Application Report
SPNA147–July 2012

Passive Go Transponder With Novel Bi-Directional Low Frequency Communications

Herbert Meier, Erik Wallander, Jim Childers — *MCU-RF*

ABSTRACT

In recent years, Passive Go (PG) systems for motorcycles have been developed that have been copied from automotive Passive Entry and Passive Start (PEPS) systems. But for bikes with no requirement to unlock doors or roll down windows at a distance, such systems are over-designed with their UHF uplinks. The MCU RF group at Texas Instruments has developed a complete low-frequency approach to this problem, eliminating the expensive UHF transmitter and receiver chipsets, matching networks, and UHF antennas as well as eliminating the need for UHF band certification while still providing Passive Go functions at distances of over 1 meter — more than enough for a bike.

Project collateral and source code discussed in this application report can be downloaded from the following URL: http://www.ti.com/lit/zip/spna147.

Contents

List of Figures

List of Tables

1 Overview

Existing low frequency (LF) solutions do not have the bi-directional range to achieve 1 meter. While the basestation downlink achieves high transmit voltages, the transponder (or fob) uplink cannot. Figure 1 shows that bi-directional communication is limited to the weakest path.

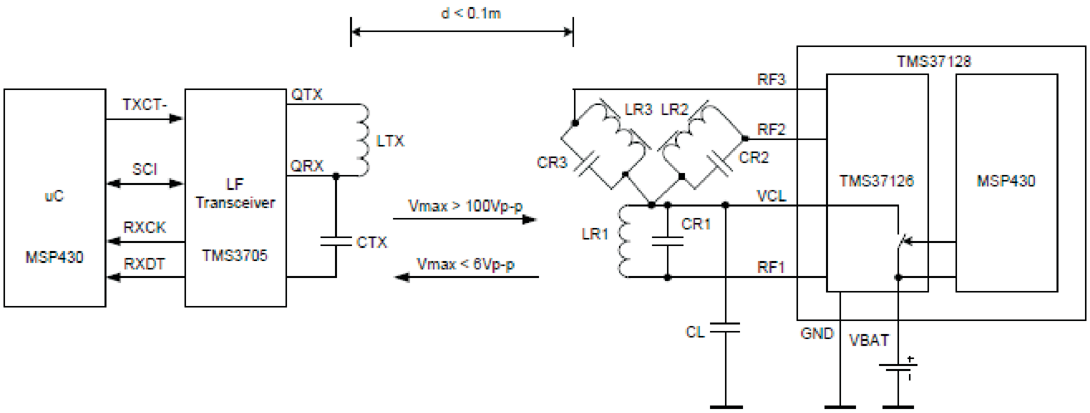


Figure 1. Typical LF Only Fob Limited to a Few Centimeters

The solution is to boost the uplink power by supercharging the fob's transmitter (see Figure 2). By adding power drivers to series-resonant antenna circuits, high transmission voltages similar to that of the basestation can be achieved in the fob.

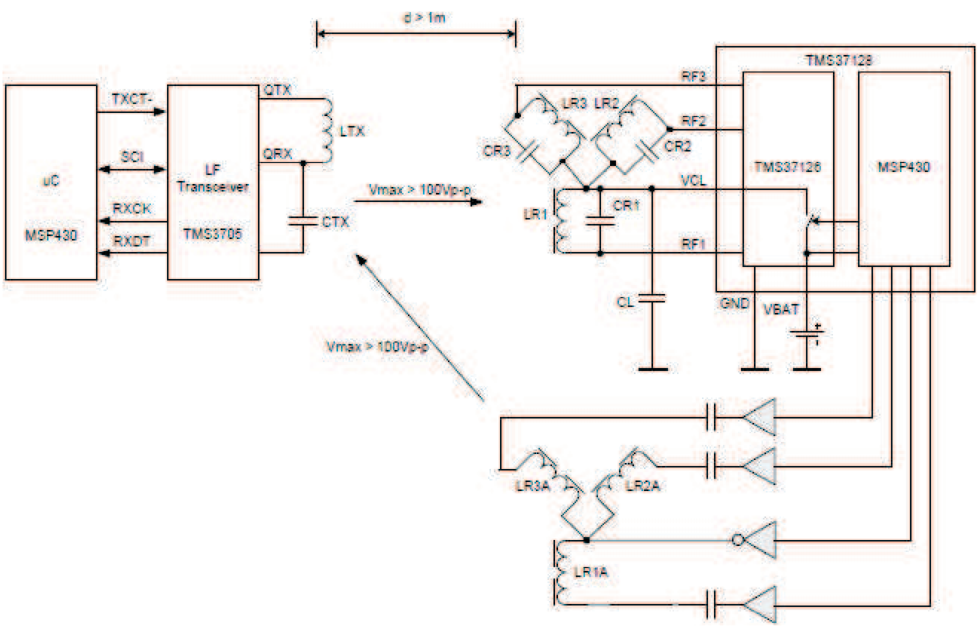


Figure 2. LF Only Fob With Supercharged Uplink

The transponder described here is based on the TMS37F128D3 Controller Remote Access Identification Device (CRAID). This is a multi-chip module (MCM) consisting of a TMS37126 3-dimensional (3D) analog frontend and immobilizer plus an MSP430F1232 microcontroller in one 44 pin package. The three orthogonal antenna coils support reception in any orientation relative to the 1D basestation antenna.

Two 3D antennas are employed to simplify the circuit and minimize the total cost of the fob: one for the receiver and immobilizer functions, and one for the high power uplink transmitter (see Figure 2). This separates the high sensitivity receiver from the high voltage transmitter.

This demo fob includes two pushbuttons that are programmed to support development by transmitting the two FSK frequencies. They can of course be reprogrammed for auxiliary functions such as baggage compartment release, etc. There is also a red LED programmed as an operational indicator. Since this is a demo board, several jumpers and connectors are included for ease of development, programming and debug. In the production design, all the jumpers can be removed and the two test connectors can be converted to distributed probe pads.

NOTE: During debug with the JTAG box connected, the pushbuttons should not be pressed as they will interfere with the JTAG communications. Also, the LED cannot be controlled by software during JTAG debug.

2 Development Tools

Besides the transponder (fob), there are three inexpensive pieces of development hardware that are needed for the fob development:

- RI-ACC-ADR2 Reader (USB-based LF transceiver is equivalent to the bike's basestation) equipped with a 4 cm Air Coil (50017-A-00)
- MSP430™ USB Debug Interface (JTAG box for software download and debug)
- Probe Test Box (PTB) (the device used to frequency-trim the immobilizer part of the fob)

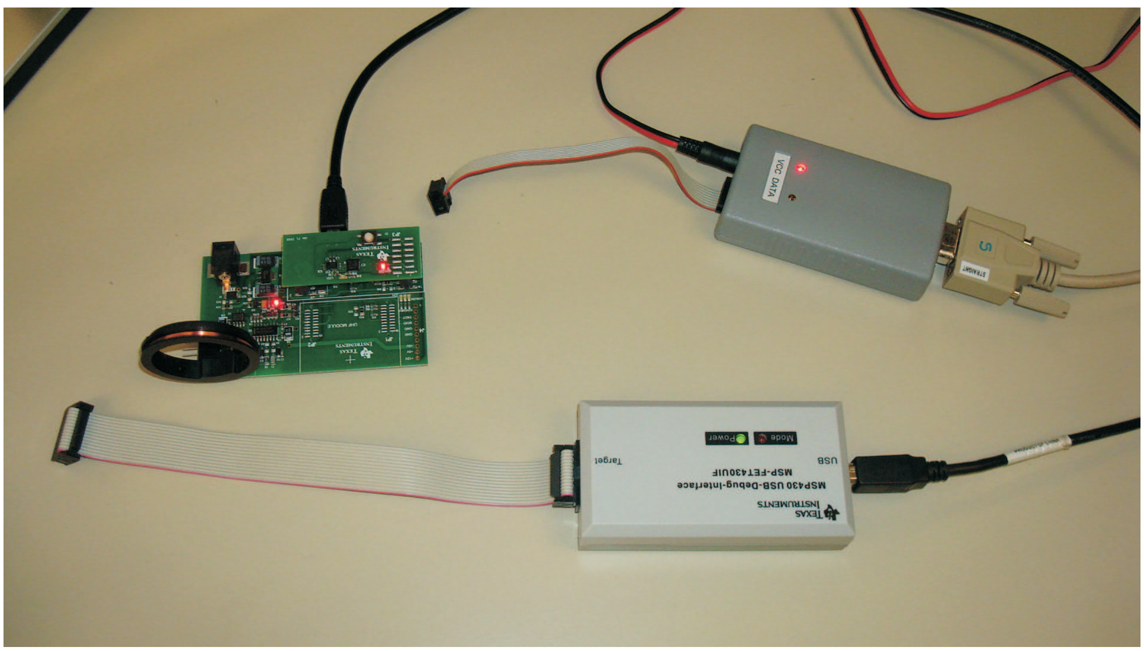


Figure 3. Tools (clockwise from left) ADR2 Reader, PTB, MSP430 JTAG

Support software for these tools is as follows:

- RFID Demo Software ver 3.06 or better (GUI for both the ADR2 Reader and the Probe Test Box)
- Automotive Demo Tool ver 0.13.9 or better (GUI for Probe Test Box, used for modifying the transponder electrically erasable programmable read-only memory (EEPROM) contents)
- Code Composer Studio™ ver 4.2.x for MSP430 (the free limited-code-size version is adequate and can be downloaded from the following URL: http://processors.wiki.ti.com/index.php/Download_CCS)

NOTE: There may be an issue using CCSv5.x for the MSP430F1232 device so CCSv4.2.x is recommended.

This is a short list of documentation that is needed. Other documents for the individual components may also be required.

- CRAID-RAID Reference Manual Industrial .pdf
- *MSP430x11x2, MSP430x12x2 Mixed Signal Microcontroller Data Sheet* (SLAS361)

The software and documentation mentioned above are provided in an associated zip file located at http://www.ti.com/lit/zip/spna147.

3 Basic System Operation

A Passive Go system is greatly simplified by the level of integration of the TMS37126; however, in order to extend the range of communications to over 1 meter, it is necessary boost the fob's transmitter power. The basestation located on the bike needs no supercharging as it already has more than enough power to reach the fob's sensitive receiver beyond 1 meter.

Referring to Figure 4, the parallel-resonant antenna circuit for the downlink consists of CR1 - CR3 and LR1 - LR3. For the uplink, a second antenna in a series-resonant arrangement consists of CR1A - CR3A and LR1A - LR3A).

The parallel-resonant circuit of the downlink maintains the ability of the CRAID/RAID device to operate with a dead battery in close proximity to the basestation by charging the energy storage cap, CL, while the series-resonant circuit of the uplink achieves high resonant voltages (150 V - 200 V), enabling uplink distances of 1 meter or more.

When the rider presses the start button on the bike, the basestation transmits an amplitude shift keyed (ASK) modulated telegram via LF to the fob. The fob's sensitive LF receiver picks up the transmission and decodes the request, then enables its frequency shift keyed (FSK) modulated LF transmitter and returns the requested information.

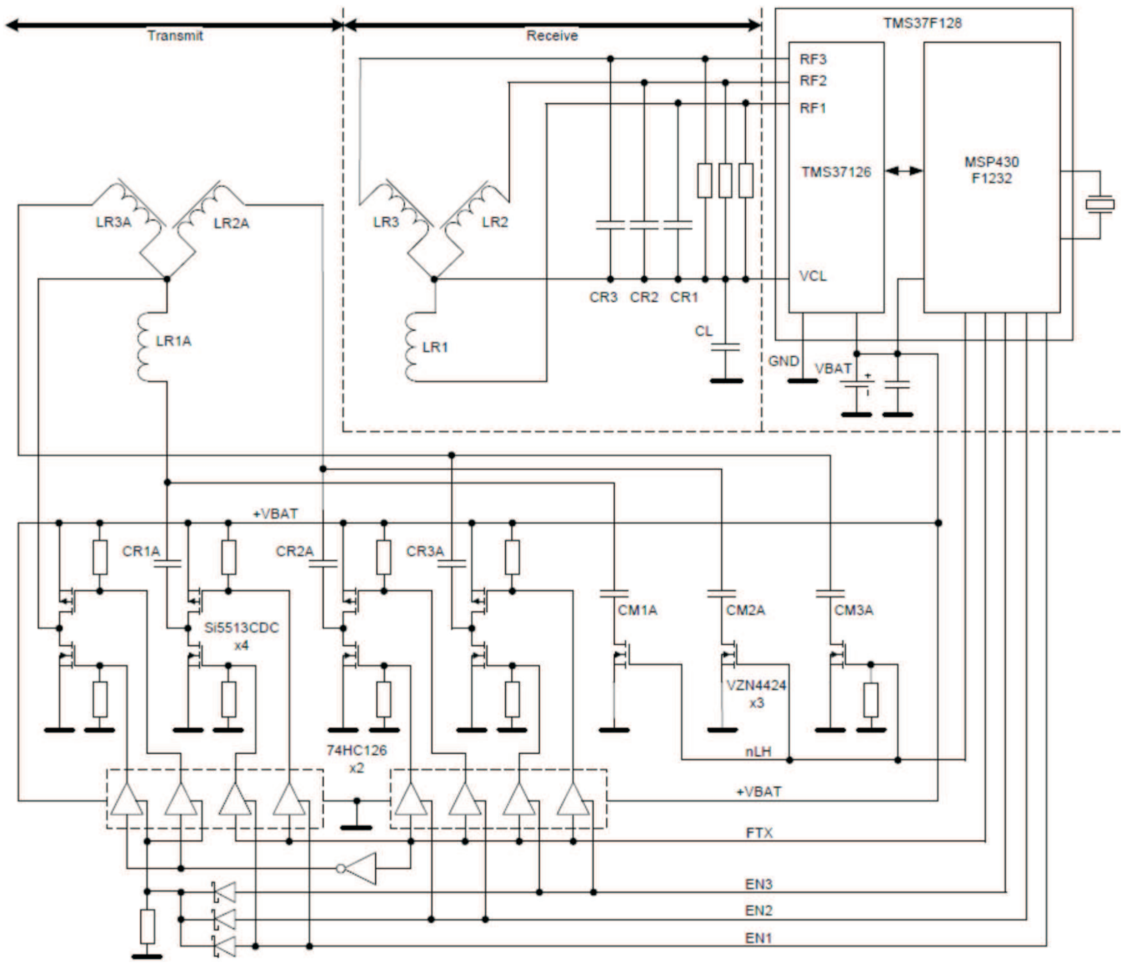


Figure 4. CRAID Fob With Dual Antennas

4 General Circuit Description

The immobilizer function is essentially autonomous. Once the internal EEPROM is properly setup (via the PTB), then it needs no software or assistance from the MSP430 uC. It can receive a telegram from the basestation and automatically respond to it even with no power from the battery, provided the distance is less than about 7-10cm.

The receiver can automatically receive a request from the basestation and wake up the MSP430 uC. The uC can then decide what to do with the received data and enable the high power transmitter. It must then emulate the response, which would have been performed by the immobilizer but at much higher power.

Another purpose of the uC is to perform more algorithm-oriented functions like scanning the pushbuttons and sending these requests to the basestation via the uplink transmitter.

The uplink is realized with a full H-bridge that drives one of the three series-resonant circuits directly. The H-bridge is controlled by the timers of the MSP430 microcontroller (uC). Since each channel of the 3D uplink antenna has one common lead (see Figure 4), only four half H-bridges are required: one for each coil's positive end and a fourth for the common negative end. Simple logic (2 x 74HC126) decodes which driver is to be enabled based on control signals from the MSP430.

The 74HC126 quad 3-state buffers disable the driver stages by entering a 3-state mode, allowing the MOSFET's gates to float. This means pullup and pulldown resistors are required on the MOSFET gates to keep them turned off when not being driven.

The uplink to the basestation uses FSK modulation at approximately 133 KHz to represent a ‘zero’ and 121 KHz to represent a ‘one’. The relatively high Q of the series-resonant circuit causes the high voltage to roll off quickly with frequency, so communication distance is significantly improved by adding a modulation circuit (capacitors CM1A – CM3A and associated transistors of Figure 4). This circuit is static (on for ‘one’ and off for ‘zero’) and simply adds enough capacitance to each of the three channels to lower the resonant frequency by about 12 KHz when transmitting a ‘one’.

5 Drivers

The H-bridges and modulation circuits can be built with either bipolar or MOSFET transistors; both types have been constructed and work well. Each type has advantages and disadvantages that should be considered.

Bipolar Advantages:

- Easy to turn on at low battery voltages (<2 V)
- Many devices available for > 200 V

Bipolar Disadvantages:

- Modulation circuits require additional Schottky diodes, which add expense and nonlinear parasitic junction capacitance to sensitive resonant circuits
- Base drive consumes current when on

MOSFET Advantages:

- Many small package types
- Inherent clamp diodes avoid additional external clamps (significant advantage)

MOSFET Disadvantages:

- Limited number of high-voltage devices available with $V_{GS(th)}$ < 2 V

6 Resonant Circuits

As with any radio receiver and transmitter, the sensitivity of the system relies on tuned resonant circuits to get the greatest signal-to-noise ratio and, hence, distance.

6.1 Receiver and Immobilizer

The receiver’s resonant circuit can be trimmed by the TMS37126 to within about ±100 Hz using the Probe Test Box via connector J2 (Figure 22) and the RFID Demo Software mentioned in Section 2. The PTB measures the receiver’s resonant frequency and determines how much on-chip trim capacitance must be added to bring the frequency into spec. The analog front end of the TMS37126 contains trimming capacitors that are used to trim the resonant circuit. Once trimmed, the amount of trimming capacitance required is stored in EEPROM. This trimming circuit functions even when there is no battery power available. Since the trimming circuit can only add capacitance, it is desirable to initially target the receiver’s resonant frequency slightly higher than the ideal frequency of 134.2 KHz, then let the trimming operation lower the frequency to the correct value by adding on-chip trim capacitance. An analysis of worst-case component values will determine the initial target frequency.

6.2 Transmitter

The extended reach transmitter circuit does not benefit from the trimming performed on the receiver so it needs to be built from components with tighter tolerances. C0G and NP0 ceramic capacitors with ratings of 200 V or more and 1%-2% are available from multiple sources. The antenna coils need to be ±3% to achieve the best results. Tighter coil tolerances are more easily achieved by using three 1D antennas to allow the manufacturer to maximize yield, although this demo application uses one 3D antenna for the transmitter.

The basestation, usually designed around the TMS3705, automatically adjusts to the incoming frequency of the transponder’s transmitter. This affords the system some timing flexibility.

6.3 Basestation (1D bike antenna)

The basestation has a key influence on the distance achievable by the system. If the basestation antenna can be mounted on non-metallic bike parts, then an air coil antenna can be used. If the antenna has to be mounted in close proximity to the metal frame or on steel, then a ferrite antenna must be used; however, a ferrite antenna can be physically smaller than an equivalent air coil antenna.

