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Analog FM Hardware Design Document

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1. INTRODUCTION

This document is part of the third deliverable of the SCAv2.2 reference implementation contract issued by the SDR Forum to the Communications Research Centre Canada.

In this document, the hardware design of the Analog FM application developed as part of this contract is described.

This document is a companion to the "Applications User Guide" also provided at http://www.crc.ca/scari.

2. RF FRONT END HARDWARE DESIGN

The emphasis of this project is on the development of algorithms and code needed to develop software radios. The software substitutes portions of the radio that would originally be done in hardware, giving users the ability to communicate with any type of radio, by downloading the necessary waveform. However, physical hardware is still needed to produce an actual electromagnetic pulse or real radio frequency (RF) signal.

In this section, a simple hardware design for a single band, push-to-talk, half-duplex transceiver is presented. The frequency band chosen is that of the Family Radio Service (FRS) or Global Mobile Radio Service (GMRS) band at 462.57 MHz. The block diagrams, schematics and list of components to build the transceiver are given. From these, one can build the basic RF hardware to perform the wireless demonstration of the Analog FM application described below.

2.1 Push-to-Talk Single Path FRS Transceiver Box

The FRS transceiver detailed here is part of the Software Defined Radio for Analog FM. Because the majority of processing is done in software, a powerful desktop or laptop computer is needed. The user who wishes to communicate via the transceiver box needs a common computer microphone and speaker to be used in conjunction with the computer audio card. The transceiver box acts as the bridge or liaison between user and computer. The connections between the transceiver, the computer and the users speaker and microphone are shown in Figure 1.The basic architecture for the transceiver box is shown in Figure 2.

When the user wishes to transmit a signal, the user clicks on the Talk button on the computer screen. A signal from the parallel port of the computer is sent to the transceiver box Analog Audio Interface (AAI) board (Figure 3), which sets-up the transmission (Tx) mode. The light emitting diode (LED) light changes to red indicating that the box is in Tx mode.

The user then proceeds and speaks into the microphone (mic). This audio signal enters the AAI board (Boom Mic input) and is switched through the transceiver box and sent to the computer (Mic Audio Card In) for FM processing using software. The processed FM baseband signal with f_{IF} = 12 KHz enters the box via the AAI once again (Computer Speaker) and is switched for transmission through the single RF path residing in the transceiver box. This 12 kHz baseband signal is first up-converted to 21.4 MHz. The signal is filtered for 25 kHz channel spacing and then up-converted once more to frequency f_{RF} = 462.56 to 462.64 MHz. This RF signal is filtered one final time and sent to the RF Antenna via the SMA connector. At this point the signal is transmitted over the FRS band.

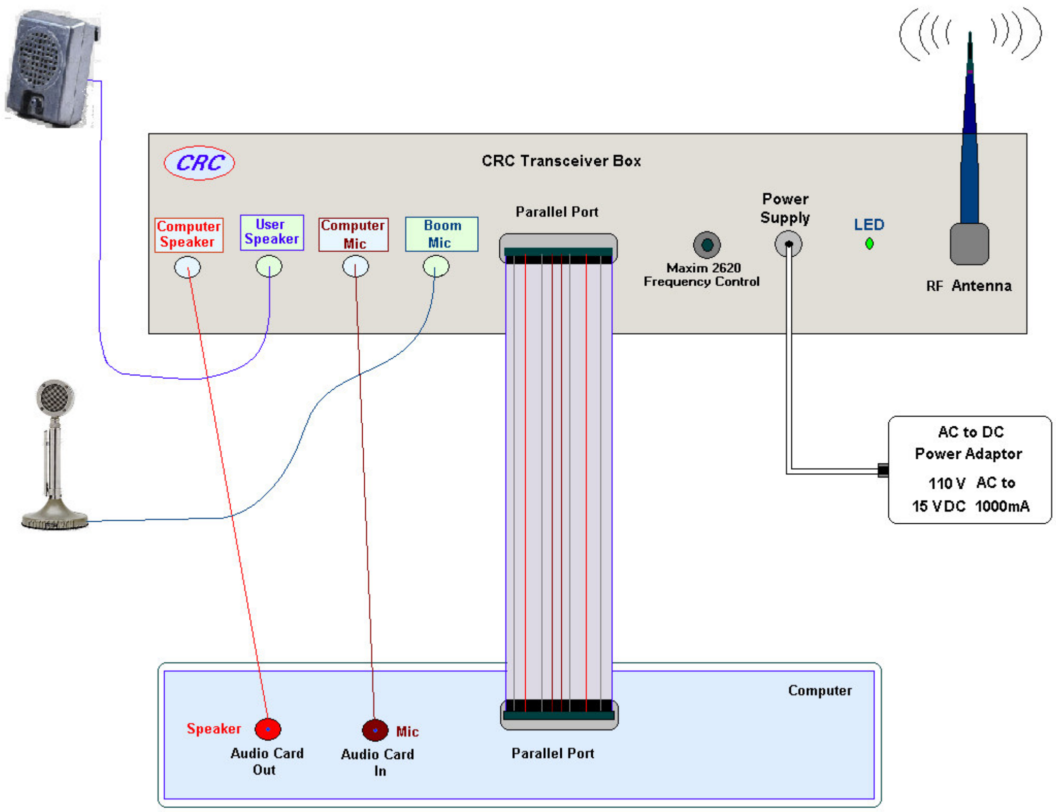

Figure 1: Connection layout between CRC Transceiver Box and the User and Computer

When the talk button is clicked again, the user is back in reception mode (Rx). In this case the LED light changes back to green. When in reception mode, any FRS RF signal received goes through the same path but in the opposite direction. This signal is then down-converted to the 12 kHz baseband and switched at the AAI board to the computer audio card in port. The software demodulates the FM signal, and reproduces the audio signal to be output to the user speaker via the AAI board.

