

## Designing an FCC Approved ASK rfPIC™ Transmitter

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### INTRODUCTION

This application note describes the design of a Federal Communications Commission (FCC) compliant board layout to give new radio frequency (RF) designers a head start using rfPIC transmitters such as the rfHCS362 and the rfPIC12C509A. It guides users through the how-to of a typical design process covering definition, design, testing, reiterations, regulatory approval and manufacturing. While focused on meeting requirements in the United States, the RF explanations are universal.

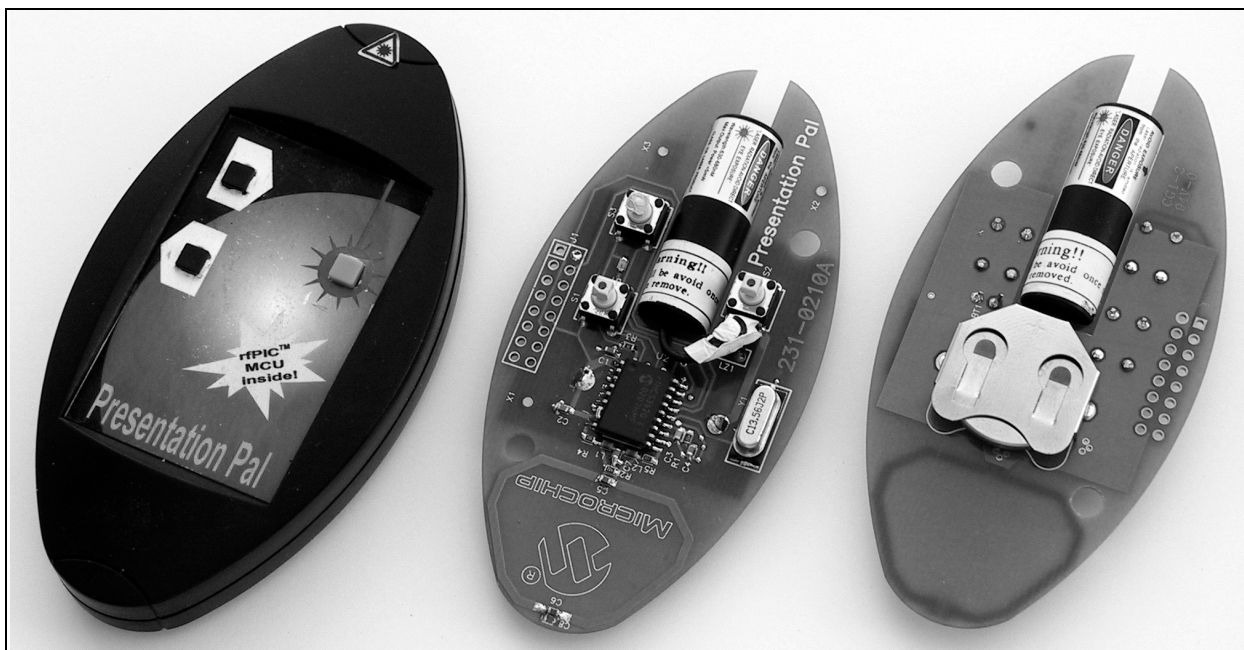
Designing your first RF transmitter is a new challenge for most embedded microcontroller gurus. While this application note cannot replace experience, it should make your first experiences less intimidating. Completely understanding RF is complex, so the key is to learn what level of detail is enough to accomplish your task.

Ohms Law still applies, but some of the electrical complexities that were conveniently simplified out at low frequencies can no longer be ignored. For example, every component becomes a network of capacitance, inductance and resistance. At low frequencies one of these elements may dominate, like a capacitor appearing mostly capacitive. As the frequency increases another may dominate, like trace or lead inductance on a capacitor.

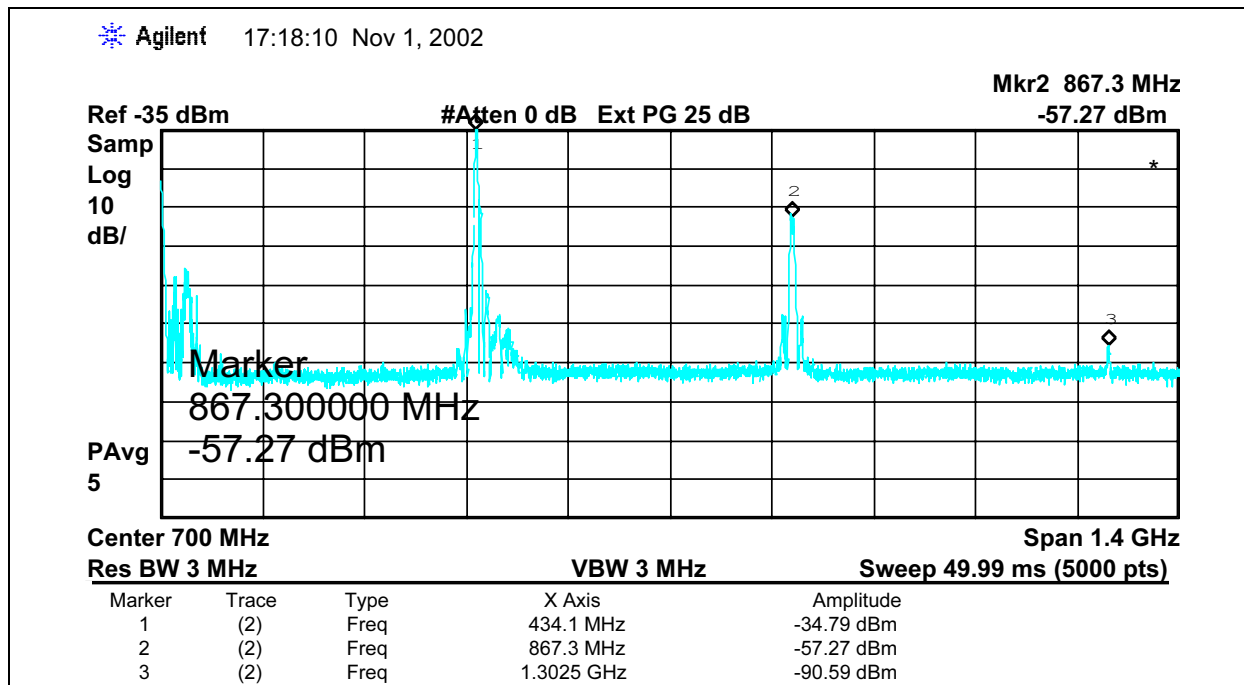
As frequencies increase, the PCB traces become better radiators, which is what we want for a transmitter antenna. The side effect is that all the traces become better antennas and the reciprocity theorem of antennas means they receive just as well as they transmit. The result is that every trace can radiate and receive noise more easily at higher frequencies. Care must be taken so that undesirable frequencies are not transmitted and sensitive nodes are filtered or shielded.

Every trace or path that current may take through a component has an associated inductance. At high frequencies this inductance has a considerable influence on the circuit. The rule of thumb is that every inch of a 40 mil wide trace is about 20 nH, or 8 nH per centimeter of a 1mm wide trace. Making the traces 4 times wider only reduces inductance to half the original, so it is much more effective to shorten traces instead of widening them.

**FIGURE 1: PICTURES OF THE COMPLETED 433 MHZ “NO TUNE” TRANSMITTER**



**FIGURE 2: SPECTRAL PLOT OF FUNDAMENTAL AND HARMONICS**



Every current must have a return path to complete the circuit. The amount of radiated power is proportional to the frequency and area of the loop that the current travels. Intentional radiators should have large loop areas while all other loops should have the smallest cross sectional area possible. Keep tracks short and directly above a ground plane because the return current in the ground plane will try to stay as close as possible under the signal trace. Breaks in the ground plane under the signal trace force the return current to take another path and increase the loop area.

Having a ground plane under a trace creates a capacitor through the PCB. The capacitance can vary widely with circuit board material, temperature, humidity and manufacturing processes. A good approximation for 0.031 inch or 0.79 mm thick FR4 circuit board is about 32 pF per square inch or 5 pF per square centimeter of copper.

With all these parasitic capacitors and inductors on the circuit it becomes important to understand resonance. At a circuit's resonant frequency the capacitance is equal magnitude to the inductance, thus they cancel each other out leaving only a resistance.

The ratio of the capacitive or inductive impedance to the effective series resistance is called Q and  $Q = X/R$ . A higher Q means a narrow range of resonance which makes the circuit a sharper filter but more susceptible to frequency shifting from component tolerances and environmental disturbances. The lower series resistance of a high Q antenna circuit also reduces resistive losses to make a more efficient radiator.

Some terminology that is important is the desired fundamental or carrier frequency and the unwanted spurious frequencies. Spurious frequencies are usually harmonics and clock spurs. Harmonics are due to nonlinearities and clock spurs caused by intermodulation. Figure 2 shows a typical plot of these frequencies from a spectrum analyzer. The fundamental at marker 1 is modulated and the antenna is likely not perfectly tuned because the upper side band is stronger. The second harmonic at marker 2 clearly shows two clock spurs. Clock spurs are the spurs that appear at multiples of the clock frequency above and below the carrier frequency. Phase noise or jitter can make spurs wide enough to fail spurious limits in adjacent and restricted frequencies.

Simple frequency sweeps like Figure 2 are not very useful because the antennas should have been reoriented to find the peak of each harmonic. To accomplish this the spectrum analyzer should be in max Hold mode as the transmitter is rotated through all orientations.

