ModularTuner Project

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Abstract

The ModularTuner project is a collection of PCB modules and software that can be used to experiment with actively tuned antenna designs. It may be used to construct a versatile automatic antenna tuner as a kit to learn about how an antenna tuner works. All of the designs are open source hardware and software to be studied and improved. Because it is modular, the design enables further experimentation with various matching networks, methods of loading antenna elements, and methods of phasing antennas. This project is intended to be educational, inexpensive, and stimulate interest and development of new smart Medium Frequency/High Frequency (1.8-30 MHz) amateur radio antennas.

Project URL:

http://www.github.com/profdc9/ModularTuner

Related projects (not affiliated with this project):

stm32duino project:

http://wiki.stm32duino.com/index.php?title=Main_Page

Installation of stm32duino on Windows:

https://www.stm32duino.com/viewtopic.php?t=32

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Introduction

Antennas designed for the medium/high frequency (MF/HF) bands (1.8 to 30 MHz amateur radio bands) have not seen innovations that have occurred for UHF and microwave communications. Because the wavelengths are comparatively large, there are usually few options for antennas as the antenna choices are often dictated by space or site limitations. Unfortunately, few have the space or resources available to deploy phased array antennas in the HF, and even these phased arrays are typically limited to a single band and a few selected radiation patterns. Wireless networks are now extremely agile and accommodate a large number of simultaneous communications channels, frequency bands, and directed beams. HF antennas need to evolve in the 21st century and incorporate technologies that allow adaptation to the communications environment. This project intends to be a toolkit for those who wish to experiment with new antenna designs that can incorporate active sensing and control of the antenna state. It also is a means to construct a simple antenna tuner, such as the L-match tuner documented here, as an educational project.

Automatic antenna tuners were greatly enhanced by the introduction of microprocessors in the 1970s and 1980s. These devices integrate the essentials of adaptive antenna control: tunable elements under automatic control, RF sensing in the form of a reflection bridge, and programming that implements feedback as to minimize the reflections from the load. Microprocessor control enabled advanced forms of feedback not easily achieved by servo mechanisms. These tuners are typically single units with all of these parts integrated together and while they are adaptable to a degree, being able to match a range of loads, their function is usually separate from the antenna. The separation of the designs of the antenna and the matching network is a missed opportunity to achieve active control of the individual parts of the antenna or antenna network which may be used to more easily realize an increased frequency range, gain, and adapt the antenna to the environment. Current antenna designs require large booms and rotators, as in Yagi antennas, or large areas dedicated to antenna arrays. The large size of HF antennas presents a challenge, but active sensing and control of the antenna elements can help overcome some of the difficulties to employing ubiquitous HF antenna networks.

This project breaks out the parts of an automatic antenna tuner into components that may be used to experiment with HF antenna concepts that contain actively controlled elements. It consists of

- A controller module which can sense the forward and reflected power in the load, as well as the current in an antenna element. Equally importantly, it can measure the phase of the reflected signal as well as the antenna current.
- A directional coupler module for sampling the power. This module also includes a bias-tee for powering the device over coaxial cable.
- Modules with switchable series inductors and parallel capacitors to form matching and loading networks on antenna elements.
- Modules to implement variable delays for phasing elements by varying the total length of coaxial cable added to the signal path.
- Modules are controlled using a shielded two-wire communications (I2C) bus.
- For QRO use, there are versions of the modules that separate the relay power control and RF signals on separate PCBs to better isolate the microcontroller from the RF.

- Communications with the controller module with a medium-range ISM wireless modem.
- An optional LCD and pushbutton interface for user interface control.
- A four-way Wilkinson divider for distribution of power to a network of four antennas.
- A switched bus multiplexer than may be used as an antenna selector.

Currently, up to 8 modules can be used simultaneously, only limited by the number of separate I2C addresses that may be independently configured and the fanout of the bus. The software enables configuration of the modules so that component values may be specified that correspond to each switched relay.

Equally importantly, these components are all open hardware and software. The hardware is licensed under the Creative Commons Attribution Share-Alike (CC-BY-SA 4.0) license, and the PCBs are designed in KiCad, an open-source PCB design program. The software is licensed under the zlib license, which is a commercial-use license similar to the MIT license.

In designing these modules, generic electrical components were preferred over more specialized devices when possible, so that the design is less likely to be obsoleted by the unavailability of a component. The STM32F103CBT6 processor is used for the main controller. The PCB used, also called the “Bluepill,” is an extremely low cost, widely available ARM Cortex-M3 processor by STMicroelectronics. It is used in a very large number of devices, like the ATMega328P used for the Arduino, and therefore is not likely to be out of production soon. The Bluepill has Arduino IDE support through the stm32duino project, which is an adaptation of the Arduino libraries to the STM32 Cortex microcontrollers.

Except for the STM32 processor, and the Microchip MCP23008 and MCP23017 I2C peripheral interfaces, the other components are largely generic 74-series logic, diodes, and transistors. Most of the generic components used in the design may be sourced on ebay or aliexpress at a low cost. The PCBs are designed to be a maximum of 10 cm by 10 cm and two layers, and therefore may be fabricated for a very low cost by JLCPCB, Seeedstudio, or other PCB prototyping services. Because of this, this design is hopefully somewhat future-proofed and will be useful for years to come.

I hope that the ModularTuner system helps stimulate new ideas in antenna design and help bring some of the revolutions of wireless communications to the HF band.

Specifications

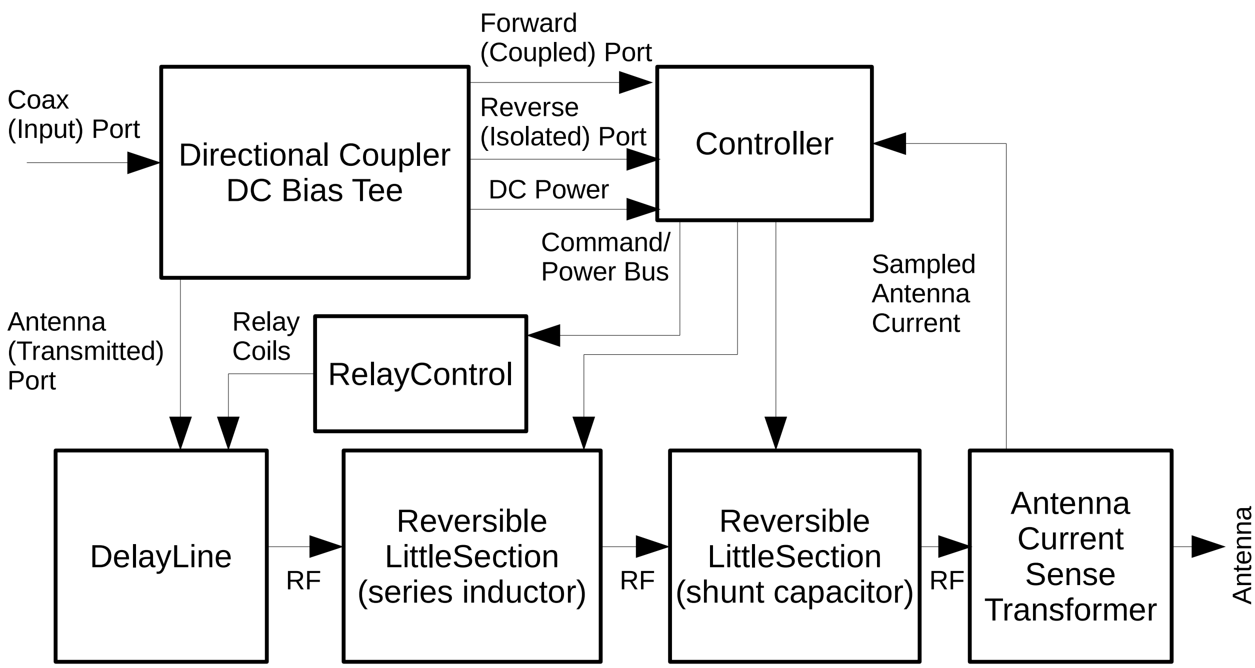
- For use at 1.8 MHz to 30 MHz amateur radio bands.
- Able to sense a minimum 1.1 SWR.
- Given component values to achieve a maximum of 4000 pF capacitance and 20 uH inductance, it is designed to match 1.5 SWR or less on 1.8 MHz to 30 MHz with 10 to 600 ohms load resistance on the 160 m band with a wider range on higher bands.
- Measures the phase of the reflected and antenna current signals to ±5° accuracy from 1.8 MHz to 21 MHz bands, ±20° accuracy from 21 MHz to 30 MHz band when 0.25 W or more reflected power is present.
- Selectable phase delay to 6° accuracy at the 10 m band, achieving a full wave of delay at the 80 m band with 26.4 m of RG-58 cable.
- Allows for 100 watt minimum operation. “Big” relays at 100 watts CW, “Little” relays are 100 watts SSB.

Features:

- Eight modules may be attached. Each of the modules may have 7 or 8 relays of switchable inductors or capacitors, or 6 or 8 switchable coaxial cable delays.
- May be operated remotely, delivering DC power over the coaxial cable, and communicating to the unit through an ISM-band wireless modem.
- A power divider is provided to split power to four antennas.
- LCD button panel for user interface control.
- May be programmed and diagnostics performed over USB or wireless.
- The passive component values may be programmed dynamically and the tuner searches for optimal combinations of passive components to match a particular capacitance or inductance.
- Rig control of ICOM transceivers through an AH-4 tuner interface.
- All software and hardware is open source for easy customization.

Architecture

The ModularTuner architecture consists of the following components, shown in a typical configuration:



The Controller contains a microprocessor and circuitry to measure the forward power, reverse power, and the magnitude of the sampled antenna current. In addition, it measures the phase of the reverse signal relative to the forward signal and the phase of the antenna current relative to the forward signal. It has a bus on it that delivers +5V, +12V, and a I2C signal to the modules which connects by a 2-by-5 pin IDC ribbon cable. This controller can have a LCD interface connected to it as well as a ISM-band wireless communications module and a GPS unit.

The Controller obtains a sampled forward and reflected signal from a directional coupler. There is a bias tee integrated with the directional coupler to allow DC power to be delivered over the coaxial cable. Most of the power is conducted through the directional coupler to the transmitted port.

There are three modules that modify the RF signal: a DelayLine, a series inductor ReversibleLittleSection, and a shunt capacitor ReversibleLittleSection.

In this example, there are two modules for the DelayLine. The two module setup (RelayControl and DelayLine) is intended for situations in which extra isolation is required between the Controller and the RF path because the digital and RF path are on separate PCBs, however a LittleDelayLine module could be used where the I2C control circuitry and the relays are on the same PCB if the extra isolation is not required. The RelayControl module receives command signals over I2C and generates a voltage for each relay coil on the DelayLine module. The RelayControl and DelayLine modules are connected by a 2-by-10 pin IDC ribbon cable connector, with one power pin and one pin for each of the 10 relay coils.   The DelayLine switches in and out different lengths of coaxial cable to add a variable amount of delay to the RF signal. This delay is sensed as a phase by the antenna current sense transformer at the antenna port.

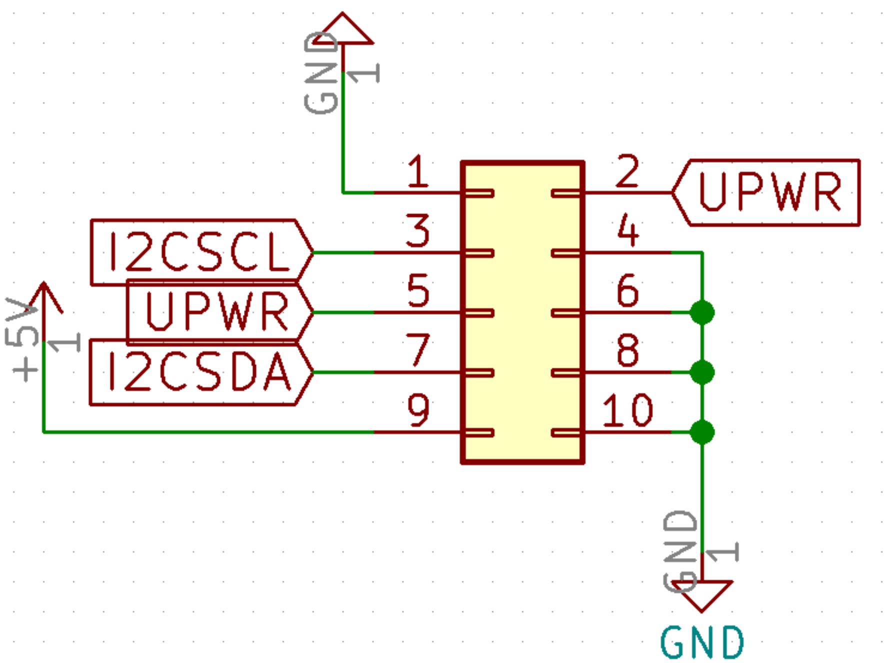
A “ReversibleLittleSection” configured as series inductors is then in the RF path. This forms part of a L-matching network with the ReversibleLittleSection shunt capacitors. The ReversibleLittleSection, ReversibleBigSection, LittleRelays, and BigRelays can be configured to either switch the elements in either a series or parallel configuration by jumpering particular pads together. In this case, the jumpers are set for series elements, and inductors are soldered into the module. The ReversibleLittleSection has both the circuitry to receive the I2C command signals, generate the relay coil voltages, as well as the relays and the inductors on the same PCB. Therefore a separate RelayControl PCB is not required for a ReversibleLittleSection or ReversibleBigSection.

The section is “reversible” because the RF and ground can be switched between two ports using a pair of relays.   One of the ports is the normally closed port and is connected when power is off, and the other is normally open. On the inductor section, the normally closed port may be wired to short out the inductor when power is off so that the inductor board is bypassed. When the inductor board is active, the relay is energized and the section switches to the normally open port and the inductance of the section is in the RF path.

A second ReversibleLittleSection is configured for parallel capacitors. In this case the reversible switch is used to switch the capacitors from a low-Z to a high-Z configuration of the L network, so that the shunt capacitor is placed on one side or the other side of the series inductor. It can be seen that the port switches on the inductor/capacitor boards may be used to reconfigure the topology of a matching network.