The Transceiver Box can be divided into five blocks (Figure 2):

Block 1 is the Analog Audio Interface (AAI) board on which both user and computer interface with each other and connect to the RF front end.

Block 2 is the initial or First Frequency Conversionstage (or final Rx down-conversion).

Block 3 is the final or Second Frequency Conversionstage (or initial Rx down-conversion stage).

Block 4 is the board needed to generate a 441.16 MHz signal to drive the LO port of the second Frequency Conversionstage mixer.

Block 5 is the voltage supply and regulator, from where all the components are powered.

In the following sections each block is described in detail, and the schematics needed to build each block presented. For each block it is recommended that all components and connections be laid out on a either 2 or 4 layer printed circuit board (PCB). If such boards are difficult to obtain or develop, or the use of surface mount devices (SMD) is not possible, one can use equivalent connectorised components.

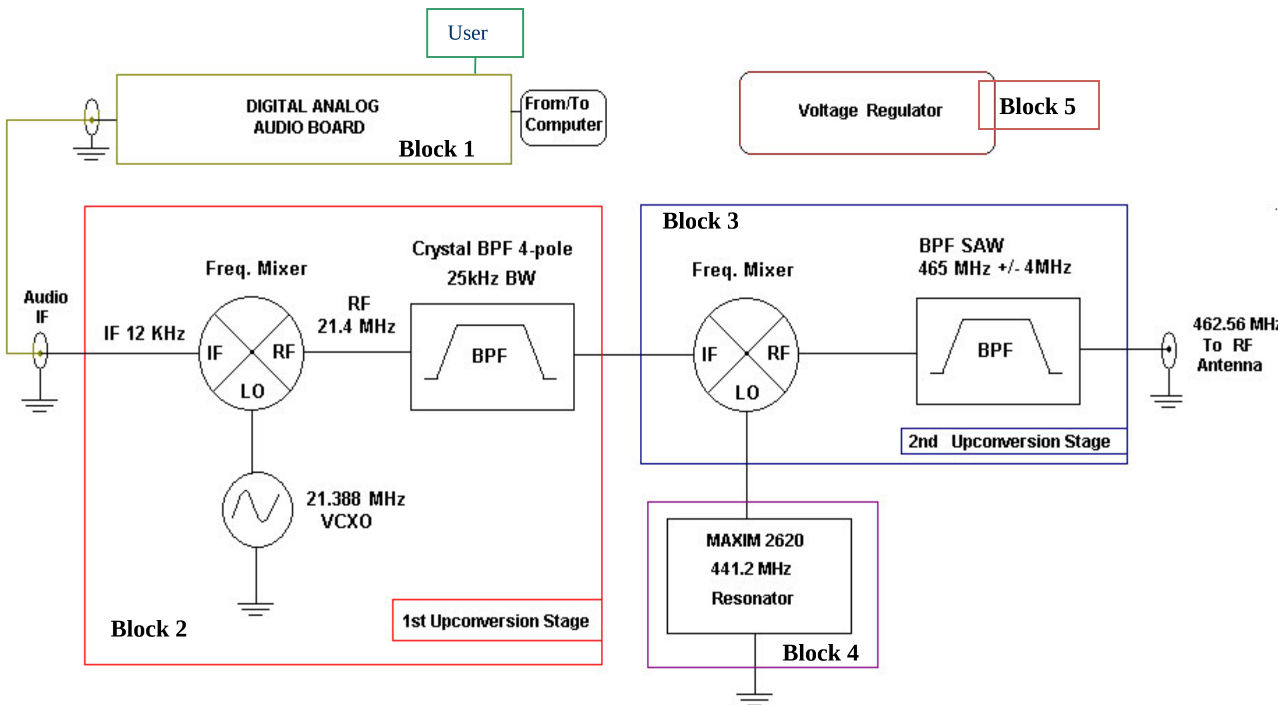

Figure 2: CRC Transceiver Box Block Diagram

2.2 Block 1: Analog Audio Interface (AAI) Board

As mentioned in the beginning of this report, the signal processing for the waveform is performed in a common desktop computer or laptop while the frequency conversion is done in the transceiver box. The interface between the two is done via the computer sound card and the Analog Audio Interface board. Figure 3 shows the detailed schematic of the AAI Board.

Four audio stereo jacks are used as the interface connectors. As shown in Figure 1, the user will connect the four female jacks shown in Figure 3, with the male jacks that are wired to the computer's mic (audio in) and speaker (audio out) ports, and the user's mic and speaker. The Tx/Rx is the connector to the parallel port pin that receives the computer command to switch the transceiver box between receive and transmit modes. The actual switching between the transmit and receive modes is performed by the relay (U1). The final output for transmission, or input for reception occurs at the AUDIO IF connector that connects the AAI with the RF front end (Block 2). A list of components for the AAI Board is presented in the following subsection (3.2.1.1).