If turning off the transmitter does not get rid of a frequency spur like the noise below 50 MHz in Figure 2, then it is environmental and can be ignored for the rest of this application note. If the environmental noise overshadows one of the harmonic frequencies, then find and remove the noise source or relocate the test setup.

With these basic RF concepts you should be able to make full use of this application note and even improve the design for better results. For more detailed RF information and explanations check out the good books and articles referenced in the Additional Information section.

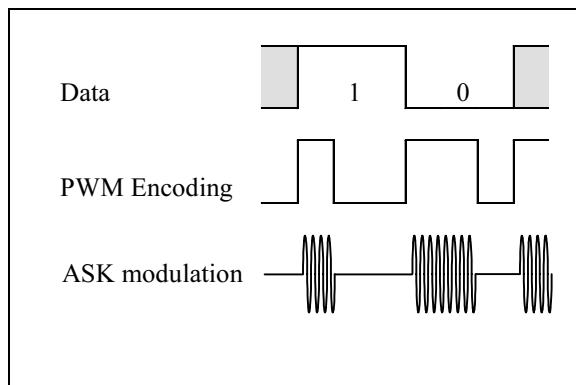
## PLANNING THE DESIGN

Every great design should start with an equally great plan. This design effort will produce a presentation remote control with a built in laser pointer. It must send one transmission to advance the presentation and another transmission to reverse the presentation. It will be marketed in the United States. It should fit comfortably in either the right or left hand. A coin cell battery should last for 20 hours of typical use and 12 months in standby. It should have a minimum open field range of 100 feet. It will only be used at room temperature but must survive 4 foot drops, -40 to +75°C storage, and at least 100,000 activations.

A good plan also needs a timeline with target dates for key achievements. Some of the major tasks will be researching the product details, designing the product, testing the design, design reiterations, preparation for manufacturing, and submitting the final product for FCC compliance testing. Pad the schedule with extra time on researching the product details for your first RF design since there are volumes of regulations that may apply. If you make any changes to this reference design then anticipate extra design iterations to improve output power while lowering spurious emissions.

The next step is to determine the type of modulation to use. The lowest cost options would be amplitude shift keying (ASK) or frequency shift keying (FSK). The rPIC transmitters with the F suffix can do either one. ASK is used in this example because it is a little easier to understand, design, and test. FSK would be preferable in cases where multipath noise or peak battery current, are the range limiting factors.

**FIGURE 3: PWM WITH ASK MODULATION**



The data bits could be sent directly, but it would be difficult for the receiver to synchronize to the data and accurately receive long streams of zeros or ones. To solve this problem we encode the bits with a pattern that ensures frequent level transitions. There are many commonly used patterns of which the most common in this type of application are pulse width modulation (PWM) and Manchester encoding. Both require relatively simple firmware to encode and decode. This example will use PWM encoding because it is easier to

decode visually on the oscilloscope although it does need 50% more bandwidth or longer transmit times than Manchester.

There are other details to research and define for your product such as encryption and error correction. There are references at the end of the application note to help you understand these technologies and choose the best options for your product. Source code for these potential features like encryption and decoding are also available in other Microchip application notes.

## REGULATORY REQUIREMENTS

The FCC requires that an acceptable test site verify the emissions of your final packaged product. The FCC must certify the test report submitted with a unique ID. This ID must be displayed on your product and customers can use it to view the conformance report on the web at:

<http://www.fcc.gov/oet/fccid/>

Try the above web site with an FCC ID from a device similar to what you plan to create to get an idea what is required. The first 3 characters are the manufacturer's code as given by the FCC and the remaining 1-14 characters are your product code.

Early in the project it will be important to search for a company that can provide the compliance testing you are looking for. Do it early because these companies may already have months of work scheduled. Compare the companies by their fees, schedules, proximity, and the level of technical help or consulting they can provide. The FCC maintains a list of contract test firms on the web at:

<http://www.fcc.gov/oet/info/database/testsite/>

The key piece of information in this plan is the target market. This will not only tell what customers to research but also where to look for the rules that may regulate our device. Regulations are important to make sure that a limited resource like radio spectrum is used efficiently and that interference between products is minimized. The FCC regulations in the USA are very different from the ETSI regulations in Europe, which is quite different from the ARIB regulations in Japan. Most other countries draft their standards to be generally compatible with one of these three examples.

- Federal Communications Commission (FCC - Part 15) <http://www.fcc.gov/>
- European Telecommunications Standards Institute (ETSI - EN 300 220) <http://www.etsi.org/>
- Association of Radio Industries and Businesses (ARIB - STD T67) <http://www.arib.or.jp/>

For example, the Canadian regulation RSS-210 is very similar to the FCC regulations. Adding Canadian certification is the only step required before marketing this product in Canada. More information on Canadian regulations is available at:

<http://strategis.ic.gc.ca/SSG/sf01375e.html>

The FCC also lists the regulatory bodies for other countries on this web page:

<http://www.fcc.gov/mb/audio/bickel/world-govt-tele-com.html>

The FCC part 15 rules can be downloaded from:

<http://www.fcc.gov/oet/info/rules/>

Examining the FCC regulations reveals that there is a control and security frequency band in part 15.231 that can be used for this type of remote control device as long as it is not a toy. After also examining the European regulations we find there is a small frequency range common to most of the world regulations from 433.05 – 434.79 MHz. By staying in this range we can create a product that could be certified for many more markets without redesign time and costs.

Choosing 433.92 MHz is nice because it is commonly used and as a result there are many receiver modules available. Another common frequency in the United States is 315 MHz, but almost any frequency within the rfHCS362 range from 310 to 440 MHz could have been used. The FCC has restricted frequency bands that cannot be used and any harmonics that fall into these bands face much tighter limits. Figure 4 shows that only the 3rd harmonic is restricted if we use 433.92 MHz. If your design keeps failing the 3rd harmonic, you could move the fundamental down to 433.2 MHz and avoid significant harmonics from falling in any restricted bands.

The bottom of Figure 4 shows that reducing the fundamental to 433.2 MHz still avoids the potential interference from the 4th harmonic of FM radio stations and the 2nd harmonic of television channel 13. Even though these higher harmonics have much less power than the broadcast frequency, the interference will impact range for the portion of your customers that use this product near a source of constant interference.

The European regulations permit higher power transmissions than the FCC at 433.92 MHz, but they also have tighter bandwidth limits. The phase noise of most low cost transmitters prevents them from being able to use the full European power. Since the noise levels are approximately proportional to the output power level, reducing the output power can make it easier to stay below the regulation limits. To keep this product more universal it will not exceed the maximum power set by the FCC or European limits.

Under rule 15.35 the FCC permits power averaging. This means that all the maximum power levels are actually the average power of the strongest 100 millisecond window. To use this advantage we measure the peak output power at each frequency and then subtract the dB of averaging benefit. In this design the power is either on or completely off, so the average is the maximum total on time divided by 100 ms. Notice that the ID bits in the Figure 5 example calculation had to be calculated using the worst case width of 8 ms times 5 for a string of all zeros. By careful selection of manufactured ID codes you can avoid bad ID codes like '00' and improve the worst case duty cycle.