Finally, an antenna current sensing transformer samples the antenna current after the matching network. This transformer is connected to the Controller which measures the relative phase of the antenna current and the forward voltage signal. This can be used with the delay section to obtain a particular phase between the forward signal and the radiated signal. This is useful for a phased array antenna as the phase reference is derived from the single forward signal at the transmitter.

Power/command bus



The pinout of the power/command bus is above. The connector is a 2-by-5 IDC ribbon cable connector with 2.54 mm spacing pins. Pins 1, 4, 6, 8, and 10 are ground. Pin, 9 is +5 VDC. Pins 2 and 5 are +12 VDC but perhaps unregulated, which is used for the relay coils which are not overly sensitive to voltage levels. Pins 3 and 7 are the clock and data lines of the I2C bus. There are power or ground lines between the digital signals to shield these digital signals from RF as they are relatively high impedance connections.

At both ends of the cable, the grounds should be connected together, the two UPWR signals should be connected together and to the ground with a 100 nF capacitor close to the connector, and the +5V should be connected to ground with a 100 nF capacitor also close to the connector, as to prevent any RF potential between the power buses. The DC ground should be connected to the RF ground through a 100 nF capacitor through a metal standoff to the chassis.

Grounding

One of the most difficult aspects of designing an antenna tuner or antenna system that spans several separate PCBs is maintaining good RF grounding. One of the more challenging aspects of designing the ModularTuner system was to ensure the grounding is thorough as to not allow any paths for the RF to affect sensitive components such as the microcontroller, and conversely to not allow the digital noise of the microcontroller to find its way into the RF path. By following the system set up by these modules, good grounding will be maintained and these problems avoided.

Typically, an antenna tuner is designed inside a single RF grounded, metal enclosure with the PCB itself grounded to the enclosure in many places. There is an intended path for the radio frequency signal, and this path is isolated from digital components by using capacitors to shunt RF energy to the grounded enclosure as well as inductors or RF chokes to provide an increased impedance to the RF to components it should not affect. Ideally, all paths around any RF susceptible components are fenced in by shunt capacitors, series inductors, or ground shields. All of these approaches are used in the ModularTuner.

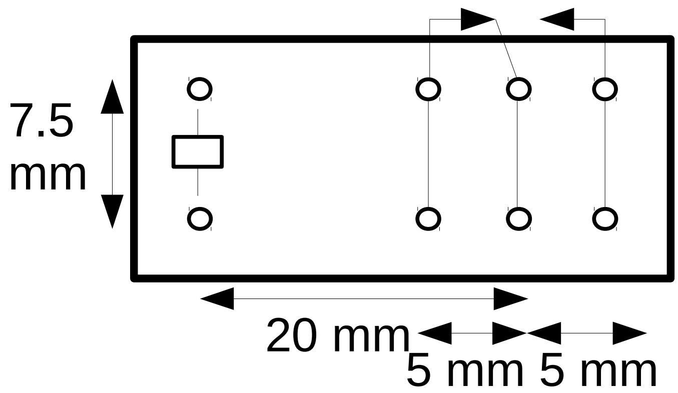
The simplest approach to grounding is to use a single enclosure or metal sheet as a ground plane. The coaxial connector shields should attach to the enclosure wall or attach with a very short grounding strap to the metal sheet. The modules are intended to be grounded to the enclosure or ground plane through metal standoffs. The standoffs contact the PCB using a widened trace intended to ensure a good contact. These standoffs are capacitively coupled to the power rails in the circuit as to shunt any RF signal in the power supply rails on all of the modules into the RF ground. The modules are designed so that the RF signal from the signal path is blocked by inductors or chokes and the return currents between the RF path and low voltage paths occur mostly through the metal standoffs and the ground plane. Therefore the best way to ensure that good grounding is achieved is to ensure all of the RF coupling capacitors to the standoffs are installed, and that all of the standoffs are installed at the four corners of each module. This is the simplest and most foolproof approach.

Unfortunately, it may not be possible to place everything into the same enclosure and ground it to a single piece of metal. For installing tunable elements that are outside of the enclosure, there are modules that separate the relay control (the RelayControl module) and tunable modules that contain only the tunable elements and relays (the BigRelays, LittleRelays, and DelayLine modules). The ribbon cable connection between the tunable modules and the RelayControl consist only of the power to the relay coils and therefore is relatively insensitive to RF interference. There are capacitors and grounds to reduce any RF signals that may be between the conductors of the cable, however, there is still a common-mode signal because the ribbon cable itself acts as an antenna. Therefore cables that are not grounded that go outside the enclosure, like the ribbon cable to the tunable modules, should have a common-mode choke placed on them. This can be achieved by wrapping the ribbon cable several times around a ferrite toroid, often a FT240-31 or FT240-43 toroid. The toroid should be placed near where the cable enters the RF shielded enclosure. In general, if a connection can not be grounded with a very short connection to the same ground as the enclosure, a ferrite choke should be used to prevent the common-mode signal from entering the enclosure.

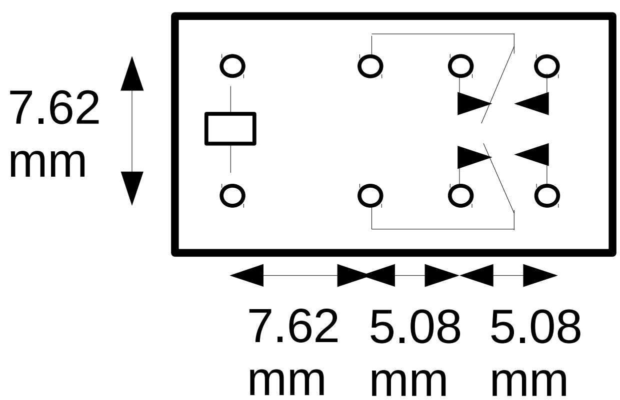
Relays

The relays used for the ModularTuner are two types commonly used for amateur radio projects. Two two types here are called the “Big” and “Little” relays. These two relay types have footprints that separate the pins of the relay coil from the pole as to minimize the capacitance between the two. The capacitance between the poles and the coil of the relay serve as a shunt capacitor to ground, which if sufficiently large, can prevent the load from being matched.

The two types of relays have the following footprints. Metric and imperial near-equivalent dimensions, e.g. 0.2 inch or 5 mm, 0.3 inch or 7.5 mm, etc. can be substituted without problems.



“Big” Relay
Single Pole,
Double Throw
(SPDT)



“Little” Relay
Double Pole,
Double Throw
(DPDT)

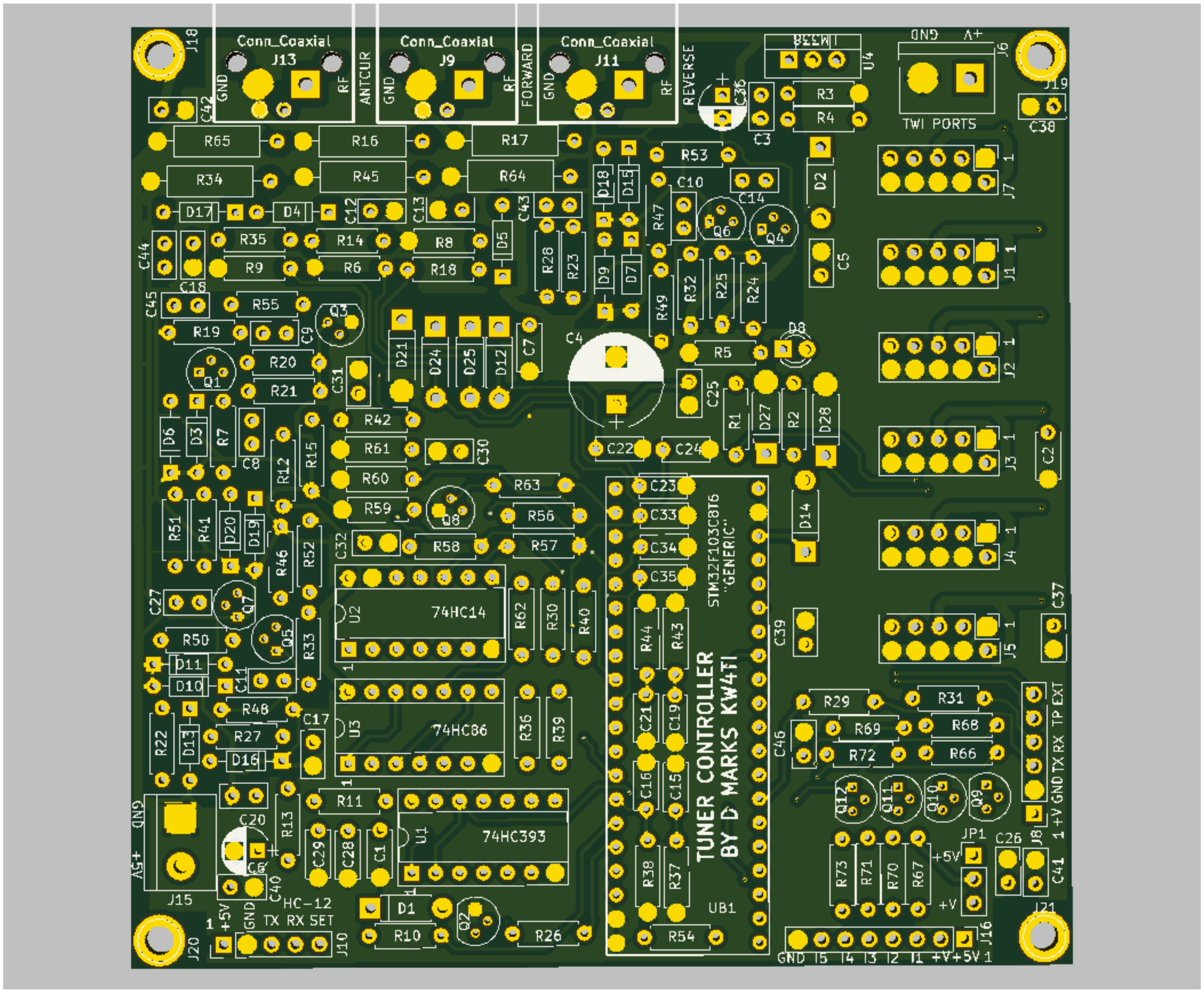
Examples of the big-type relays are the Omron G2RL-1, Schrack RTH14012, Songle SMIH-12VDC-SL-C, and Hui Ke HK14F relays. These are single pole, double throw (SPDT) relays that are rated for up 15 to 16 amps (not RF) typically. These types of relays have been used in QRO antenna tuners and have a very low pole-coil capacitance around 1 pF.

Examples of the little-type relays are the Omron G5V-2, Axicom D2N, Hongfa HFD27 relays, and the Hui Ke HK19F relay. These are double pole, double throw (DPDT) signal relays and are good perhaps up to 100 watts.   These relays have a pole-coil capacitance per pole of about 2 pF and total of about 4 pF for both poles. Because the relays generally have a lower current capacity, typically around 2 A per pole, these are more susceptible to damage from high power switching. The software is designed to minimize the possibility of hot switching the relays with full power applied by not tuning if excessive power is detected, however, if excessive hot switching occurs, the lifetime of the relays will be greatly reduced.

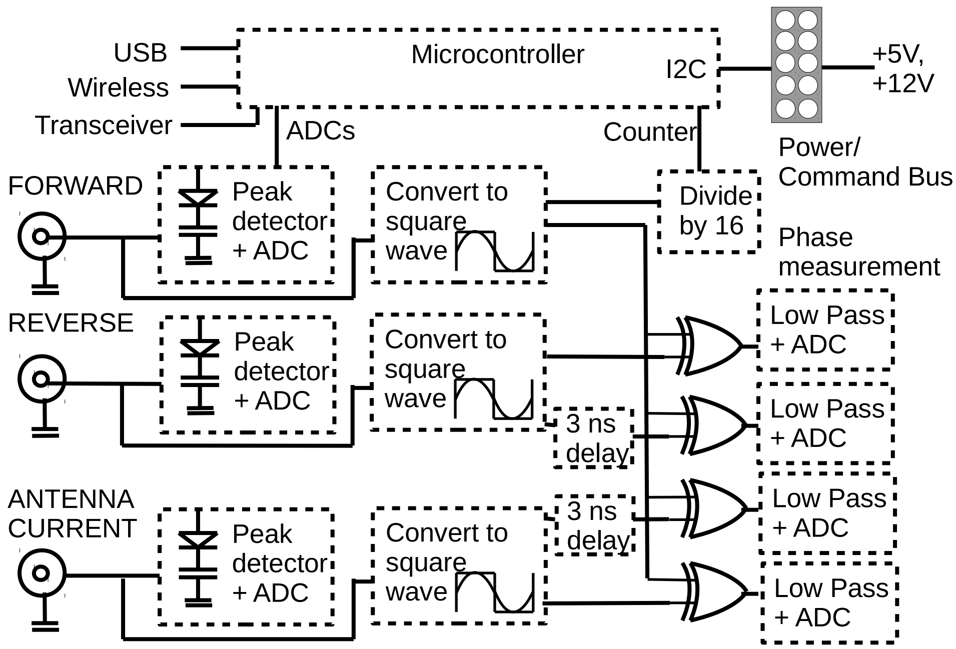
Unfortunately, not every relay that has these footprints will work as it depends sensitively on how the relay is constructed. If you are using an unknown relay, measuring the pole-coil capacitance with a LCR-meter or a vector network analyzer may help identify if excessive RF energy will leak out of the coil to ground.

Description of Modules

Controller Module



Simplified Schematic



The Controller Module contains the microcontroller that senses the state of the antenna system and adjusts the elements accordingly. It is intended to be isolated from the RF path through the two transformers of the Directional Coupler board. It contains the following components:

The silkscreened boxed component in the central lower portion of the PCB is where the STM32F103C8T6 Bluepill board is attached. It is a very inexpensive, readily available Cortex M3 processor running at 72 MHz with 64k/128k of flash (almost all Bluepills contain 128k flash parts currently), 20k of static RAM, ten 12-bit A/D converters, and many other common microcontroller peripherals such as SPI, I2C, and UART ports.