Preferably, the ferrite antenna is mounted in parallel to the metal surface at a distance greater than the ferrite core diameter. Any metal at the ends of the ferrite coil must be avoided. The inductance and the quality factor decrease dramatically with decreasing distance to metal. An aluminum shield 1 - 3mm thick should be mounted on the metal surface in between that surface and the antenna. Depending on the distance between ferrite antenna and aluminum plate, the inductance will still decrease but the quality factor will be maintained. The loss of inductance has to be compensated using a higher value resonance capacitor.

Preferably the resonance capacitance should be determined with the inductor mounted in its final position. The resonant frequency of the basestation antenna should be chosen exactly midway between the two FSK frequencies (133.3 + 121.2) / 2 = 127.25 kHz). In this case, the quality factor should not be higher than QRX = 10. For help calculating QRX and other key parameters, see the *LF-LF Demonstration System Calculations* documentation included in the associated zip file. The resonance and quality factor must be measured with the antenna connected to the reader (reader powered-on, but in the receive state). Series filter resistors, driver transistor resistances, and capacitances influence resonance and quality factor.

In general terms, the higher the inductance in the basestation antenna, the greater the distance that can be achieved. Also, the larger the cross-sectional area of the antenna, the greater the distance. The typical inductances (100 - 440 µH) used in Passive Entry and Passive Start applications yield insufficient communication distances due to a low coupling factor. Higher inductances (e.g., 2.5 - 4.5 mH) similar to the transponder antennas are more suitable for this application.

In the first demonstration system, a 2.5 mH ferrite coil with a diameter of 7.9 mm and a length of 100 mm (HANA coil: 00CTUBEX900G, ferrite: 18FERTUBE00G) was used (top coil of Figure 5).

A second demonstration was performed with an air coil antenna (Toko: LA-M283) having an inner diameter of 52 mm, an outer diameter of 79 mm, and a thickness of 0.7mm (bottom coil of Figure 5). This air coil achieved, in an open air environment, the same communication distance as the above ferrite coil.

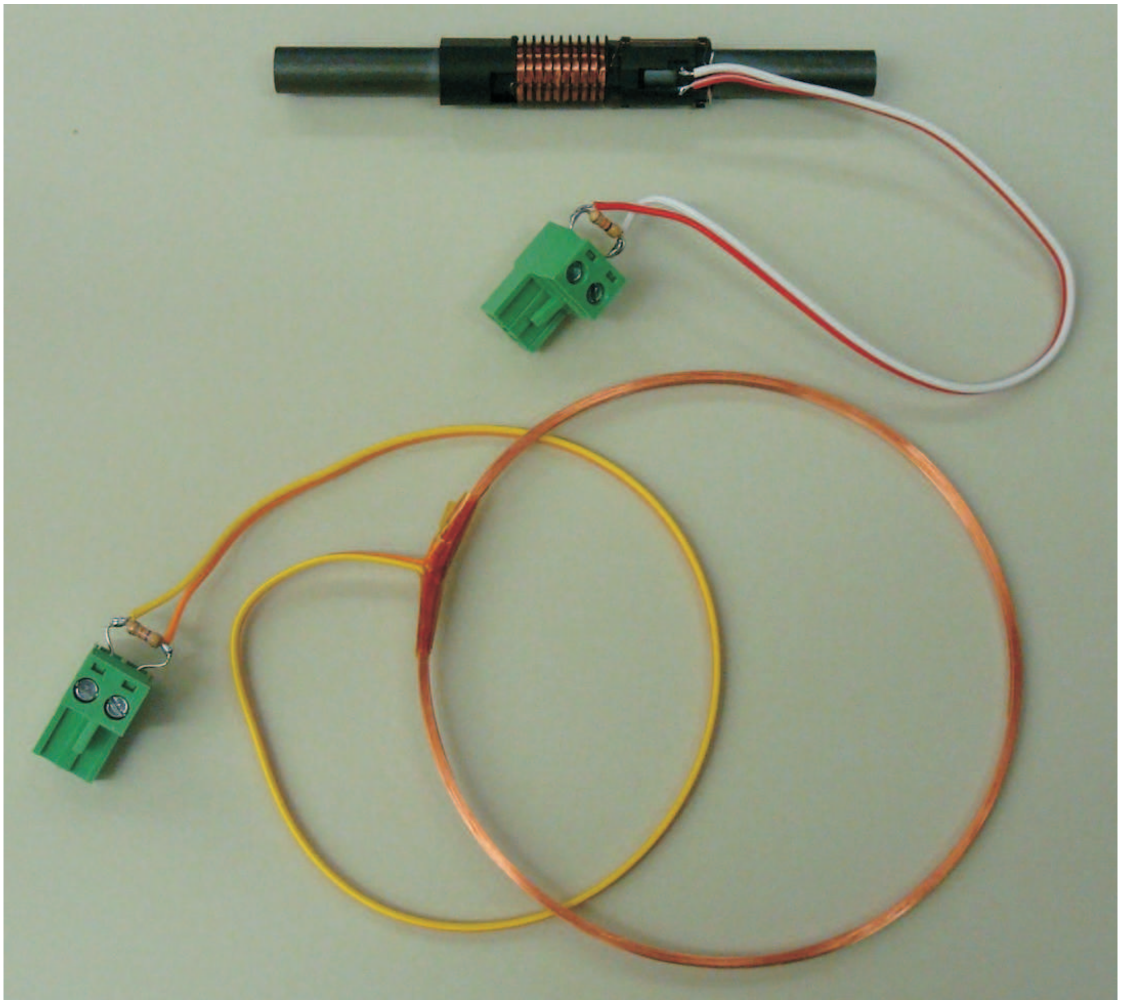


Figure 5. Basestation Ferrite and Air Coil Antennas

Note that in the photograph of Figure 5, discrete resistors have been paralleled with the coils at the ends of their lead wires to reduce their Q = 10. The ferrite coil required 47K Ω and the air coil required 51K Ω.

7 Timing

The timing in the receiver and immobilizer is covered in detail in the CRAID-RAID Reference Manual Industrial and is not duplicated here; however, the timing of the transmitter section is detailed below.

When a signal is received, the receive signal strength indicator (RSSI) is examined by the software in all three axes, and the axis with the strongest RSSI signal is chosen for the response. For example, if the Z-axis of the receiver has the strongest RSSI signal, then the Z-axis of the transmitter is used as the response channel. For this reason, it is important to understand which transmitter coil's orientation matches a particular receiver coil as they have to work in pairs.

For an accurate and strong uplink carrier, it is recommended to use a crystal for the uC. It is easy to obtain suitable frequencies from an inexpensive 4 MHz resonator. Since the basestation automatically adjusts to small deviations in the transponder's frequency, it is not necessary to achieve exactly 134.2 KHz and 123.2 KHz. A 4 MHz crystal divided by 30 yields a 'zero' frequency of 133.3 KHz (-0.6% error) and divide by 33 yields a 'one' frequency of 121.2 KHz (-1.6% error). Note that the receive and transmit frequencies are slightly different. This does not matter.

Only one axis of the transmitter can be used at a time, depending on which RSSI signal is strongest. The other two transmission channels are left floating (3-stated) by manipulating EN1–EN3 appropriately (see Figure 22 and Figure 23).

The MSP430 internal timer is used for generation of the transmitter's carrier frequency (either divide-by-30 or divide-by-33). The resonant peak of the transmitter's series-resonant circuit is shifted to match the carrier frequency using the modulation circuit. This is done in software by switching the modulation transistors on and off synchronously by changing the timer division ratio. Synchronization of these two events is discussed in Appendix C.

Both 'ones' and 'zeros' are transmitted for 16 cycles. When the transmitter is off, it should be 3-stated to minimize power consumption and to avoid interference with the receiver antenna.

8 LF and SPI Communication Timing and Telegrams

The downlink and uplink timings and telegrams for the passive functions, like the programming of the encryption key and the challenge and response modes (for example, the encryption mode), is covered in detail in the CRAID-RAID Reference Manual Industrial and is not duplicated here. It is recommended to use pulse position modulation (PPM).

The downlink and uplink timing and telegrams for the active battery-supplied functions (such as Passive Go) are shown in detail, because of special requirements.

8.1 Passive Go LF Downlink

The Passive Go downlink uses burst width modulation (BWM) as shown in Figure 6.

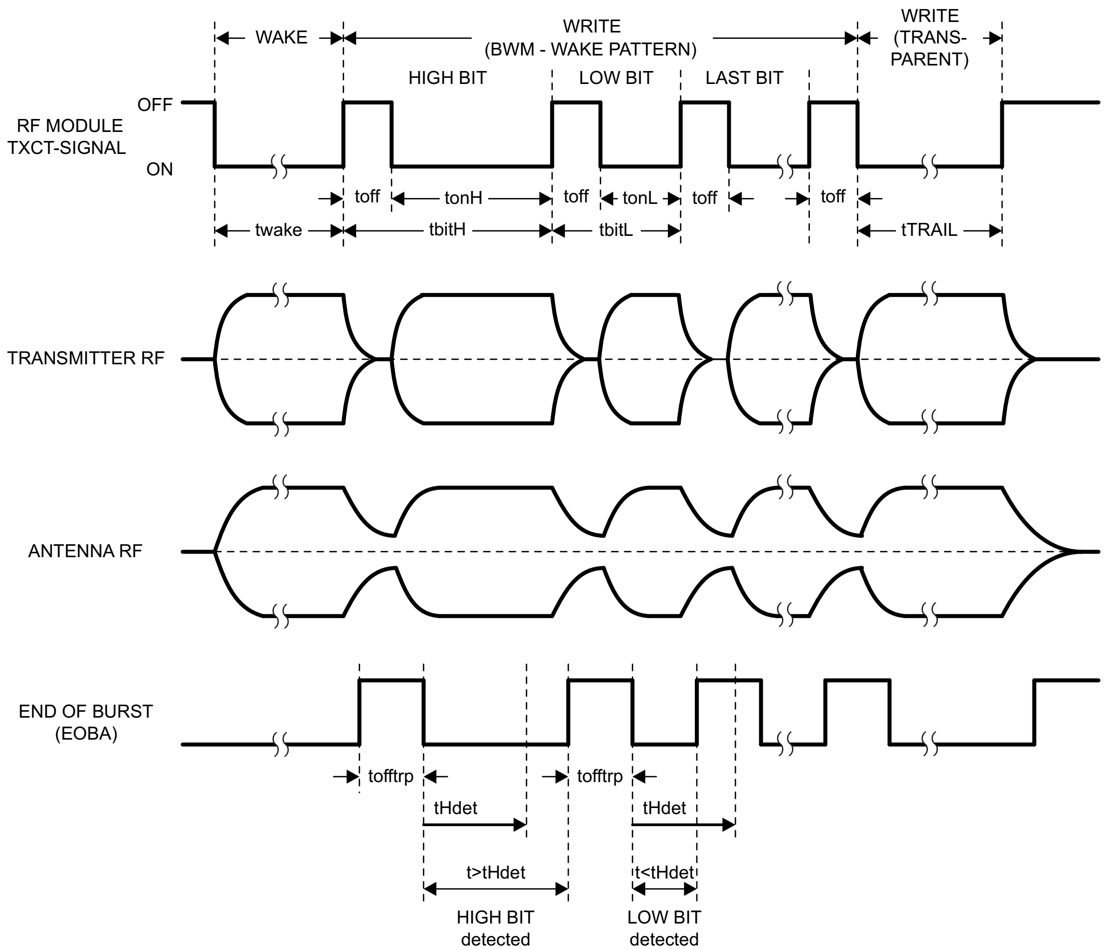


Figure 6. Burst Width Modulation Timing

Before communications can be established between the Reader and the fob hardware, the following parameters must be input into the RFID Demo Software.

1. Start the software.
2. Click on the CRAID PEPS tab.
3. Click Settings on the toolbar; a new screen will appear.
4. Enter the following data in the 7 fields.
5. Click Finished near the bottom of the screen.

Wake Burst Time (t_{wake})	→	4 ms
Data Delay Time (t_{TRAIL})	→	1 ms
RSSI Burst Time	→	16 ms
Low Bit Off Time (t_{off})	→	170 µs
Low Bit On Time (t_{onL})	→	230 µs
High Bit Off Time (t_{off})	→	170 µs
High Bit On Time (t_{onH})	→	600 µs

An overview of the PG downlink telegram timing is shown in Figure 7.

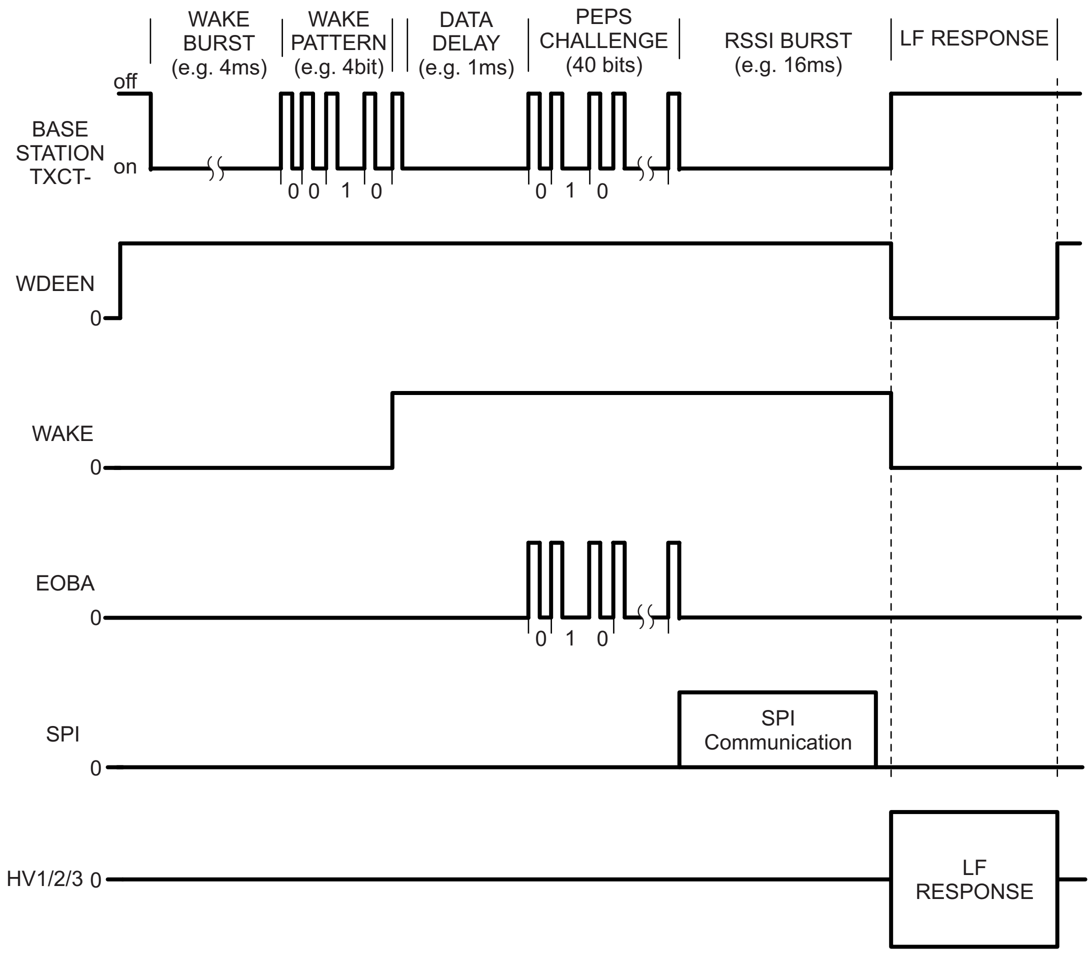


Figure 7. Passive Start Downlink Telegram Overview

8.2 LF Uplink

For the LF uplink telegram to be compatible with the immobilizer encryption mode uplink telegram, the following information is required (see Figure 8):

- Serial number of TMS37126 front end (unique and locked)
- Signature (result of challenge encrypted with encryption key)
- Read address (lock status of encryption key)
- Read frame block check character (BCC)

All of this information can be obtained via SPI communications with the TMS37126 front end.

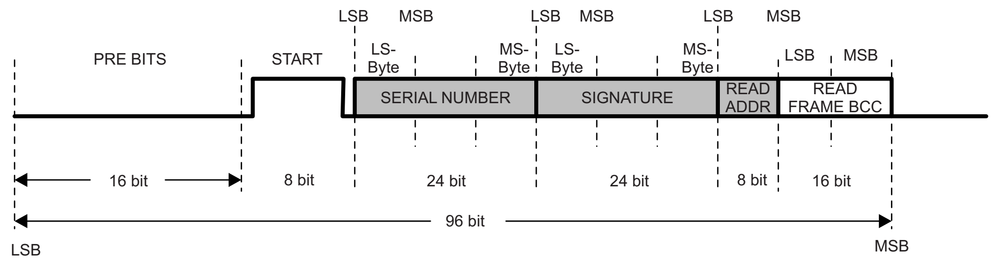


Figure 8. LF Uplink Telegram

NOTE: The LF uplink telegram is sent LS-bit first, LS-byte first.

8.3 SPI Communication

The received 40-bit Challenge is decoded by the MSP430, which analyzes the EOBA signals and temporarily stores them in RAM. To determine the proper LF response for the received challenge, SPI communication is used. The input data (SIMO) and output data (SOMI) are clocked by SPI_CLK and are controlled by the BUSY handshake signal (see Figure 9). The next data byte can be sent when BUSY indicates it is ready by a short Low pulse. In case BUSY stays high or low, this indicates an error. These cases need to be handled by a software timeout counter in the MSP430, otherwise, the software can hang.

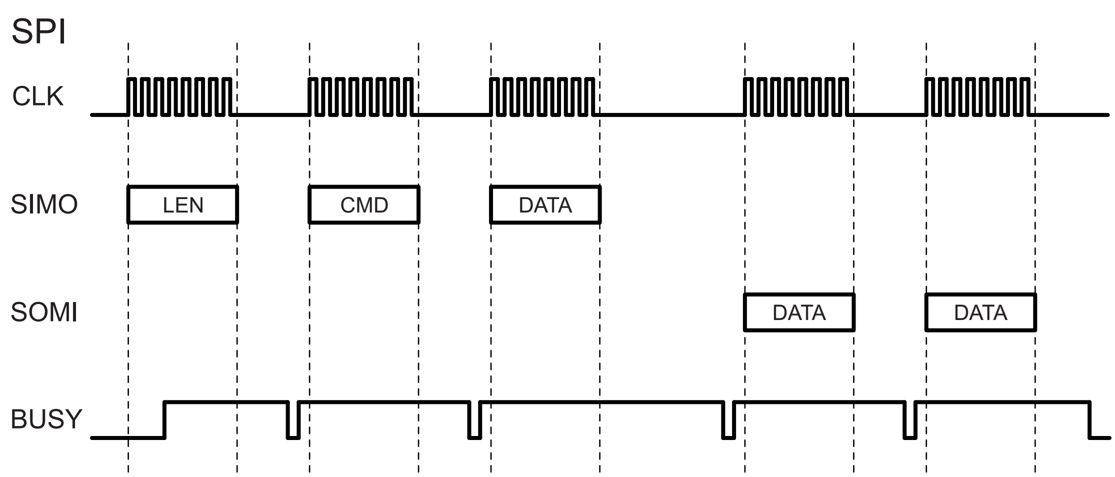


Figure 9. SPI Communication Control by BUSY

The challenge is sent via SPI to the front end using the *encryption mode* transponder access command (see Figure 10). Either the 40-bit or 80-bit encryption algorithm can be selected in the Command Byte (CMD), depending on configuration of the front end. The MSP430 demonstration firmware includes only 40-bit encryption.