**FIGURE 4: SPECTRUM USAGE IN THE UNITED STATES**

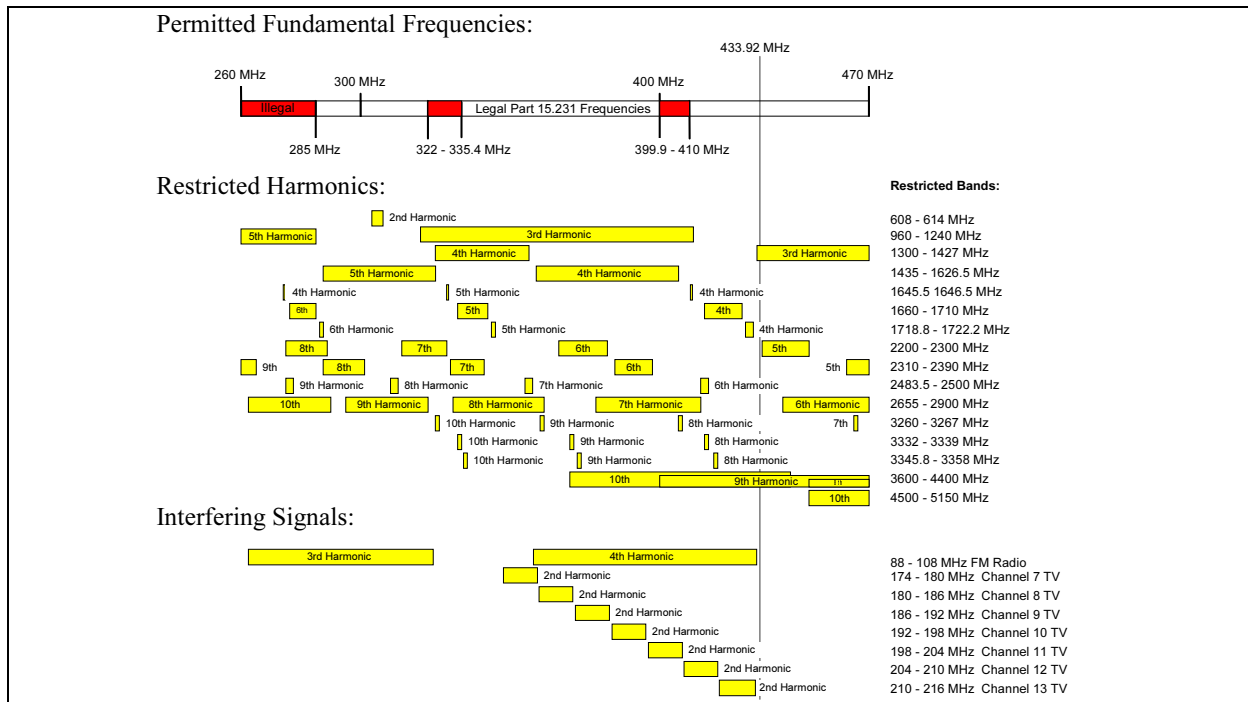
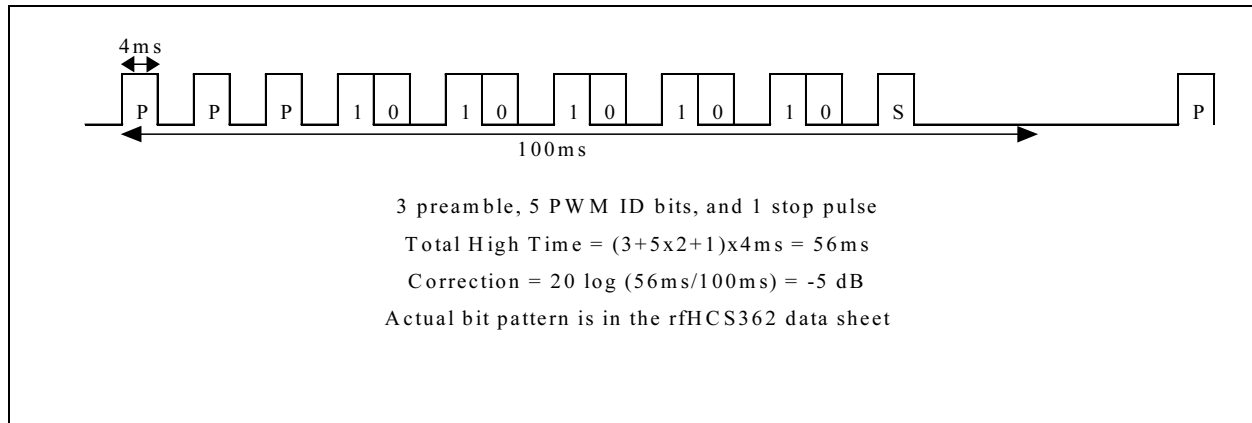


FIGURE 5: POWER AVERAGING EXAMPLE



Using PWM we must assume the worst case of a 67% on time for data bits. This could be improved to 50% with Manchester encoding or down to 33% with Pulse Position Modulation. The total on time can also be reduced with less preamble pulses, shorter transmission packets, and longer guard or blank times between repeat transmissions. However, not all these options are available on the HCS362 and some of them can make the receiver design more difficult. This example is for ASK only, but FSK can also benefit from averaging if the packet length is less than 100 ms.

The FCC limits this averaging benefit to 20 dB. With this small loop antenna this transmitter is not powerful enough to take full advantage of the extra 20 dB available on the fundamental, but the 20 dB benefit on the harmonics make it much easier to pass spurious regulation limits.

Increasing the output power above the regulation limits is not the legal way to extend your range. Instead you can choose a more sensitive receiver with a narrower bandwidth, but this will usually cost extra. There are also system level improvements that can be made to encoding patterns, adding forward error correction, and simply repeating the transmission. These ideas can greatly expand your range but achieving this application's range of 100 feet should not be too difficult.

One last issue that needs to be addressed is the FCC ID marking. Plan to list all the countries' approval ID codes somewhere permanent on the outside of the final product. It could be printed on a sticker or directly on the product, it can even be inscribed in the plastic molding. An issue that can hold up production is that you may not get the ID number from some countries until after the product is approved. In the USA, apply early for the 3 character manufacturer's code if you do not yet have one. Then append your own product code and prepare your packaging while the FCC approves the test report.

## CIRCUIT DESIGN

With a detailed plan in place, the product is ready for the first design iteration. This first iteration will firm up the design plan as it reveals missing information. The success or failures of the first prototype may even modify large portions of the plan.

This design example uses the rfHCS362 instead of the rfPIC12C509A to avoid any firmware development and concentrate on the RF portion of the design. Use the rfPIC12C509A for projects that can afford the firmware development time to create different packet structures, different encoding schemes, variable output power, or require some kind of processing before transmission. Use the rfHCS362 for projects that need unique serial numbers, non-volatile event counters, 2.2 volt operation, low battery indication, or encrypted security. Both parts can be programmed before mounting to the board or in-circuit with the Pro Mate<sup>®</sup> II programmer.

To switch to the pinout compatible rfPIC12C509A you would need to tie the switches to ground instead of VBAT. Critical applications like the microcontroller enabling the laser pointer or updating an EEPROM may require a 2.5V low battery RESET such as Microchip TC54VC25 Brown-out Reset device. The pinout may need to change for the rfPIC12C509A because not all of its pins have internal pull-up resistors for the switches and GP3 is only an input. Be sure to bring the In-Circuit Serial Programming<sup>™</sup> (ICSP<sup>™</sup>) pins out for easier manufacturing.

Firmware development is simplified by making some extra boards with an 8-pin PIC12C509A DIP socket next to the surface mount rfPIC12C509A. Connect the 8 common pins to each other in the layout. Cut the 8 common pins off the rfPIC before soldering it down. Now insert the emulator or windowed PIC12C509A in the DIP socket for development. The DIP socket can be eliminated in production. Be sure to use the final production board with the final firmware version for the final RF verification.



TABLE 1: BILL OF MATERIALS

Part	Qty	Description	Value	Part Number	Source	Price/1000
	1	Oval enclosure		OVO-2IR.9	www.teko.it	\$5.94
LZ1	1	Laser module		TIM-201-3	www.transverse.com	\$4.00
BT1	1	Lithium battery	3V	CR2032	www.digikey.com	\$0.24
	1	Battery holder		3003K	www.digikey.com	\$0.17
U1	1	RF transmitter		rfHCS362/SO	www.microchip.com	\$2.14
SW1, 2, 3	3	Switch		B3F-1052	www.digikey.com	\$0.12
	2	Switch Cap	Lt Gray	B32-1000	www.digikey.com	\$0.09
	1	Switch Cap	Red	B32-1080	www.digikey.com	\$0.09
C1, 2, 4, 7	3	Capacitor, 0603	100pF	ECJ-1VC1H101J	www.digikey.com	\$0.02
C3	1	Capacitor, 0603	12pF	ECJ-1VC1H120J	www.digikey.com	\$0.02
C5	1	Capacitor, 0603	5pF	ECJ-1VC1H050C	www.digikey.com	\$0.03
C8	1	Capacitor, 0603	4pF	ECJ-1VC1H040C	www.digikey.com	\$0.03
C6*	1	Optional Trimmer	2-10pF	JZ100	www.voltronicscorp.com	\$1.80
R1, 2	1	Resistor, 0603	4.7K ohm	ERJ-3EKF4751V	www.digikey.com	\$0.02
R3*	1	Optional Resistor	0 ohm	ERJ-3GEY0R00V	www.digikey.com	\$0.02
R4, 5	2	Resistor, 0803	100 ohm	ERJ-3EKF1000V	www.digikey.com	\$0.02
D1*	1	Optional LED	Red	160-1182-1-ND	www.digikey.com	\$0.11
L1, 2	2	Inductor, 0603	120nH	0603CS-R12SJB	www.coilcraft.com	\$0.08
Y1	1	Crystal	13.56 MHz	016877	www.crystek.com	\$0.40
J1*	1	Optional Connector	16 pin F	HLE-108-02-6-DV-TE	www.samtek.com	\$1.15
PCB	1	1 ounce FR4 gold	0.031 in			\$3.00

The output power level can be adjusted by using one of 7 voltage levels on the PS/DATAASK line. A voltage divider circuit is the simplest way to provide the programmability, but its voltage is relative to the battery level. In most cases a voltage divider will work if designed to the data sheet specification and tested over the voltage range. To tolerate wide fluctuations in the battery voltage when using lower output power levels it may be necessary to regulate the voltage. In this example the maximum power is desired so the DATA output is tied directly to the PS/DATAASK input and battery voltage is not an issue.