The three connectors at the top of the board from left to right, also in silkscreen boxes, are the input coaxial cable ports for the antenna current transformer, the forward sensed power, and the reverse sensed power from the TandemMatch. The connector footprints can take either a plastic body right-angle PCB BNC panel mount, or a 5.08 mm two position screw terminal block. This combination footprint is used throughout the board to allow either BNC connectorized or bare-ended RG-58 coaxial cables to be used. At the upper right is the power connector for +12V.

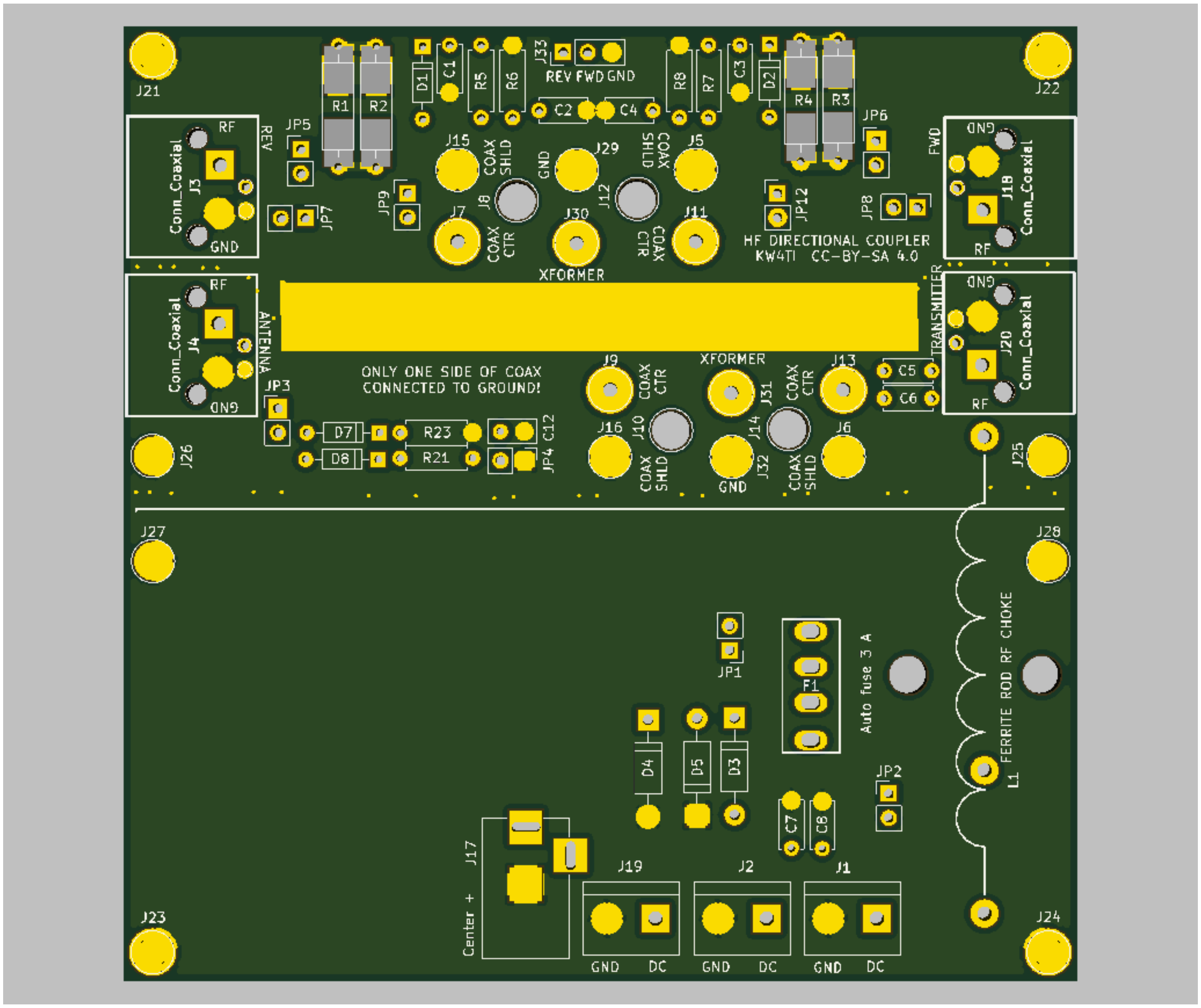
There are six power/command bus connectors that connect to modules using 2-by-5 IDC ribbon cables.

At the lower left, there is a 5-pin connector for a HC-12 433 MHz ISM band wireless module for medium-range communication between the shack and the Controller. At the lower right there are two connectors. The connector on the right side of the board is for a NEO 7M GPS module, but it also breaks out the UART1 pins that may be used to program the flash of the Tuner/Controller. Finally on the lower edge of the board on the right, there are several pins that have MOSFET level shifters. These are intended to be connected to transceivers for rig control, for example, to initiate a tuning cycle of the Controller.

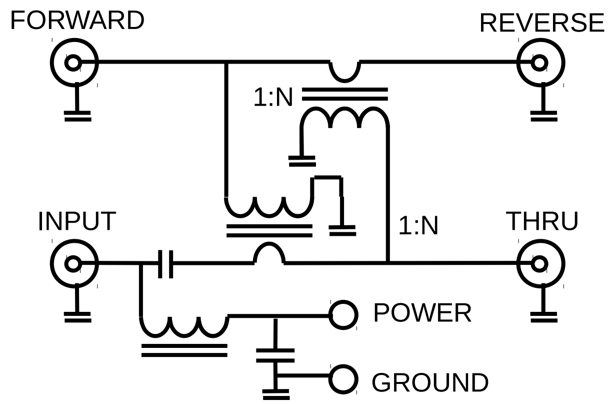
There are peak-detector diodes to measure the power in the forward, reverse, and antenna current ports which are sampled by the microcontroller. Furthermore, there is circuitry to measure the relative phase of the forward and reverse signals as well as the forward and antenna current signals. The phase measurement is implemented by transforming the sine wave signals into square waves and then using an exclusive-or gate to produce a signal with a phase proportional to the duty cycle of the square wave. Measuring two relative phases, with one of the signals slightly delayed, disambiguates positive and negative phase. These phases may be used to estimate the complex load impedance of the antenna as well as provide feedback to control the phase of the radiated signal relative to the incoming signal.

On the Bluepill microcontroller board, there is a USB port that is programmed to present a serial port to be connected to a PC. A command-line interface may be accessed through this port to control the ModularTuner through a PC. These commands are documented in a later section. If the ModularTuner is in a remote location, this command-line interface may also be accessed through the HC-12 wireless interface, however, this is a much slower access method.

DirectionalCoupler Module



Simplified Schematic



The DirectionalCoupler module is a directional coupler that supplies samples of the forward and reverse signals to the Controller. It has several diagnostic components that may be jumpered in and out to test the DirectionalCoupler.

Two transformers are used to sample the voltage and current from the input port J20. These transformers are typically FT50-43 ferrite cores with 15 secondary turns for 100 watt operation. The sampled forward signal is at the connector J18, and the sampled reverse signal at J3. Again, the combined footprint ports are present to allow either a connectorized BNC cable or bare-ended RG-58 to be used to connect the boards. The transmitted port is J4.

The following diagnostics are present on the board:

JP3: by closing JP3, the peak voltage on the input port may be sensed at JP4.
JP5: by closing JP5, the reverse port may loaded with 50 ohms.
JP6: by closing JP6, the forward port may be loaded with 50 ohms.
JP9: by closing JP9, the peak voltage on the forward port may be sensed at J33.
JP12: by closing JP12, the peak voltage on the reverse port may be sensed at J33.
JP7: by opening JP7, the reverse port coaxial connector may be disconnected so that the 50 ohm load may be connected using JP5.
JP8: by opening JP8, the forward port coaxial connector may be disconnected so that the 50 ohm load may be connected using JP6.

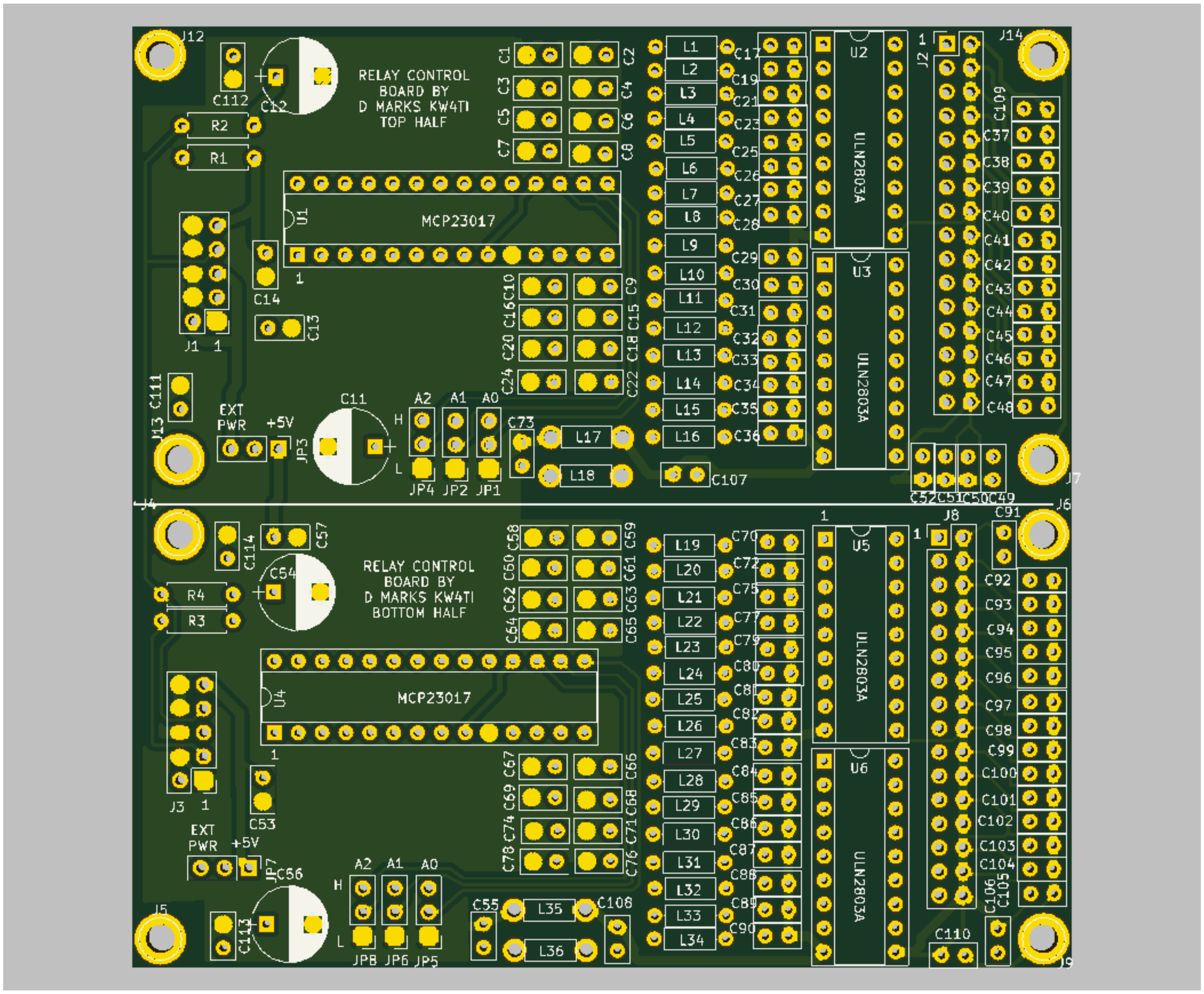
For normal use, JP7 and JP8 should be closed, and JP3, JP5, JP6, JP9, and JP12 should be open.

These jumpered diagnostic connections can help ensure that the DirectionalCoupler is working properly to sample the forward and reflected signal.

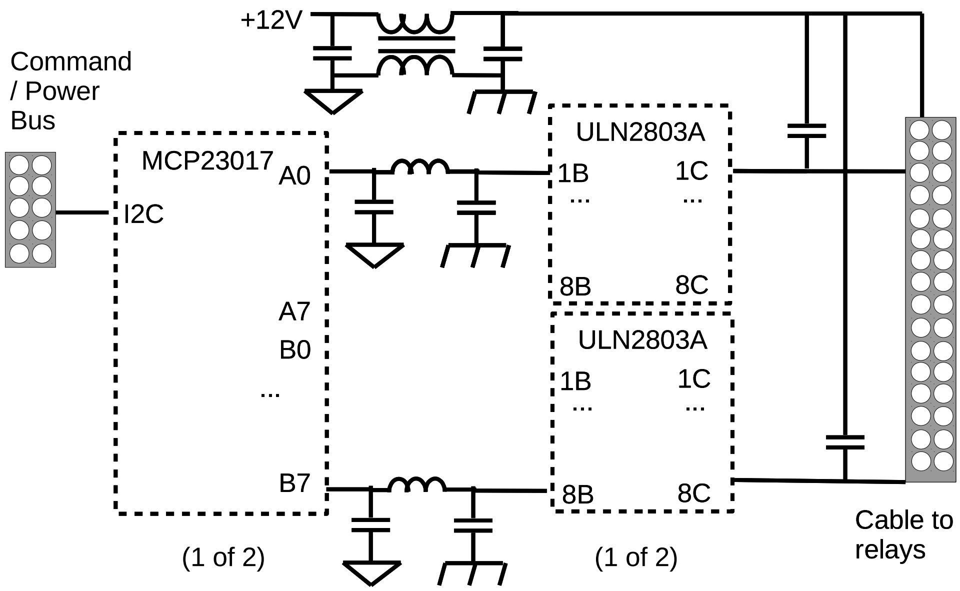
There is also a bias-tee on the bottom of the board. A RF choke is placed close to the input port J20 to conduct the DC power on the coaxial cable but block the RF signal. This power is made available at several connector blocks. The power may also be injected through these ports or a barrel connector.

