subset of sensor networks (HAN, NAN, mesh network), collector/concentrator structures, etc.
	Gas meter	1-way	868MHz, 915MHz	FSK	—
	Electric meter	2-way	868MHz, 915MHz	FSK	Occasionally designed as the "collector" for a home area network (HAN)
Home automation (HA)	Wireless remote control	1-way	434MHz	ASK, FSK	IR replacement, AV systems, set-top boxes, multiroom controls, wireless data streaming (control channel)
	Lighting	1-way	390MHz, 418MHz, 434MHz	ASK	Mood lighting, coordinated with AV
	Motor control	1-way	434MHz	ASK	Projector screens, blinds/shades, coordinated with HVAC
	Security/fire	1-way 2-way	345MHz, 434MHz	ASK	—
	GDO	1-way	315MHz, 390MHz	ASK	Gate opener, driveway security

	Heat allocation	1-way	—	—	—
	Energy management	2-way	—	—	Programmable thermostats, watt-meter displays
	Home weather stations	1-way	—	—	Remote sensing
RFID	Product tracking	2-way	915MHz, 2.45GHz, 5.8GHz	ASK, FSK, BPSK	—
	Rail trucking	2-way	915MHz, 2.45GHz, 5.8GHz	ASK, FSK, BPSK	—
Wireless networking	Bluetooth LE	2-way	2.45GHz	FHSS	IEEE 802.15.1
	Wi-Fi	2-way	2.45GHz, 5GHz	DSSS, FHSS, OFDM	IEEE 802.11
Wildlife tracking	Land/aquatic/air	1-way	410MHz	PSK	ARGOS satellite system

Tradeoffs

Each application, market, and design will be different and thus each will have different priorities. **Table 8** summarizes the various tradeoffs encountered by ISM radio system designers and provides suggestions for operating bands and modulation.

Table 8. Operating Band Tradeoffs

Priority	Band	Modulation	Reasoning	Tradeoffs
Range	Lower, mid	ASK	Assuming a large antenna, lower frequencies allow for better RX sensitivity. ASK commonly has better RX sensitivity than FSK. Midband regulation allows for more radiated TX power.	Cost, battery life, size, simplicity, DR, IR
Cost	Lower	ASK	Small and simple circuits. ASK is a preferred modulation for a simple TX. ASK RX chips tend to require the fewest peripheral components.	Range, battery life, DR, IR, tolerance
Battery life	Lower	ASK	Lower current drain at lower operating frequencies for both the TX and RX provide longer life from a limited source. ASK only requires a duty cycle % versus constant transmissions for FSK.	Range, cost, LOS, simplicity, DR, IR
Size	Mid	—	If size includes the antenna, then the 868MHz/915MHz bands are the best target because small antennas can be used with reasonable aperture sizes and electrical lengths. If there is no restriction on the	Range, LOS

			antenna, then refer to the "Cost" priority.	
Line-of-sight (LOS)/obstacles	Lower	FSK	Lower frequencies penetrate obstacles, bend around objects more easily, and suffer less absorption than higher frequencies. FSK is less influenced by multipath and possible amplitude changes caused by motion (TPMS example).	Battery life, size
Simplicity	Lower	ASK	ASK is an easier and more tolerant modulation scheme to handle. Larger wavelengths (lower frequencies) are less influenced by board and component sizes.	Range, battery life, DR, IR, tolerance
Data rate (DR)	Higher	FSK, PSK spread spectrum	Higher data rates will require wider bandwidths for operation and the regulatory requirements are easier in the higher bands. High data rate, spread spectrum, and the high bands all require more operating current. Smaller aperture and wider bandwidth negatively impacts the range.	Range, cost, battery life, simplicity
Interference rejection (IR)	Mid, Higher	Spread spectrum	Spread-spectrum modulation rejects carriers and other interference very well. The wider bandwidths needed for operation are available in the higher bands.	Range, cost, battery life, simplicity
Frequency tolerance	Lower	—	More important at higher bands. Narrower IF filters will provide better sensitivity and longer range. Absolute frequency accuracy is easier to obtain at lower bands. TCXOs are more expensive than standard crystals.	Cost, simplicity

Guidelines

All ISM radio products offered by Maxim include a good typical application circuit in the product data sheet. These circuits provide a nice place to start for the design of a system. When building up a schematic for transmitters, typically the only other components necessary are a microcontroller or simple encoder interface, an antenna matching network, and some form of power supply. For the receivers, a number of tuned circuits will have to be configured for the frequency of interest and data rate, in addition to the microcontroller or decoder interface and the power-supply system. Once the schematic is ready, keep in mind that most of the design problems encountered in RF systems can be traced back to a bad PCB layout. Reading up on the most common critical issues to avoid in PCB layout can save some time in the testing and debug phases of system development. Refer to tutorials 4636, "Avoid PC-Layout 'Gotchas' in ISM-RF Products" and 5100, "General Layout Guidelines for RF and Mixed-Signal PCBs" for more information.

For Maxim's ISM transmitters be sure to consult these application notes:

Application note 1954, "Designing Output-Matching Networks for the MAX1472 ASK Transmitter"

Application note 3401, "Matching Maxim's 300MHz to 450MHz Transmitters to Small Loop Antennas"

For Maxim's ISM receivers, refer to these application notes:

Application note 1017, "How to Choose a Quartz Crystal Oscillator for the MAX1470 Superheterodyne Receiver"

Application note 1830, "How to Tune and Antenna Match the MAX1470 Circuit"

Application note 3671, "Data Slicing Techniques for UHF ASK Receivers"

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Related Parts		
MAX1470	315MHz Low-Power, +3V Superheterodyne Receiver	Free Samples
MAX1471	315MHz/434MHz Low-Power, 3V/5V ASK/FSK Superheterodyne Receiver	Free Samples
MAX1472	300MHz-to-450MHz Low-Power, Crystal-Based ASK Transmitter	Free Samples
MAX1473	315MHz/433MHz ASK Superheterodyne Receiver with Extended Dynamic Range	Free Samples
MAX1479	300MHz to 450MHz Low-Power, Crystal-Based +10dBm ASK/FSK Transmitter	Free Samples
MAX7032	Low-Cost, Crystal-Based, Programmable, ASK/FSK Transceiver with Fractional-N PLL	Free Samples
MAX7033	315MHz/433MHz ASK Superheterodyne Receiver with AGC Lock	Free Samples
MAX7034	315MHz/434MHz ASK Superheterodyne Receiver	Free Samples
MAX7036	300MHz to 450MHz ASK Receiver with Internal IF Filter	Free Samples
MAX7042	308MHz/315MHz/418MHz/433.92MHz Low-Power, FSK Superheterodyne Receiver	Free Samples
MAX7044	300MHz to 450MHz High-Efficiency, Crystal-Based +13dBm ASK Transmitter	Free Samples
MAX7049	High-Performance, 288MHz to 945MHz ASK/FSK ISM Transmitter	Free Samples
MAX7057	300MHz to 450MHz Frequency-Programmable ASK/FSK Transmitter	Free Samples
MAX7058	315MHz/390MHz Dual-Frequency ASK Transmitter	Free Samples
MAX7060	280MHz to 450MHz Programmable ASK/FSK Transmitter	Free Samples