## ANTENNA DESIGN

Any wire can be used as an antenna, but optimizing antenna designs is an entire field of study on its own. Thankfully there are a number of proven topologies that we can choose from. Some of the most common topologies are shown in Figure 7. Smaller antennas have lower efficiency and narrower bandwidths. In the antenna world, small means about 1/10th of a wavelength, in this case:

$$\lambda / 10 = c / f / 10 = 3 \cdot 10^8 / 433.92 \text{ MHz} / 10 = 69 \text{ mm}$$

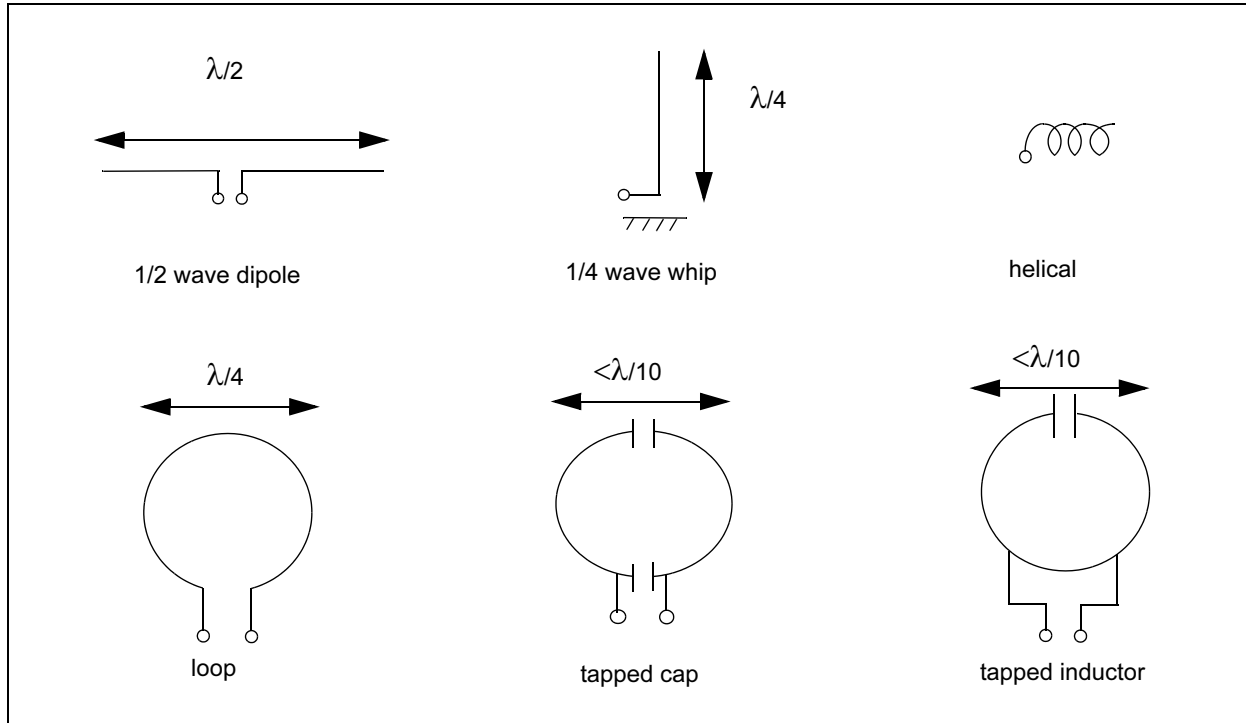
To make transmitters that do not need to be tuned in production, it is necessary to increase the bandwidth. This can easily be done by adding series resistance or reducing parallel resistance to lower the Q. Some other transmitters try to tune the antenna using on die active

circuitry. Each method has its advantages but in both cases efficiency suffers over a manually tuned antenna. Saving the production line tuning costs will typically cost about 3 dB in output power. The lost output power can be restored with stronger RF power amps or more efficient antennas. Optionally the range can be improved with a more sensitive receiver and better protocol designs.

The product packaging must be determined next since it will impose limits on the antenna size and position. Marketing desires and purchasing costs are often the largest factors in determining the final package. This means the RF designer must work closely with these groups to keep them aware of the trade-offs. Things to keep in mind are the space requirements, orientation, PCB layout issues and package material. Obviously if the package blocks RF signals it will require an external antenna. As well, imposing a smaller antenna area will reduce the communications range.

The criteria for selecting this antenna will be that it is low cost and gets close to the maximum allowed output power while preventing spurious signals from exceeding regulations. Comparing the antennas performance shows that small loop antennas have 6 to 20 dB less output power than dipoles. However, studies have also shown that if this antenna is going to be held very near the human body there will be slight advantage for the loop antennas.

**FIGURE 7: POPULAR ANTENNA CHOICES**



Since this application is almost surrounded by the hand it is an obvious choice to use one of the loop antennas. The tapped inductor antenna is well analyzed in application note AN831. However, the tapped inductor antenna has a large primary loop feeding the antenna. This primary loop can be a strong source of unwanted harmonics, so minimizing its area with the tapped capacitor antenna makes regulatory approval easier. This application note uses the tapped capacitor antenna even though it requires 3 more components and thus has a slightly higher cost.

There is an in-depth analysis of this tapped cap antenna in Radio Systems: Part 5 and 6 articles referenced in the Additional Information section. The antenna capacitors must be selected so that in series they resonate with the loop inductance at the transmit frequency. During design we find target capacitor values and loop dimensions from simulations but plan to tweak them for better performance in the testing phase. Choose initial loop dimensions that will permit the use of standard value capacitors.

There is one more resistor in the antenna circuit and it is used to reduce the Q. Since electrically small antennas have an inherently high Q, it is necessary to force it lower if you desire to avoid hand tuning every board in production. This parallel resistor value can be increased later for additional output power if there are no tuning issues.

The antenna outputs are open collectors driven 180 degrees out of phase. Tying these pins to VBAT with inductors squeezes more power out of the amplifier. Much like a DC/DC step up regulator, the energy stored

in the inductor is released as the open collector transistor turns off. The ideal value of the inductors is mostly determined by the antenna trace capacitance to ground. The inductor must resonate out the capacitance in order to deliver more output power with lower harmonics content. The 120 nH inductors are a good match for this layout, but plan to try larger and smaller values to tweak your implementations. The two inductors may end up having different values after tuning to reduce harmonic emissions.

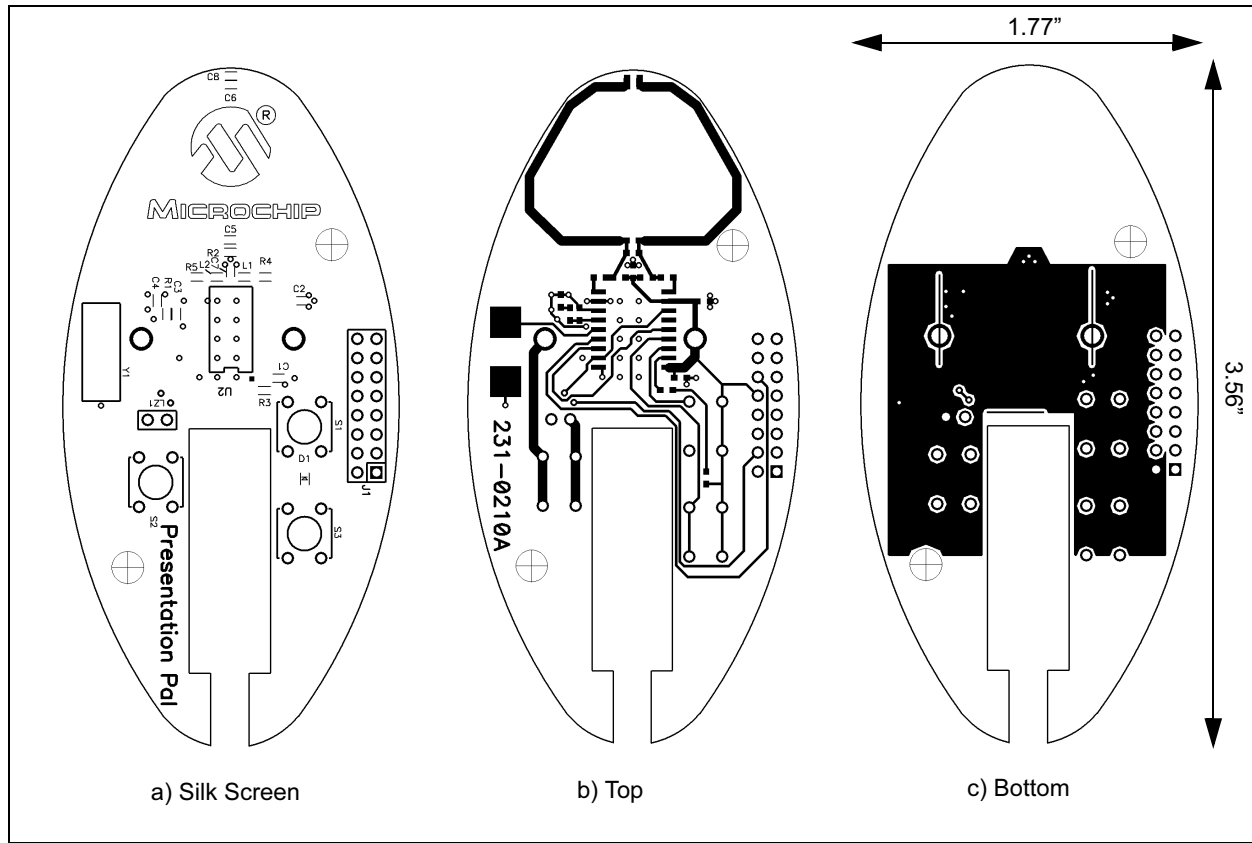
An extra 100 ohm series resistance is required directly on each antenna output pin to keep the power amplifier stable for some antenna designs. Testing for stability as described later can determine if the resistors are required in your implementation.

## BOARD LAYOUT

The layout of this circuit will have a significant impact on the RF performance. It is important that you replicate this layout to the smallest detail to reproduce these results. For this reason the Gerber files are available from the same web page where you downloaded this application note. The rest of this section will explain our design choices so that you can use similar methodology to design your own product.



FIGURE 8: LAYOUT LAYERS



To get the most output power, the loop antenna must be as large as possible yet try to avoid infringing on other circuits. As important as a large antenna is, it is more important to isolate those high power signals from sensitive nodes such as the crystal oscillator and PLL filter. Noise on these nodes and the power supply will be converted up by the VCO and appear as phase noise or spurious noise on the output spectrum. A ground plane, shielding and low pass filtering are the best ways to reduce spurs. Do not worry about isolating circuitry, such as analog sensors, that are not used while the RF transmitter is turned on.