A fuse holder at F1 can hold a SL-506P auto-fuse holder. A 3 A auto fuse should be fitted into the holder.

RelayControl Module



Simplified Schematic



The RelayControl module receives I2C commands from the Controller and provides output voltages to control relay coils. On each RelayControl module, there are two Microchip MCP23017 I2C peripherals, each of which can control up to 16 relay coils. Only one of the two connectors J1 and J3 need be connected to the Controller.

This module is intended to isolate the RF path from the digital signals. The left half of the board is the digital portion, while the right half is the relay control portion. Every connection between these two halves have a common-mode choke or inductor in the path. L17/L18 and L35/L36 are common-mode chokes, while L1-L16 and L19-L34 are 100 uH axial inductors. The RF current is blocked from crossing between the two halves of the board by the chokes and inductors and only low frequency return currents cross to provide the slow relay signals. The RF current is returned mainly through the metal standoffs at the four corners of the board. Therefore the standoffs at the four corners should be attached to the chassis.

The jumpers at JP3 and JP7 choose the relay coil voltage either from the +5V supply or the EXT PWR. Almost always, EXT PWR will be used with 12 volt coil voltages to minimize the current carried on the bus cables.

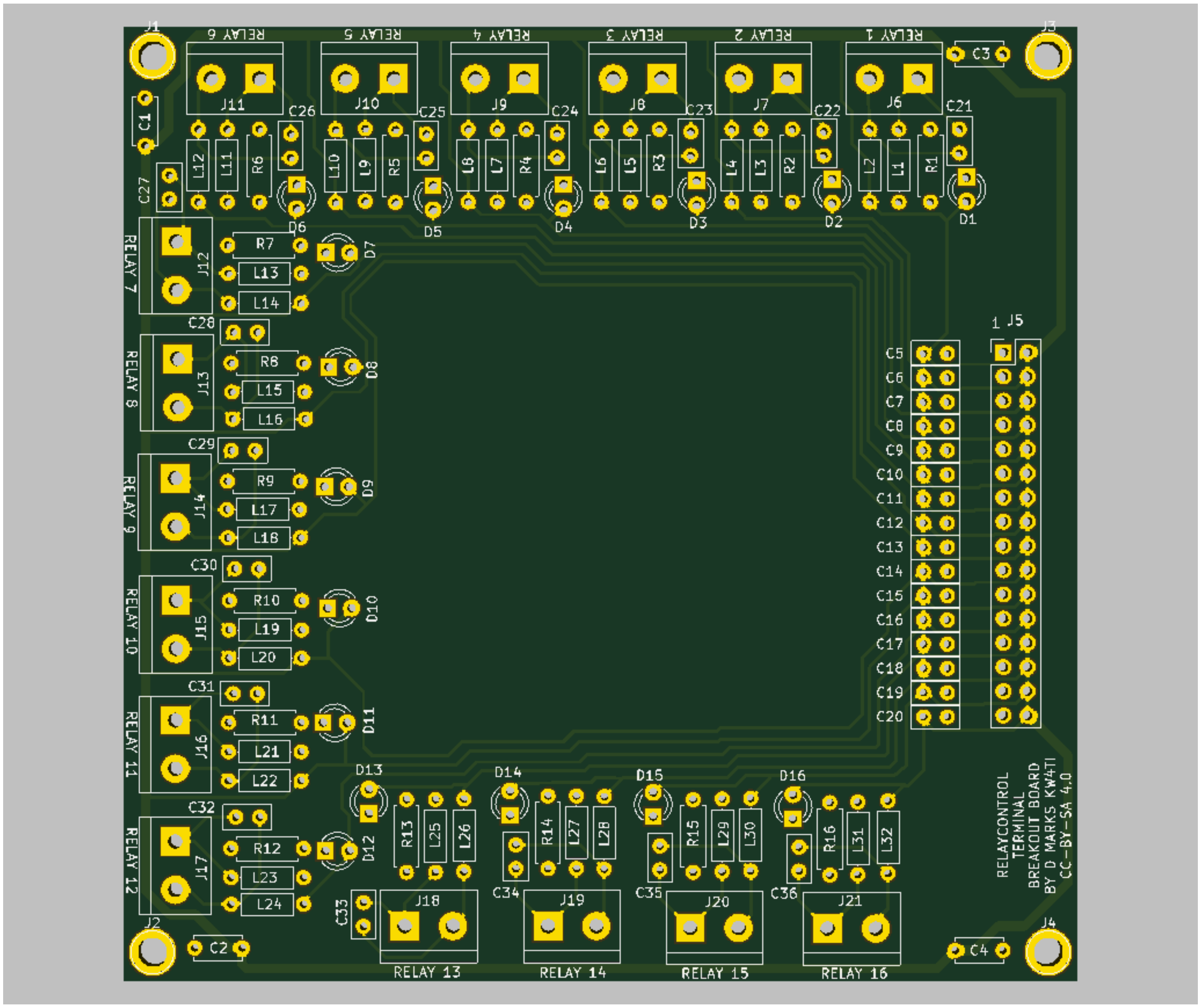
The I2C address for the 16 relays on the top half of the board are selected using the jumpers JP4, JP2, and JP1, while the I2C address for the 16 relays on the bottom half of the board are selected using JP8, JP6, and JP5.

The coil voltages are at the connectors J2 and J8. There is a positive supply pin for each coil and a coil voltage pin that is grounded to energize the coil. The power supply pins on both sides of the ribbon cable connection the RelayControl module and the relay module must be grounded through capacitors on both sides of the ribbon cable, and there should be capacitor between every the power supply pin and the coil voltage pin on every coil. The relay modules designed for ModularTuner ground the power supply pins through the metal standoffs. If it is not possible to ground both sides of the ribbon cable, a common-mode choke should be placed on the cable.

Usually, not all 16 relay coil outputs of each MCP23017 are used. The relay coils that are used start at the 1-pins of the J2 and J8 connectors, so that the first relay coil is connected to pins 1 and 2, the second coil to 3 and 4, etc. Therefore, for example, when controlling 10 relays as in the BigRelays, LittleRelays, and DelayLine boards, pin headers need only be soldered into the first 20 pins of the J2 and J8 connectors, and the other pins 21 to 32 should not be used so that a 2-by-10 IDC ribbon cable will fit over the 20 pin header without interference from the unused pins.

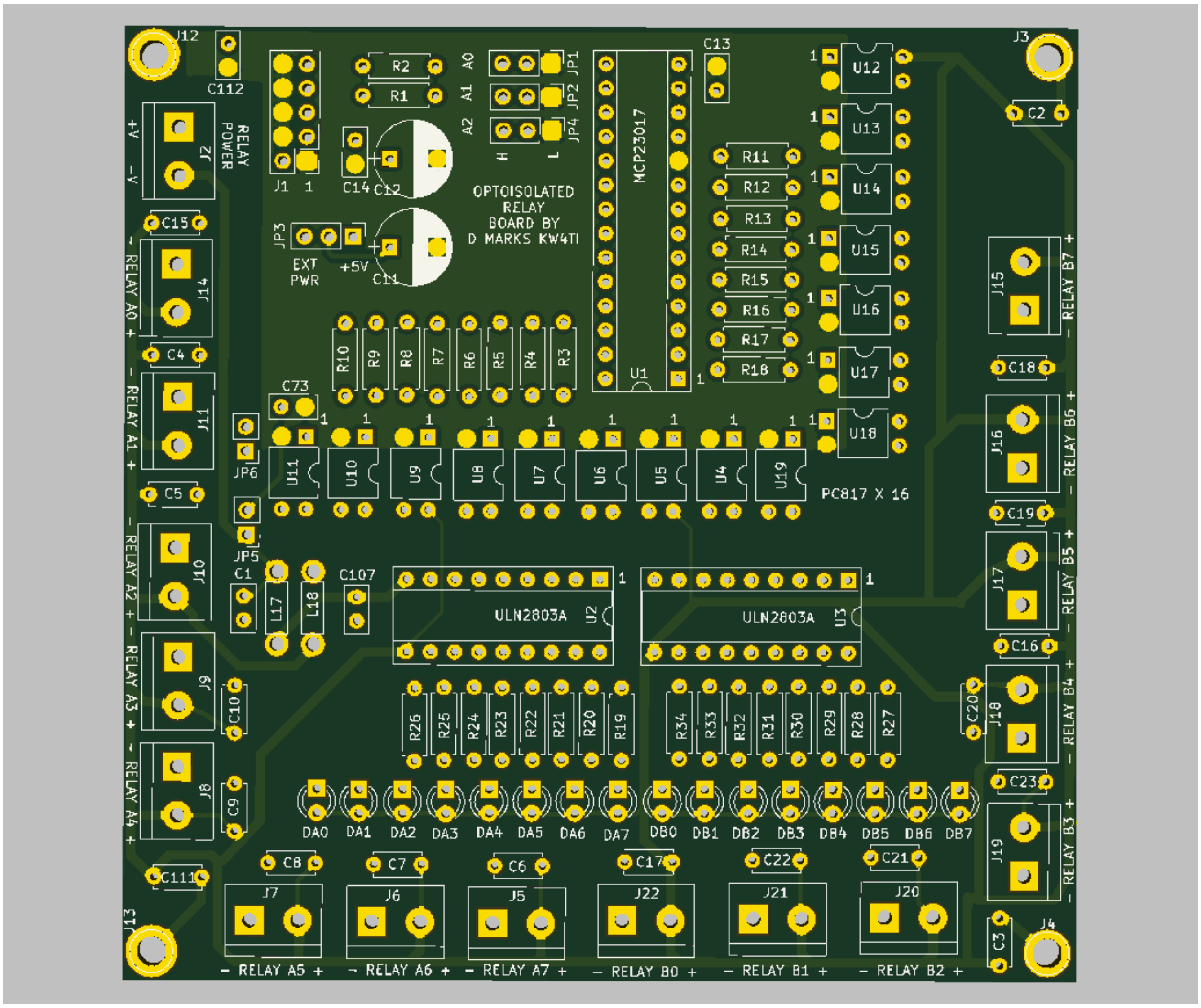
If you are using the RelayControl module to control your own relay board design, it is important to ensure that 10 to 100 nF capacitors are placed across all of the coils of the relays, the positive power rail of the relays are all joined together, and that the relays are all collectively grounded through the positive power rail to the RF chassis ground through another capacitor, usually a 1 kV or higher 10 nF capacitor, or perhaps even several capacitors in parallel to reduce impedance. If the board is large, it may be necessary to ground the relay coils in several places to the chassis to ensure short connections from any relay coil to RF ground. If too much RF energy is transmitted to the RelayControl board and has to be shunted to ground there, it may damage the small capacitors that shunt the RF power at the RelayControl board, as the RelayControl board is designed so that most of the RF power should be shunted to ground near its source. Failing that, a common-mode choke can be placed on the ribbon cable as well.

RelayBreakout Module

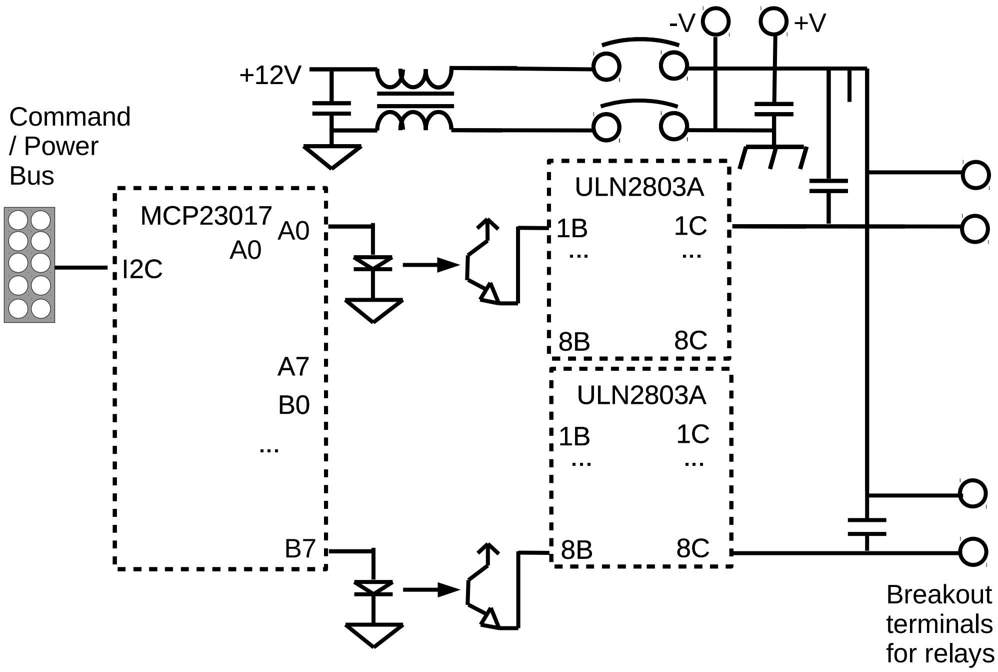


The RelayBreakout module is a simple module that breaks each of the relay coil terminals into separate screw terminal blocks. It also adds an extra layer of RF isolation because this board contains 100 uH chokes in series with both terminals. It is intended for those who wish to wire their own relays to the RelayControl board, but want the convenience of screw terminals and the extra isolation. It may be used, for example, to switch relays that load parasitic elements on vertical antenna arrays or Yagi antennas. The relays for these applications are likely to have high RF leakage into them and therefore extra isolation is desirable. The remaining RF that passes through the chokes is grounded to the chassis through capacitors at all four corners of the PCB.

