Design and Laboratory Evaluation of the Phase II LMR Multiband Antenna System

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Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Introduction and Background</td>
<td>2</td>
</tr>
<tr>
<td>2 Design of the Phase II Antenna System</td>
<td>2</td>
</tr>
<tr>
<td>3 Laboratory Evaluation of the Phase II Antenna System</td>
<td>9</td>
</tr>
</tbody>
</table>

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1 Introduction and Background

This report documents the design, construction, and laboratory evaluation of a prototype land mobile radio (LMR) multiband antenna system, intended for vehicular installations. This antenna system is being developed as part of our project “Antenna Systems for Multiband Mobile & Portable Radio” [1]. The overall goal of this project is to develop and demonstrate LMR antenna systems which can operate in the VHF-Low (25–50 MHz), VHF-High (138–174 MHz), 220–222 MHz, UHF (406–512 MHz), and 764–862 MHz bands without physically changing antennas. In Phase I of the project, we developed a simple monopole-type antenna augmented with an electronic antenna tuner, and demonstrated the prototype; see [2] and references therein. In [3], we presented the Phase II design concept, which proposed a number of improvements including:

- A reconfigurable monopole consisting of a “base element” supporting VHF-High and above (similar to the Phase I design), plus a switchable “extension element” supporting lower frequencies including the VHF-Low band.
- An improved frequency detection scheme in which transmit frequency is determined using a frequency counter, replacing the approach used in Phase I which used a filter bank with incoherent power detection.
- Dynamic monitoring of the impedance match to the antenna, enabling “closed loop” optimization of the match in lieu of the Phase I “open loop” approach in which match configurations were determined in advance and could not be optimized in response to installation details and varying field conditions.
- Ability to utilize and control all 10 stubs of the Phase I stubline tuner (only 6 could be controlled previously).
- Ability to support up to 10 W transmit power, whereas the Phase I design was able to support only up to 1.5 W transmit power.
- Implementation in an enclosure suitable for field demonstration.

The reader is referred to [3] and references therein for analysis leading to the decisions represented in the Phase II design presented here. Sections 2 and 3 of this report describe the design and laboratory testing, respectively, of the Phase II antenna system.

2 Design of the Phase II Antenna System

System Overview. Figure 1 shows a block diagram of the Phase II system. It consists of a monopole-type antenna, an automatic electronic antenna tuner, and cable sufficient to connect the system to an existing multiband transceiver. In the event that this antenna system were to be used with an existing installation consisting of multiple transceivers covering different frequency bands in lieu of a single multiband transceiver, an RF multiplexer would be used, but no change to the antenna or tuner would be required. A block diagram of the tuner is shown in Figure 2.

Reconfigurable Monopole. The design of reconfigurable monopole has been fully documented in [4].

Antenna-to-Tuner Cable. The cable connecting the antenna to the tuner is 91.44 cm (36 in) of United Microwave Products (Inc.) “Microflex150” semirigid coaxial cable, plus an SMA-female to N-male adapter which adds about 3 mm to the total length. Although this type and length of cable is not critical, the open-loop tuning solutions (i.e., those determined from detected transmit frequency) assumes this particular choice, and would need to be changed if the cable type/length were different. This is a firmware-only change. Closed-loop tuning (i.e., dynamic adjustment using measurements of forward and reverse power) would not depend on the length of this cable.
Figure 1: Block diagram of the Phase II antenna system.

Figure 2: Block diagram of the antenna tuner.
Figure 3: The stubline. When installed, open- or short-circuited lengths of coaxial cable are attached to the SMA connectors along the length of the board. Each green module is a latching relay which connects or disconnects the stub to the 50Ω microstrip line running horizontally from end to end.

**Stubline.** As in the Phase I approach, matching is accomplished using switchable open- or short-circuited stubs located along a “stubline” inserted in the path between transceiver and antenna. The design of the stubline is unchanged from the Phase I design [5], shown in Figure 3.