NOTE: While the LF downlink is received LS-bit first, LS-byte first, the data via SPI are sent and received MS-bit first and LS-byte first.

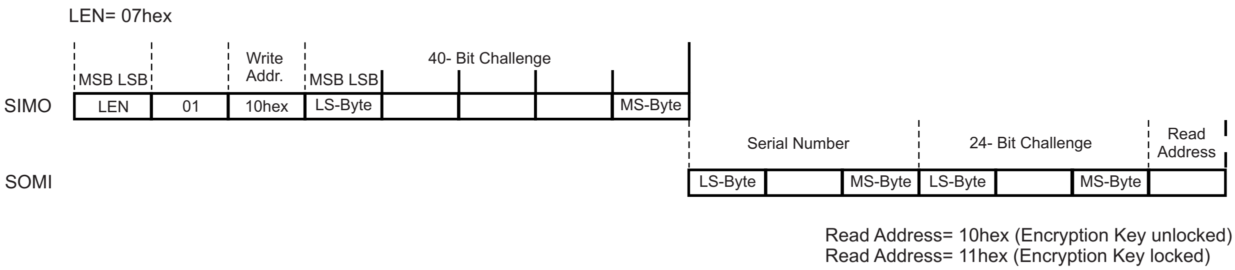


Figure 10. SPI Communication to Get Serial Number and Signature

For a valid response via LF, a frame block check character (BCC) is required. For generation of the 16-bit BCC, the total dataset is again sent to the front end (see Figure 11).

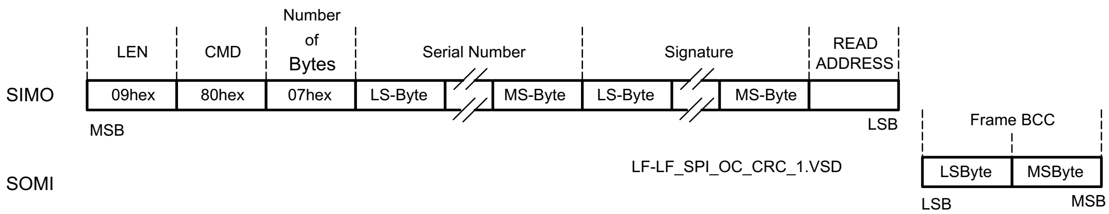


Figure 11. SPI Communication to Get Frame BCC

During a wake-up sequence, only one channel is initially selected. For the RSSI measurement to occur on all three channels, the unselected channels must be temporarily activated (see Figure 12).

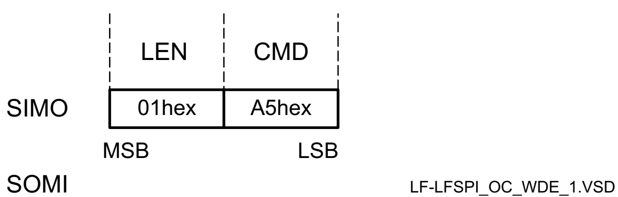


Figure 12. SPI Communication to Switch on Unselected Channels

To determine the strongest receive channel, the RSSI signals have to be switched to the RSSI output, one after the other (see Figure 13). The strongest channel has the lowest output voltage. After all measurements are completed, the RSSI output and the unselected channels must be switched off again (see Figure 13 and Figure 14).

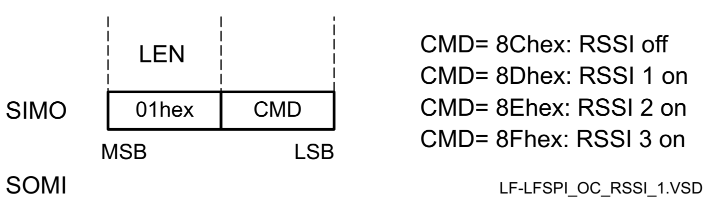


Figure 13. SPI Communication to Activate and Deactivate RSSI Output

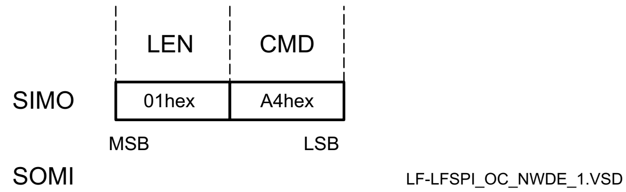


Figure 14. SPI Communication to Switch Off Unselected Channels

9 Transmitter Voltages

The voltages of the series-resonant circuit can easily reach over 150 Vp-p depending on the quality factors of both the caps and coils, and the driver strength; therefore, appropriate capacitors for CR1A - CR3A and CM1A - CM3A (Figure 4) have to be selected with high breakdown voltages and good RF performance (high Q, low ESR). To avoid these issues, as well as temperature drift, C0G and NP0 caps must be chosen.

The MOSFETs used for *modulation* must be able to withstand the full peak-to-peak voltage during a *zero* transmission. This is because when the MOSFET is turned off, its intrinsic source-drain diode shifts the 150 Vp-p waveform up and makes it 150 Vpeak-to-zero at the MOSFETs drain and at the caps. When turned on during ‘one’ transmission, it sees about 15 mA of peak current.

A coil driver made from MOSFETs has one big advantage over bipolar drivers when 3-stated. Any parasitic voltage greater than +VBAT plus two diode drops that is coupled into the idle antennas from the driven antenna is clamped to either GND or +VBAT through the MOSFET’s intrinsic clamp diodes. This avoids voltage overstressing of the MOSFETs. If using bipolars, an external clamp diode for each driver transistor should be provided, and these diodes are essential if using bipolar transistors for the modulation circuit.

The driver MOSFETs can be rated for 10 V or so with a current rating of 100 mA. And a gate-source threshold voltage ($V_{GS(th)}$) of 2 V or less is essential for when the fob battery nears the end-of-life.

10 Software Overview

The demo software for the fob is designed to aid in the debug of the LF-LF system. It is not intended as production code, but rather it demos all the critical functions like 40-bit authentication, low-power mode entry and exit, and hand shaking with the basestation.

The two pushbuttons S1 and S2 are programmed for diagnostic purposes. The ‘Z’ antenna refers to Figure 25 transmitter antenna, A2.

- While S1 is depressed, the fob wakes and transmits 121.2 KHz on the ‘Z’ antenna.
- While S2 is depressed, the fob wakes and transmits 133.3 KHz on the ‘Z’ antenna.
- While both S1 and S2 are depressed, an alternating pattern of ‘zero’ and ‘one’ is transmitted on the ‘Z’ antenna.

For detailed software flowcharts and matching fob demo code, see Appendix C and the Code Composer Studio project that is provided inside the *Transponder Source Code for CCS4.x* folder in the associated zip file.

Figure 15 shows the basic software flow for both the basestation and the fob. This flow implies that 40-bit authentication (encryption) is being used. The 40-bit authentication is public-domain and can be freely used; however, if your application requires 80-bit encryption, contact your TI field sales office. The details and proprietary algorithms of TI’s 80-bit encryption system and its usage can only be disclosed under the Non-Disclosure Agreement (NDA).

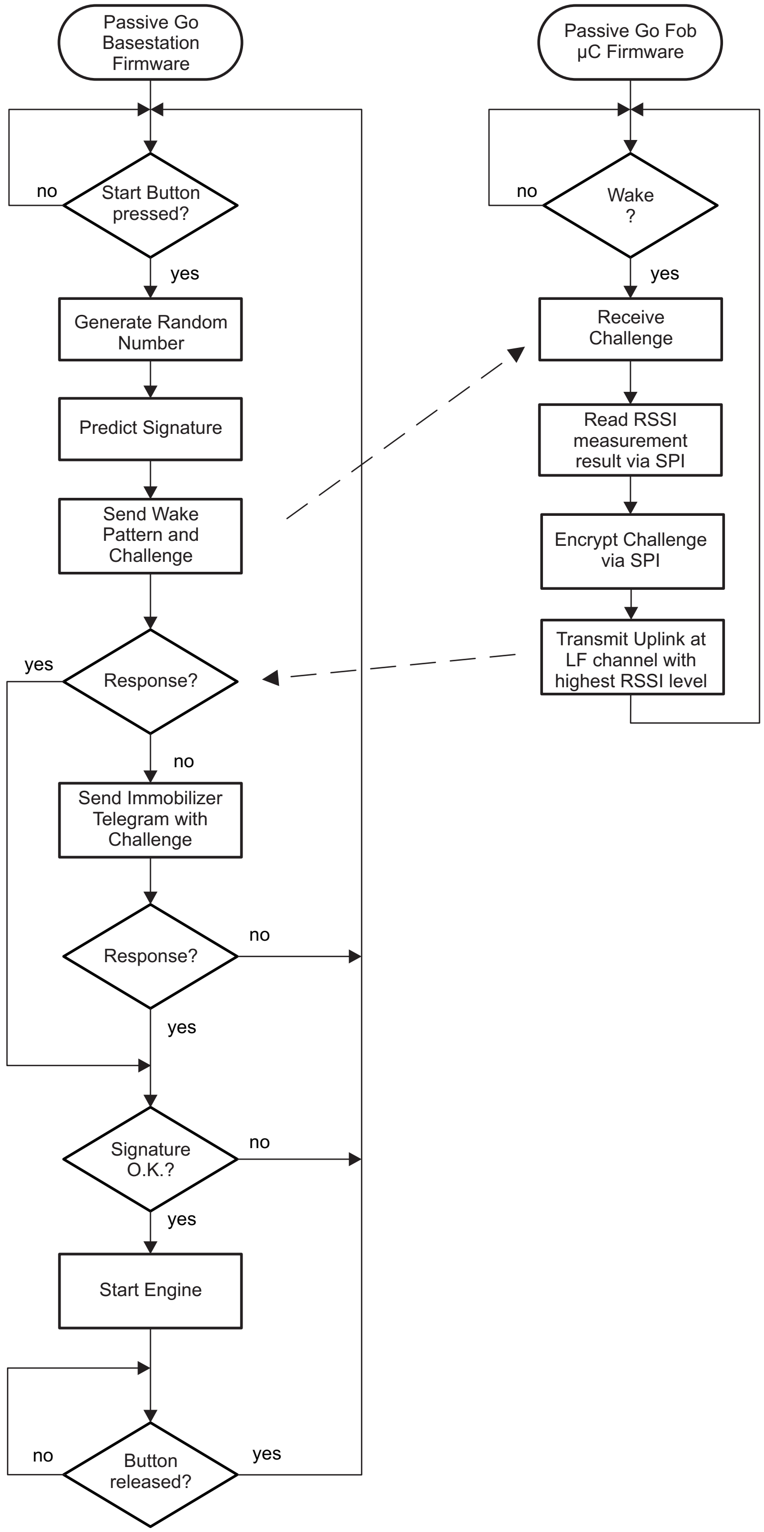


Figure 15. Flowcharts of Basestation and Fob Firmware

11 Important Parameters

11.1 Important Specification Characteristics

The TMS37126 device has several parameters and functions that must be taken into consideration for power stage design:

- Input capacitance CRFx (all trimming capacitances switched off)
- Sum of the trimming capacitances (CT)
- Modulation capacitance (CM)

Table 1 shows important characteristics of the RAID device.

Table 1. Important Characteristics of TMS37126

PARAMETER	SIGN	NOTE	MIN	NOM	MAX	UNIT
Input Capacitance	CRF1	All CTx = off	23	27	31.1	pF
Input Capacitance	CRF2	All CTx = off	11.9	14	16.1	pF
Input Capacitance	CRF3	All CTx = off	11.9	14	16.1	pF
Maximum Trimming Capacitor (CT = CT1+ CT2....+ CT7)	CT	All CTx = on	63.5	74.7	85.9	pF
Modulation Capacitance	CM	LR = 4.6mH	50	60	70	pF
Low Bit Transmit Frequency	fL	25 °C, Qop = 30..100	132	134.7	136.5	kHz
High Bit Transmit Frequency	fH	25 °C, Qop = 30..100	120	123.7	126.5	kHz
Wake Sensitivity, Antennas 1,2,3	VwakeA, 1,2,3	Configured to highest sensitivity, VBAT = 2.8 V, WDEEN = 2.8 V, t_{WAKE} = 2 ms, 25°C	3.8	4.9	6	mVpp
Rise and fall time	t_r, t_f	COL = 10 pF, RL = 100 kÙ, VBAT = 1.8…3.6 V, WAKE, EOBA, CLKA and CLKM, BUSY	50		500	ns

11.2 Important Recommended Operating Conditions

Table 2 includes the important recommended operating conditions of the TMS37126 and TMS37128D3.

Table 2. Important Recommended Operating Conditions of TMS37126

SYMBOL	PARAMETER	NOTE	MIN	NOM	MAX	UNIT
LR	Antenna Inductance (ΔLR = ±2.9%)	25°C, f = 134.2 kHz, CR=250 pF ± 2%	4.37	4.5	4.6	mH
CR	Resonant Circuit Capacitor (ΔCR = ±2%)		245	250	255	pF
f_{RES}	Resonant Circuit Frequency	25°C	134.1	134.2	134.3	kHz

12 Calculations

A detailed paper on the theory of and providing example calculations for all the antennas discussed above is the *LF-LF Demonstration System Calculations.pdf*, which is included in the associated zip file.

For additional information, there is an excellent discussion on *Electrically Small Loops* that can be found in the following source: Loop Antennas, by Glenn S. Smith, Georgia Institue of Technology.

13 Transponder Setup and Checkout

The following sections detail the steps to setup and test the transponder board.

NOTE: Work surfaces with anti-static mats significantly interfere with the communications distance when testing. The ADR2 and transponder should either be elevated above the mat about 20 cm or tested on a non-metallic work surface with no anti-static mat to achieve expected results.

13.1 Setting up the ADR2 Reader (Basestation) and Antenna

The ADR2 reader was not designed to be an LF-LF basestation but can be modified to work as one using the larger antennas and a 12 V power source. Figure 16 shows the following modifications that need to be performed on the ADR2 Reader board.

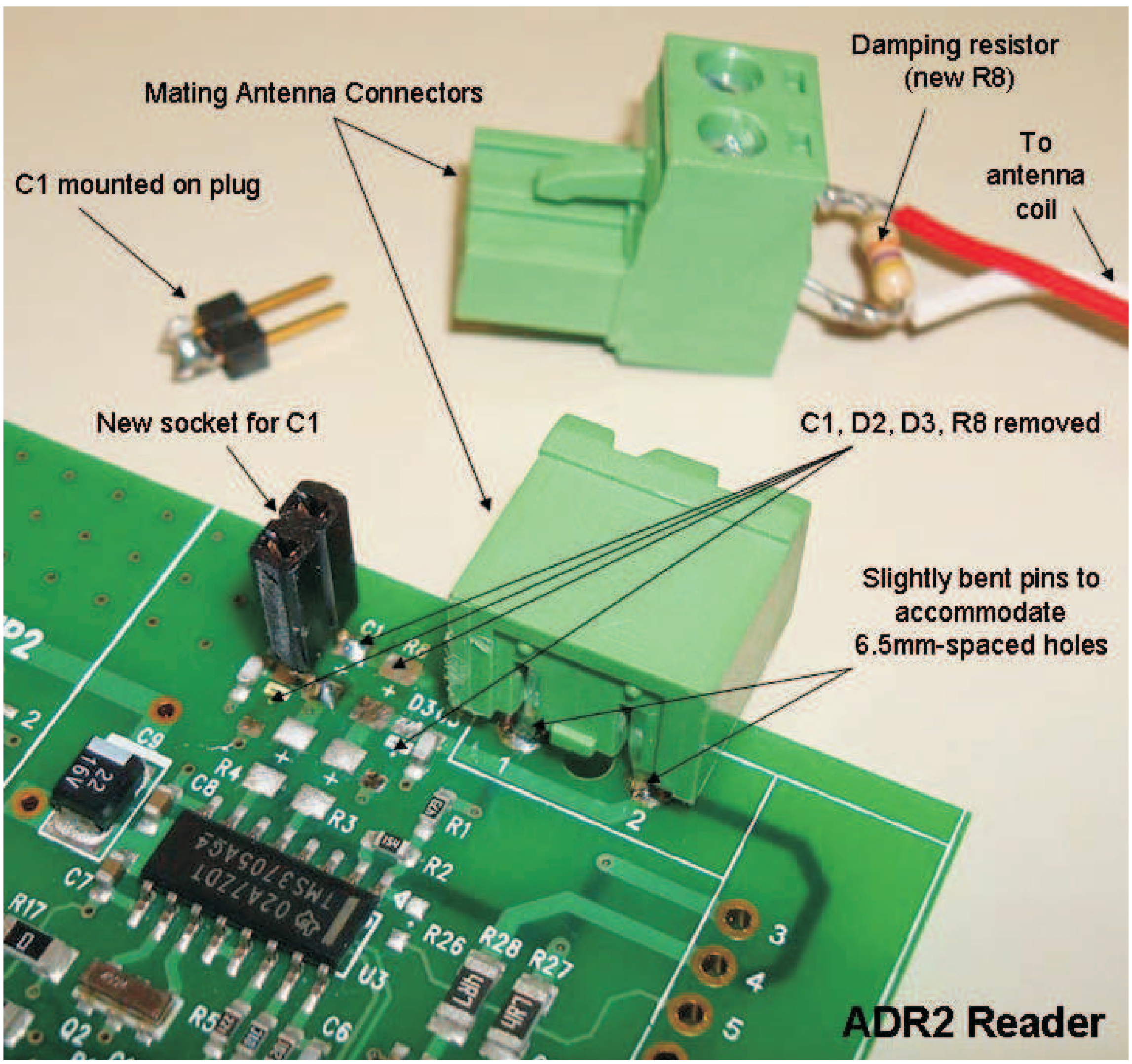
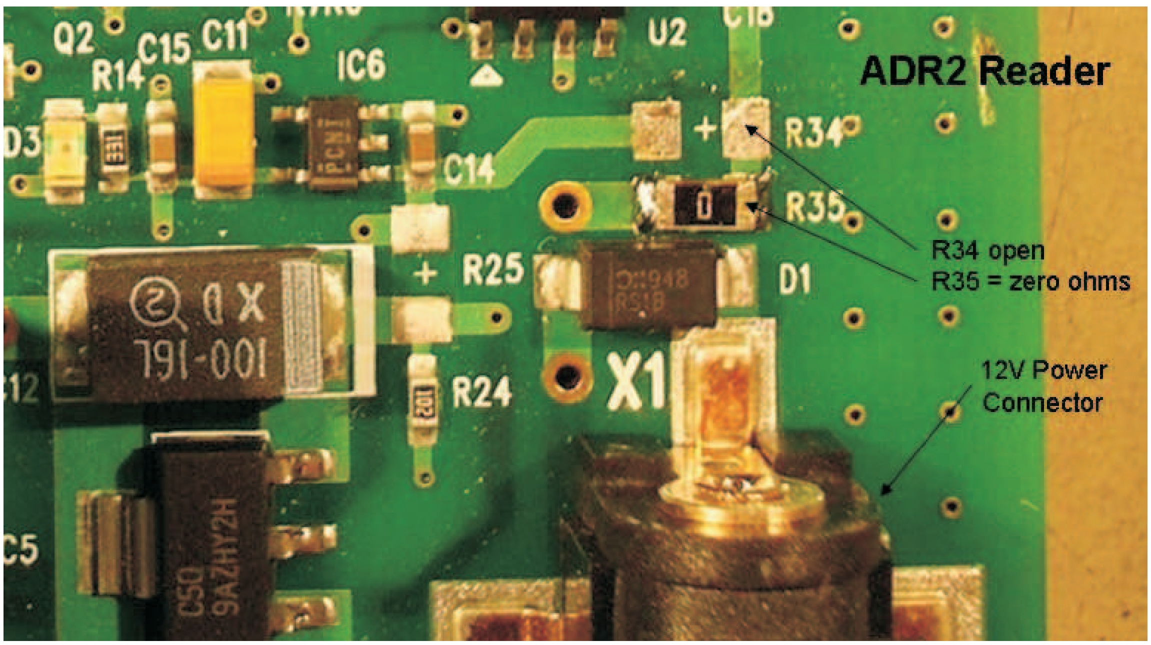


Figure 16. ADR2 Reader Board Modifications

- Remove zener diodes D2 and D3. They are currently 6.2 V and cannot handle the 12 V drive to the resonant circuit. If the extended ESD protection provided by the diodes is desired, these diodes can be replaced with 15 V zeners, MMSZ4702T1 or equivalent.