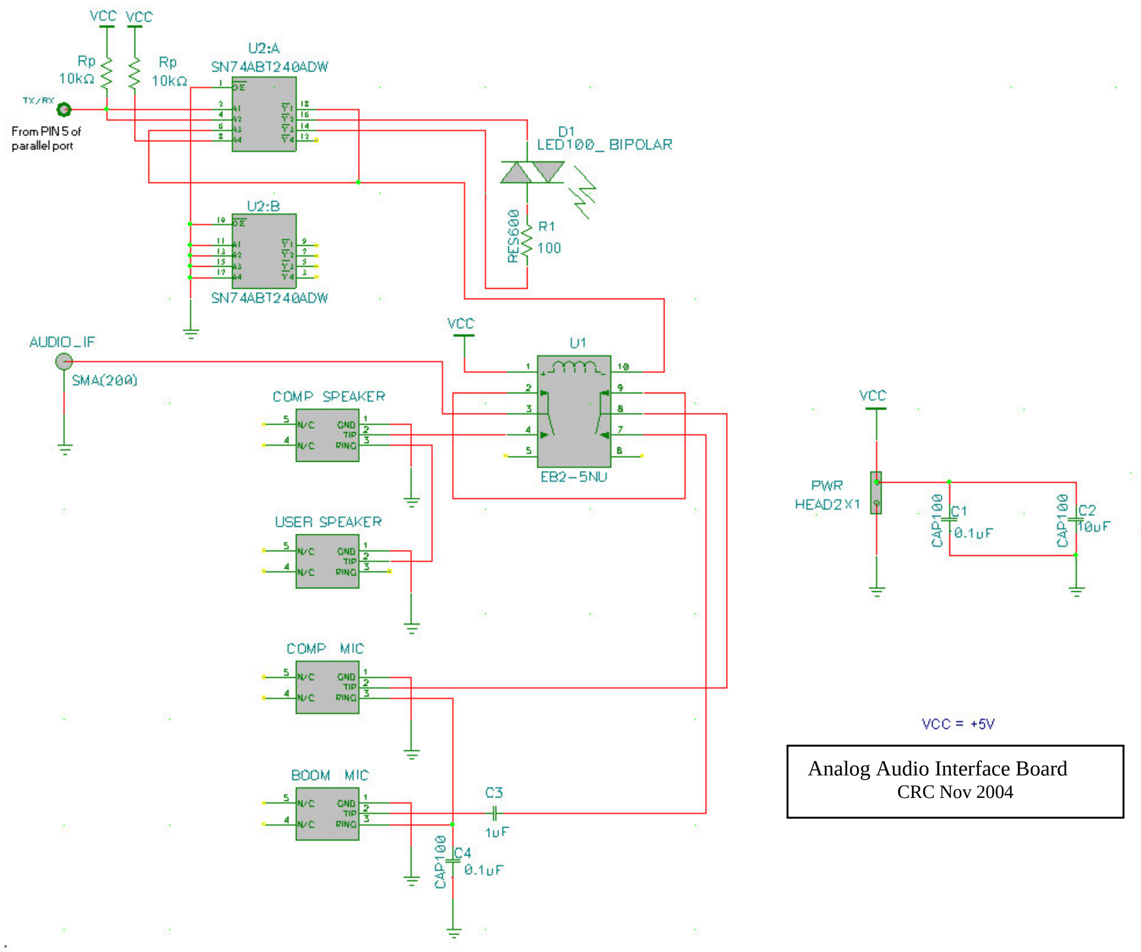

Figure 3: Analog Audio Interface Board Schematic (Block 1)

2.2.1 List of AAI board (Block 1) Components

To build the AAI Board using SMDs and the schematic of Figure 3, the following components are used:

- Four (4) Audio Stereo Jacks of Female type

- One (1) Texas Instruments SN74ABT240A signal octal buffer/line driver
- One (1) Double pole double throw relay (NEC EB2-5NU is used)
- Two (2) Resistors 10 kΩ or greater with +/- 5% or better tolerance
- One (1) Resistor 100 Ω with +/- 5% tolerance
- Two (2) Capacitors 0.01 μF and 10 μF (micro or uF in diagram) with +/- 5% or better tolerance
- One (1) 2-pin header for DC power
- One (1) SMA connector (female)
- One (1) Bipolar LED MV5491A-ND from Digi-Key

2.3 Block 2: First Frequency Conversion Stage

When in Push-to-Talk (transmission) mode, after the audio signal has been processed, modulated and switched out of the AAI board, this modulated audio IF signal is sent to Block 2 for the first stage of up-conversion. Here an FM signal with a centre frequency of 12 kHz, is mixed with a 21.388 MHz sine wave from the CPPC7 VCO, and then filtered through a narrow bandpass crystal filter to produce a 21.4 MHz IF signal with 25 kHz of bandwidth to be sent to the second and final Frequency Conversion stage in Block 3. When in listening (receive) mode, the incoming signal from Block 3 is downconverted from 21.4 MHz to 12 kHz, and then sent to the AAI board and switched to the computer input for processing.

It must be noted that the transformers are primarily used for impedance matching, but also help to filter and isolate the signals from noise. Additional filtering could be added before the audio IF signal is mixed to improve sound quality. Maxim Dallas provides a series of audio filters for this purpose. However, to simplify the circuitry and reduce cost, these filters were not used in this design.