**Open-Loop Tuning.** A top-level description of the open-loop scheme for setting the stubline relays is as follows: A small fraction (−20 dB = 1%) of the power flowing from the transceiver to the antenna is diverted from the transmitted signal using a Mini-Circuits (Inc.) SYDC-20-13HP surface mount directional coupler. The frequency of the transmitted signal is measured using the frequency counting scheme described below, which employs an RF prescaler integrated circuit (IC) and a Microchip (Inc.) PIC16F887 (“PIC”) microcontroller. Using a lookup table, the microcontroller maps the measured frequency to a set of stubs to use (the “tuning solution”), and connects those stubs to the microstrip line. A decision as to whether to use the low-frequency extension of the reconfigurable monopole is also part of the tuning solution. We have not yet conducted a thorough study to determine an optimum set of stubs to populate the 10 positions on the stubline. We have, however, chosen a set of stubs which yields adequate performance for one frequency in each of the five bands VHF-Low, VHF-High, 220 MHz, UHF, and 800 MHz. This is shown in Table 1, which also defines the current algorithm (implemented as PIC firmware) for choosing among tuning solutions.

**Closed-Loop Tuning.** Simultaneously, tiny fractions of the forward (desired) and reverse (reflected) transmitted power are obtained at the antenna port using another SYDC-20-13HP coupler. These signals are detected using an Analog Devices (Inc.) AD8364 dual-channel RF detector IC, which outputs voltages which are log-linearly proportional to the input RF powers. These outputs are measured by the PIC microcontroller and used to determine the quality of the match to the antenna. This provides confirmation that the selected tuning solution is suitable; alternatively, if the match is determined to be unacceptable, the PIC microcontroller may try small changes to the tuning solution in an attempt to determine the present best choice for the frequency currently in use. At the present time we have not yet implemented a closed-loop learning algorithm. However we have tested the operation of the forward/reverse power measurement scheme (see Section 3), and have implemented an LED indicator on the exterior of the enclosure that turns on when the VSWR at the antenna port is determined to be > 3.
Table 1: Stubline configuration and tuning solutions used in the current implementation of the tuner. Stubs are numbered 1 (closest to the antenna) through 10 (furthest from the antenna). “ON” means the associated relay is closed, so the indicated stub or antenna extension is connected. Stubs not indicated are not used (i.e., “off”). “Ant. Ext.” refers to the low-frequency extension element of the reconfigurable monopole. “Opt. Freq.” is the frequency at which this tuning state presents optimum VSWR to the transceiver. “Opt. VSWR” is the VSWR at the optimum frequency for the indicated tuning state. “Test Freq.” and “Test VSWR” indicate frequencies for planned field testing, and VSWR at those frequencies.

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<td>851.150</td>
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Stub 3 is 15.5 cm of RG-58, terminated in a short circuit.
Stub 5 is 22.5 cm of RG-58, terminated in an open circuit.
Stub 10 is 67.0 cm of RG-142, terminated in an open circuit.

**Hardware Implementation.** As in the Phase I design, the PIC microcontroller used by the Phase II tuner is installed on a Microchip (Inc.) DM164120-2 “PICkit 2 44-Pin Demo Board”, shown in Figure 4. This board requires about 20 mA at +5 VDC. The stubline control signal is fed to a custom “tuner board”, shown in Figure 5, which demultiplexes this signal into separate TTL logic outputs for each stub relay as shown in Figure 6. In addition to demultiplexing the PIC stubline control signal and driving the stubline relays, the tuner board also contains the couplers, prescaler, and dual-channel log-power detector described above. Control signals are connected in pairs to the relay coil terminals on the stubline tuner (i.e., neither side of the relay coil is grounded) as shown in Figure 7. When a relay state change is required, one of the two outputs is pulsed high while holding the other low. The relays are of the latching variety and require no power to maintain state. Thus, the tuner will remain functional – albeit fixed in its last state – even if all power to the unit is lost. The PIC microcontroller, tuner board, stubline, and all interconnections are mounted to the lid of a Hammond Mfg. Model 1550N aluminum enclosure, as shown in Figure 7. The tuner is made RF-tight simply by reassembling the enclosure. The completed and fully-assembled tuner is shown in Figure 8.

**Scheme for Estimating Transmit Frequency for Open-Loop Tuning.** Figure 9 shows the schematic for transceiver-side coupler, prescaler, and associated circuitry, which are implemented on the tuner board. The signal from the coupler is input to an ON Semiconductor (Inc.) MC12080 prescaler IC. The prescaler divides the input frequency by 80, obtaining a frequency range between 0.3125 MHz (corresponding to 25 MHz) and 10.7750 MHz (corresponding to 862 MHz). The output of the MC12080 prescaler is amplified to 1.9 V peak-to-peak, which is necessary to properly trigger the PIC’s TMR0 (timer) clock input. This amplifier is implemented as a cascade of two common-emitter transistor amplifier stages. TMR0 is an 8-bit timer configured to increment on the rising edge of the signal from the prescaler. TMR0 rolls over on the 256th cycle, triggering an interrupt.