The ground plane should be as uninterrupted as possible. Do everything in your power to avoid laying out the board with traces that must via onto the ground layer to cross over each other. Every opening in the ground plane creates an extra antenna radiating noise. If you have no other choice, then at least keep the ground plane disruption as small as possible and do not cross traces that carry RF current such as the antenna circuitry and the trace between the battery supply and the VDDRF pin. Critical connections to the ground plane like bypass capacitors and VSSRF should have multiple vias to reduce inductance. Ideally the vias should be very close to the component pads and on the same side of the pad as the component to reduce the loop areas.

Another circuit that must be reduced as small as possible is the primary antenna loop formed by the two antenna pins through the 100 ohm resistors to the

antenna. Use the smallest components your manufacturing process permits to reduce this area. Use small, low value bypass caps for the most effective RF filtering. The two capacitors in the loop antenna should be chosen for lowest ESR at 433.92 MHz to improve the antenna efficiency.

Some of these measures may seem extreme at 433.92 MHz, but it is actually the harmonic emissions that we are trying to suppress. The FCC is concerned up to the 10th harmonic which in this case is at 4.3 GHz while the European regulations only go up to 4 GHz. In reality this circuit typically radiates very little power above the 6th harmonic, but that is already at 2.6 GHz.

Lay out multiple copies of your first design such that the loop length is varied  $\pm 3\%$ ,  $\pm 6\%$  and  $\pm 9\%$ . This way at least one of your first boards should resonate with standard value capacitors. On your next board revision use the best first iteration board and do smaller variations like  $\pm 1\%$  and  $\pm 2\%$  to center the PCB variations on the middle of the capacitor value tolerances. These extra boards are not required if you plan to hand tune each board with a trimmer cap. For best results, make your prototype boards with the same manufacturer and processes that your production boards will use.

The circuit boards for this application note were made with 10 ul of gold over 50 ul of nickel on 1 oz. copper using a 0.031 inch (0.8 mm) FR4 substrate to meet ANSI/IPC-A-600F Class 2 acceptance levels. The gold finish was used to improve battery contacts and could be eliminated to reduce costs. Any changes to the circuit board manufacturing or layout must be tested for their impact on the RF performance.

## TEST PREPARATION

There are a few critical test tools required to get your design finished. The most important is a spectrum analyzer and a receive antenna. With this minimal setup you will be able to experiment with your board layout and component choices to optimize the output power while reducing the spurious noise. If your antenna is calibrated and you have the correct environment then you will even be able to do your own pre-compliance testing. Do not overlook RF CAD software which can make your calculations, antenna designs, and board layout much easier.

The next most important tools would be a signal generator and a low noise amplifier (LNA). The signal generator would be used to vary the carrier frequency by varying the reference at the crystal input, sweep your RF test setup through 10 harmonics for calibration, and test your receiver designs. The LNA may already be included in a high end spectrum analyzer. It's purpose is to amplify the small spurious noise signals to a level above the spectrum analyzer's noise floor.

It will also be very useful to have engineering sample kits of RF inductors and RF capacitors near the values of the parts in the Table 1 bill of materials (BOM). Sometimes it is useful to try components with different characteristics or from another manufacturer but more often you will need to modify the component value to retune the circuit. The crystal is likely a special order long lead time part so ordering early and buying extra is a good idea. Be sure to get lots of batteries and some trimmer caps with a good non-metallic tuning tool.

To reduce your costs you can get the test equipment used or lease it for the length of your project. Be sure to over estimate how long you think you will need to lease the tools. Another option that gets you to market faster without tools is to hire a consultant. Be sure to carefully consider each option in light of your budget, current experience, time to market and future designs.

For good test results you will have to understand your equipment, its limitations and its preferences. For example, a spectrum analyzer has the best amplitude accuracy when the spurs are near the top of the screen with minimal attenuation. This is similar to getting the best oscilloscope readings by setting the vertical vernier for the widest possible trace swings on the screen. Be sure to read the equipment manuals and get training on new pieces of equipment.

The previously mentioned application notes on crystal selection and PLL filter have their own test procedures so this application note will only focus on testing the RF performance.

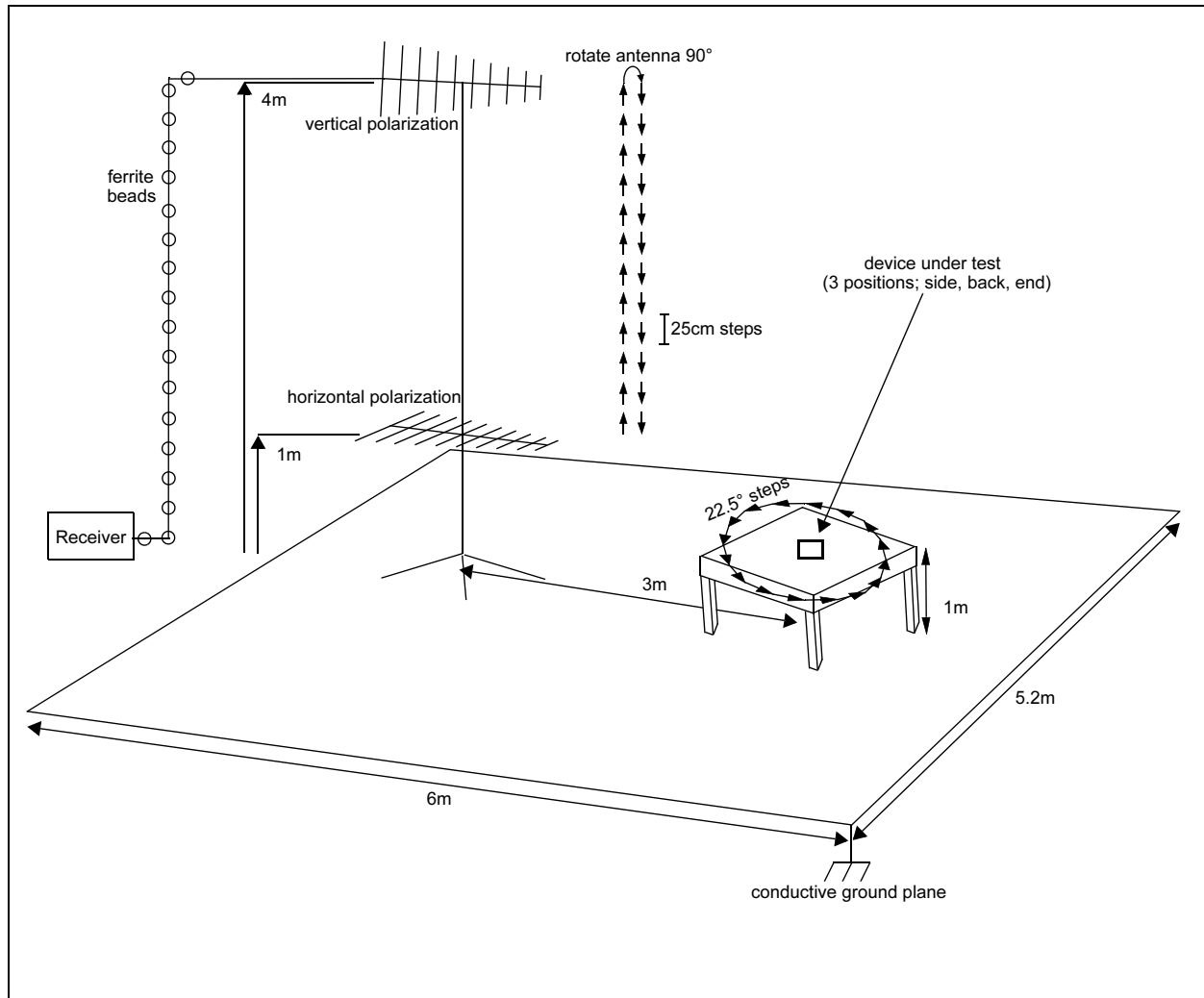
There are two types of tests to complete: absolute measurements to pass regulations and relative measurements to compare and improve your designs. The absolute measurements must be accurate and match the methods and results obtained by a standards lab. The relative measurements can be uncalibrated as long as they are repeatable.

You must be able to get the same results today that you got yesterday. If not, try your best to find the problem before continuing. The problem will typically be a small change in the environment like equipment, cables, or people moving around. After experimenting a little you will get a feel of which things influence your readings the most. An acceptable variation of a 1 or 2 dB can be achieved with good equipment and controlled environment. The variation must be less than the safety margin between your signal levels and the regulation limits.

The best way to get comparative results is to change only one small thing at a time. If you are changing a component inside a tuned circuit you also need to decide whether or not to retune the circuit each time. To find a new component value for higher output power you should retune the circuit each time. To isolate the effect of the individual component min and max tolerances on the circuit you should not retune the circuit.

Until you prove that something has insignificant effects on the measurable results, assume that it does. This includes the entire PCB layout, components, packaging, voltage, temperature, test equipment, cabling, test bench, chairs and people. Often you can eliminate variables by removing them, repositioning them, or turning them off while watching the spectrum analyzer. This does not mean that the variable does not have other effects, but the current test can be completed without further concern. In general, attack the variables in the closest proximity to transmitter and test equipment first. An example is a static mat on the lab bench, it has a large effect on the antenna impedance as long as the unit under test is within a couple of inches. Simply lifting the transmitter off the mat with a dry cardboard box will minimize the problem.