2.3.1 List of First Frequency Conversion Stage (Block 2) Board Components

To build Block 2, the first Frequency Conversion stage, based on the schematic of Figure 4, the following components are used:

- One (1) Citizen CPPC7 3.3 V tristate VCO from digi-key or other type VCO/VCXO programmed or cut @ 21.388 MHz with +/- 20ppm stability or better. If cost is not an issue, much better performance can be obtained by using a VCXO or TCXO with +/- 5 ppm stability or better.
- One (1) Mini-Circuits LAT-3 Attenuator or other 6 dB attenuator if using the CPPC7

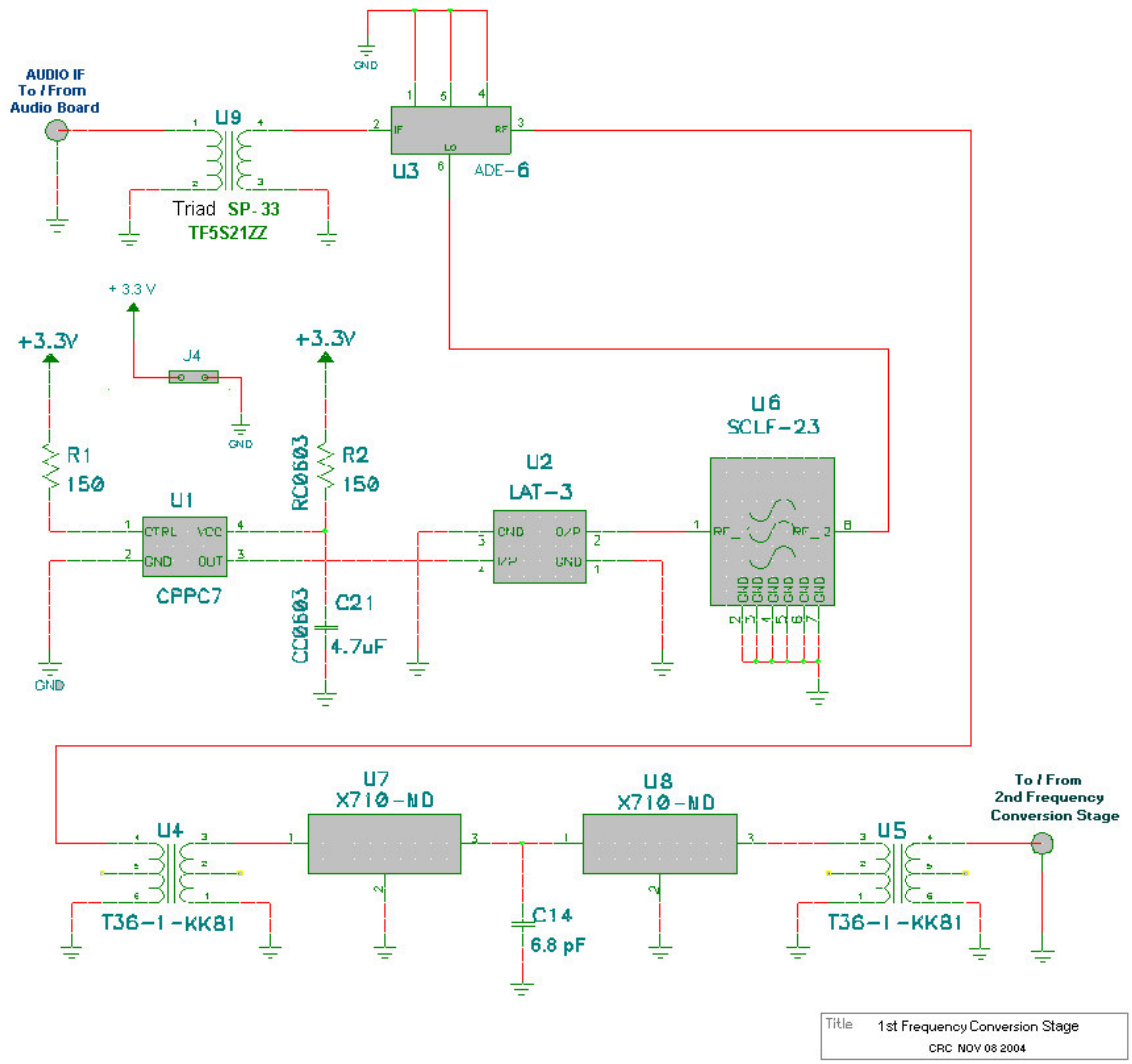

Figure 4: First Frequency Conversion Stage Board Schematic (Block 2)

- One (1) Mini-circuits SCLF-23 or SCLF-21.4 lowpass filter with a cutoff frequency around 22 MHz,
- One (1) ADE-6 Mini-Circuits Mixer or other frequency mixer for audio and low frequency mixing (IF / RF less than 100 MHz) (www.mincircuits.com)
- One (1) Triad SP-33 TF5S21ZZ or other 1000 to 50 Ohm transformer (www.triadmagnetics.com). For circuit simplicity, this transformer can be omitted, but an impedance mismatch between the AAI board and RF circuit may cause problems
- Two (2) ECS 2115 25 kHz bandwidth 4-pole (Mini-Circuits X710-ND) Crystal (X-tal) Filters. If a very stable TC-VCXO is used, use 8-pole filters.

- Two (2) T36-1-KK81 transformers or other transformers for 1500 to 50 Ohm impedance matching between crystal filters and circuit
- Two (2) Capacitors 6.8 pF and 4.7 µF (uF)
- Two (2) Resistors 150 Ohms
- Two (2) SMA connectors

2.4 Block 3: Second Frequency Conversion Stage Board

This third block is the second Frequency Conversion stage. A very simple block compared to the previous ones, but critical for transmission, it is also the first down-conversion stage when in receive mode. Here the signal is up-converted to 462.6 MHz so one can transmit in the FRS band. The components must have good performance characteristics, be 50 Ohm impedance matched, and be low noise.