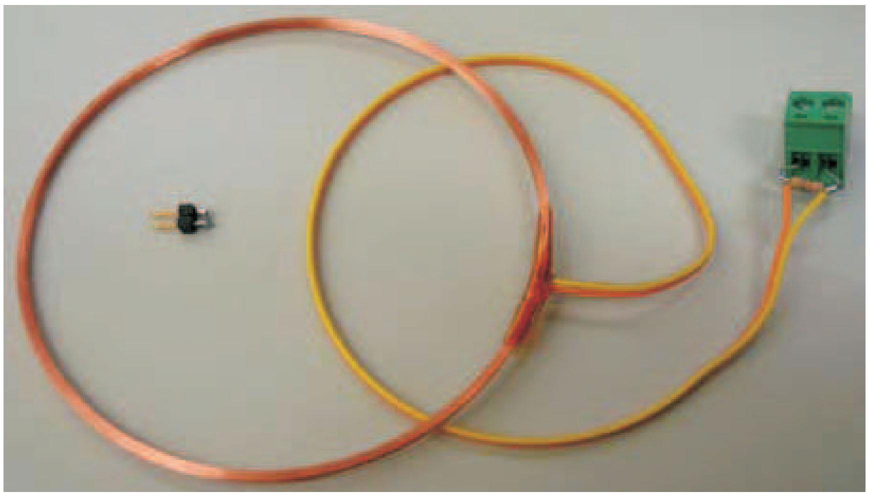
- Remove the 15 KΩ resistor, R8. This resistor is the proper value for the small air coil antenna that comes with the ADR2 reader, but the resistor is not used here. The proper damping resistor for the selected coil has already been soldered across the coil leads. This resistor is needed to reduce the quality factor (Q) of the coil to around 10. If the original air coil is to be used later, solder a 15 KΩ axial resistor across its leads.
- Remove 3.3 nF capacitor C1 and replace it with a 2 pin socket. This capacitor can be soldered to a pair of male pins in case the original air coil is to be used later.
- Adding a male connector block to the board and a matching female connector to each antenna coil to be tested is recommended. While there does not seem to be a terminal block header with a 6.5 mm pin pitch, a little bending on the thru-hole pins of a 5.08 mm header (Wurth Electronics, part# 691313510002) works reasonably well.
- Check R34 and R35. Make sure R34 is open and R35 is 0 Ω. The production ADR2 board is shipped so that it works from USB 5 V, but this needs to be changed to 12 V in order to achieve the expected range.



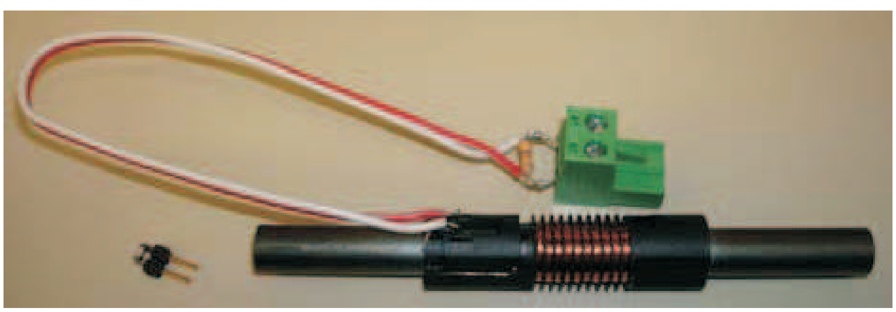
For the antennas, if the Wurth header was mounted on the ADR2 board, then a matching screw-type terminal block plug (Wurth Electronics, part# 691351500002) can be screwed to each antenna to be tested, making antenna-swapping relatively painless. Screw the plug to the antenna leads with the damping resistor already soldered across them.

Each time one antenna is swapped with another, the matching plug-in capacitor must also be swapped. Keep the coil and matching cap together to avoid confusing them. If this happens, the resonant frequency will be significantly shifted and the resulting distance will be poor.

- The 9.3 cm diameter, 2.29 mH, air coil uses:
  - 68 KΩ damping resistor
  - 560 pF || 47 pF caps (607 pF total) mounted to a 2-pin connector



- The 10 cm long, 2.56 mH, ferrite antenna uses:
  - 47 KΩ damping resistor
  - 560 pF || 33 pF caps (593 pF total) mounted to a 2-pin connector



- The original 4 cm diameter, 440 µH, ADR2 air coil antenna uses:
  - 15 KΩ damping resistor
  - 3300 pF cap mounted to a 2-pin connector

13.2 Demo Code Installation

It is necessary to download the demo code to the transponder now that the basic hardware modifications have been made to the basestation. To do this, follow these steps:

1. Install either Code Composer Studio ver 4.2.x for MSP430 or IAR Imbedded Workbench™ for MSP430 KickStart Addition according to the instructions found at the installation site.
2. Connect the MSP430 USB Debug Interface to a USB port.
3. Install the CR2032 battery into the transponder.
4. Set the LED jumper to the 'W' position as shown in Figure 17. The LED will blink when the transponder receives a large-enough in-band signal to trigger the WAKE signal.
5. Set the power jumper on the transponder board to the BAT position as shown in Figure 17.
6. Connect the 14-pin JTAG ribbon cable to the transponder.

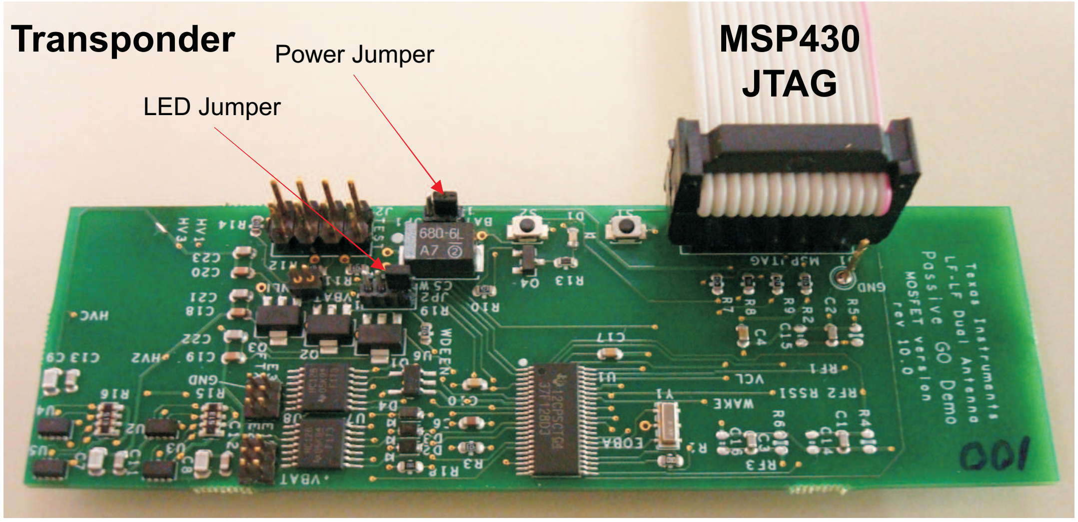


Figure 17. Transponder

7. Load the demo code into Code Composer Studio or IAR™, compile it if necessary, and download it to the transponder. The transponder comes pre-loaded with the demo code.
8. Disconnect the JTAG cable for now, assuming the demo code downloads properly.

13.3 System Hardware Setup

1. Connect a 12 V power supply to one end of the power cable (red lead positive) and plug the other end into the 2.5 mm power jack (center positive) on the ADR2 reader. The red LEDs (LED1, 2, 3) on the ADR2 should light.
2. Connect a USB cable from the host PC to the ADR2 mini-USB connector. The LED1 should go off after the USB hub enumerates the port.
3. Plug the antenna into the ADR2 antenna connector.
4. Plug the matching cap into the female connector installed at C1.
5. Connect the PTB to an RS-232 port on the host PC. If needed, the USB-to-RS232 adapters work well with the PTB. If you have the newer PTB2, it is USB-based.
6. Connect the PTB's 8-pin ribbon cable to the test port on the transponder board.

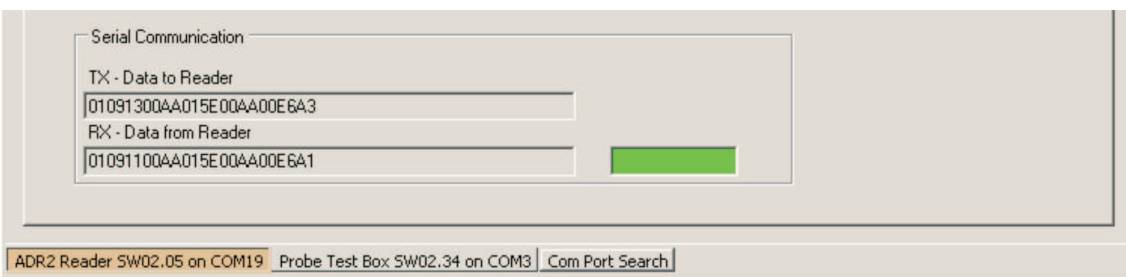
13.4 Host Software Installation

1. Install the RFID Demo Software on the Host PC to control the ADR2 as a basestation.
2. Install the Automotive Demo Tool on the Host PC to modify the transponder configuration via the PTB.

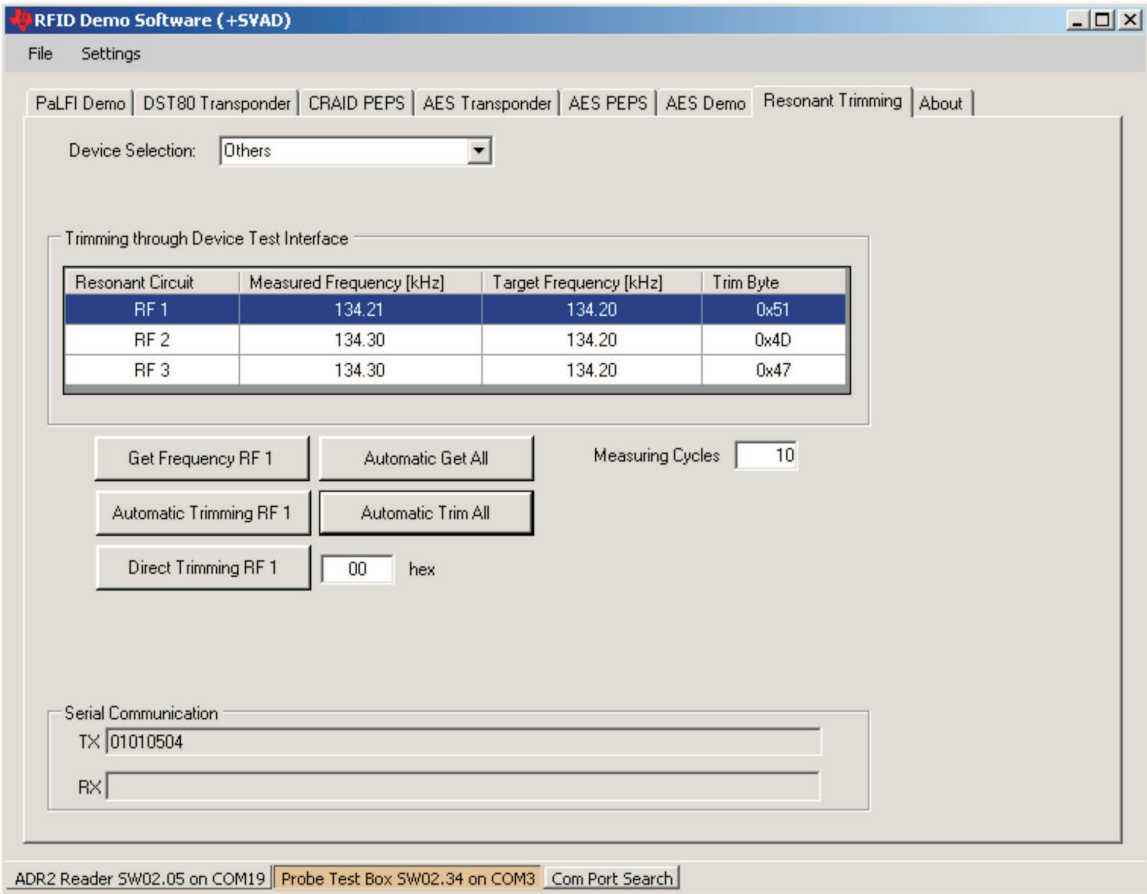
13.5 Transponder Receiver and Immobilizer Antenna Trimming

With the PTB connected, execute the RFID Demo Software installed above.

1. Examine the status bar at the bottom of the GUI. It should list the ADR2 Reader and the Probe Test Box, which are command buttons used to select the appropriate hardware.



2. Click on *Probe Text Box…* on the status bar to select PTB as the hardware to control; take note of the Com Port being used (for later).
3. Click on the *Resonant Trimming* tab at the top of the GUI.
4. Click *Automatic Get All*.. The *Measured Frequency [kHz]* column should fill in for all three antennas: RF1 through RF3. If trimming has not been previously performed on this board, then the numbers represent the untrimmed frequencies. They should all be at or above 134.2 KHz.
5. Click *Automatic Trim All*.
6. After a few seconds, the *Measured Frequency [kHz]* column should fill in for all three antennas with values near 134.20. If any antenna in the column says, infinity or zero, there is either a connection problem with the antennas on the transponder or the voltage to the PTB may be too low.

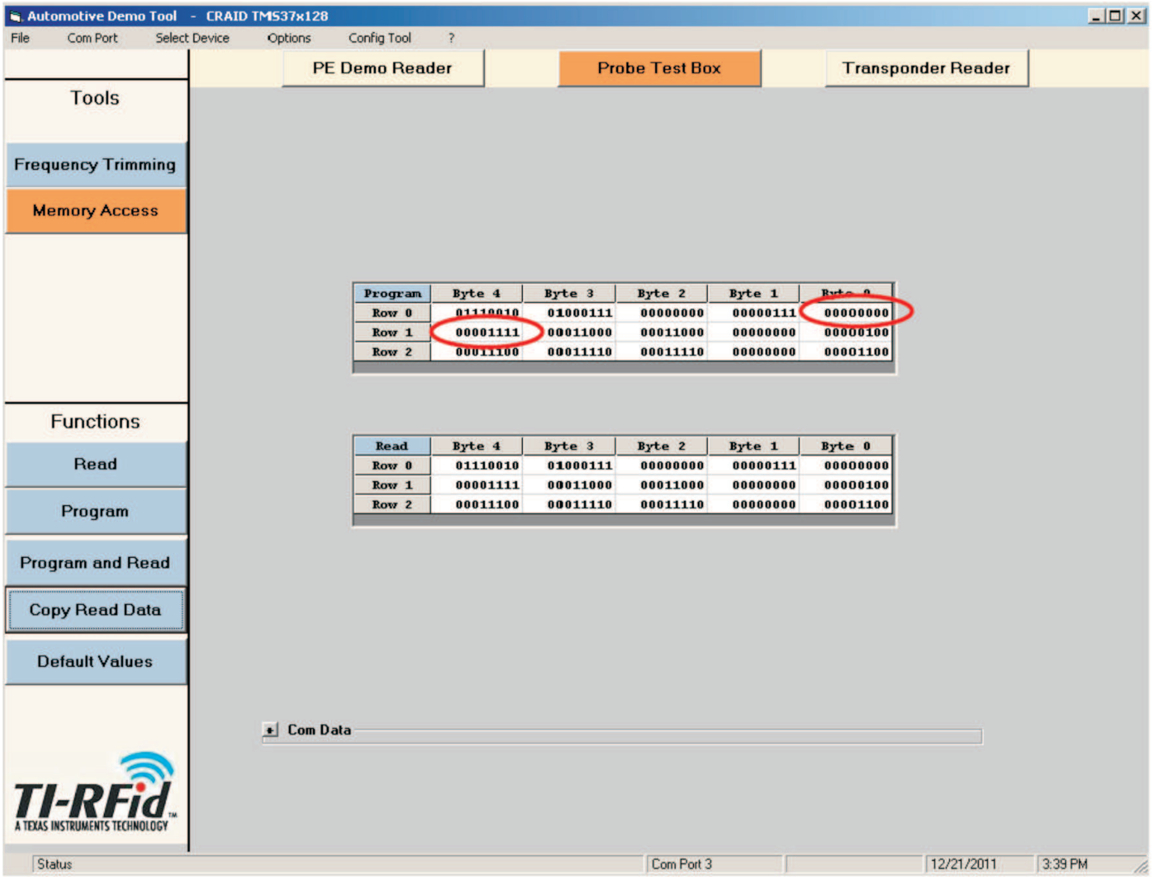


7. Note the values in the *Trim Byte* column if the frequencies are within ±100 Hz of correct. The hexadecimal numbers (between 0 and 0x7F) will ideally be in the center of the range or around 0x40 indicating the best manufacturing margin. If the number is too near zero, it may be necessary to reduce the capacitance on C1 and C14 or C2 and C15 or C3 and C16 by as much as 35 pF. Conversely, if the number is too close to 0x7F, the caps may need to be increased by as much as 35 pF. The demo transponder has already been trimmed.