FIGURE 9: FCC TEST SETUP



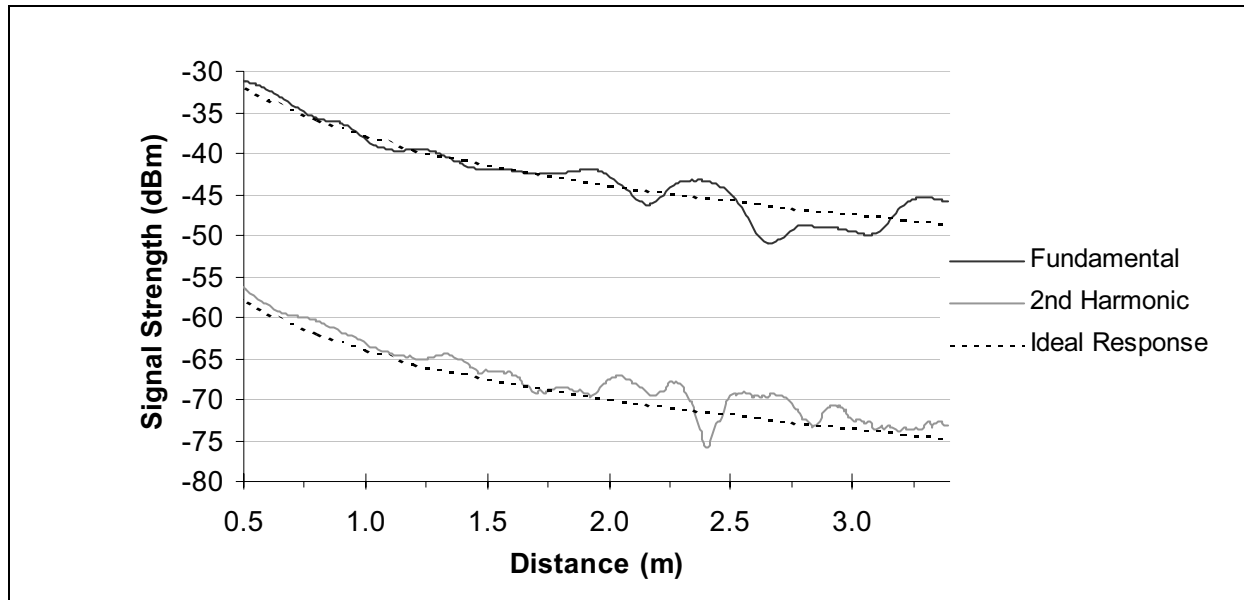
For the 3 meter FCC range test, try to clear as much area as possible, ideally 6 m by 5.2 m, to reduce reflections from other surfaces. The floor should be conductive and tied to ground or else cover it with grounded aluminium foil or a metal screen. Setup the antenna 3 m from the wooden test table such that both are centered on the ground plane as far as possible from other clutter. This setup is shown in Figure 9. The separation distance is important to reduce the power of reflected signals to several dB below the direct signal path.

Set the spectrum analyzer on frequency with a span of 0 Hz and a 20 second sweep time. Start a single acquisition and then slowly move the transmitter back from the antenna through the 3 meter point at the table and a little beyond. Turning the transmitter off momentarily at each meter from the antenna can help correlate the readings to the range later. Figure 10 shows typical data that you should see. Be sure to orientate the transmitter for the strongest signal at each frequency being characterized. Do this test with transmitter in your hand or on the table as you plan to test it for the actual readings later.

The dips in the Figure 10 sweeps show positions where the ground and other metallic reflectors are interfering with the signal. Draw the best curve through the readings that follows a  $1/\text{distance}^2$  trajectory. If the ideal line is below the measured line at 3m then subtract the difference from future readings, else add the difference in the Table 2 Setup Errors column. Modify the antenna height or reposition equipment and repeat the test to get a nice smooth response around the 3 meter point. A wide smooth response will permit more flexibility in positioning the transmitter for testing.

Repeat the procedure at harmonic frequencies until the response looks good for all the harmonics. If any of the equipment must be moved to flatten a harmonic response curve then go back and remeasure the previous frequency response curves. It is possible to do the precompliance measurements at a more suitable distance and apply the  $1/\text{distance}^2$  correction factor to the reading.

**FIGURE 10: RESPONSE CURVES WITH IDEAL LINE**



## RF TESTING

The first thing to do with your prototype board is to measure the output power at the fundamental frequency. Even the most poorly designed board should have a noticeable spur on the spectrum analyzer every time one of the transmitter buttons is pressed. The rfHCS362 does not need to be programmed to test the RF circuitry, the encryption key and baud rate can be set later. The baud rate will affect FSK and bandwidth measurements, but those can be completed once the antenna is finished. To make initial testing even easier it is best not to modulate the carrier. In the full power ASK case this can be done by lifting the PS/DATA pin and shorting it to VDDRF. If a resistor is used to set the power then modify the circuit accordingly to remove the data modulation and keep the PS/DATA line at the desired level. For FSK this can be done by removing the capacitor on the FSKOUT pin.

In the design phase we only approximated the capacitors in the antenna. Quite likely the RF output power is very low because they are not perfectly tuned. The fastest way to tune them is to remove C8 and place a 2-10 pF trimmer cap at C6. Tweak the trimmer while watching the spectrum analyzer for peak output power. The trimmer can be removed and measured later to determine the closest fixed value to use in production. It is a little more difficult to tune with a sample kit of fixed capacitor values, but the results are closer to the final product and there is no need for a capacitance meter. A trimmer cap is still preferred for tests which will require frequent retuning as other components are swapped.

A trimmer capacitor usually has each capacitance value twice so there should be two distinct peaks as the trimmer is fully rotated. If you only get a single peak at the maximum or minimum marker then you will need to get a trimmer with a wider capacitance range or add a fixed cap in parallel or in series.

The second test is to measure the current drawn from the battery. Removing the battery and inserting a power supply with an ammeter is the easiest way to do this. Use the transmitter power select table in the data sheet to determine if the current is approximately correct for the desired RF output power level. Then sweep the power supply voltage through the range that the battery will discharge. At 100 mV steps try the functionality and measure the current. The current should stay about the same. Any jumps or drops in current indicate that the transmitter jumped power levels. This problem commonly occurs with voltage dividers on the PS/Data pin that are not centered at the correct output level. Recalculate the resistor divider values and try again. For very large battery swings you may need to consider a voltage regulator circuit. A resistor divider network is not required for the highest output Power mode.

TABLE 2: SPREADSHEET OF FCC LIMITS

Spurious Frequency (MHz)	Analyzer Reading (dBm)	Antenna Factor (dB/m)	Preamp Gain (dB)	Cable Loss (dB)	Setup Errors (dB)	Duty Cycle Benefit (dB)	Measured Level (uV/m)	FCC Limit (uV/m)
420.36	-78.07	16.54	0	0.35	6.00	-6.00	195	1100
433.92	-45.66	16.74	0	0.34	6.00	-6.00	8336	10997
447.48	-84.16	16.96	0	0.26	6.00	-6.00	101	1100
867.84	-70.06	22.04	0	0.47	6.00	-6.00	939	1100
1301.76	-98.00	25.19	0	0.68	6.00	-6.00	55	500
1735.68	-76.86	27.88	0	1.15	6.00	-6.00	909	1100
2169.60	-98.00	30.49	0	1.34	6.00	-6.00	110	1100

The next task is to find the harmonic levels. For each of the frequencies in Table 2 find the peak output power using a calibrated antenna. This spreadsheet was created for FCC testing and is included in the attached .zip file.

The FCC testing requires finding the orientation with the maximum signal strength and ensuring that it is below the regulated limit. This requires setting the spectrum analyzer on peak Hold mode and rotating the product through every orientation for each frequency of interest.

Since the test will take some time the board will have to be modified to keep transmitting. If your test can be completed in 30 seconds before the HCS362 automatically times out then soldering a jumper across one of the switches will save a lot of batteries. Press a switch that was not shorted, to restart the transmission. Disable the time out option in the rFHCS362 configuration and the transmitter will stay on until the jumper or battery is removed.

It may be tempting to hook up a power supply instead of burning through all those batteries, but don't. Even with great bypass capacitors, the power supply still supplies some RF current and the leads will radiate it into the receiver's antenna as well. Even in the next section where the readings are all relative, be careful that the power supply and leads do not create, or hide other problems.

The FCC limits in the spreadsheet were written for a 3 meter open range test. This means that you would go outside on a wide flat conductive ground and measure 3 meters from the center of the product to the center of the antenna. As shown in Figure 9 the product would be placed on the center of a 1 meter tall rotating wooden table. The receiver antenna would take horizontally polarized readings as the table rotated in 12.5 degree steps. After every complete rotation the antenna would step up 0.25 meters from 1 meter until it reached 4 meters high. The antenna would then be rotated for vertically polarized readings and begin stepping back down.

It is possible to do this indoors with an anechoic chamber that has absorbent walls and ceiling to prevent reflections. While a chamber costs more than a outdoor range, it can be used in any weather and shields the test from outside noise sources like TV, cellular and radio stations. This setup can be simplified to get approximate results in your lab. Start by creating the largest available space to reduce reflections from conductive materials. Then make a wooden or cardboard table that can be rotated. Instead of lifting the antenna it is easier to lift one side of your product in steps through 90 degrees as the table rotates. Repeat for the other dimension by lifting one end of your product through steps to 90 degrees. At each point the fundamental through 10th harmonic is recorded. The maximum recorded value for each harmonic is the test result.