OptoisolatedRelay Module

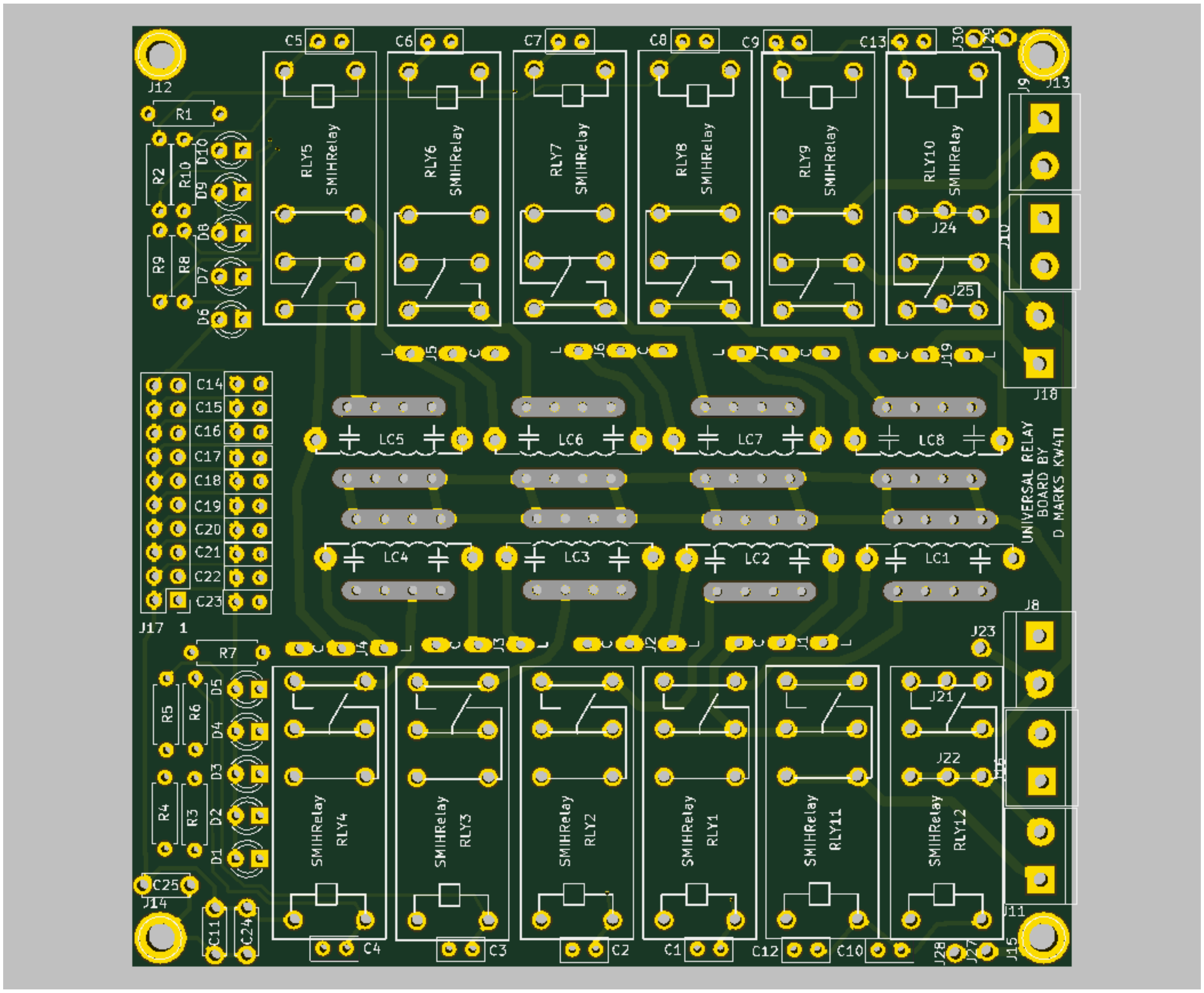


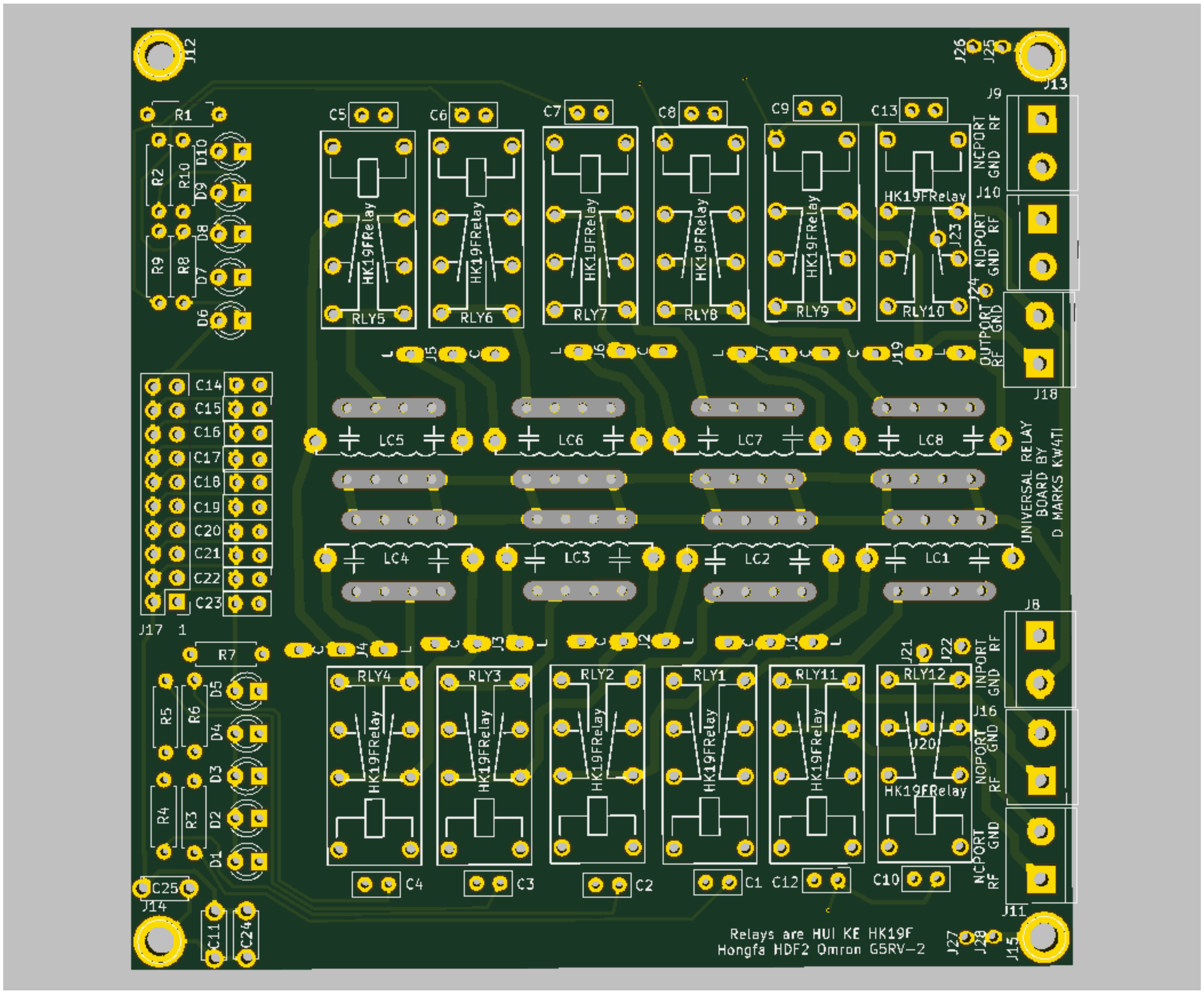
Simplified Schematic



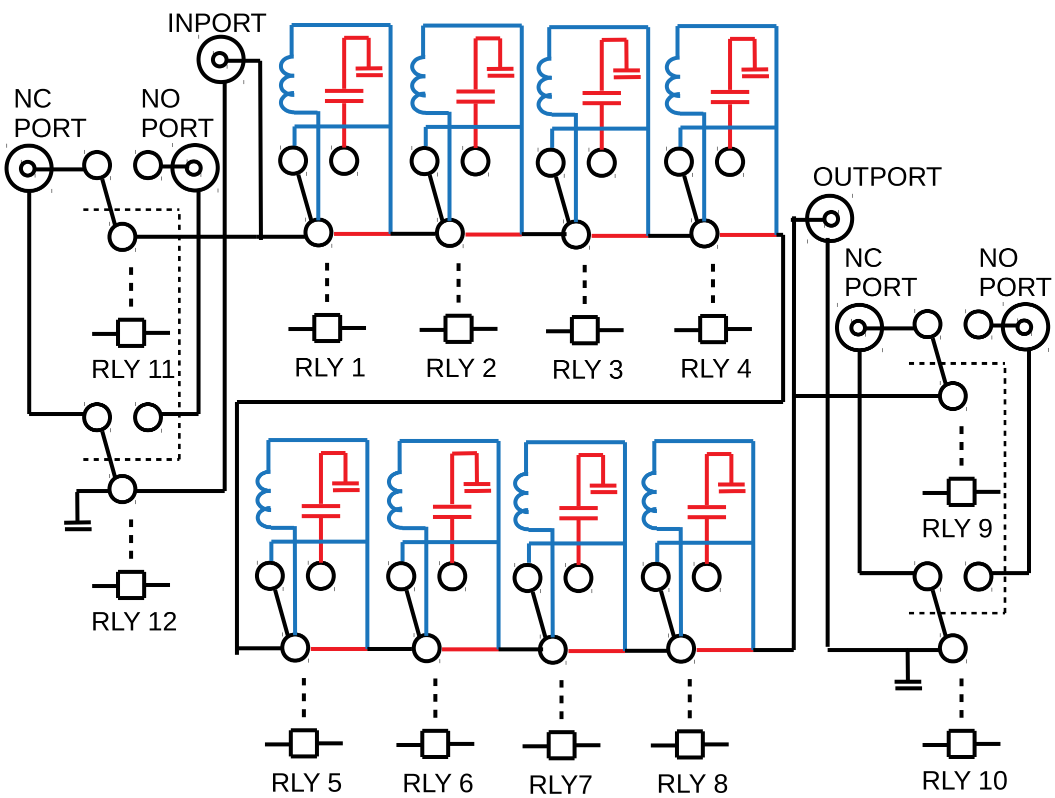
The OptoisolatedRelay module provides a drive for 16 relay coils. The drive circuity is optoisolated from the digital circuitry. The power may be provided by the command/power bus, in which case the jumpers JP5 and JP6 are closed, and the RF is isolated by a common-mode choke. Alternatively, it may be provided by a completely separate supply, in which case the command/power bus is completely galvanically isolated from the relays and RF path. This module is intended to interface to relays that are require isolation because they are in high power RF environments with high voltages, for example, loading parasitic vertical antennas or parasitic elements of a Yagi antenna. Common-modes choke may be placed on the cable sto the relay coils to add further RF isolation. The module should be grounded to the chassis/RF ground through the standoffs at the corners of the PCB as even with optoisolators, any RF signal at the PCB must be shunted.

BigRelays and LittleRelays Modules



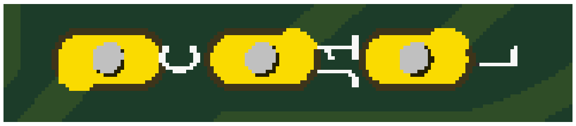

UNIVERSAL RELAY BOARD BY D MARKS KW4TI
Relays are HUI KE HK19F
Hongfa HDF2 Omron G5RV-2
NCPORT GND RF
NOPORT GND RF
OUTPORT GND RF
INPORT GND RF

Simplified Schematic

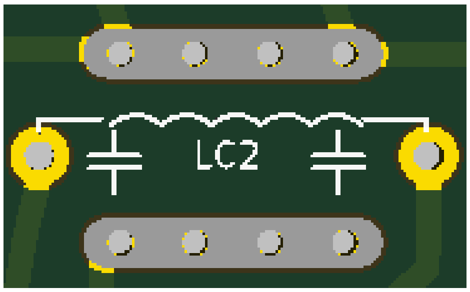


The BigRelays and LittleRelays boards can connect either series inductors or parallel capacitors to the RF path. The blue components in the schematic note the paths taken when wired for series inductors, and the red paths are for the parallel capacitor configuration. It takes a 2-by-10 IDC ribbon cable that connects to J17. These control 10 relays. Eight of these relays, RLY1-RLY8, select an inductor or capacitor for the RF path. RLY9 and RLY10 form a DPDT switch that selects one of two ports, port J10 (normally closed) or J9 (normally open) for the RF and ground connection of that side of the board to be connected to, while J18 is always connected. Likewise, RLY11 and RLY12 form a DPDT switch that selects one of two ports J16 (normally closed) or J11 (normally open), with J8 always connected. Therefore either side of the series inductors or parallel capacitors may be connected to two different ports. This allows, for example, a module to be changed from being a series to shunt element, or allows the module to be connected to different parts of a matching network. There is silkscreening on the back of this board marking the RF and GND pads of the normally closed, normally open, and always connected terminals.

Whether the board uses series or parallel elements is selected using the jumpers J1, J2, J3, J4, J5, J6, J7, and J19. Each of these jumper points looks similar to:



To select the series configuration, solder a jumper wire between the center pad and the pad marked “L” for inductor, or for the parallel configuration, solder a jumper wire between the center pad and the pad marked “C” for capacitor. All of these jumper points should be soldered the same way. Then the component is soldered to pads that appear as:



If the series inductor configuration is used, the component should be soldered between the two circular pads that have an inductor symbol connection them. If the parallel capacitor configuration is used, one or more capacitors may be soldered between the two long pads. Both sets of pads should not be used at the same time.

The relay coils are grounded to the chassis through the capacitors C11, C24, and C25 to the lower left standoff. At least one capacitor should be placed here with a 630 V rating and 10 nF capacitance.

On the BigRelays board, points J21, J22, J23, J24, and J25 are connections to the grounds of the RF path, which except for J23 are switched by the relays. These may be connected by jumper wires to the point J27, J28, J29, and J30 which are connected to the standoffs, so that the RF path may be grounded if needed. For example, generally when using capacitors in a shunt configuration, J23 is connected to ground through a jumper wire.   On the LittleRelays board, the points J20, J21, J22, J23, and J24 are connections to the grounds of the RF path, and the points J25, J26, J27, and J28 are connected to the standoffs.

Optionally, resistors and LEDs may be fitted so that the state of the relay coils may be seen by which LEDs are illuminated.