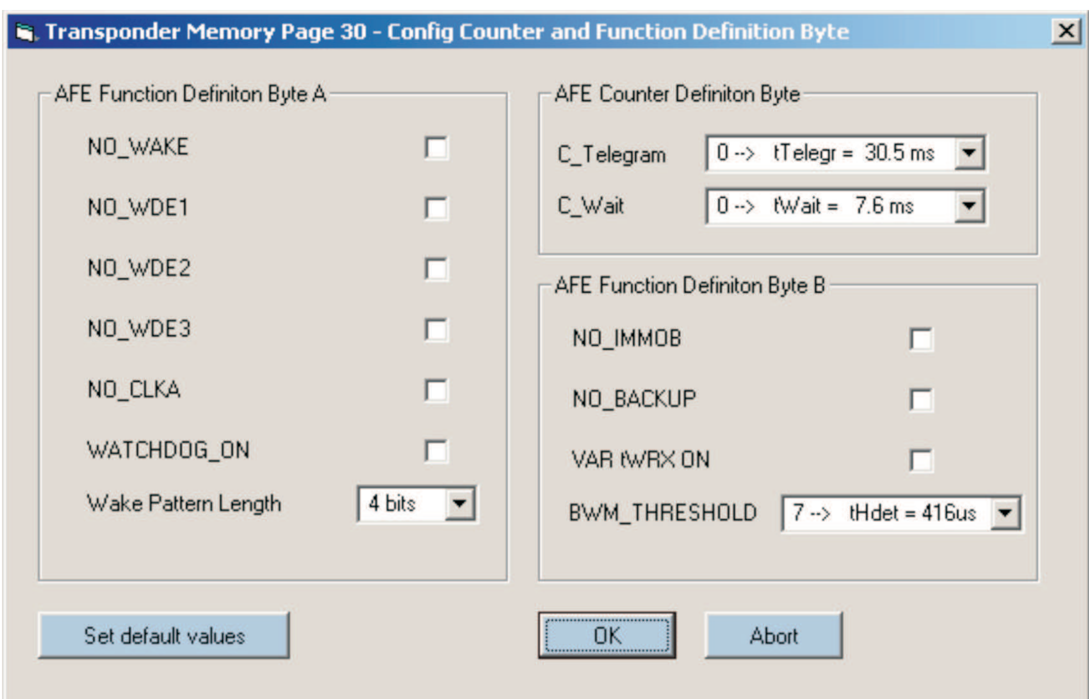
13.6 Transponder Memory Modification

With the PTB connected to the transponder, close the RFID Demo Software and execute the Automotive Demo Tool.

1. Click on the *Probe Text Box* tab at the top of the GUI. It may be necessary to click on *Com Port* (top-left corner) and manually set the port number using the number noted in Section 13.5.
2. Select *Device* as *CRAID TMS37x128*.
3. Click on the *Memory Access* tab under *Tools* along the left column. There are 15 bytes of data displayed in each of the two windows. The upper window is initially filled with the default memory values and the lower window is empty.
4. Under *Functions* in the left column, click *Read*. The lower window will fill with the data read from the TMS37F128 device on the transponder (assuming the 8-pin PTB cable is plugged in, the PTB is powered, and the Com Port is properly configured).
5. Click *Copy Read Data*. The contents of the lower window will be copied to the upper window.

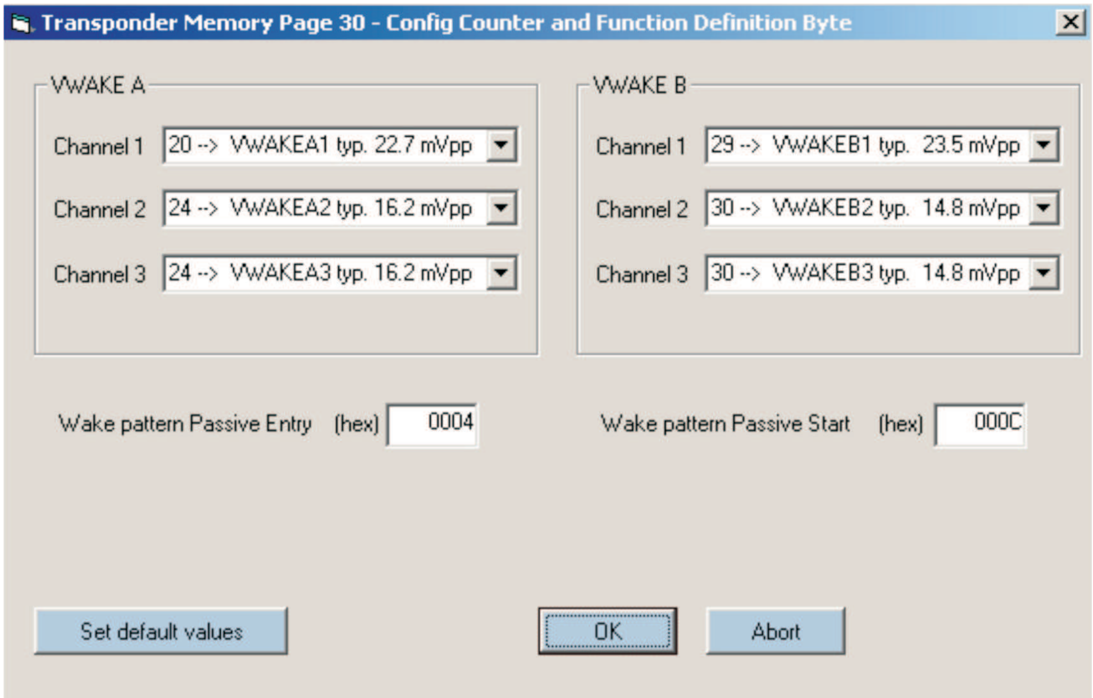


6. In the upper *Program* window, double-click the table entry at Row 0 and Byte 0 (that's the upper right-hand byte). A new window (shown below) will appear.



7. Deselect all the check boxes in the left column.

8. In the *Wake Pattern Length* drop-down select “4 bits”.
9. In the right column, setup the three drop-downs as shown above.
10. Uncheck all check boxes on the right.
11. Leave the window by clicking OK.
12. In the upper *Program* window, double-click the table entry at Row 1 and Byte 4 (that’s the center row, left-hand byte).
13. Set each of the six drop-down boxes to match the window below.

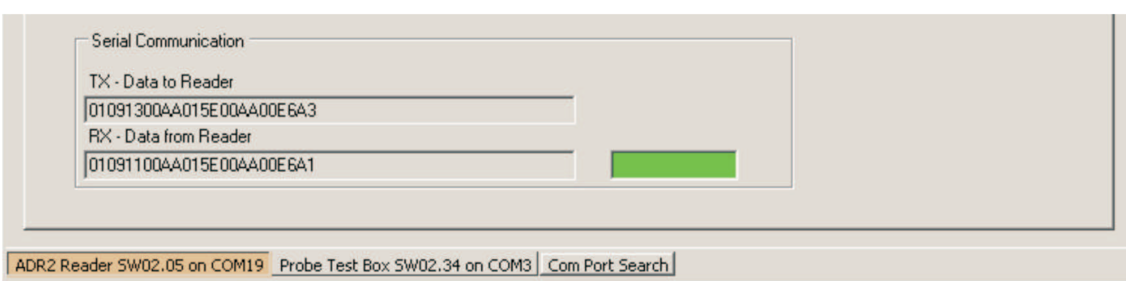


14. Set the *Wake Pattern Passive Entry* to 0004.
15. Set the *Wake Pattern Passive Start* to 000C.
16. Click OK to finish the entry.
17. Under *Functions* in the left column, click *Program and Read*. After programming the device EEPROM, the data is read back and placed in the lower window. The data in the two windows should look identical now (except for Row 0 Byte 3 and 4).

13.7 Setup Procedure

Once the RFID Demo Software is installed on the Host PC, it is necessary to configure it one time so that it controls the basestation properly for use with the transponder. Start the software (there should be a desktop icon) and follow the procedures below:

1. Examine the status bar at the bottom of the GUI. It should list the ADR2 Reader and the Probe Test Box. These are command buttons used to select the appropriate hardware.



2. Select the *DST80 Transponder* tab at the top.
3. Click on *Settings* at the top-left corner of the GUI.
4. Setup all the entries as shown in Figure 18 when the page below appears:
5. Be sure to select the *PPM* radio button in the ‘Coding’ area.
6. Confirm with *Transfer Settings* and *Finished*, once all changes are verified.

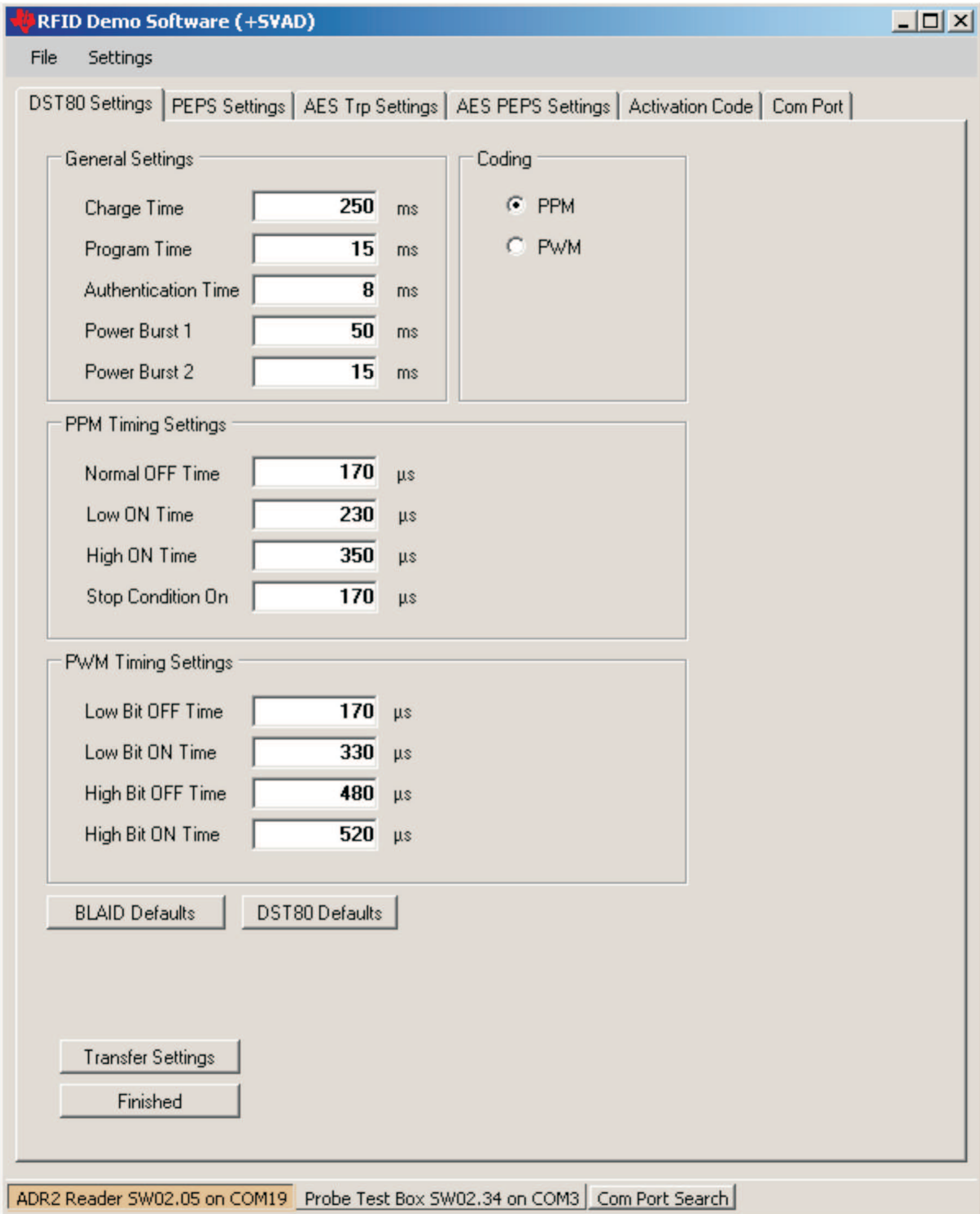


Figure 18. RFID Demo Software (DTS80 Defaults)

7. Select the *CRAID PEPS* tab.
8. Select *Settings* at the top-left corner of the GUI. The *PEPS Settings* window should appear.

9. Setup all of the entries as shown in Figure 19.
10. Confirm with *Transfer Settings* and *Finished*, once all changes are verified.

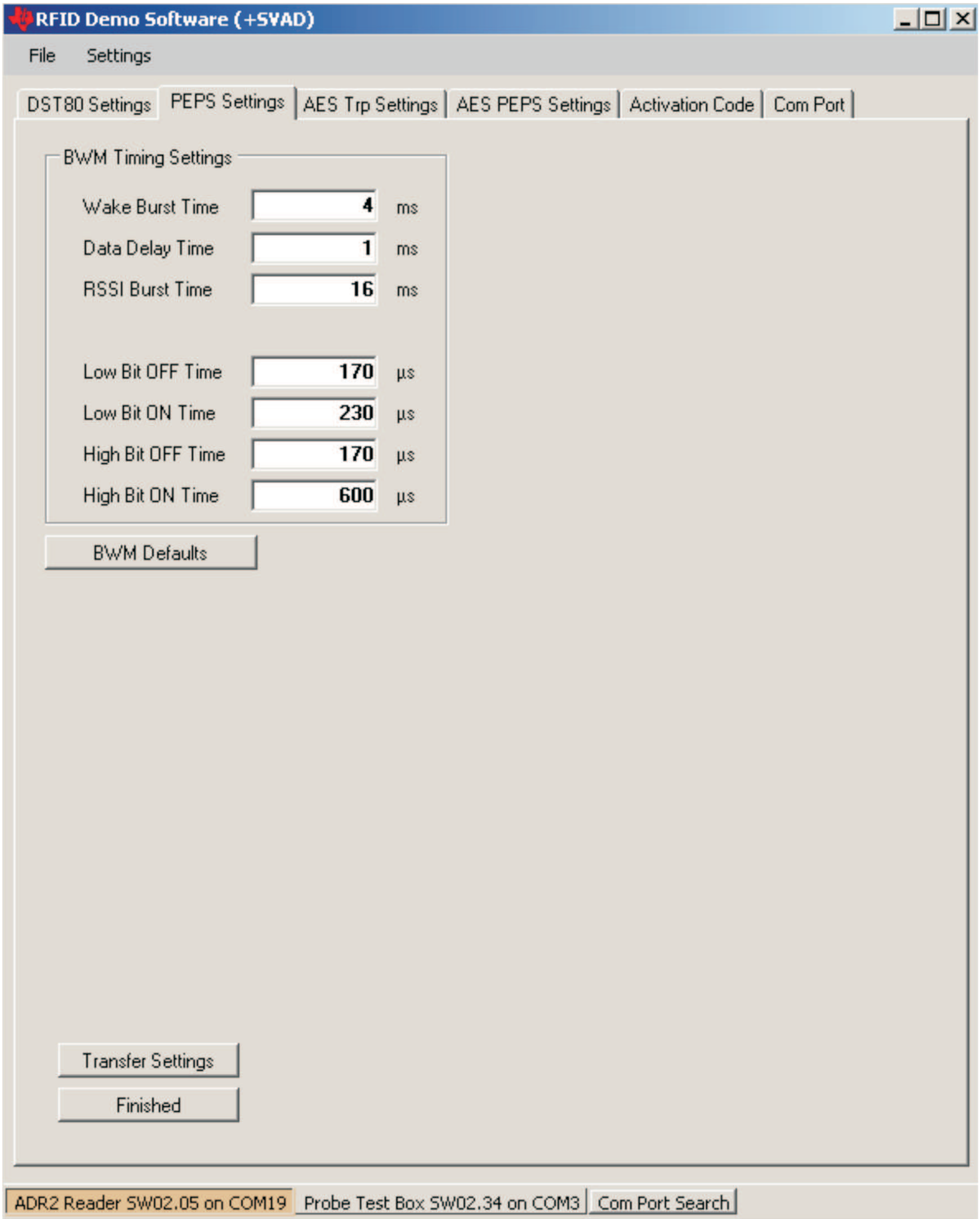


Figure 19. RFID Demo Software (BWM Defaults)

11. Select the *CRAID PEPS* tab as shown in Figure 20.
    - Configure field *Wake Pattern A* to:
      – Wake Pattern Length: 4
      – Wake Pattern: 4
      – Additional Data: C212345678 (Challenge)
    - Configure field *Wake Pattern B* to:
      – Wake Pattern Length: 4
      – Wake Pattern: C
      – Additional Data: 5555555555 ← there are ten ‘5’s (Challenge)
    - Configure *Telegram Mode* to:
      – Click the radio button *LF Response*
      – Click the check box *continuous transmission* for a transmission burst at approximately 1 second intervals (if desired).
12. Click the button *Send Wake Pattern A String* under *Commands*. If the transponder board is still powered and in communication range and if the encryption key is still zero (default), then in the *Serial Communication* window, data will appear in the RX area.
13. The following data appears in the gray box below the TX and RX areas:
    - Serial number (unique number assigned to each TMS37F128)
    - Signature: CEEA8F
    - Read address: 10
    - BCC (depends on data)
14. Click the button *Send Wake Pattern B String* under *Commands*. If the encryption key is still zero, then under *Serial Communication* window, data will appear in the RX area.
15. The following data appears in the gray box below the TX and RX areas:
    - Serial number (unique number assigned to each TMS37F128)
    - Signature: 555555
    - Read address: 10
    - BCC (depends on data)

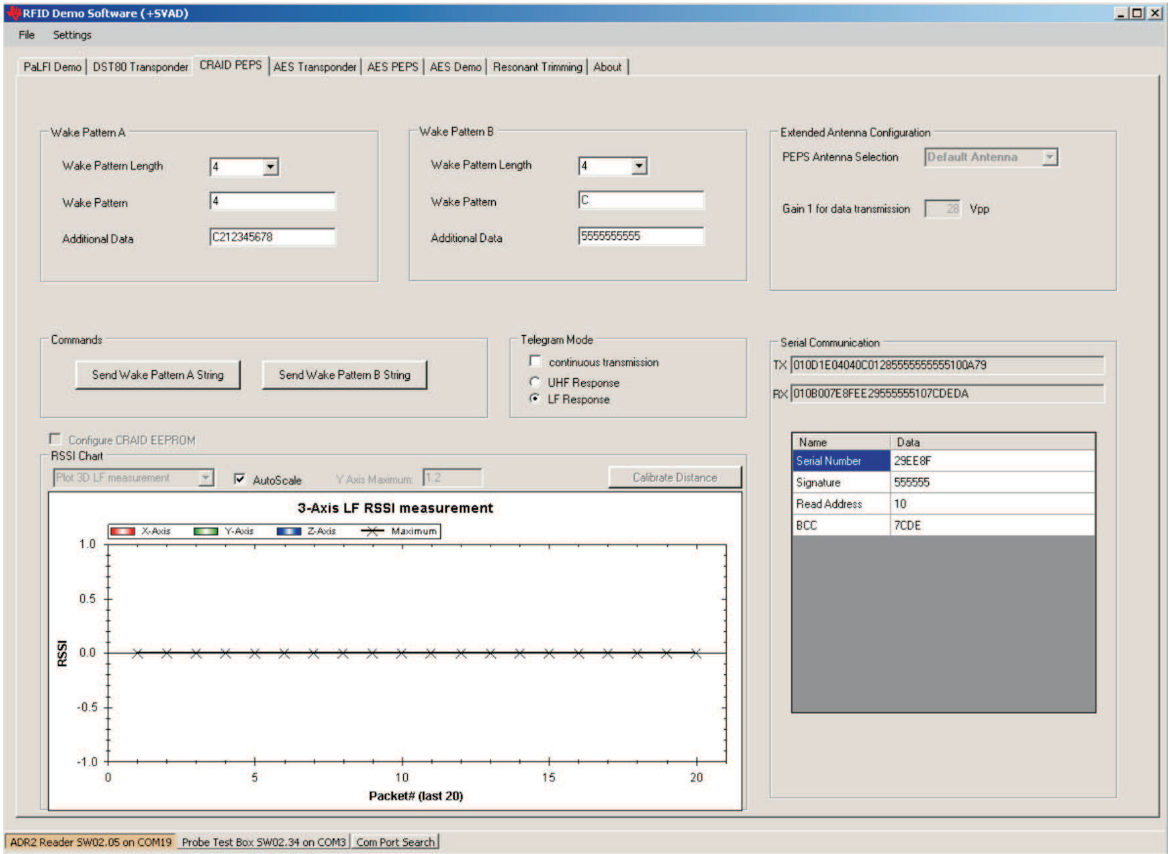


Figure 20. CRAID PEPS Tab

13.8 Testing Transmitter Resonance

Once the board has proven to work at some distance, it is necessary to check the natural resonant frequency for the three channels for both ‘one’ (121.2 KHz) and ‘zero’ (133.2 KHz) transmit frequencies. This can be done with a real-time spectrum analyzer; however, it is quite easy to test for resonance with a frequency generator and an ammeter.