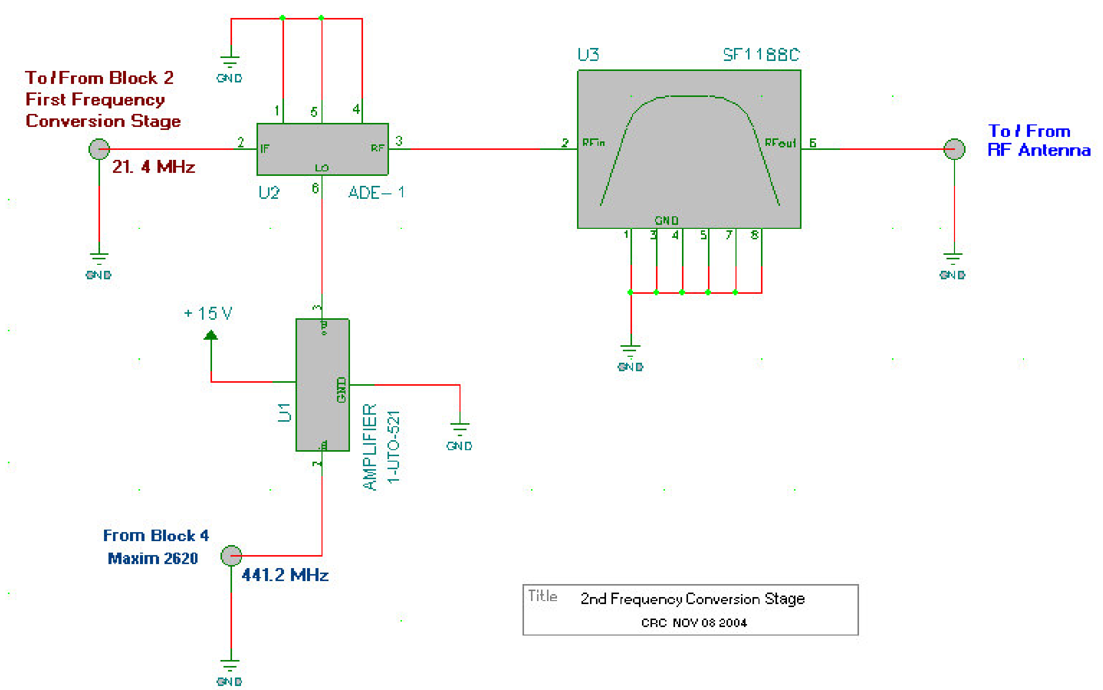

Figure 5: Second Frequency Conversion Stage (Block 3) schematic

The filter must be narrow enough to permit transmission in the FRS/ GMRS band, but cut out all frequencies below and above. Also due to the bi-directional nature of each circuit path, amplifiers could not be used without the use of additional switching circuitry, thus making the design more complex and increasing cost. Therefore the power levels at the output are low, making transmission and reception distances only a few metres from the source.

2.4.1 List of Second Frequency ConversionStage (Block 3) Board Components

To build the Block 3 second Frequency Conversionstage using the schematic of Figure 5, the following components are used. Always try to ensure the components are 50-Ohm impedance matched with the circuit, and in particular very well matched with the antenna.

- One (1) 1-UTO-521 Avanter Amplifier or other 27 to 30 dB amplifier if the Maxim 2620 chip is used as described in section 3.3. Otherwise use appropriate amplifier to bring the Local Oscillator (LO) signal to 7dBm
- One (1) SF-1188C bandpass SAW filter with fcentre = 465 MHz with +/- 4MHz cutoff from RFM Monolithics (www.rfm.com), or other such bandpass SAW filter
- One (1) ADE-1 Mini-Circuits mixer or other frequency mixer that is specified for IF and RF up to 500 MHz (www.mincircuits.com)
- Three SMA connectors

2.5 Block 4: MAXIM 2620 Board for Generation of Second Stage LO

In Block 2 of the transceiver box, a VCO or VCXO was used to generate a signal at 21.4 MHz to drive the LO port of the mixer. To perform this function, the Maxim 2620 Evaluation Kit Board was purchased (Figure 6). The MAXIM 2620 EVKIT provides the user with a developmental board fully populated. It's an RF Oscillator (Maxim 2620 chip) with a tank circuit that can be tuned from 10 to 1000 MHz. Its cost, considering a PCB and components are provided, is relatively low. The lead-time is also very good, usually within 5 business days from time of order.

However, as shipped, Maxim Dallas Semiconductor provides this board set at a frequency between 885 and 915 MHz. Therefore one must change a few components on the board to obtain the frequency needed. Which capacitors and inductors can be changed are highlighted in Figure 6. The capacitors in red, numbered C3, C4, C5, C6 and C17 were replaced with new capacitors for values shown in Figure 6. The 10-pF capacitor CD1 shown in blue (part of the varactor diode component) was not changed. One could use another varactor diode with other capacitance value or add another capacitor to change its value. The inductor L1, also in blue, is part of the ceramic resonator provided on the EVKIT board. If one does not purchase this board, but makes their own layout using just the Maxim 2620 chip, an inductor can be used. In that case, other values apart from the 6nH estimated here can be used.