For use at the 160 meter band, a maximum capacitance of about 4000 pF is needed. Therefore the capacitors may be picked to be related to each other by near powers-of-two with 2000 pF as the maximum capacitance.   The capacitors are usually ceramic or silver mica capacitors rated 1 kV or higher depending on power levels. Multiple capacitors are generally used in parallel to minimize effective series resistance. Some suggestions for values:

2000 pF = 1000 pF || 1000 pF
1980 pF = 470 pF || 470 pF || 470 pF || 470 pF || 100 pF
987 pF = 470 pf || 470 pF || 47 pF
980 pF = 220 pF || 220 pf || 220 pF || 220 pF | 100 pF
500 pF = 100 pF || 100 pF || 100 pF || 100 pF || 100 pF

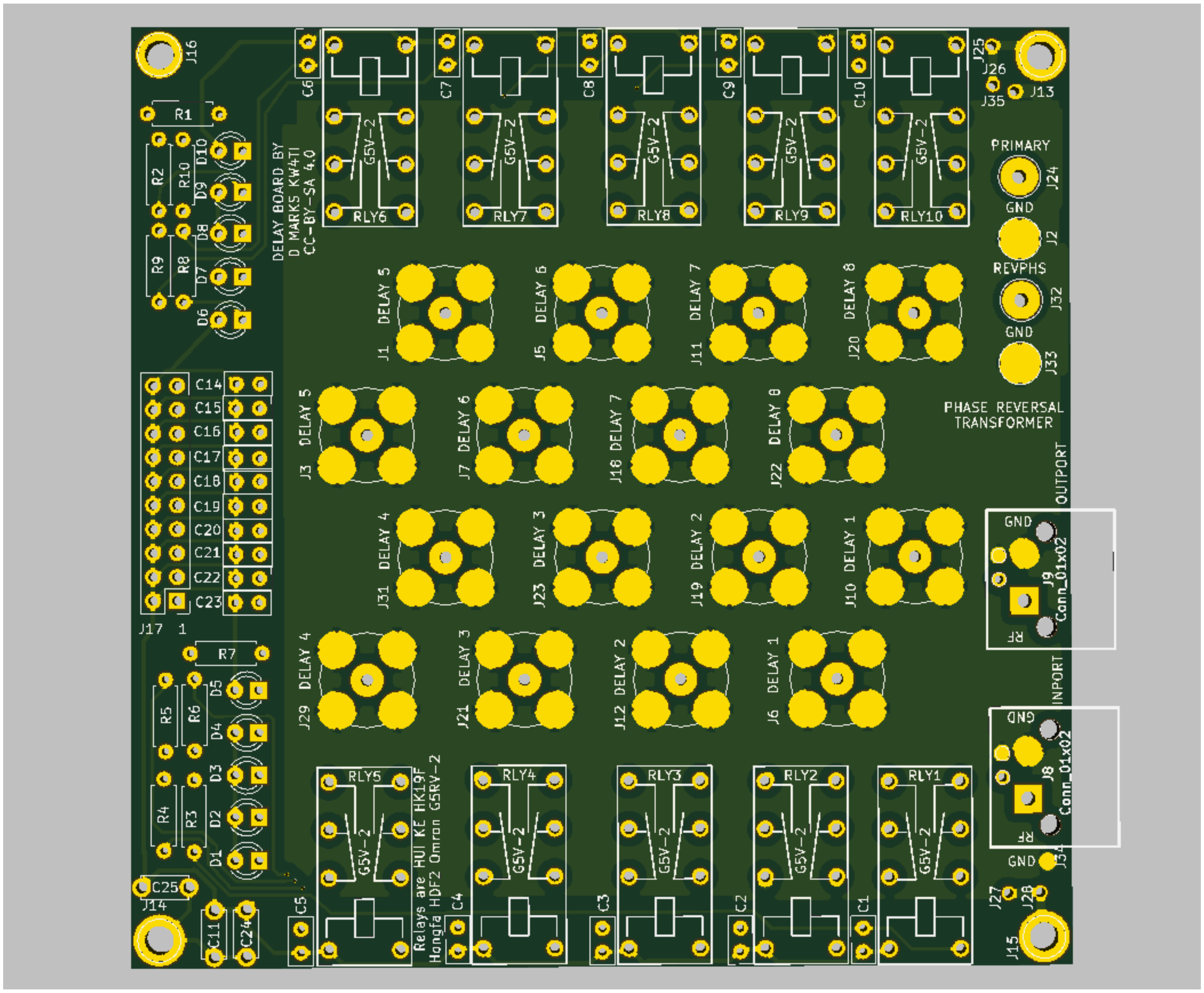
487 pF = 220 pF || 220 pF || 47 pF
257 pF = 47 pF || 47 pF || 47 pF || 47 pF || 47 pF || 22 pF
247 pF = 100 pF || 100 pF || 47 pF
127 pF = 47 pF || 47 pF || 33 pF
124 pF = 47 pF || 47 pF || 10 pF || 10 pF || 10 pF
120 pF = 22 pF || 22 pF || 22 pF || 22 pF || 22 pF || 10 pF
62 pF = 22 pF || 22 pF || 18 pF
32 pF = 22 pF || 10 pF
16 pF = 33 pF in series with 33 pF
9 pF = 18 pF in series with 18 pF

For the small capacitance values, an open stub of RG-58 or RG-316 may be used, which have a capacitance of approximately 100 pF/m. If the measured capacitance values are programmed into the Controller, the Controller software exhaustively finds the best approximation of capacitances to a particular desired value. Because stray capacitances for the PCB are on the order of several pF, the precision of the capacitors need not be excessive.

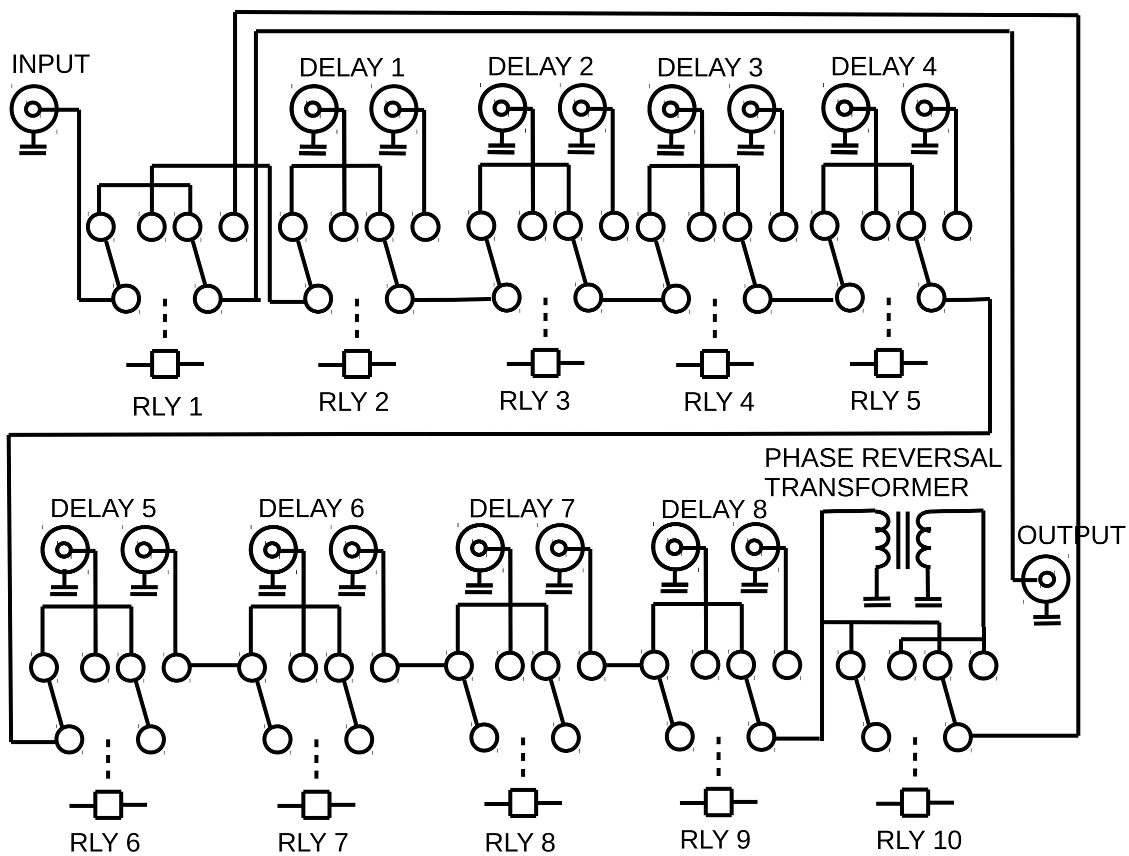
For inductors, a maximum capacitance of about 20 uH is needed for the 160 meter band. One way to achieve this is to use stacked T68-2 iron powder toroids, which can be purchased in quantity cheaply:

10 uH = 4 stacked T68-2 cores, 21 turns
5 uH = 2 stacked T68-2 cores, 21 turns
2.5 uH = one T68-2 core, 21 turns
1.25 uH = one T68-2 core, 15 turns
0.63 uH = air core 5 turns of 1 mm diameter magnet wire around 20 mm diameter form
0.32 uH = air core 4 turns of 1 mm diameter magnet wire around 15 mm diameter form
0.16 uH = air core 3 turns of 1 mm diameter magnet wire around 12 mm diameter form
0.08 uH = air core 2 turns of 1 mm diameter magnet wire around 12 mm diameter form

DelayLine Module



Simplified Schematic



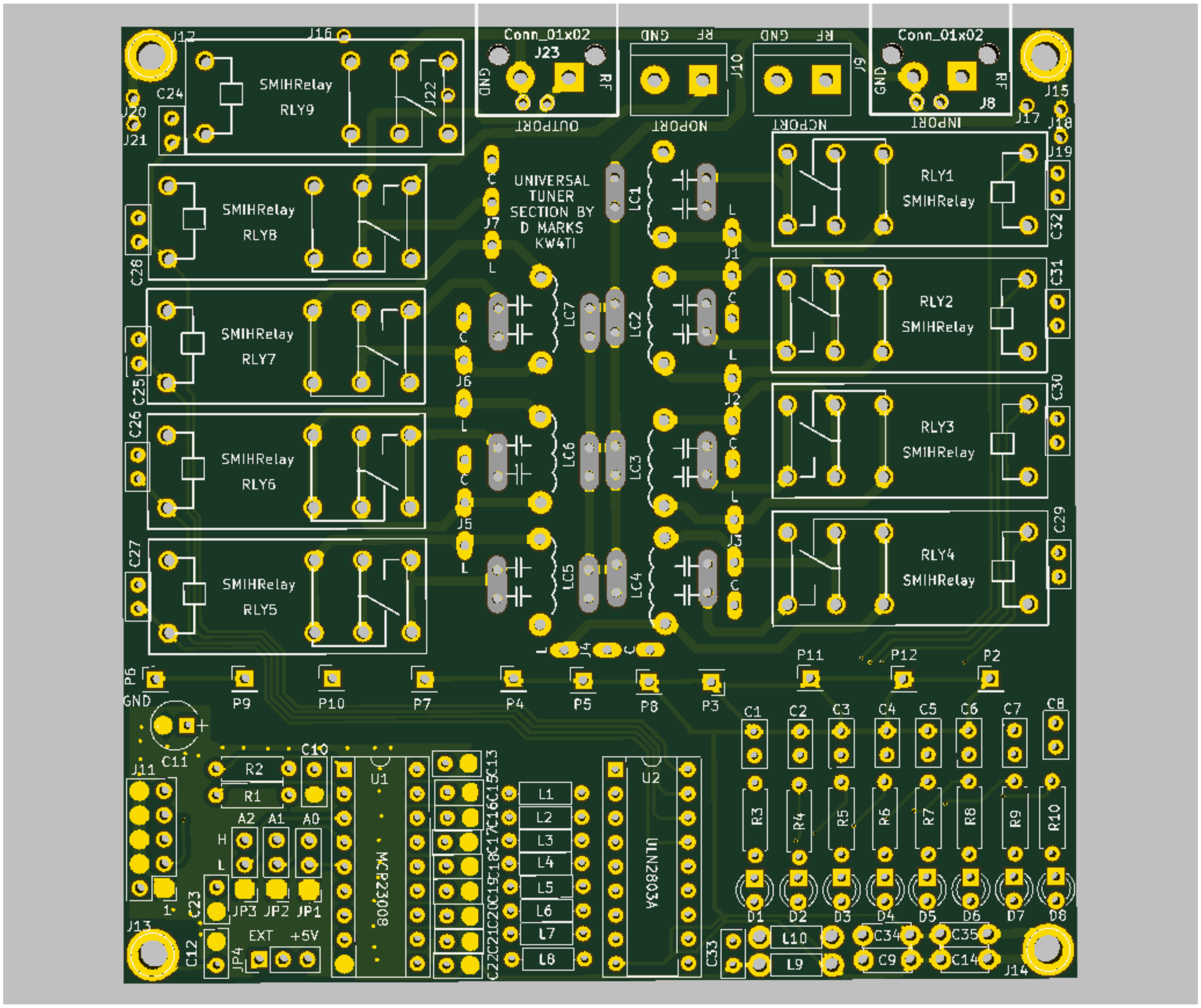
The DelayLine module generates a selectable delay by adding lengths of coaxial cable into the RF path. Like the BigRelays and LittleRelays modules, the DelayLine module is intended to be connected to a RelayControl module. The DelayLine and LittleDelayLine modules use only the “Little” Relays, not the “Big” Relays, because the Big Relays do not fit on a 10 by 10 cm board, and the Big Relays are SPDT not DPDT.

A length of BNC connectorized coaxial cable is intended to be placed between the two connections marked for the given relay, for example J6 and J10 are for DELAY 1. Up to eight coaxial cables may be switched into the path, switched by RLY2-RLY9. The input port J8 and output port J9 are symmetric and the ports may be exchanged. These ports have the dual footprint that allows either a BNC right-angle connector or a two position screw terminal block to be used. RLY1 is the bypass relay, which in the normally closed position bypasses all of the delays and directly connects the input and output ports.