The transponder has jumpers that were not previously mentioned, which make this process quite simple. Rather than writing software to properly setup the antennas for testing, it can be done by simply placing jumpers on the transponder board (see Figure 21).

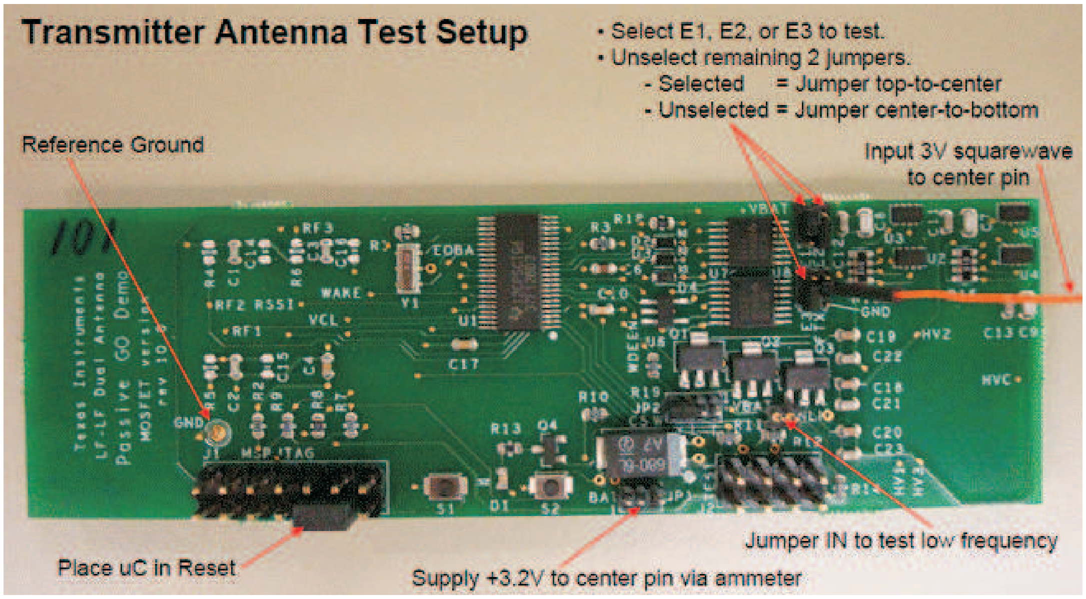


Figure 21. Transmitter Antenna Test Setup

- It is very important to disable the uC before installing other jumpers. Place a 0.1” jumper plug on J1 (MSP JTAG connector) between pins 9 and 11 to hold nPOR low.
- There are four 3-pin jumpers labeled E1, E2, E3, and TX shown in Figure 21. E1 is associated with channel 1 (RF1, HV1, Z-axis), E2 is associated with channel 2 (RF2, HV2, Y-axis), and E3 is associated with channel 3 (RF3, HV3, X-axis). To select E1, place a 0.05” jumper between the top and center pins. You must disable channels E2 and E3 by placing two other jumpers between the center and bottom pins of E2 and E3.
- The TX jumper is used to drive in a frequency between ~110 KHz and 150 KHz (orange wire shown in Figure 21). The signal swing must be from 0 V to 3 V. Be sure to check the output swing of the frequency generator as they usually assume a 50 Ω load. Without this load, they output 2X the expected voltage, which could damage the board. The lower pin of the TX jumper can be used as the ground reference for the frequency generator, or use the large GND pin at the lower-left corner of the board.
- Connect an external power supply in series with an ammeter, and supply the center terminal of JP1 with +3.2 V. Set the ammeter to read ‘mA’.
- Drive in a frequency and monitor the supply current. As the series resonant LC circuit approaches resonance, the current will peak (typically around 44 mA). Locate the frequency at which the current is maximum. This is the natural resonant frequency of ‘transmit zero’.
- Now install a jumper plug on the 2-pin jumper labeled ‘NLI’ (actually ‘nLH’ in the schematic) located near the lower-right corner of the board. This enables the modulation capacitors for ‘transmit one’.
- Sweep the frequency and locate the peak current again. The associated frequency is the natural resonant frequency of ‘transmit one’.
- Repeat this process for E2 and E3 for both ‘zero’ and ‘one’ frequencies.

The six frequencies obtained in this procedure must be within ± 5% of ideal or the resonant and modulation caps will need to be adjusted. These errors are usually caused by parasitic capacitance and interaction between the main resonant capacitors and the modulation capacitors.

13.9 Supporting Material

Be sure to explore all the materials included in the zip file located at http://www.ti.com/lit/zip/spna147. There are theoretical formulas, Allegro schematic and layout, software source code, PC software, data sheets, and so forth.

14 References

- *MSP430x11x2, MSP430x12x2 Mixed Signal Microcontroller Data Sheet* (SLAS361)

Appendix A Circuit Schematic

Figure 22 through Figure 25 show the specific implementation of the demo transponder with comments about the different components.

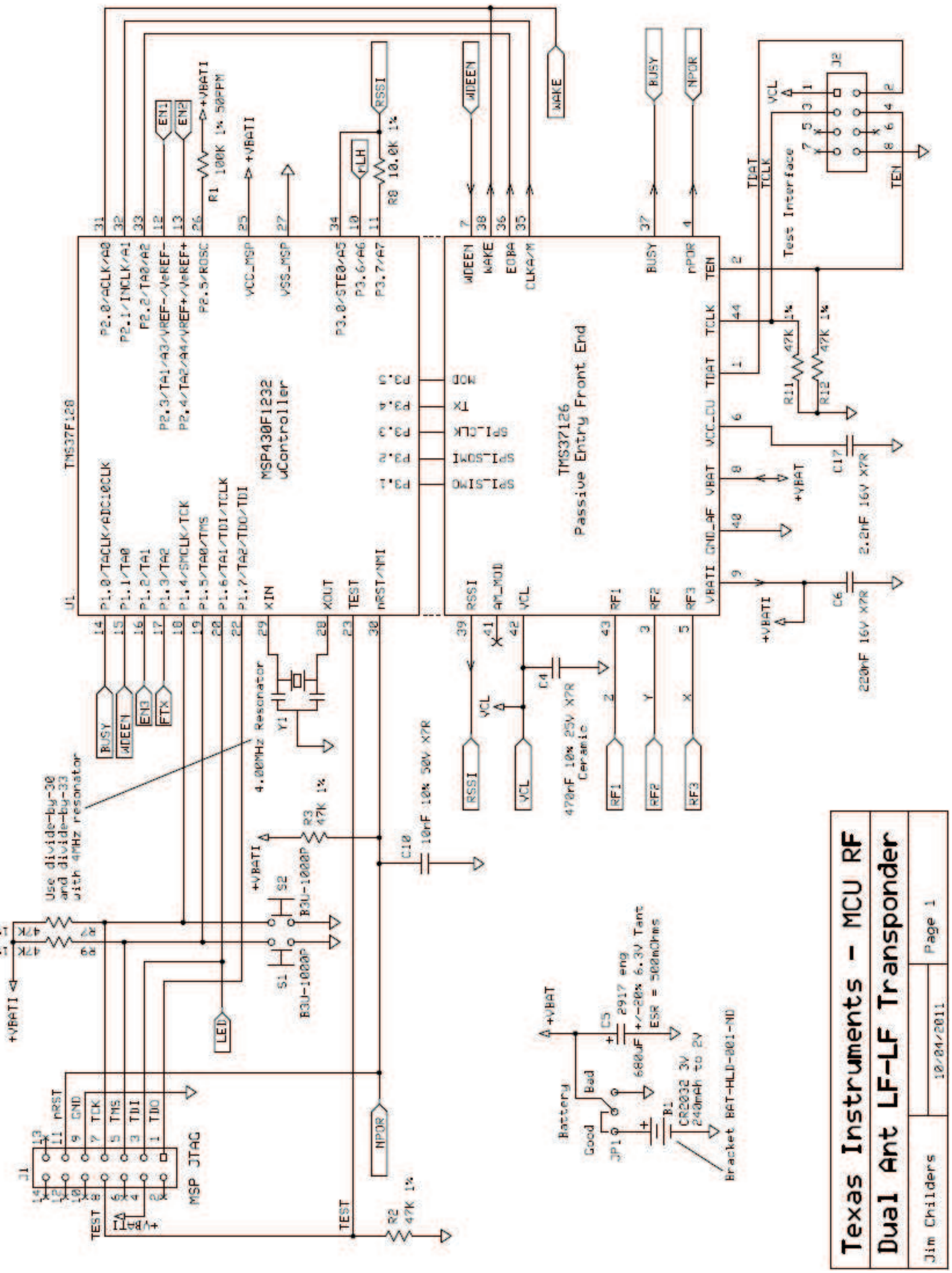


Figure 22. Fob Schematic - TMS37128 and Pushbuttons

With this wiring, the JTAG cable can remain plugged-in except when testing the pushbuttons and LED functionality. Pullups R7 and R9 are needed only for the pushbuttons.

RSSI (pin 39) is a signal-strength-dependent current sink. R8 (10.0K) is used to change this current into a voltage by driving P3.7 high and converting P3.0 with the analog-to-digital converter (ADC). After conversion, P3.7 should be driven low or floated.

JP1 is used to simulate a dead or shorted battery.

R1 is 100 KΩ 1% 50 PPM and is used to set internal references.

C5 stores energy for the transmission burst as the battery can only supply about 23 mA while the transmitter requires about 50 ma for 300 mS to achieve maximum distance. Note that C5 can be reduced to 100 µF with only minimal impact to up-link distance. An estimate of battery life assuming 10 starts per day and 25°C is over four years. Be mindful of the leakage characteristics of C5 as system leakage (and not transmission time) dominates battery life.

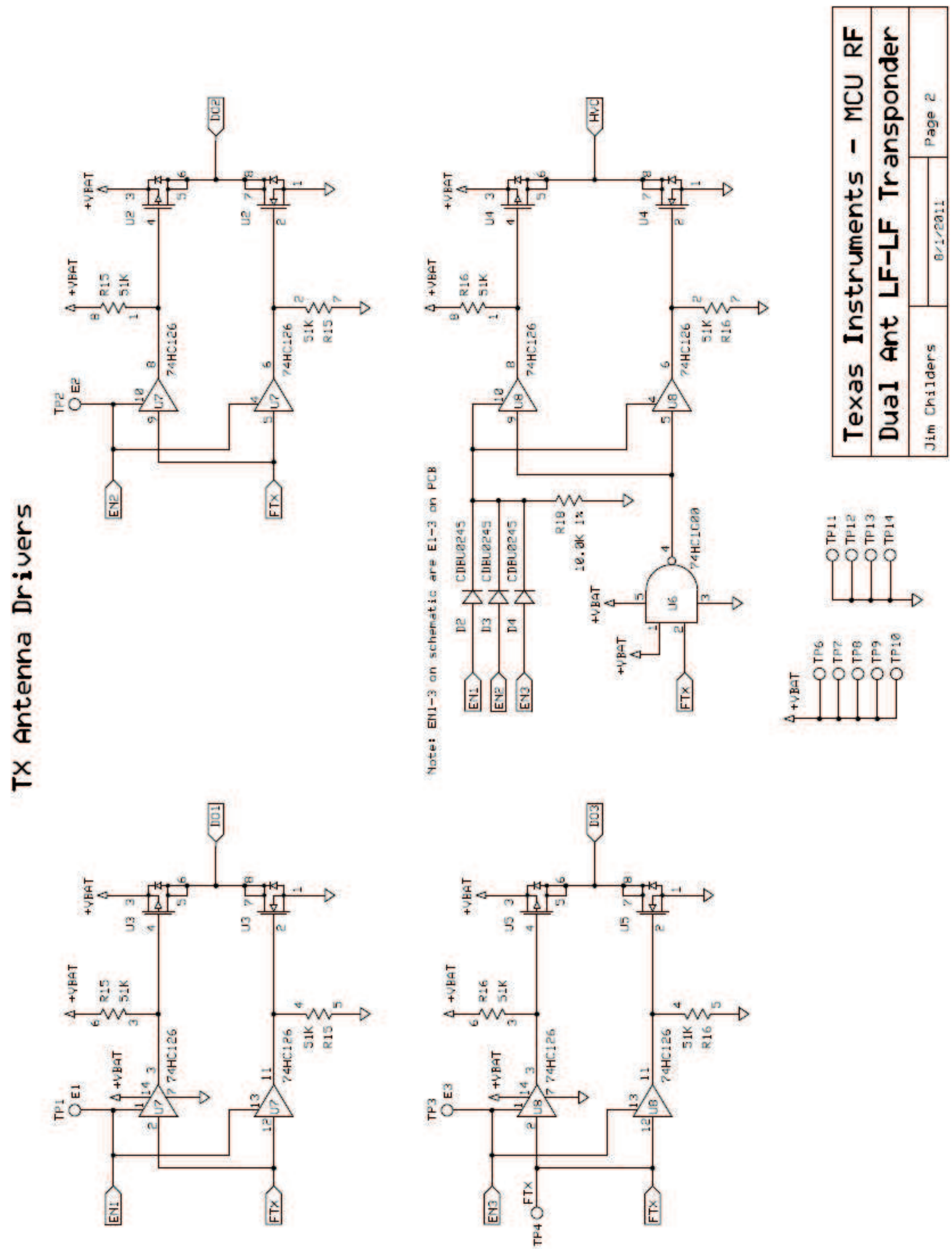


Figure 23. Fob Schematic - Drivers

U2 - U5 are N+P MOSFET pairs in a 1206-8 package and with a $V_{GS(th)}$ = 1.5 Vmax.

R15 and R16 are quad resistor packs that serve to hold the MOSFETs off when a driver is disabled (for example, when the 74HC126 is 3-stated).

D2 - D4 and R18 serve as a 3-input OR gate. Schottky diodes were used here due to the low minimum battery voltage requirement of 2 V.

The test points are configured physically to allow 0.05” jumpers to force the drivers on or off for transmitter resonance measurements. Before installing any of these jumpers, first install a 0.1” jumper between pins 9 and 11 of the JTAG connector, J1 (see Figure 22). This disables the MSP430 so its outputs do not become shorted.

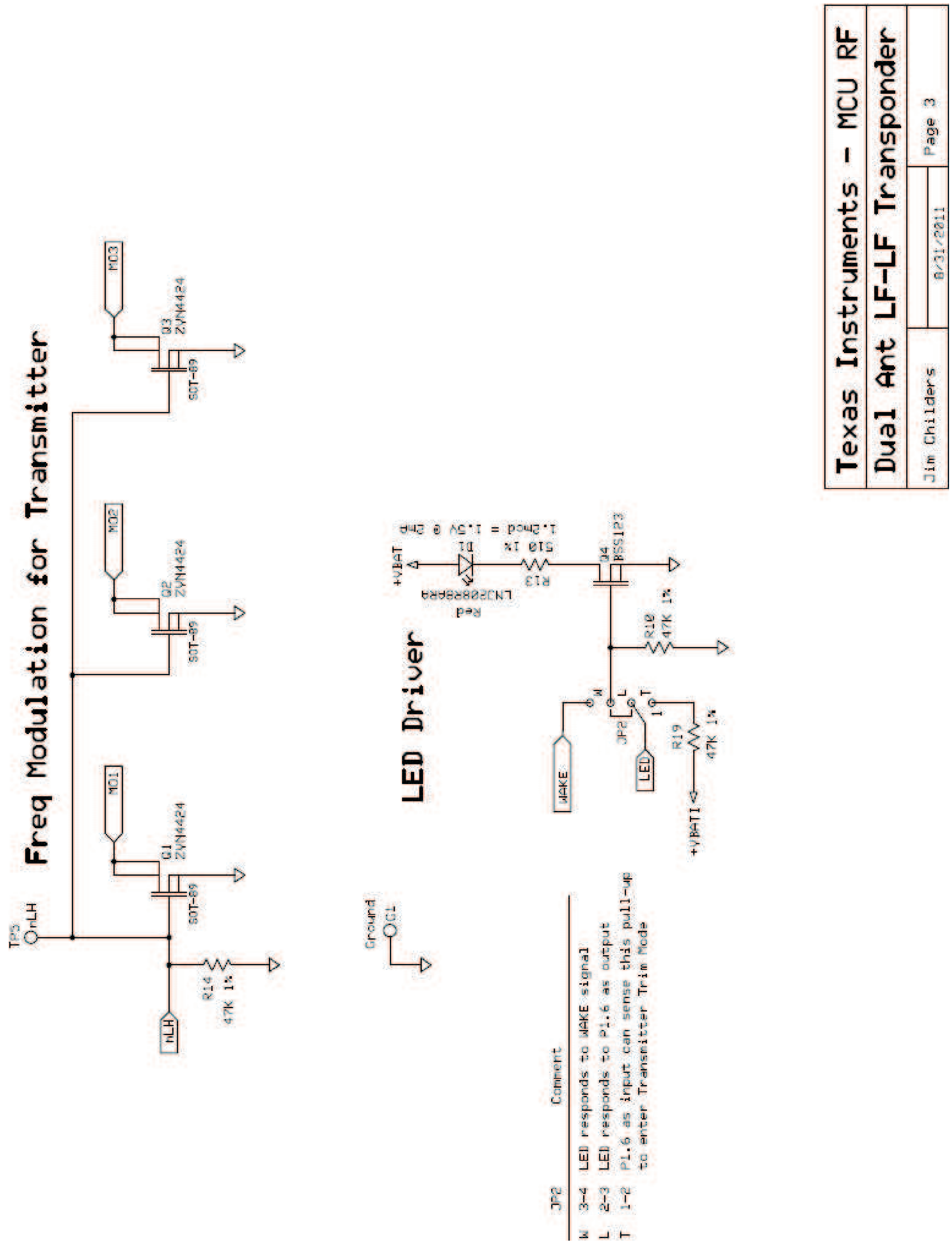


Figure 24. Fob Schematic – Modulation and LED

Q1 – Q3 are 240 V MOSFETs with a $V_{GS(th)}$ = 1.8 Vmax.