Since the complete test could take hours, it is best to first get close to the results you want with a good approximation. Taping the product to a cardboard or wooden stick will isolate it from your hand. Then start the readings while rotating the product through all possible orientations. Try and keep the center of the product at the point 3 meters from the center of the antenna. After a couple tries you will know the peak positions for each frequency, but watch out because the peak position can change as you modify your circuit.

The final circuit should be tested for stability before committing it to the lab for compliance testing. A stable transmitter is not on the verge of unwanted oscillations that could make mass production a nightmare. Instability is easy to detect as unwanted spurs in the transmitted spectrum.

Good stability is harder to prove. The biggest impact on stability is the antenna impedance. The rFHCS362 and rPIC12C509A RF power amplifiers can go unstable at particular load impedances. Test your design for this by reducing R4 and R5 by 50%. Then sweep the antenna impedance around resonance with a trimmer cap at several different voltages. No extra spurs at the spectrum analyzer means that for the tested range in tolerances this transmitter is stable. The extra spurs

may be close to the fundamental or up to 100 MHz away. The spurs will move as the antenna is tuned and may have amplitudes almost as high as the fundamental.

Provided all the limits were met and you got enough output power then the RF testing is completed by testing again with the modulation turned on. Finally, scan through the rest of the spectrum for any additional noise spurs. If everything looks good, repeat all these tests on a mini production run and analyze any large deviations from normal.

## INCREASING OUTPUT POWER

Often there will be a little more work involved to meet spurious regulatory limits and/or transmit more signal power. Sometimes it is better to reduce output power for longer battery life and instead increase the receiver sensitivity. This section goes through some hints and ideas to get better performance out of your rPIC transmitter.

The biggest impact on output power is tuning the antenna. Assuming the PS/DATAASK input is already tied high, the best place to start improving output power is the antenna loop area. As discussed in the layout section, make the antenna loop as large as possible. Come as close to the PCB edges as your manufacturing guidelines will permit while staying about 5mm away from metallic obstacles such as mounting screws and ground planes. Try to limit circuitry inside the antenna loop. If you must place components inside the loop, then build an extra PCB with the internal components and traces removed to compare performance.

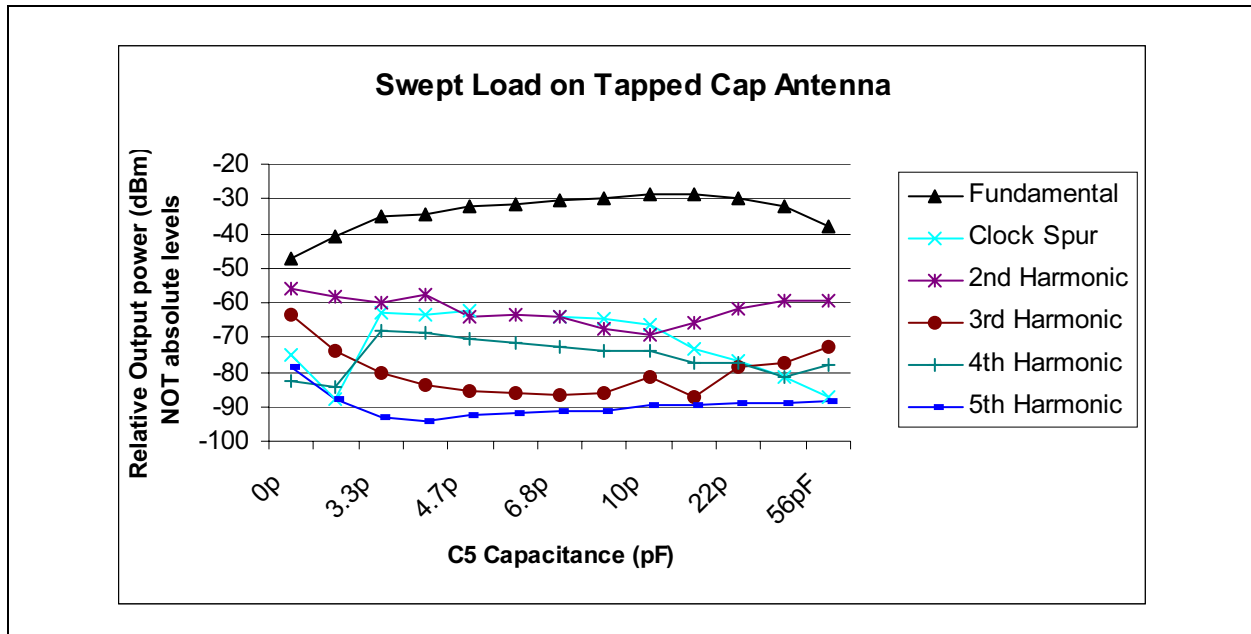
The antenna loop can also be improved by reducing resistance with wider traces. Long traces have more resistive loss so it may seem better to make the loop circular. However, most PCBs are rectangular so rectangular loops would maximize the loop area. Within the available PCB space there are more positive benefits from increasing area than the losses due to the extra length.

Reducing the ESR of the tuning capacitors will also increase the output power. Two capacitors in parallel will drop the ESR in half. Comparing the ESR of the same capacitor in various standard sizes shows a slight advantage for the 0805 size. Changing your capacitor type from a standard NP0 ceramic to one of the low ESR or RF varieties can also slightly increase your output power.

To get as much power to the antenna as possible, any loading on the antenna traces should be reduced or resonated out. The R2 resistor can also be increased to increase output power or decreased to improve stability. Dropping the R4 and R5 resistances to 50 ohms or less will increase the output power but may also make the power amp unstable for some antenna designs. An unstable amp wastes power creating spurs that will likely exceed regulations. Use the tests in the previous section to prove the design is stable after changing the R4 or R5.

The transmitter will deliver the most power when the antenna impedance matches its output impedance. The antenna impedance can be calculated using the formulas in Article 5 and measured with a network analyzer. Manually swapping a bunch of capacitor values into the two antenna capacitors is another way to do this. For each value inserted in C5 find the value for C6 that gets the highest output power. Plot the output power versus the value of C5 and find the value that delivers the peak power. An example is shown in Figure 11 for a similar antenna. The carrier frequency for that antenna required C5 set to 10 pF to maximize the output power while minimizing harmonics. Changing the position, resistance, inductance, capacitance, or ESR of any component in the antenna may require slight retuning these capacitor values for peak power.

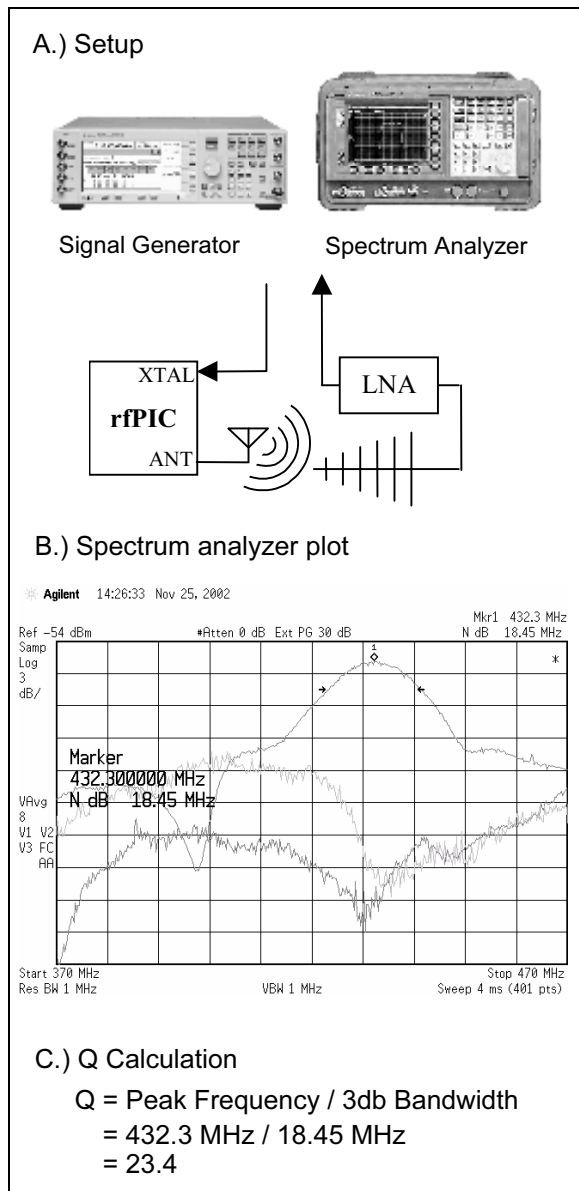
FIGURE 11: IMPEDANCE MATCHING TAPPED CAP ANTENNAS



With any resistive change the Q of the antenna will also be affected. A higher Q will increase the output power but the antenna will be more difficult to tune, possibly requiring manual tuning.

One of the easiest ways to measure the Q of the antenna is to replace the crystal with a signal generator. Set the capacitively coupled signal generator to about -20 dBm at the desired crystal frequency. Measure the peak output power with an antenna on the spectrum analyzer. Then sweep the signal generator frequency up and down until the spectrum analyzer power drops 3 dB. The power may actually go up to another peak if the antenna is not perfectly tuned. The Q is calculated by dividing the peak frequency by the 3 dB bandwidth as shown in Figure 12.

**FIGURE 12: MEASURING Q OF ANTENNA**



The antenna orientation should not make much difference for this measurement, but record it so that the measurement is repeatable. If the receive antenna response is not fairly flat over the 3 dB bandwidth of the transmit antenna then you will need to correct for this with the receiver antenna's calibration data.