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1In contrast to what we reported in [3], we found this prescaler worked sufficiently well to 25 MHz that a separate VHF-Low frequency detection scheme was not necessary.
Figure 4: The PIC microcontroller board.

Figure 5: The tuner board. The left third of the board is transmit frequency detection support circuitry, the center third is stubline control demultiplexing, and the right third is forward/reverse power measurement support circuitry. Note that the PIC microcontroller board is mounted mezzanine-fashion underneath the tuner board.
Figure 6: Tuner board schematic: Stubline control demultiplexer.

Figure 7: Interior of fully-integrated antenna tuner.
Figure 8: Exterior of fully-assembled antenna tuner. The dimensions are 25 cm (W) × 25 cm (D) × 10 cm (H). The antenna and transceiver ports are Type N connectors. The white plastic locking Molex connectors are for DC power and antenna switch control.
service routine (ISR) which resets TMR0 and increments a count variable. Separately, Timer 1 (TMR1) of the PIC is used to track elapsed time. TMR1 is a 16-bit timer with a 3-bit prescaler, which is driven by the PIC board's internal 25 MHz clock oscillator. TMR1 is preset with a value selected such that it rolls over after 0.5 s. The frequency of the signal from the prescaler can thus be determined from the change in the TMR0 rollover count between TMR1 rollovers, and the actual transmit frequency is this value times 80.

Scheme for Estimating Antenna Match Quality for Closed-Loop Tuning. Figure 10 shows the antenna-side coupler and forward/reverse power measurement scheme. Note that all four analog voltage outputs from the AD8364 power detector IC are provided to the PIC microcontroller, however in the current implementation only OUTN is actually used. OUTN is proportional to transmitted power (in dB) minus reflected power (in dB); thus OUTN nominally increases monotonically with the quality of the impedance match between antenna and tuner.

3 Laboratory Evaluation of the Phase II Antenna System

In this section we report on laboratory testing of the Phase II antenna system.

Reconfigurable Monopole. Laboratory testing of reconfigurable monopole is documented in [4]. See below for additional details concerning the combined antenna + tuner system.
Power Consumption. The tuner consumes 150 mA (quiescent) at +12.5 VDC input. The input is regulated and will accept 12–15 VDC, so it is compatible with vehicle electrical systems.

Insertion Loss. Figure 11 shows insertion loss for the system. The signal path is end-to-end through the tuner and includes the stubline (all relays open) and both couplers. The insertion loss is seen to vary between 0.5 dB and roughly 4.0 dB between 25 MHz and 900 MHz. The loss in 17 ft (a typical length for vehicular installation) of RG-58 ranges from about 1 dB to about 3 dB over the same frequency range, so the insertion loss of the tuner may significantly limit performance at the higher frequencies and thus is an area for future improvement. The distribution of loss in the antenna system is as follows: The rated insertion (mainline) loss for each coupler is between 0.1 dB and 0.7 dB, increasing with increasing frequency. Thus the contribution of both couplers to the insertion loss is 0.2–1.4 dB. It is known from [5] that the stubline contributes less than 1 dB to the insertion loss (roughly 0.4 dB from loss in the microstrip line and roughly 0.5 dB from parasitic loss associated with interconnects to relays). The ripple in the frequency response is due in part to the portion of each relay which is always in contact with the microstrip line, thus presenting a very short stub which perturbs the impedance.

Impedance Match to Antenna. Figures 12–16 show the frequency response for each of the five tuning solutions specified in Table 1, represented in terms of the magnitude of reflected power (|s11|) measured at tuner’s transceiver-side port. Note that these measurements include the insertion loss described above; that is, these measurements are “as is” at the tuner port, and no attempt is made to discriminate between transmission from the antenna and loss within the antenna tuner.

We also made a measurement for the case in which all stubs are off and the extension element is ON, shown in Figure 17. This does not correspond to any particular tuning solution, but is included to show the “untuned” performance of the reconfigurable monopole with the extension element ON.