Q4 has a $V_{GS(th)}$ = 2 Vmax.

When JP2 is removed for production, hardwire the default center position.

R19 is not needed as the software test mode is not implemented.

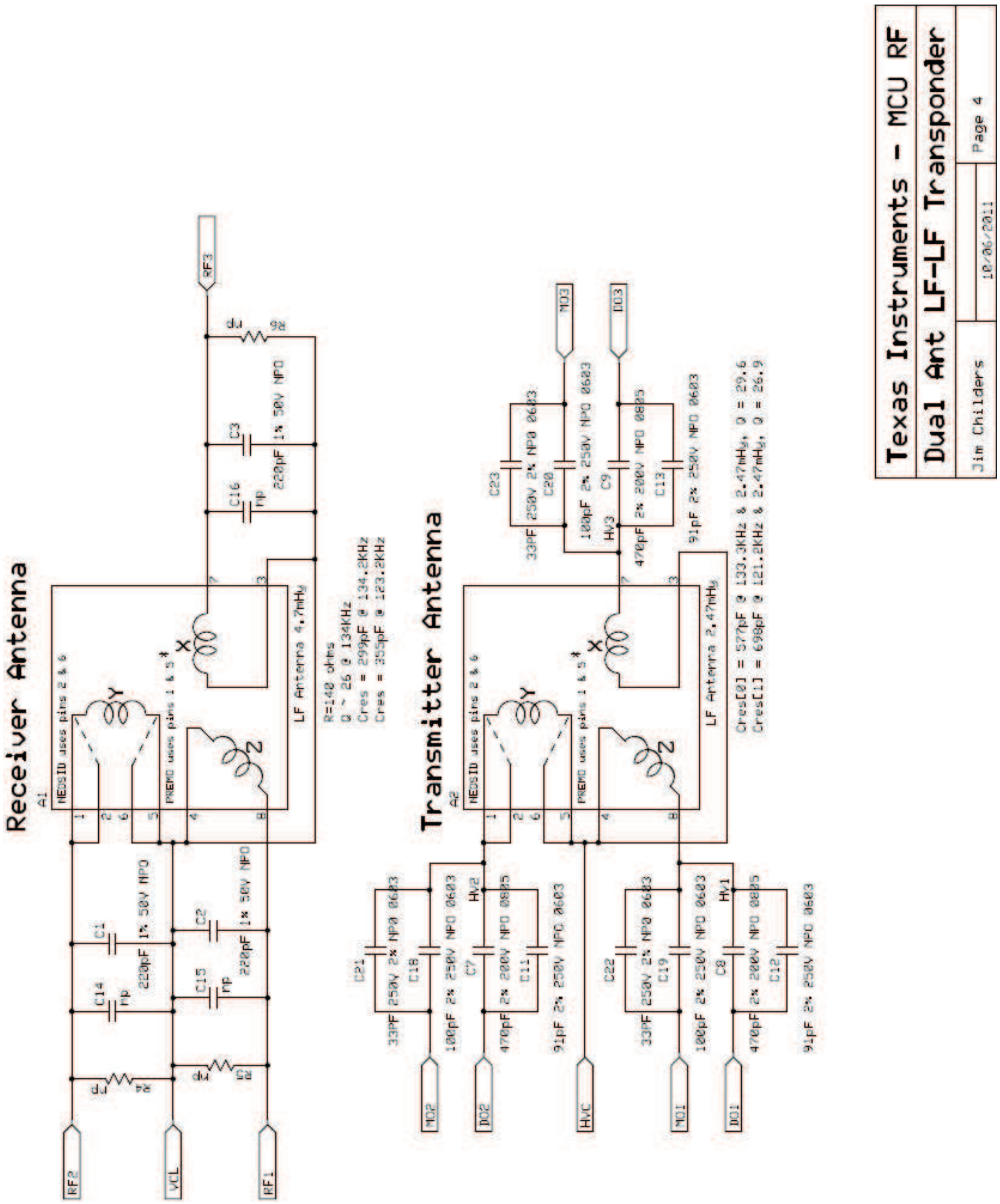


Figure 25. Fob Schematic – Antennas

The 3D receiver antenna, A1, must be around 4.7 mH for the trimming procedure to function properly over the entire tolerance range.

C1 – C3 should be 1% C0G/NP0 types and 50 V is adequate. They should be selected for a resonant frequency slightly higher than 134.2 KHz to allow for trimming. Be sure to consider board parasitics and the input pin capacitance of RF1 – RF3 (listed in Table 3). The 7-bit internal trim capacitor range is 0 to 75 pF nominally so this trim range has to overlap the tolerance range of the inductor and capacitor.

R4 – R6 are only needed if the Q of the circuit is too high. Very high Q coils can make it difficult to transition between bits as it takes too long for the resonant energy to decay, ultimately impacting data integrity.

Consider breaking transmitter antenna A2 into three separate 1D antennas to improve inductance tolerance to 3% or better. Lower inductance here increases antenna current, which translates to increased transmission distance. However, if the current is too high, the battery cannot support the instantaneous demand, so a good tradeoff is 2.47 mH.

The target resonant frequency of 133.3 KHz is achieved by paralleling large and small capacitors to get as close as possible to the required value for (C7 + C11), (C8 + C12), and (C9 + C13). These capacitors should be 1 – 2% C0G/NP0 types with at least 200 V breakdown. One such capacitor family is listed below. The ‘xx’ or ‘xxx’ in the part number represents the capacitance code. For example, yyy = 470pF, xxx = 471, etc.

- AVX → 08052Uxx0FAT2A → CAP CER yyPF 1% 200 V NP0 0805 → (< 100 pF)
- AVX → 12062AxxxFAT2A → CAP CER yyyPF 1% 200 V NP0 1206 → (100 pF and over)

C18 – C20 are chosen such that (C19 + C7 + C11), (C18 + C8 + C12), and (C20 + C9 + C13) along with their respective coils resonate at 121.3 KHz.

Some experimentation is needed to optimize the two resonant frequencies. Off-state drain-source capacitance of Q1 – Q3 and parasitic wiring capacitance will affect the actual values determined. These values should then be adequate for production.

NOTE: Failure to use C0G capacitors (Class I) will result in a significant performance decrease due to the lower quality factor, Q, of Class II and Class III caps. The lower Q of the cap arises from the inherent increase in effective series resistance (ESR) of Class II and III caps.

Appendix B Physical Board Layout

While the frequency in this circuit is relatively low, there are still precautions in the layout that need to be observed.

- The input impedance of inputs RF1-RF3 is quite high, so these inputs are susceptible to noise coupling. Routing near high voltage or high-speed signals must be avoided.
- Components and traces under the antennas should be avoided as much as possible as they affect the Q of the resonant circuit as well as detune the resonant frequency from what was calculated.
- The transmitter voltages HV1-HV3 are quite high (as much as 244Vp-p was observed) so observe trace spacing rules. Also the trace widths in the transmitter current path need to handle 50 mA minimum.
- The two antennas should be at least 15 mm apart (measured edge-to-edge).

Appendix C Software Implementation for LF-LF Transponder

C.1 main()

In the main function, the ports, clock, and SPI interface are initialized. Then, the software enters an infinite loop, where interrupts for the pushbuttons and the WAKE pin are reset and the MSP430 enters low-power mode 4.

The MSP430 awakens when S1 or S2 are pressed or when a correct wake pattern is detected, setting the WAKE signal to high. If WAKE is high, *PEPS()* is executed, else the *pushbuttons()* routine is entered.

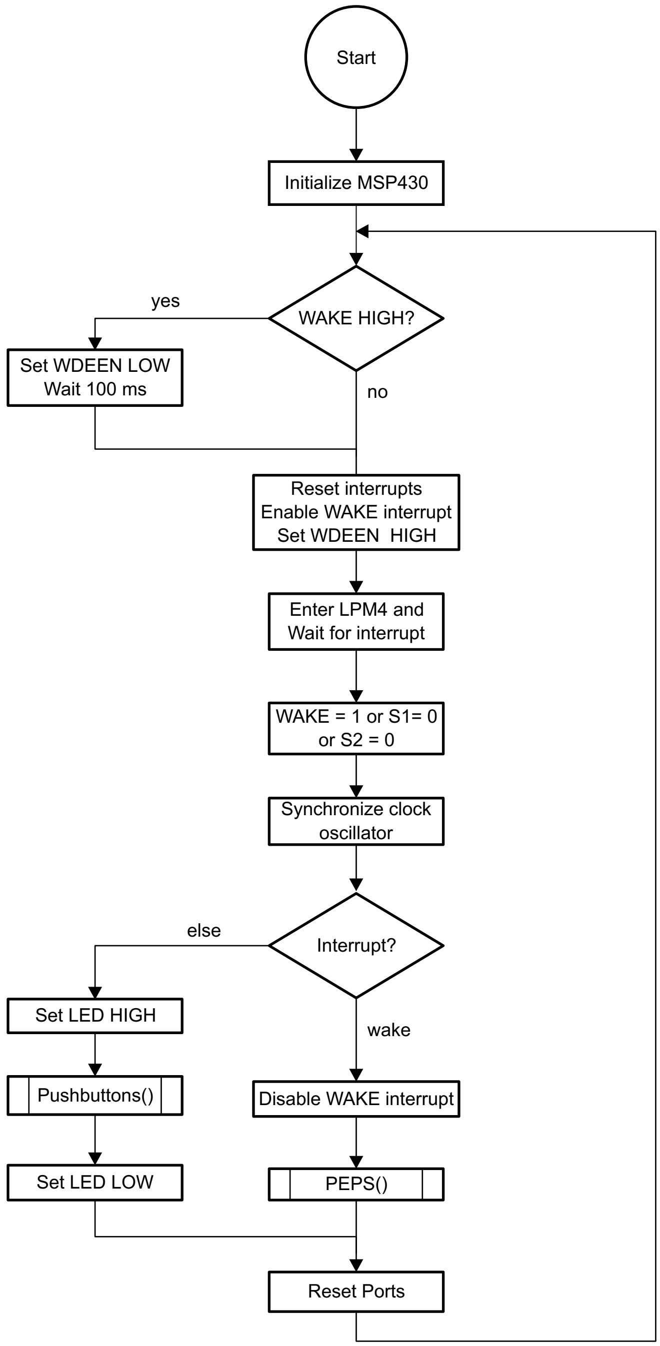


Figure 26. main.c

C.2 Pushbuttons()

If a pushbutton is pressed, the MSP430 wakes up, and,

- If S1 is pressed, 121.2 kHz is sent on Driver1.
- If S2 is pressed, 133.3 kHz is sent on Driver1.

As long as one pushbutton is pressed, the MSP430 continues sending.

If both pushbuttons are pressed, 16 periods of 133.3 kHz and 16 periods 121.2 kHz are alternated on Driver 1. To detect if Driver1 stops sending when no button is pushed anymore, set JP2 to the LED position (2-3), then the LED will be on when transmission is active.

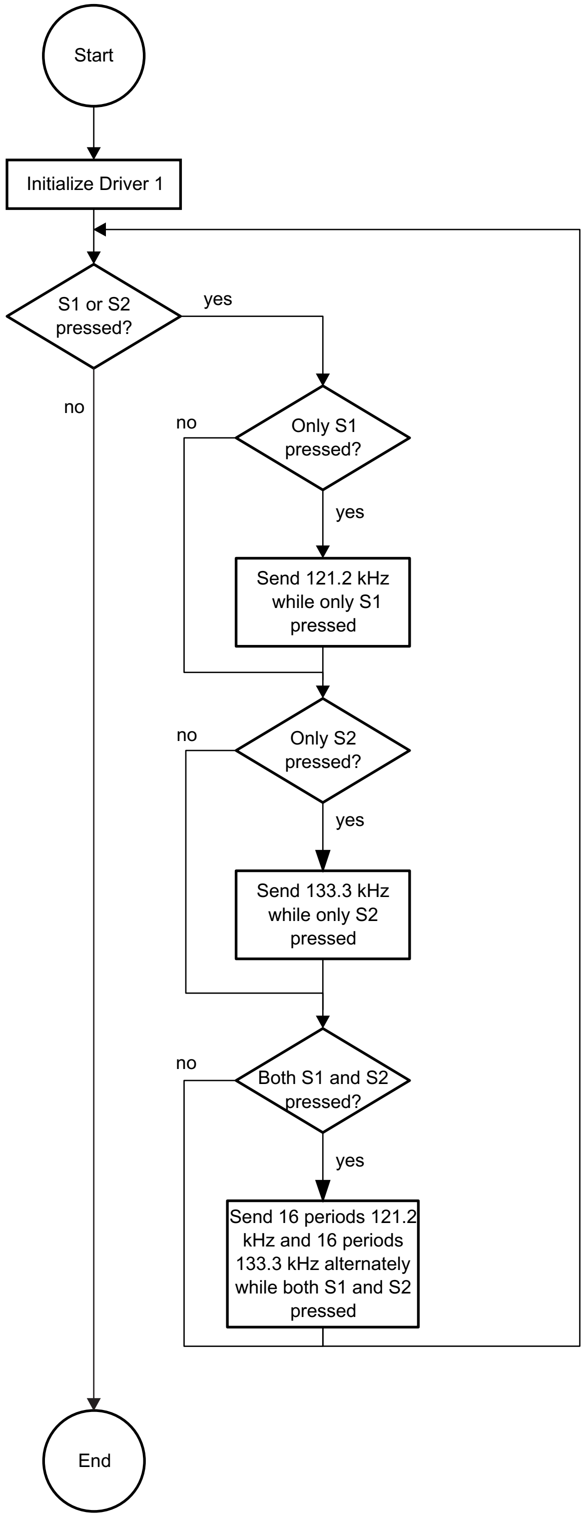


Figure 27. pushbuttons()

C.3 PEPS()

The passive entry routine can be divided into three parts:

- In the first part, the transponder wakes up and the MSP430 reads the sent challenge on the EOBA pin.
- In the second part, the MSP430 communicates via SPI to get the data out of the transponder memory and selects the Driver for transmission based on RSSI measurements.
- In the last part, the data is transmitted to the reader.

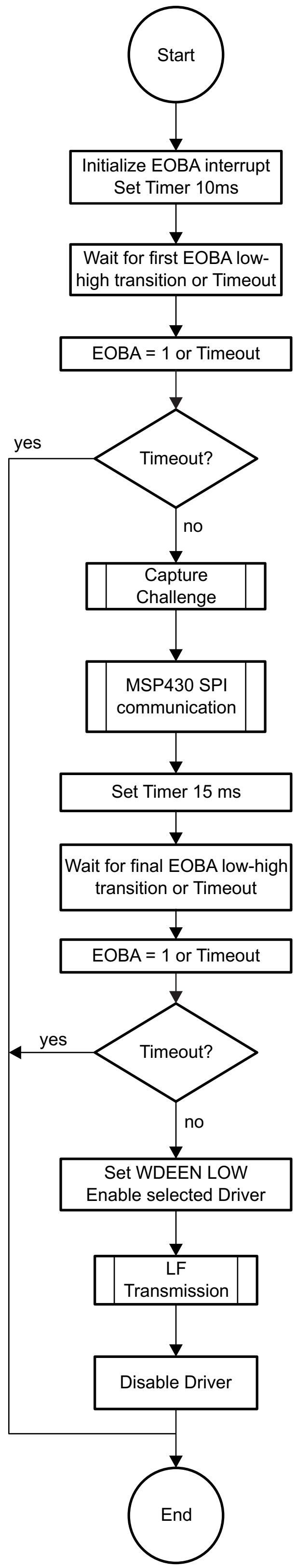


Figure 28. PEPS()

Figure 29 describes the signals as they appear on the pins during the three steps.

- Yellow - Downlink data is being received by the transponder as indicated by pulses on the end of burst (EOBA) signal. When the final EOBA pulse after Power Burst 2 (PB2) is finished, this indicates that the reader is ready to receive data.
- Pink - The relative receive signal strengths of the three antennas are measured via the RSSI signal. In this case, the 'X' direction was the strongest that corresponds to Driver 3.
- Cyan – Driver 3 drives node HV3 for uplink transmission burst.