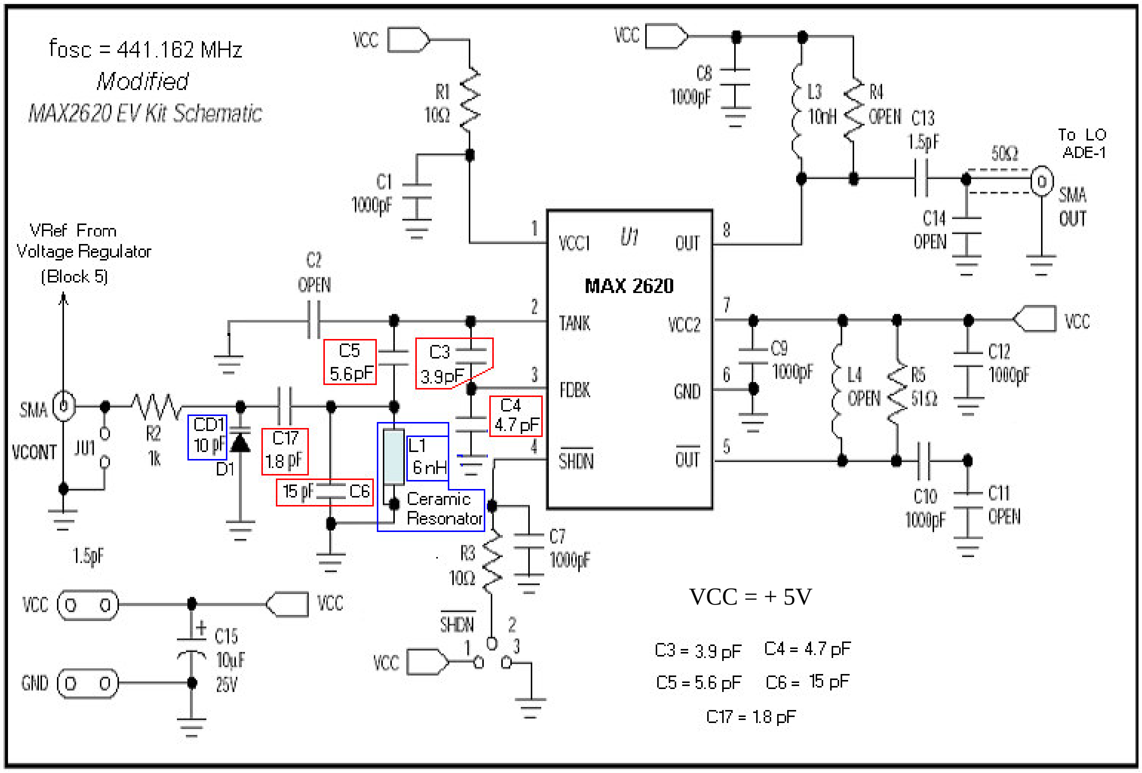

Figure 6: Maxim 2620 Evaluation Kit Board Schematic with modified values for use with FRS

The main difficulty in changing the oscillation frequency is choosing the proper component values to ensure oscillator start up. To do this, Maxim provides a calculator in Excel, that gives the user the equations necessary, and the conditions needed, to ensure the best component values possible for the frequency needed. This excel sheet is free and downloadable from the maxim web site at:
http://www.maxim-ic.com/appnotes.cfm/appnote number/2028
then click on MAX2620calc.xls.

With the values chosen in Figure 6, the frequency obtained was 440 MHz. The frequency calculated was 441.36 MHz as shown using the excel sheet in Figure 7. The difference between observed value and calculated value is due to the capacitance and inductance tolerances, which are usually +/- 5% of the value stated. To tune the circuit to the desired oscillation frequency, the VCONT is used. A reference voltage is applied anywhere from 0.5 to 3.0 Volts, to tune to the exact frequency. In the design above, the VCONT has a reference voltage from to 2 to 3 Volts provided from Block 5. With this, the tank circuit was tuned, and generated a signal at 441.163 MHz with a –20dBm output (SMA OUT). This signal is then sent to Block 3, amplified with the 27dB amplifier of Block 3, and then sent to the LO port of the ADE-1 Mixer.

For further details on the Maxim RF Oscillator and Tank Circuit and VCO design, go to: http://www.maxim-ic, type in MAX 2620 at the part search, and read the related application notes, such as: http://www.maxim-ic/appnotes.cfm/appnote number/698.