Minimum Transmit Power Required for Frequency Detection. The minimum transmit power required from the transceiver for frequency detection is shown in Figure 18. Note that the tuner is quite sensitive, requiring no more than +12 dBm (16 mW) at 25 MHz and −14 dBm (43 μW) at 900 MHz from the transceiver to properly determine the frequency.
Figure 12: Magnitude of reflected power ($|s_{11}|$) measured at tuner’s transceiver-side port for the 40.000 MHz test frequency indicated in Table 1.

Figure 13: Magnitude of reflected power ($|s_{11}|$) measured at tuner’s transceiver-side port for the 155.535 MHz test frequency indicated in Table 1. The glitches just above and below 100 MHz are interference from FM broadcast signals.
Figure 14: Magnitude of reflected power ($|s_{11}|$) measured at tuner’s transceiver-side port for the 221.000 MHz test frequency indicated in Table 1.

Figure 15: Magnitude of reflected power ($|s_{11}|$) measured at tuner’s transceiver-side port for the 453.6 MHz test frequency indicated in Table 1.
Figure 16: Magnitude of reflected power (|s_{11}|) measured at tuner’s transceiver-side port for the 851.150 MHz solution indicated in Table 1.

Figure 17: Magnitude of reflected power (|s_{11}|) measured at tuner’s transceiver-side port with all stubs off and the extension element ON. This measurement is shown only to demonstrate that the extension element is operational, and does not represent an attempt to tune the system within the VHF-Low band. Note this measurement (only) was made inside.
Frequency Estimation Error. The scheme described in Section 2 estimates transmit frequency by counting cycles of the prescaler output over a period of time determined by the PIC’s internal oscillator. Frequency counting imparts a quantization error, since partial cycles are not counted. Figure 19 shows a laboratory measurement of frequency error, where the PIC’s estimate of frequency was determined by routing the necessary bits to pins where the values could be determined. The quantization error is apparent as a sawtooth pattern, which is worse at lower frequencies as expected. The peak error is less than 7% above 138 MHz, but can be as much as 30% in the 25–50 MHz band. Since the impedance bandwidth of the reconfigurable monopole is on the order of 5%, this error is acceptable above 138 MHz, but is obviously not reliable in 25–50 MHz band except as a means to determine that the transmit frequency is somewhere in this band. Fortunately, the forward/reverse power measurement scheme is reliable in this band, and can be used for closed-loop tuning. It should also be noted that the PIC microcontroller’s 25 MHz oscillator is not perfectly stable, thus there is some bias in elapsed time that manifests as an additional error that increases monotonically with frequency. This error was not measured explicitly, but is represented in the Figure 19 since the transmitter and tuner were not synchronized.

Accuracy of Forward/Reverse Power Measurement. The AD8364 IC on the tuner board measures forward (transmit) and reverse (reflected) power at the output of the tuner. These are presented to the PIC microcontroller as the voltage signals OUTB and OUTA, respectively. Figure 20 shows OUTB and OUTA for a +20 dBm carrier applied to the transceiver side of the tuner, as the carrier is swept from 25 to 900 MHz. As expected, the measured transmit power (OUTB) is approximately independent of termination and frequency. Also as expected, the measured reflected power (OUTA) tends to be less when the antenna port is terminated into a matched load. However, there is quite a bit of variation in absolute measured reflected power as a function of frequency, and the difference is ambiguous between 500 and 600 MHz. The current implementation of the tuner uses the AD8364’s OUTN output as the metric of match quality, where OUTN = OUTB − OUTA + a reference voltage (about 2.5 V). Thus, a larger value of OUTN corresponds to better impedance match. The OUTN signal corresponding to the data shown in Figure 20 is shown in Figure 21. Note that the OUTN signal corresponding to an ideal (50Ω) match is unambiguously larger than that corresponding to a very poor match (an open circuit), except in the range 450–700 MHz. Thus, the problem with the OUTA (reflected power) measurement needs to be fixed before this tuner could be
used in the upper portion (i.e., above 450 MHz) of 406–512 MHz public safety band. Outside this range, however, the performance is satisfactory.
Figure 20: The AD8364 IC’s OUTB (transmit) and OUTA (reflected) signals in response to a +20 dBm carrier applied to the transceiver side of the tuner. *Left:* Antenna port terminated into a 50Ω load, *Right:* Antenna port left open-circuited.

Figure 21: The AD8364 IC’s OUTN signal in response to a +20 dBm carrier applied to the transceiver side of the tuner.
References