## REDUCING SPURIOUS EMISSIONS

The other area of frequent improvement is reducing the spurious emissions. The most important step is to discover the source of the frequency. Turn off the transmitter and ensure frequency spur disappears to make sure it is not from the environment. Emissions that are not multiples of the carrier frequency plus or minus multiples of the clock frequency come from other sources.

An example is a spur at  $\pm 4$  MHz from the carrier, this is most likely caused by the microcontroller and could be fixed with better by-pass capacitance on the VDD pin or rerouting VDD traces. Another example that was discussed in the test section was the unstable power amp spurs, these may occur 70 MHz from the carrier or in the range of the crystal frequency/4. They will move or disappear as the antenna is tuned and can be eliminated by inserting the 100 ohms in the antenna traces as shown in Figure 7 schematic.

Using the same sweeping signal generator setup as before in Figure 12, measure each harmonic frequency. This will identify points on the spectrum that have harmonic nulls. The second the third harmonic nulls are shown as the bottom two traces in Figure 12B. They were captured at two and three times the sweep start and stop frequencies, and then overlaid on the fundamental frequency sweep. Watch what happens to the nulls as you tune the antenna, change components and modify layout. The ground plane is an important component, cut away at it slowly or add to it with copper foil tape. Modify its boundary nearest the antenna and try opening and closing holes under other RF components and traces.

Modify the antenna to shift the nulls of the strongest harmonics as close to multiples of the carrier frequency as possible. Moving a null will influence the fundamental and other harmonic power levels. Focus on the harmonic that exceeds the FCC limit the most, and stop when all the harmonics pass. This will be a compromise and may cost a little output power. This design is easily tuned by tweaking the trimmer cap for the minimum on the 2nd harmonic which happens to be the peak for the fundamental.

The inductors are chosen to resonant with the trace capacitance at the carrier frequency. Several dB of harmonic rejection is possible by tuning the individual antenna outputs separately. This can be done with different inductance on each pin or adding a capacitance to one or both traces.

If the spurs causing the problems are at the reference crystal frequency/4 from the carrier, then the cause is most likely the CLKOUT signal mixing with the carrier. Keep the CLKOUT traces as short as possible, over a ground plane, and far from the LF, FSK, antenna and crystal circuitry.

The spurs at multiples of the reference crystal frequency from the carrier are usually from the charge pump in the VCO circuitry. Decreasing the PLL filter bandwidth reduces them but increases the phase noise. For more details study application note AN848.

Here are some additional methods to get those uncooperative spurs to stay below FCC limits. Reduce the output power with a resistor divider on the PS/DATA pin earlier. Change the transmission format to get better averaging as shown in Figure 5. Start your layout over with more board space or try smaller components like



the TSSOP parts. Change carrier frequency to move fundamental, clock spurs, or harmonics further from restricted bands. Or even change the VDD to operate at a different voltage.

Remember the goal is to meet the regulatory limits as quickly and cheaply as possible. This will keep the focus on those inevitable days when nothing seems to work. Sometimes you may find that you have to repeat days of testing after discovering that something like the test equipment was not setup correctly. Do not get discouraged, this happens to everyone. Document what you learned so that others do not have repeat your experience and move on.

## PRODUCTION

The mini production run done in the test section should have proven that the part is ready for full production. Make any final cosmetic, feature, performance, or cost reduction improvements now because once the FCC approves your design it will be more difficult to make changes.

Anyone can apply or reapply for FCC approval on this product, or resell this product once approved. Only the FCC grantee is allowed to make changes to the certified product. Minor changes that do not increase radio emissions are permitted without filing with the FCC. Minor changes that do increase radio emissions must be tested, reported and accepted by the FCC before marketing. Major changes like changing the transmitter, PLL filter, crystal frequency, or case shielding properties must be submitted for testing as a new product with a new ID.

The FCC permits hobbyists to build and operate up to five of these Part 15 transmitters for personal use without authorization. However, the transmitters must still be designed to comply with all the rules. You do not have to get any expensive equipment for testing but you should be reasonably sure that your board could pass testing. One way to be sure is to copy this example design layout and parts list to the smallest detail. The hobbyist boards cannot be prototypes of products intended for future marketing.

At this point the final product must be tested for FCC compliance. Hopefully the test facility was scheduled to receive your board at this time so that you do not have to wait. Plan that testing and writing the FCC report will take several days.

If one test fails, some labs may not continue to find all the failures unless you specifically request them to. If it does not cost too much extra, try and find out everything that fails so you will know all the problems that need to be fixed.

Use the results of the test lab to correct your precompliance readings as much as possible. Try and figure out why your readings were off from the labs. For example, is there a pattern in the difference between readings? Was the difference due to the procedures or the test equipment? Change your setup to see what you have to do to get the same readings. Make sure that you can still go back to your previous setup to repeat your old tests with new circuit board improvements.

Hopefully your product passed on the first attempt and you now have about 30 days to wait for approval from the FCC. This should give enough time to finish those manufacturing and test procedures and get everyone to sign off on the documentation. Do not hold the release party yet. The FCC may still require a product to repeat the testing, more information for incomplete forms, or otherwise delay your product launch.

Once the FCC approves your report you can start shipping the conforming product. Make sure to randomly sample the production line with simplified tests for continued compliance. Although not required, this shows good faith in case your product ever faces a legal challenge. Breaking the FCC rules is against federal law and large penalties can be enforced.

Do not use this design guide as the rulebook, instead refer directly to the Part 2 and Part 15 regulations. Get clarification directly from the FCC or a communications lawyer on areas you do not understand. This guide was written to the best of our knowledge at the time of publication, but rules do change and we still have much to learn so use it accordingly. The most recent revision of this document is available on the Microchip web site. Microchip does not assume any responsibility for the use of this information.

### Associated files in 00242.zip:

FCCTest.xls	Testing Spreadsheet
00242.top	Top Signal Layer
00242.bot	Bottom Signal Layer
00242.tsk	Top Silkscreen Layer
00242.bsk	Bottom Silkscreen Layer
00242.tsm	Top Soldermask Layer
00242.bsm	Bottom Soldermask Layer
00242.fab	Fabrication Drawing for PCB manufacturer
00242.drl	Drill Coordinates
00242.pdf	Assembly Drawings
00242.tsp	Top Solder Paste Layer

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"Understanding Regulations, Part 2" (Microwaves & RF [October 2001] 79-96)

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"Tracking Phase Noise, Part 4" (Microwaves & RF [March 2002] 57-64)

"Introducing Loop Antennas for Short-Range Radios, Part 5" (Microwaves & RF [July 2002] 80-88)

"Matching Loop Antennas to Short-Range Radios, Part 6" (Microwaves & RF [August 2002] 72-84)

RF Engineering Resources

<http://www.rfcafe.com/>

Microwaves & RF Magazine

<http://www.mwrf.com>

RF Products and News

<http://www.rfglobalnet.com>

World Wide Wireless Regulations

<http://www.beepworld.de/members27/hfworld/certification.htm>

RF Test Equipment

<http://www.agilent.com>

RF Measurement Terms and Calculations

<http://www.ets-lindgren.com/pdf/Ant11.pdf>

## APPENDIX A - HCS362 CONFIGURATION

The screenshot displays the KeeLoq Evaluation Kit II software interface. The main window, titled "KeeLoq Evaluation Kit II - setup.cfg", shows two configuration panels: "Encoder 1" and "Decoder 1".

**Encoder 1 Configuration:**

- Name = HCS362
- Serial N. = 00001002
- Config0 = FD30
- Config1 = 2000

**Decoder 1 Configuration:**

- USB receiver
- Type = Custom - Normal Learn
- Config = 0000
- Manuf.Code(msb)= 01234567
- Manuf.Code(lsb)= 89ABCDEF

Below these panels is a 3D rendering of the HCS362 evaluation kit hardware. In the foreground, the "HCS362 Programming" dialog box is open, showing detailed configuration options:

- Decoder:** 1 - USB receiver
- Serial Number:** 00001002 (with  Auto Increment)
- Modulation Format:** PWM
- Baud Rate:** 400us
- Low Voltage Select:** 2.3V
- Timeout:** 25.6s
- Overflow Bits:** None
- Minimum Code Words:** 4 Code Words
- Guard Time:** 76.8 ms
- Transmit CRC/Time:** CRC bits
- Led:** 25ms on / 500ms off
- Sync. Counter:** 0000
- Discrim. Value:** 002
- Oscillator Tuning:** Auto (with  Serial Nr. 10 ls)
- Seed:** Random (with  Random)
- Seed Mode:** No SEED
- Seed Button:** S0+S3 1mm, S0+S1 delayed 3.2
- Extended Serial Number
- 3 x Te Header
- RF Enable

At the bottom of the dialog box, it states "ADVANCED MODE: All the options are available" and includes buttons for "Program Mode", "Default Values", "Normal Mode", "Close", and "Help".

**Warning:** Remove the battery prior to in-circuit programming the rfHCS362.

# AN242

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NOTES:

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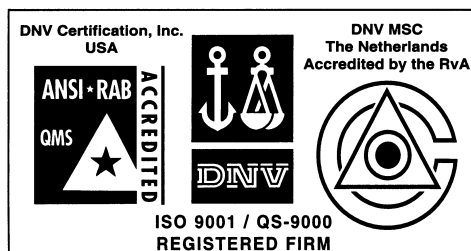
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