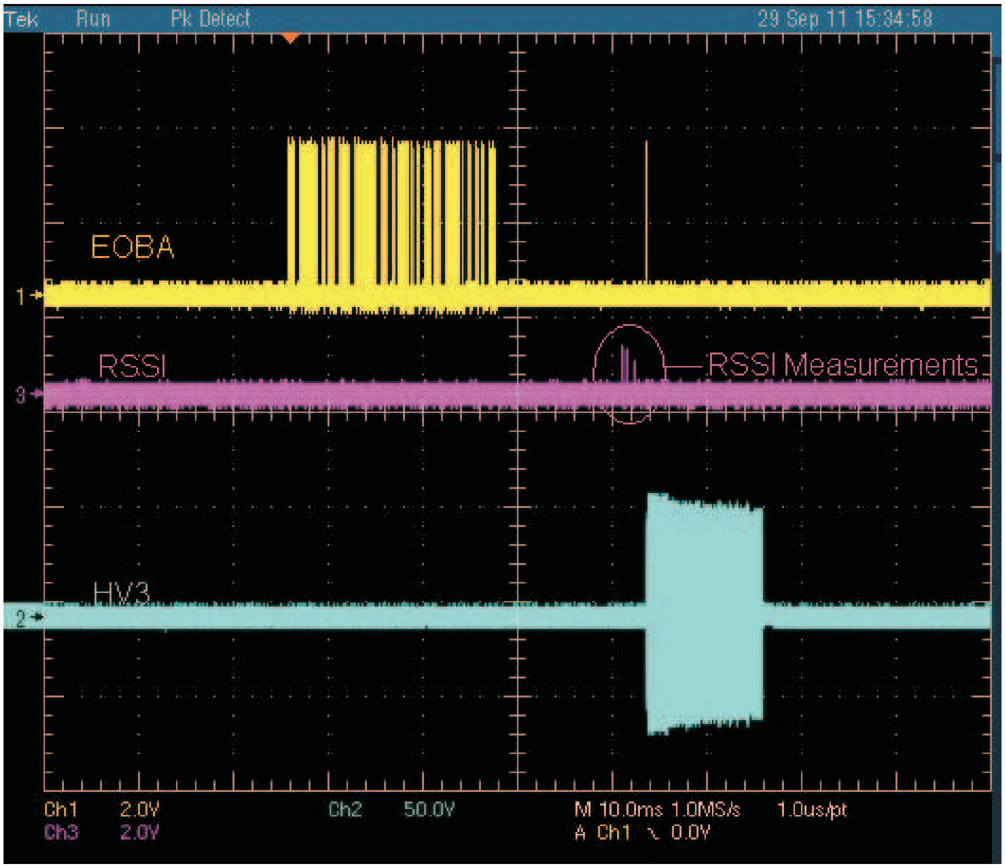


Figure 29. Signals After Wake Pattern Were Detected

C.4 Capture Challenge

C.4.1 Wake Up and Reception of Data

Example TX serial communication: 0x 01 0D 1E 08 04 06 01 28 C2 12 34 56 78 10 0A E0

- If the correct wake pattern (WP) was detected, the transponder wakes up: WAKE = HIGH and the MSP430 exits LPM4.
- Data delay of 1 ms ensures that the first EOBA pulse is detected.
- EOBA is read and the challenge is determined. The MSP430 expects 40 bits on the EOBA pin.
- The t_{bit} time of the PPM signal received determines if the bit is high or low: if t_{bit} > 550 µs, then it is a high bit, otherwise it is a low bit.

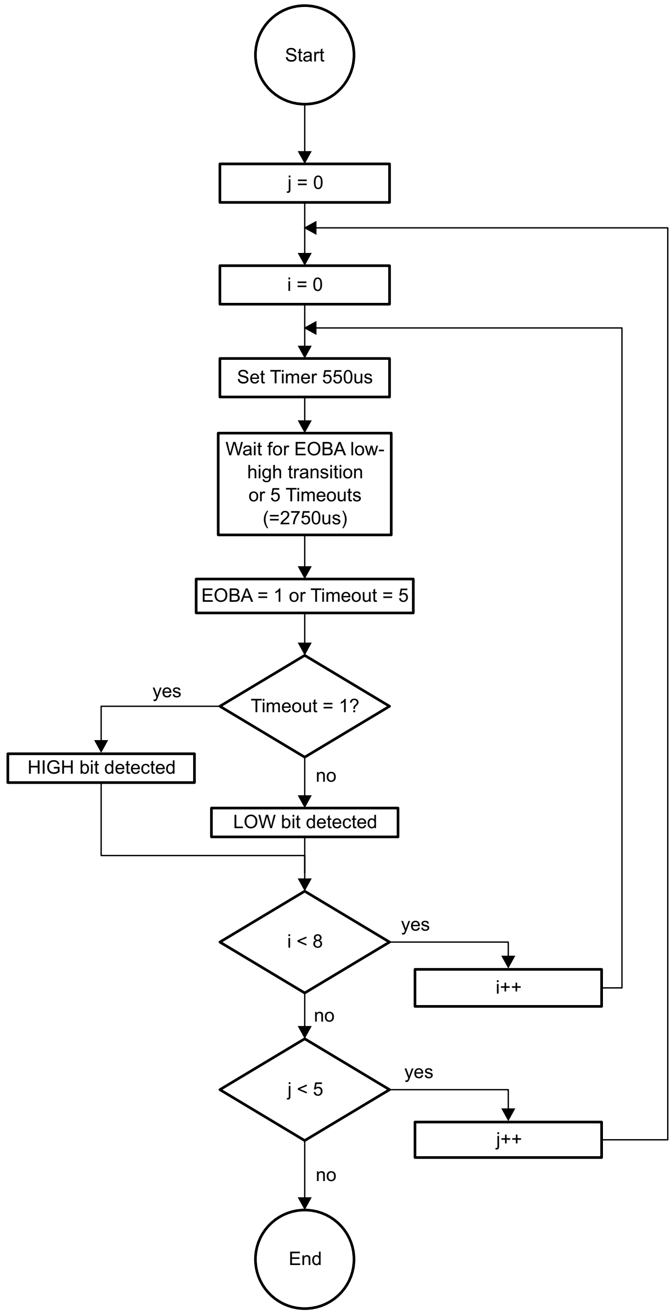


Figure 30. Capture Challenge

C.5 MSP430 SPI Communication

During Powerburst 2:

- The MSP430 interaction with the transponder takes approximately 15 ms; therefore, Powerburst 2 has to be longer than 15 ms. Powerburst 2 is sent in the downlink and is a parameter setup in the basestation.
- SPI transponder access command: sends write address and challenge to the transponder and receives a signature, serial number, and read address.
- SPI CRC calc: sends LF data to be transmitted to the transponder and receives CRC

- SPI RSSI measurement: Turn on all non-selected write distance expanders (WDEs) and wait 2 ms to be certain that all WDEs have been switched on. Execute all three RSSI measurements one after another with ADC. Turn off all non-selected WDEs.
- When the final EOBA pulse after Power Burst 2 (PB2) is finished, this indicates that the reader is ready to receive data. The LF response starts directly after the last EOBA pulse.

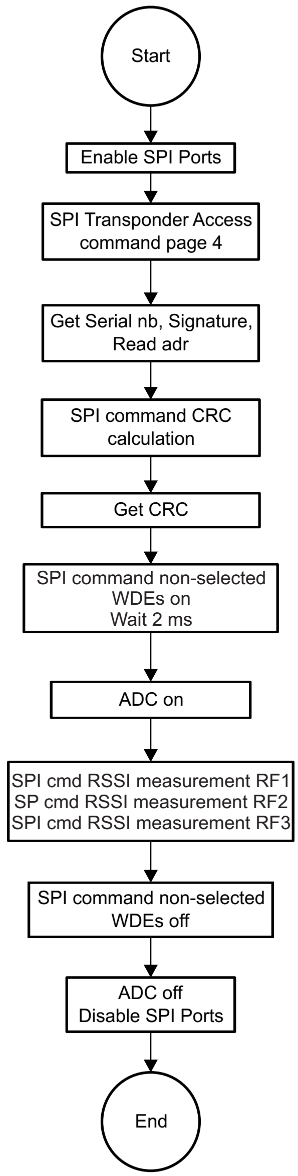


Figure 31. MSP430 SPI Communication

C.6 *Transmission of Data*

Example RX serial communication: 0x 01 0B 00 7E 0F 52 20 8F EA CE 10 25 E3 75

- Transmit 16 LOW pre-bits
- Transmit LF data: start byte, serial number, signature, read address, CRC
- Transmit final low bit: end of transmission
- Only the characters underlined in Figure 32 are transmitted over LF with LSB first.

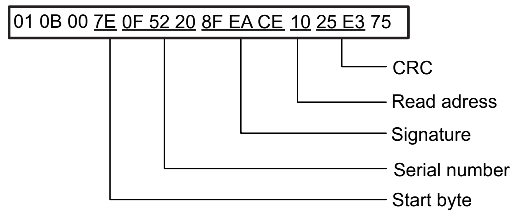


Figure 32. Listing of Transmitted Data

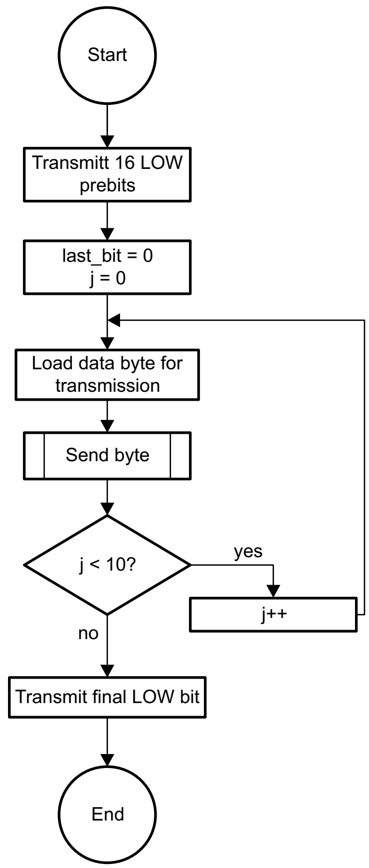


Figure 33. LF Transmission

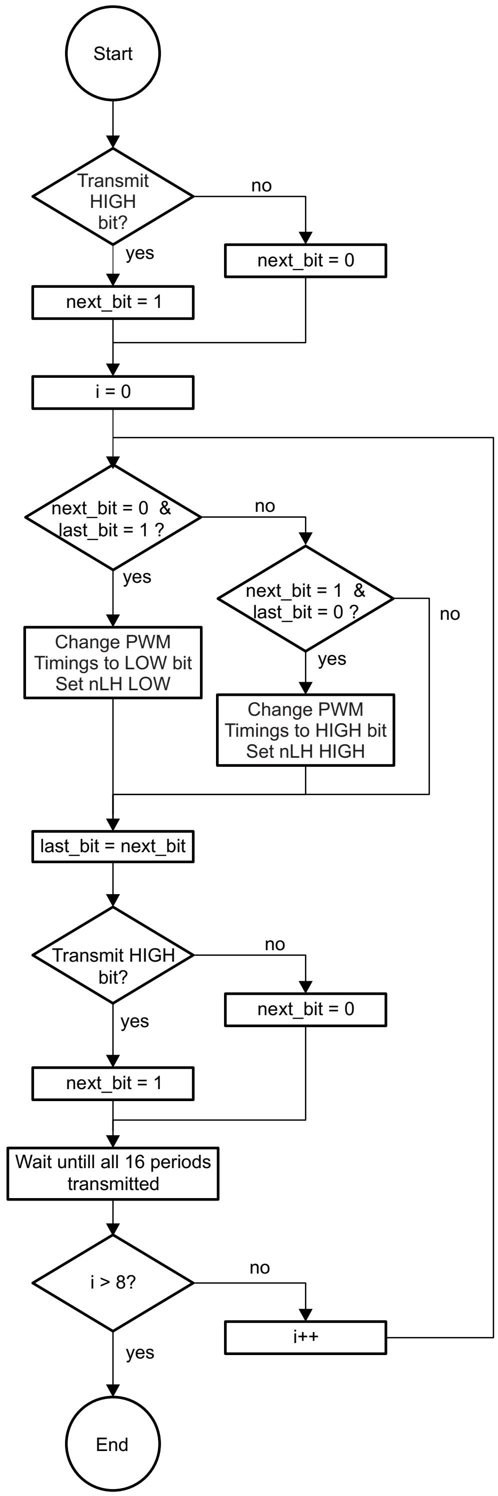


Figure 34. Send Byte

C.7 Other Comments on Software Implementation

In the *PEPS()* routine, when switching between high and low bit transitions, the changing of the PWM timings is done in 2 periods: first the CCR2 time is changed, then in the next PWM period the CCR0 time is changed and the nLH signal is set.

At 4 MHz, the MSP430 cannot do all three operations within one PWM period and nLH is switched one half period late; however, this does not affect the correct reception of the LF signal by the basestation.

- Yellow - FTX: Frequency modulated transmit data to the selected Driver
- Pink - nLH: Modulation signal that shifts resonant frequency down by approximately 11 KHz when high

In Figure 35, the lower window is an expansion about the yellow box of FTX and nLH from the upper window.

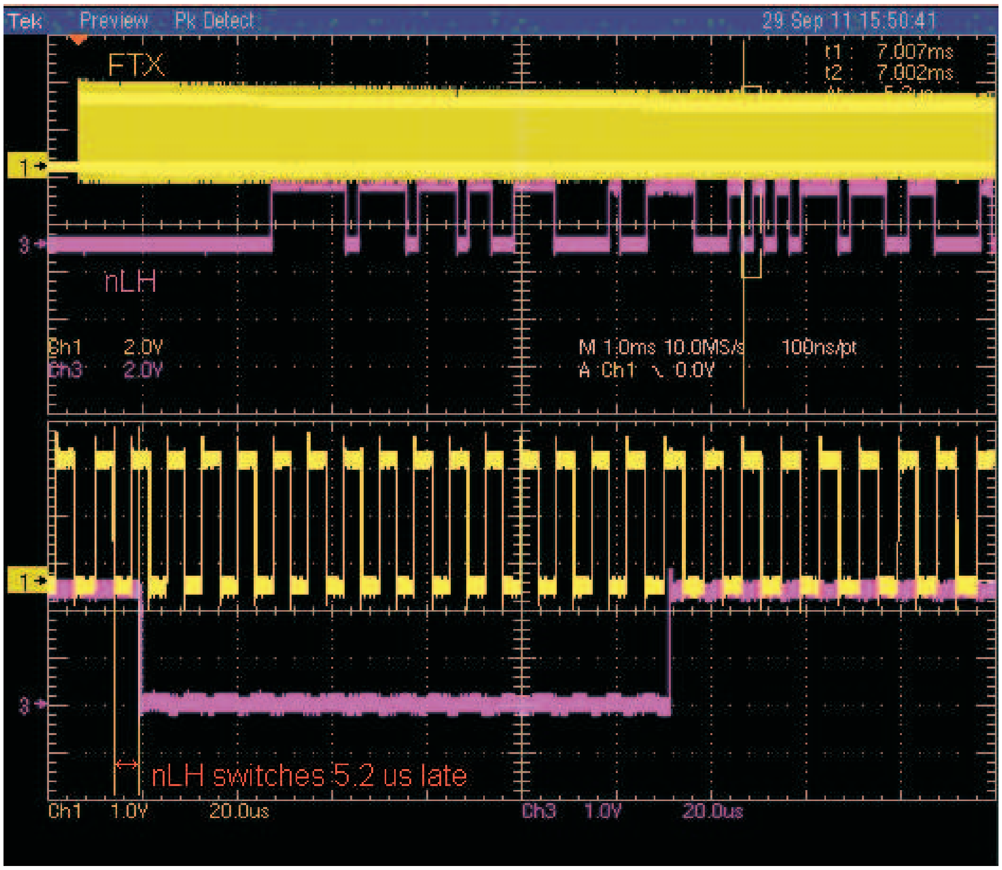


Figure 35. Transmission Burst and nLH Switching Delay Expanded

If the SPI is not correctly switched off, an additional current of 25 µA is consumed. If the ADC is not switched off, an additional 160 µA is consumed. In sleep mode, only 4 to 5 µA should be consumed by the entire board.

Before making the RSSI measurements, all WDEs have to be turned on. After all three measurements have been made, all WDEs have to be properly turned off. If they are not turned off, the last EOBA pulse indicating the end of Powerburst 2 may not be detected.

NOTE: No Watchdog has been implemented for the MSP430 in this demo software as this can interfere with the debug process. Currently the MSP430 jumps over critical while-loops when timeouts occur without resetting the MSP430.

Appendix D Bill of Materials

Table 3. Bill of Materials

BOM - LF-LF Dual Ant Transponder With MOSFETs				
Qty	**Reference Number**	**Description and PartNumber**	**Supplier**	**Supplier Part Number**
1	A1	LF Antenna 4.7 mH	Neosid	00 6115 22
1	A2	LF Antenna 2.47 mH	Neosid	00 6115 16
		or LF Antenna 2.5 mH	Toko	SA3D20-X1431 (different footprint)
1	B1	CR2032 3 V	DigiKey	N189-ND
1		Battery Holder	DigiKey	BAT-HLD-001-ND
3	C1,2,3	220 pF 1% 50 V NPO	DigiKey	478-3719-1-ND
1	C4	470 nF 10% 25 V X7R	DigiKey	490-3291-1-ND
1	C5	680 µF ±20% 6.3 V Tant	DigiKey	718-1754-1-ND
1	C6	220 nF 16V X7R	DigiKey	445-1318-1-ND
3	C7,8,9	470 pF 2% 200 V NPO 0805	Yagio	CC0805GRNPOABN471
1	C10	10 nF 10% 50 V X7R	DigiKey	478-1227-1-ND
3	C11,12,13	91 pF 2% 250 V NPO 0603	MuRata	ERB1885C2E910GDX5D
	C14,15,16	np		
1	C17	2.2 nF 16V X7R	DigiKey	478-6210-1-ND
3	C18,19,20	100 pF 2% 250 V NPO 0603	DigiKey	712-1309-1-ND
3	C21,22,23	33 pF 250 V 2% NP0 0603	DigiKey	712-1341-1-ND
1	D1	LNJ208R8ARA	DigiKey	P524CT-ND
3	D2,3,4	CDBU0245	DigiKey	641-1284-1-ND
1	G1	Pin, gold, 25 mil		
1	J1	CONN 2x7 0.1 sp "		
1	J2	CONN 2x4 0.1 sp "		
1	JP1	Jumper, 3 pin, 0.05 sp "		
1	JP2	Jumper, 4 pin, 0.05 sp "		
3	Q1,2,3	ZVN4424	DigiKey	ZVN4424ZCT-ND
1	Q4	BSS123	DigiKey	BSS123NCT-ND
1	R1	100K 1% 50 PPM	DigiKey	MCT0603-100K-CFCT-ND
9	R2,3,7,9,10,11,12,14, 19	47K 1%	DigiKey	P47.0KHCT-ND
	R4,5,6	np		
2	R8,18	10.0K 1%	DigiKey	P10.0KHCT-ND
1	R13	510 1%	DigiKey	P510HCT-ND
2	R15,16	51K	DigiKey	YC164J-51KCT-ND
10	TP1,2,3,4,5,6,7,8,9,10	pin		
2	S1,2	B3U-1000P	DigiKey	SW1020CT-ND
1	U1	TMS37F128	Texas Instruments	TMS37F128D3
4	U2,3,4,5	Si5513CDC	DigiKey	SI5513CDC-T1-GE3CT-ND
1	U6	74HC1G00	DigiKey	MC74HC1G00DTT1GOSCT-ND
2	U7,8	74HC126	DigiKey	296-26462-1-ND
1	Y1	4.00 MHz Resonator	DigiKey	490-1200-1-ND

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46C and to discontinue any product or service per JESD48B. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components which meet ISO/TS16949 requirements, mainly for automotive use. Components which have not been so designated are neither designed nor intended for automotive use; and TI will not be responsible for any failure of such components to meet such requirements.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Mobile Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265