MAX2620 resonant circuit component value Calculation			
Refer to MAX2620 datasheet page 9 and 10 electrical model and the MAX2620 Evaluation kit.			
Let the parasitic capacitance, Cs, C03, and C04 be 2.7pF, 2.4, and 2.4pF, respectively.			
Cs	2.7	pF	pc board parasitic capacitor
C17	1.8	pF	Adjust value for desired frequency of oscillation, fo. Keep C17 value low to maximize loaded Q.
CD1	10	pF	Adjust value for the desired fosc. Replace with a varactor diode for VCO applications.
C6	15	pF	Adjust value for desired fosc.
L1	6.1	nH	Adjust value for desired fosc. As providede by Maxim in Evaluation Kit
C5	5.6	pF	Adjust value for desired fosc. Keep C5 value low to maximize loaded Q.
C03	2.4	pF	parasitic capacitor
C04	2.4	pF	parasitic capacitor
C3	3.9	pF	Adjust C3 to minimize Rn.
C4	4.7	pF	Adjust C4 to minimize Rn. For fosc < 200MHz, increase C4 to guarantee oscillation.
g_m	18	mS	transconductance
Q	100		Quality factor of inductor L1
f_o	441.169	MHz	desired frequency of oscillation
Calculate fo:			
Rp	1690.891367	Ohm	parallel impedance of L1 with quality factor Q
Rn	-52.37257103	Ohm	Rn= - g_m(1/(2*Pi*f*(C3+C03))*(1/2*Pi*f*(C4+C04))
Cn	3.338059701	pF	Cn=(C3+C03)*(C4+C04)/(C3+C03+C4+C04)
f_o	**441.359892**	MHz	f_o=1/(2*Pi*SQRT(L1*(Cs+C17*CD1/(C17+CD1)+C6+C5*Cn/(C5+Cn)))
RsL1	0.169089137	Ohm	Series impedance of L1 with quality factor of Q
Calculate Rs:			
Cp	19.22542373	pF	Cp=Cs+C6+C17*CD1/(C17+CD1), total capacitance of resonant tank circuit.
XCp	18.76459621 j	Ohm	XCp=1/j(2*Pi*fo*Cp), imaginary impedance part of Cp
XL1	16.90891367 j	Ohm	XL1=j2*Pi*fo*L1, imaginary impedance part of L1
Re[Rs]	17.14730306	Ohm	Real impedance part of the resonant tank circuit. Keep < 1/3 of Rn to guarantee oscillation.
Im[Rs]	169.4198812 j	Ohm	imaginary impedance part of the resonant tank circuit
Checking the imaginary impedance:			
XC5	64.42079814 -j	Ohm	imaginary impedance of C5
XCn	108.073702 -j	Ohm	imaginary impedance of Cn
XC5+XCn	172.4945002 -j	Ohm	(~ - Im[Rs]), imaginary impedance part Xs looking to the right of C5. This should be equal to Im[Rs].
B33 and B39 serve as a check. Both should be close in value if you desired frequency B19 is close to B25.			

Figure 7: Maxim 2620 Excel Sheet for Calculating Component Values for Oscillation

2.5.1 List of MAXIM 2620 Board (Block 4) Components

To simplify the design process, it is recommended that one buys the Maxim 2620 evaluation kit, for US$95.00, with a lead-time of usually one week, and then purchase five (5) capacitors based on the values chosen in Figure 6, or six (6) capacitors and one (1) inductor if one buys only the chip and not the board. For the design in Figure 6 and Figure 7 one needs:

- One (1) MAXIM 2620 EVKIT Oscillator Evaluation Kit (www.maxim-ic.com)

- Five (5) Ceramic capacitors with values of 1.8 pF, 3.9pF, 4.7 pF, 5.6 pF and 15 pF of +/- 5 % or better tolerance from Johanson Technologies (www.johansontechnologies.com) or other ceramic component company.

2.6 Block 5 Voltage Regulator and Reference Supply

When developing and testing the first four RF boards, the use of function generators, and voltage sources found in most laboratories is common. When it is time to connect all components into the box, an ample and stable power supply must be provided. The CRC Transceiver Box uses a standard 110 VAC to 15 VDC adaptor from Radio Shack. This AC to DC adaptor provides the input to the Voltage Regulator. The Voltage Regulator supplies the reference voltage used for tuning the Maxim 2620 oscillator tank circuit, and powers the rest of the circuitry. The design is shown in Figure 8.

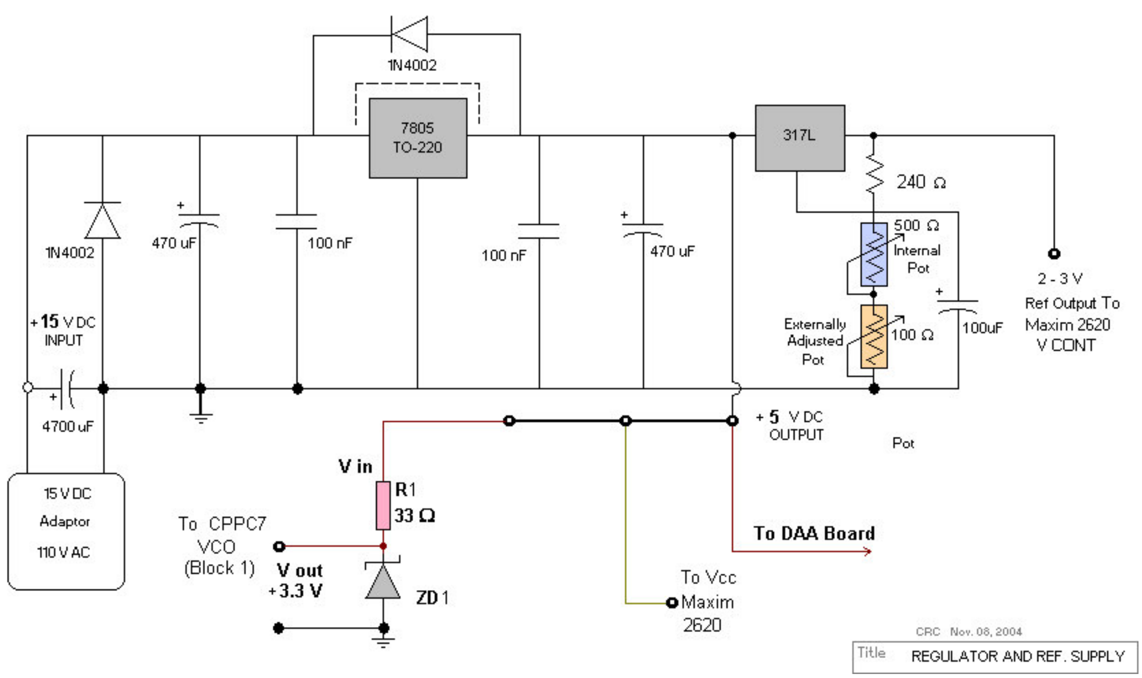

Figure 8: Voltage regulator and Reference Supply

2.6.1 <u>List of Voltage Regulator and Reference Supply (Block 5) Components</u>

To build the voltage regulator and reference supply of Figure 8, the following components are needed:

- One (1) 110V AC to 15V DC @1000mA adaptor (from Radio Shack)

- One (1) 1000 µF (uF) rated 25V or larger (4700 uF for this design) radial electrolytic capacitor
- Two (2) 470 uF electrolytic capacitors
- One (1) 100 uF electrolytic capacitor
- Two (2) 0.1 uF capacitors
- Two (2) 1N4002 Diodes
- One (1) 240 Ohm Resistor (1/4 watt)
- One (1) 33 Ohm Resistor (1/4 watt)
- One (1) 500 Ohm Trim Potentiometer internally set,
- One (1) 100 Ohm Potentiometer externally set with rotating knob on panel of box (frequency control adjust knob)
- One (1) 7805 + 5V Regulator in TO-220 case
- One (1) Heat Sink suitable for above regulator
- One (1) 317L Regulator in TO-92 case

2.7 RF Transceiver Board Summary and Component List

The RF transceiver board in this report is a simplified radio designed for single channel transmission and reception use in the FRS band. By rotating the Frequency control adjust knob, one can tune to any one of the eight FRS channels in the 462 MHz range. The cost of one such a box using the Maxim 2620 evaluation board would range from $200 to $400 depending on the distributor and the quantity of components ordered, and the number of SMA connectors used. If just the Maxim 2620 chip is ordered and everything is connected directly (no SMAs), the price drops to $100 to $300. However, with more units produced at one time (i.e. 100), the cost per box will drop.

If cost is not an issue, better components and additional filters can be used to improve audio quality and signal range. This design can also be used as a starting point for multiple channel and multiple band radios, however modifications and additions to both the hardware components and software applications are necessary.

For the reader’s convenience, a complete list of all the components used in the design of this single channel Analog FM radio (Figure 3 to Figure 8) is provided on the next page as a final checklist for ordering components.

List of all the components used in the design of this single channel Analog FM radio:

- Four (4) Audio Stereo Jacks of Female type
- One (1) 110V AC to 15V DC rated to 1000mA adaptor (Radio Shack)
- One (1) Double pole double throw switch or relay
- One (1) Texas Instruments SN74ABT240A signal octal buffer/line driver
- One (1) 2-pin header for DC power
- One (1) Bipolar LED (Digi-Key)
- One (1) VCO @ 21.388 MHz with +/- 20ppm stability, or a VCXO or TCXO with +/- 5 ppm stability or better if cost is no issue.
- One (1) ADE-6 Mini-Circuits Mixer or other similar mixer
- One (1) ADE-1 Mini-Circuits Mixer or other similar mixer
- One (1) SCLF-21.4 lowpass filter, or one bandpass filter @ 19 to 24MHz
- One (1) RFM SF-1188C bandpass SAW filter with centre frequency at 465 MHz with +/- 4MHz cutoff, or other such bandpass SAW filter
- Two (2) ECS 2115 25 kHz bandwidth Crystal (X-tal) filters or other 4-pole or higher filter.
- Two (2) T36-1-KK81 transformers or other transformers for 1500 to 50 Ohm impedance matching between crystal filters and circuit
- One (1) Triad SP-33 TF5S21ZZ or other 1000 to 50 Ohm transformer
- One (1) 1-UTO-521 Amplifier or other 27 to 30 dB amplifier for Maxim 2620 chip
- One (1) MAXIM 2620 EVKIT Oscillator Evaluation Kit (www.maxim-ic.com)
- One (1) Capacitor 0.01 µF (uF)
- One (1) Capacitor 10 µF (uF)
- Two (2) Capacitors 0.1 µF (uF)
- Two (2) Capacitors 4.7 µF (uF)
- Six (6) Ceramic capacitors with values of 1.8 pF, 3.9pF, 4.7 pF, 5.6 pF, 6.8pF and 15 pF of +/- 5 % or better from Johanson Technologies or other company
- One (1) Radial electrolytic capacitor 4700 µF (uF) capacitance rated to 25V
- One (1) 100 µF (uF) electrolytic capacitor
- Two (2) 470 µF (uF) electrolytic capacitors
- Two (2) 1N4002 Diodes
- Two (2) Resistors 10 kΩ or slightly greater
- Two (2) Resistors 150 Ohms with +/- 5% tolerance
- One (1) Resistor 100 Ω with +/- 5% tolerance
- One (1) 240 Ohm Resistor (1/4 watt)
- One (1) 33 Ohm Resistor (1/4 watt)
- One (1) 500 Ohm Trim-pot set internally
- One (1) 100 Ohm Potentiometer set externally from front panel knob
- One (1) 7805 + 5V Regulator in TO-220 case
- One (1) Heat Sink suitable for above regulator
- One (1) 317L Regulator in TO-92 case
- Six (6) SMA connectors