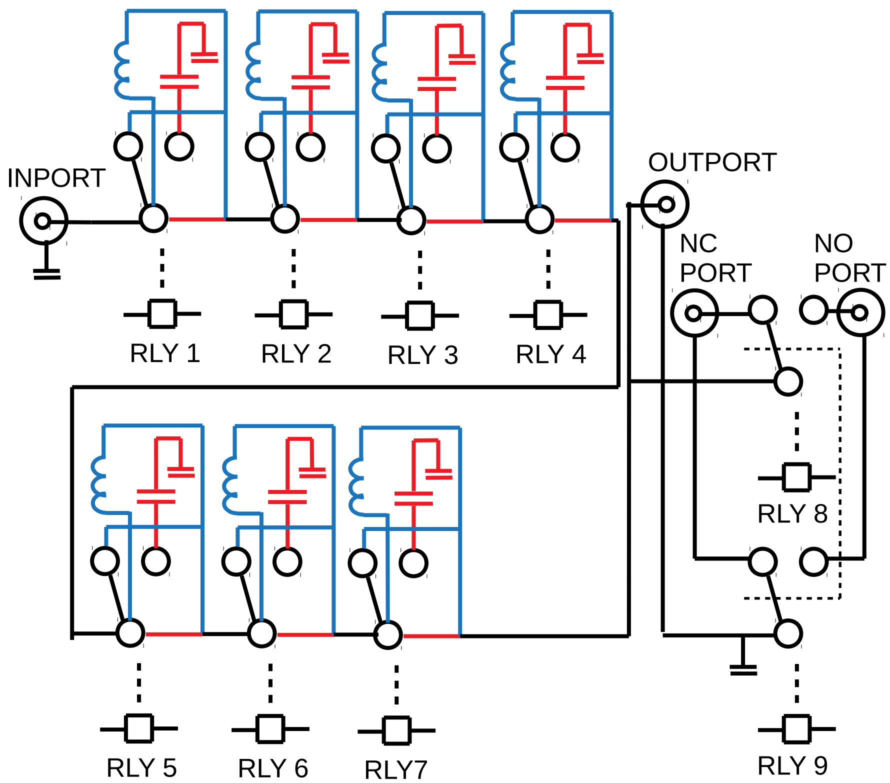
RLY10 controls phase reversal. A common-mode choke placed at J24, J32, J33, and J2 is used to invert the phase of the signal. The normally closed position selects a signal that is not phase reversed, while the normally open selects the phase reversed signal. Using a phase reversal transformer, enough total delay is needed to apply half a wave of retardance at a frequency, with the phase reversal transformer adding 180º so that an entire wave of retardance may be achieved. Typically the longest delay coaxial cable corresponds to a quarter wavelength or 90º at the lowest frequency used, with each subsequent cable being half the length of the next longer cable. For example, to cover the 10-80 m band, an equivalent 20 m of delay in free space would be required to achieve a 90º phase delay at the 80 m band. For RG-58 with a 0.66 velocity factor, this corresponds to 13.2 m of cable. The next seven cables could be selected so that each has half the delay, for example 6.6 m, 3.3 m, 1.65 m, 83 cm, 41 cm, 20.5 cm, and 10.2 cm. At the shortest wavelength 10m, the ability to adjust the delay with 10.2 cm steps corresponds to a phase resolution of 5.5º. This phase resolution is likely much smaller than required unless the absolute maximum gain must be obtained from an antenna array. The total length of cable required is always less than half a wavelength at the lowest frequency, or 26.4 m for RG-58 at 80 m wavelength.

To ground the BNC shield to the RF chassis ground at the board, the pad J34 may be connected via a jumper wire to any of J25, J26, J27, or J28.

ReversibleBigSection and ReversibleLittleSection Modules



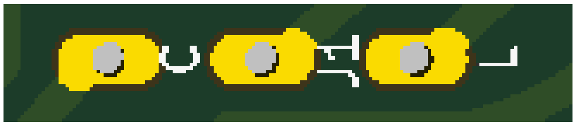
Simplified Schematic



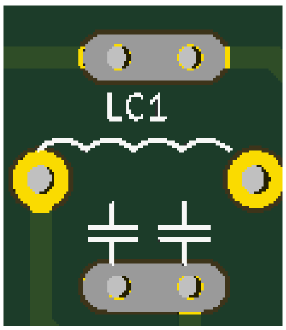
The ReversibleBigRelays and ReversibleLittleRelays modules combine the I2C decoding circuity, relays, and series inductors or parallel capacitors on the same PCB. The blue components on the schematic indicate the paths taken when configured as series inductors, and the red paths when configured as parallel capacitors. Because of this, there is less isolation between the RF path and the digital circuitry than when a separate RelayControl module is used. These modules control up to seven relays RLY1-RLY7, each of which switch a series inductor or parallel capacitor. The two relays RLY8 and RLY9 switch the output port RF and GND between a normally closed port J9 and normally open port J10. The port J23 is always connected. This switchable port may be used to reconfigure the network. For example, it may be used to implement a bypass function by shorting out the matching network, or alternatively it may be used to switch a L network from a low Z to high Z configuration.

The RF connections to the board are combined footprints that accommodate either a BNC right-angle connector or a 2 position screw terminal block.

To configure the module to be either series inductors or parallel capacitors, the pads J1, J2, J3, J4, J5, J6, and J7 must be jumpered. These look like:



To configure as a series inductor, a jumper is soldered between the center pad and the L pad. To configure for parallel capacitors, a jumper is soldered between the center pad and the C pad. All of the pads should be soldered the same way. The inductors or capacitors are soldered to the following pads:



If the series inductor configuration is used, the component should be soldered between the two circular pads that have an inductor symbol connection them. If the parallel capacitor configuration is used, one or more capacitors may be soldered between the two long pads. Both sets of pads should not be used at the same time.

The RF grounds are at pads J16, J17, and J22, with J17 being normally open switched ground and J22 being normally closed switched ground. These may be connected to chassis grounded standoffs through the pads J18, J19, J20, and J21 with jumper wires. The relay coils are grounded to the chassis through capacitors C14 and C35.

For use at the 160 meter band, a maximum capacitance of about 4000 pF is needed. Therefore the capacitors may be picked to be related to each other by near powers-of-two with 2000 pF as the maximum capacitance. However, because there are only seven switchable capacitors, the capability of the tuner to match the load with a low reflection at the 10 m band may diminished as the minimum adjustable capacitance increment is 15 pF. If a lower SWR is required on the higher bands, a smaller maximum capacitance may be desirable. The capacitors are usually ceramic capacitors or silver mica rated 1 kV or higher depending on power levels. Multiple capacitors are generally used in parallel to minimize effective series resistance. Some suggestions for values:

2000 pF = 1000 pF || 1000 pF
1980 pF = 470 pF || 470 pF || 470 pF || 470 pF || 100 pF
987 pF = 470 pf || 470 pF || 47 pF
980 pF = 220 pF || 220 pf || 220 pF || 220 pF | 100 pF
500 pF = 100 pF || 100 pF || 100 pF || 100 pF || 100 pF
487 pF = 220 pF || 220 pF || 47 pF
257 pF = 47 pF || 47 pF || 47 pF || 47 pF || 47 pF || 22 pF
247 pF = 100 pF || 100 pF || 47 pF
127 pF = 47 pF || 47 pF || 33 pF
124 pF = 47 pF || 47 pF || 10 pF || 10 pF || 10 pF

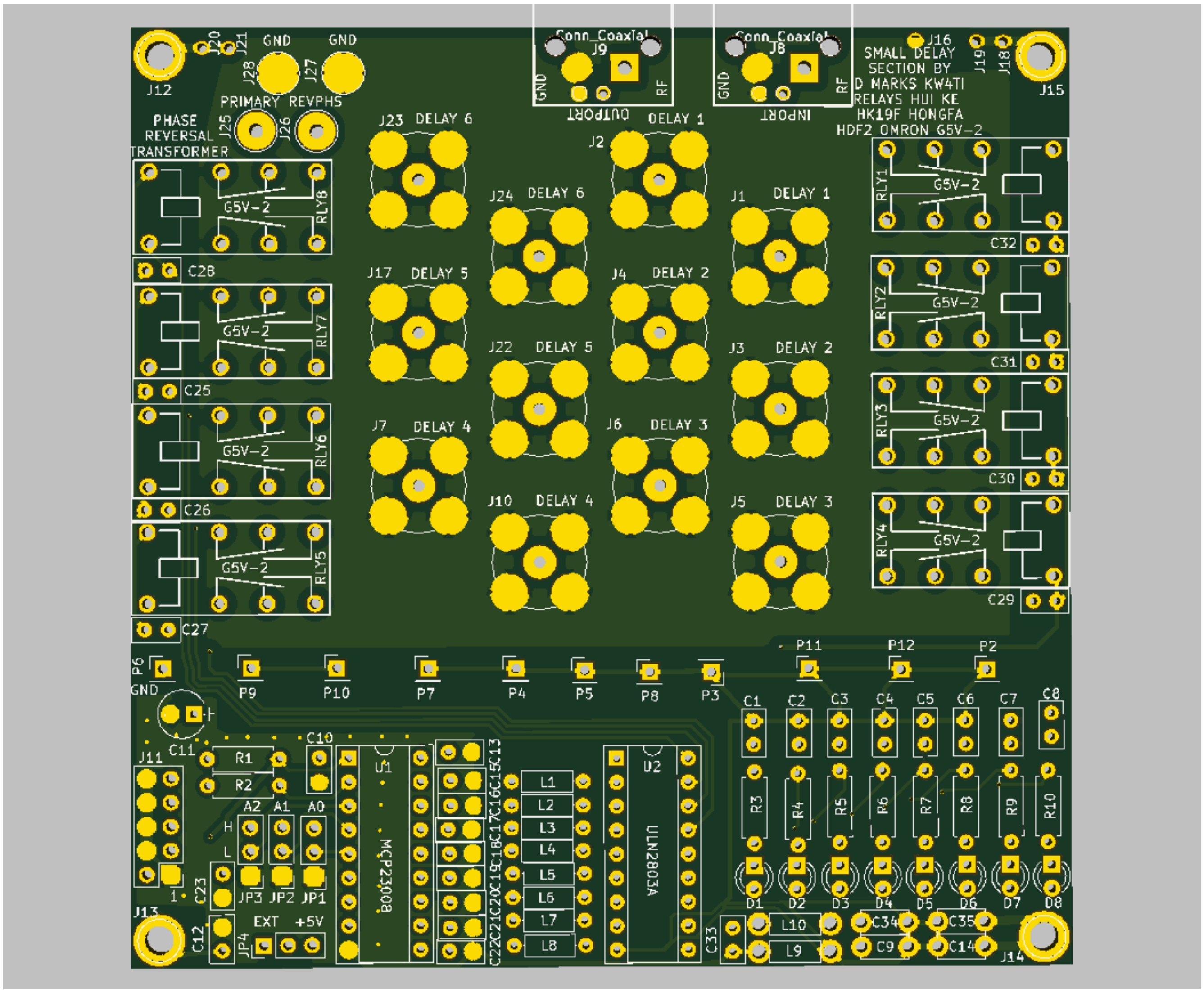
120 pF = 22 pF || 22 pF || 22 pF || 22 pF || 22 pF || 10 pF
62 pF = 22 pF || 22 pF || 18 pF
32 pF = 22 pF || 10 pF
16 pF = 33 pF in series with 33 pF
9 pF = 18 pF in series with 18 pF

For the small capacitance values, an open stub of RG-58 or RG-316 may be used, which have a capacitance of approximately 100 pF/m. If the measured capacitance values are programmed into the Controller, the Controller software exhaustively finds the best approximation of capacitances to a particular desired value. Because stray capacitances for the PCB are on the order of several pF, the precision of the capacitors need not be excessive.

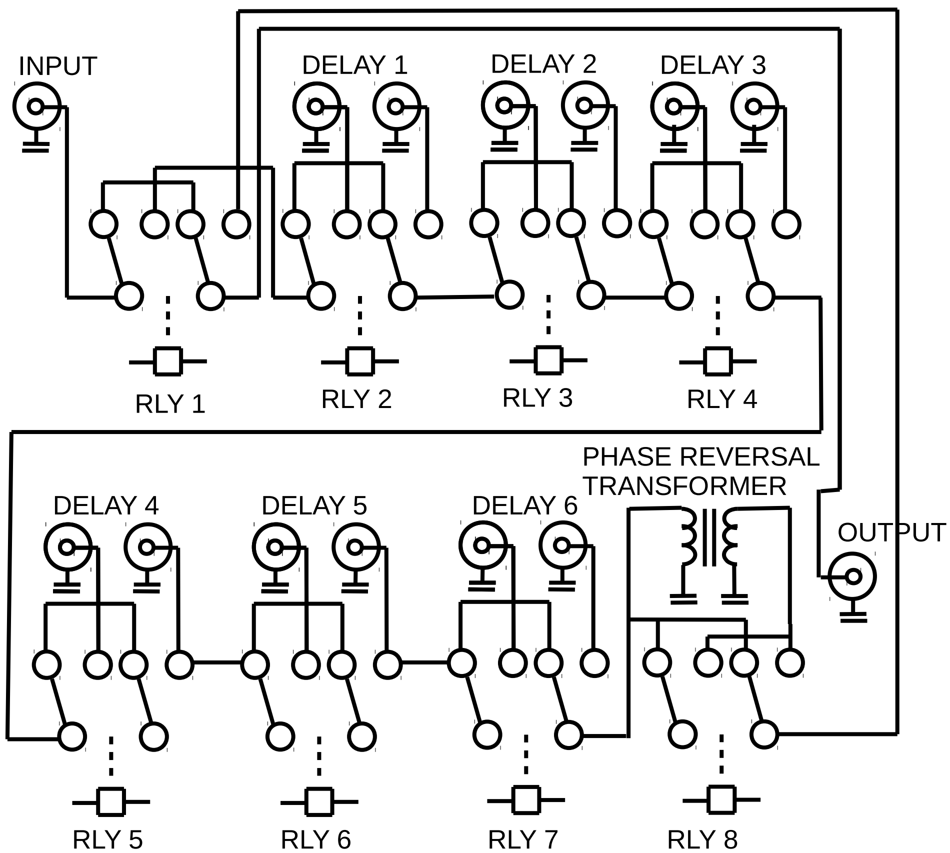
For inductors, a maximum capacitance of about 20 uH is needed for the 160 meter band. One way to achieve this is to use stacked T68-2 iron powder toroids, which can be purchased in quantity cheaply:

10 uH = 4 stacked T68-2 cores, 21 turns
5 uH = 2 stacked T68-2 cores, 21 turns
2.5 uH = one T68-2 core, 21 turns
1.25 uH = one T68-2 core, 15 turns
0.63 uH = air core 5 turns of 1 mm diameter magnet wire around 20 mm diameter form
0.32 uH = air core 4 turns of 1 mm diameter magnet wire around 15 mm diameter form
0.16 uH = air core 3 turns of 1 mm diameter magnet wire around 12 mm diameter form
0.08 uH = air core 2 turns of 1 mm diameter magnet wire around 12 mm diameter form

LittleDelayLine Module



Simplified Schematic

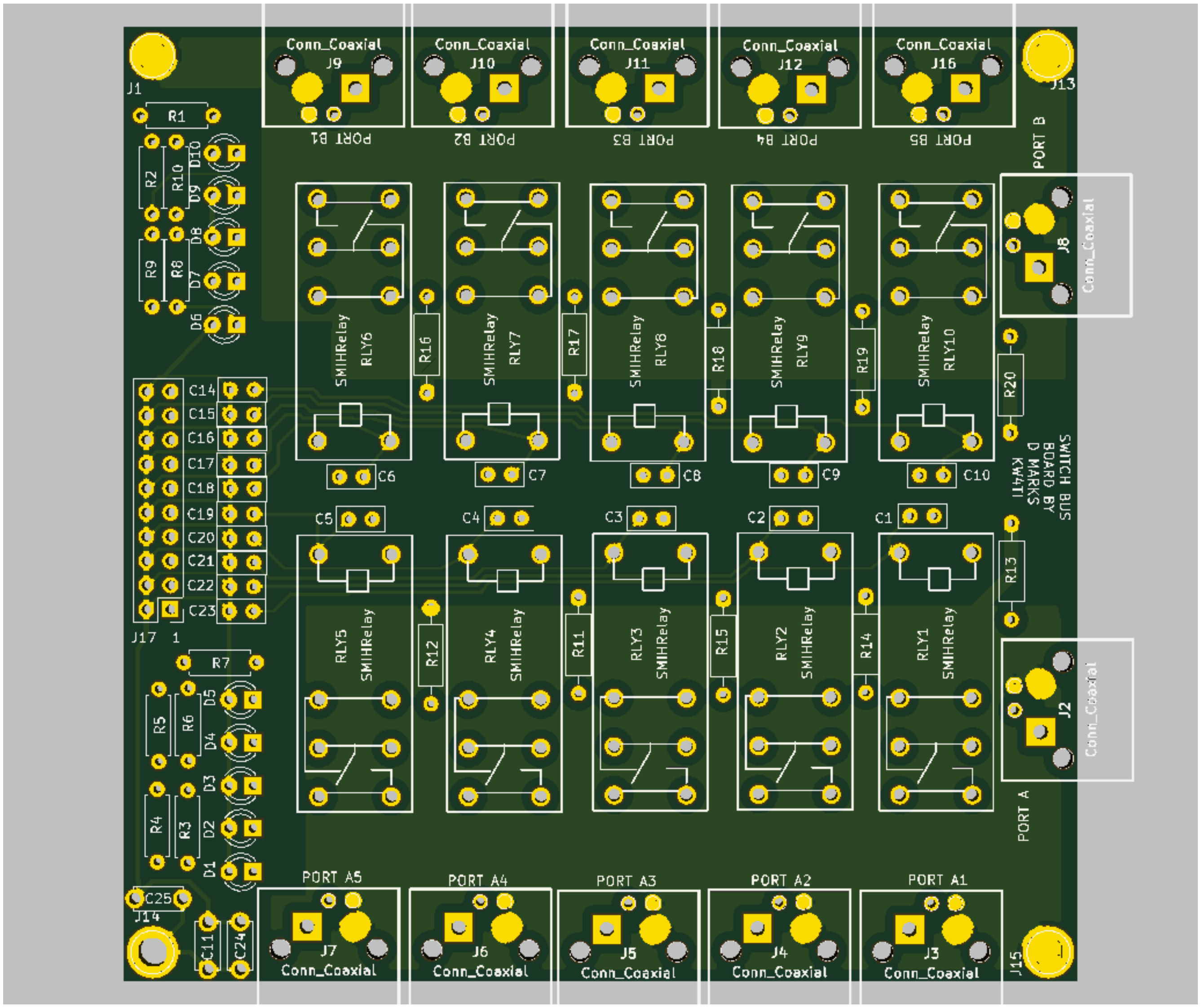


The LittleDelayLine module generates a selectable delay by adding lengths of coaxial cable into the RF path. This module combines the I2C control, relays, and coaxial cables on the same PCBs. A length of BNC connectorized coaxial cable is intended to be placed between the two connections marked for the given relay, for example J1 and J2 are for DELAY 1. Up to six coaxial cables may be switched into the path, switched by RLY2-RLY7. The input port J8 and output port J9 are symmetric and the ports may be exchanged. These ports have the dual footprint that allows either a BNC right-angle connector or a two position screw terminal block to be used. RLY1 is the bypass relay, which in the normally closed position bypasses all of the delays and directly connects the input and output ports.

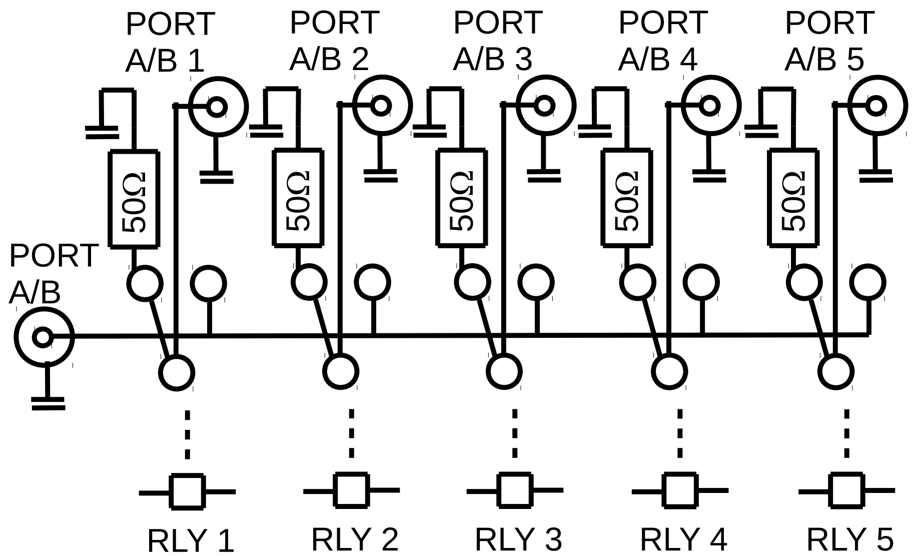
RLY8 controls phase reversal. A common-mode choke placed at J25, J26, J27, and J28 is used to invert the phase of the signal. The normally closed position selects a signal that is not phase reversed, while the normally open selects the phase reversed signal. Using a phase reversal transformer, enough total delay is needed to apply half a wave of retardance at a frequency, with the phase reversal transformer adding 180º so that an entire wave of retardance may be achieved. Typically the longest delay coaxial cable corresponds to a quarter wavelength or 90º at the lowest frequency used, with each subsequent cable being half the length of the next longer cable. For example, to cover the 10-80 m band, an equivalent 20 m of delay in free space would be required to achieve a 90º phase delay at the 80 m band. For RG-58 with a 0.66 velocity factor, this corresponds to 13.2 m of cable. The next five cables could be selected so that each has half the delay, for example 6.6 m, 3.3 m, 1.65 m, 83 cm, and 41 cm. At the shortest wavelength 10m, the ability to adjust the delay with 41 cm steps corresponds to a phase resolution of 22º. This phase resolution is likely adequate to achieve gain with a small antenna array. The total length of cable required is always less than half a wavelength at the lowest frequency, or 26.4 m for RG-58 at 80 m wavelength.

To connect the coaxial cable RF shield to chassis ground at the board, J16 may be jumpered to any of J18, J19, J20, or J21.

SwitchBus Module

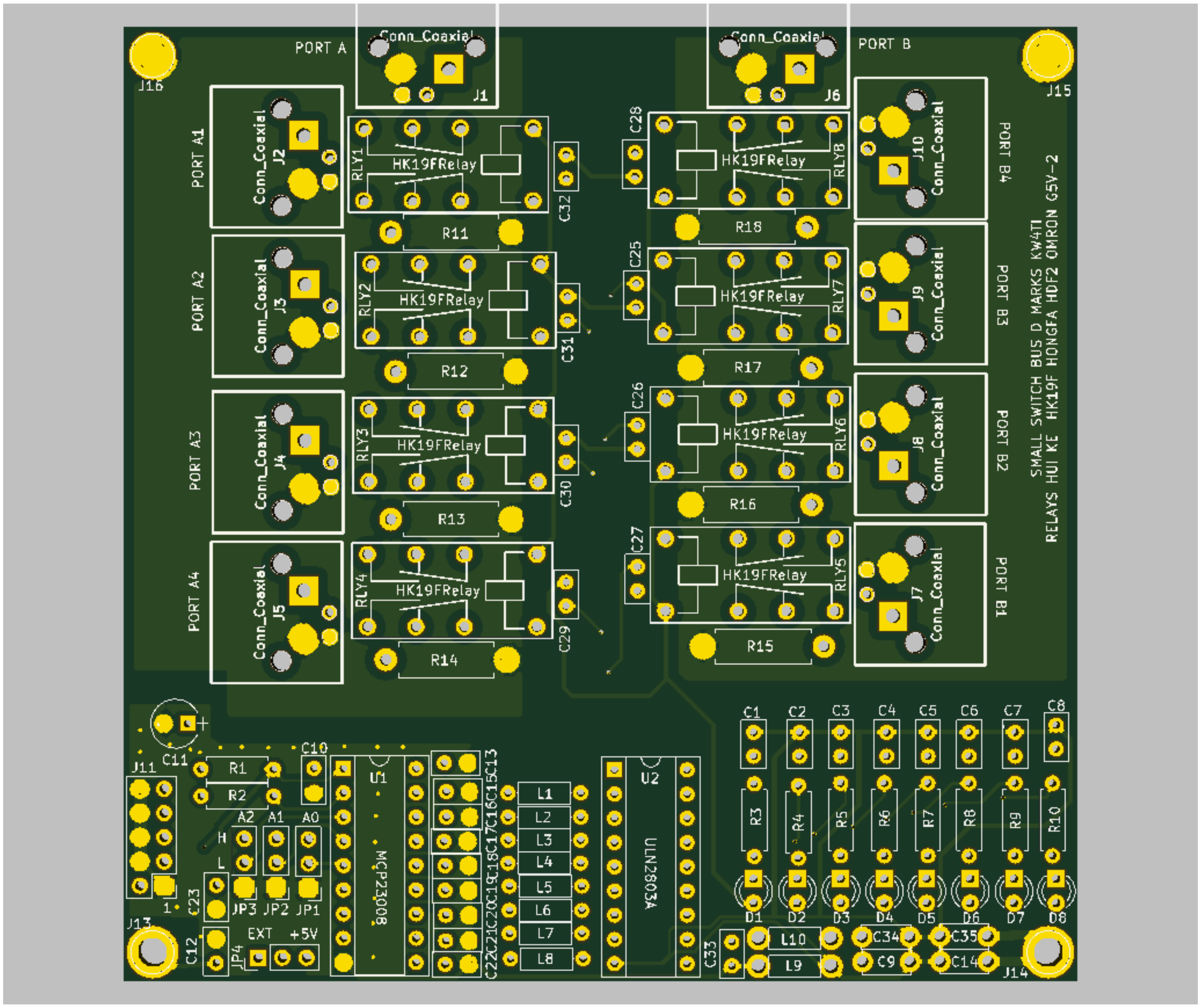


Simplified Schematic

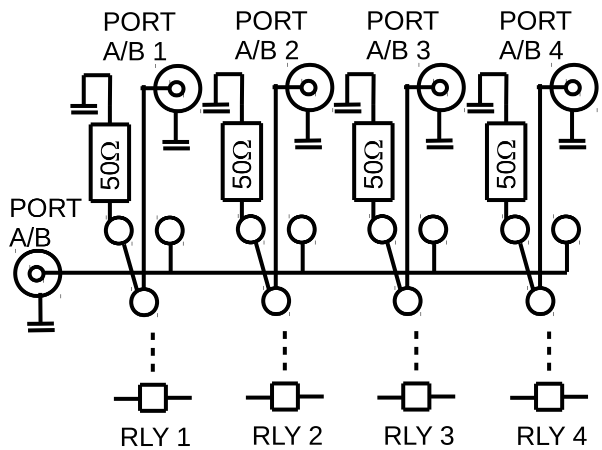


The SwitchBus module may be used for many purposes. The port connects a single port A/B to one or more of five ports PORT A/B 1-5. There are two independent switch multiplexers on the module. It may be used, for example, to select an antenna, so that the ModularTuner system may be used as an antenna selector as well. The two multiplexers on the module may be used together, for example, to place a filter into the signal path, or to form a single 5-by-5 multiplexer by joining ports A and B together. The other ports may be terminated or grounded by placing the appropriate resistor on the normally closed contact of the selection relays. This module must be used with a RelayControl as it does not have any I2C drive circuity. When used to select antennas, it is intended to provide the greatest isolation between the antennas that are not selected and the Controller so that any nearby lightning or electrostatic discharges are shunted to ground through the relay normally closed contacts. If used for this purpose, a separate ground connection should be made to this module to provide the path for the discharge.

LittleSwitchBus Module

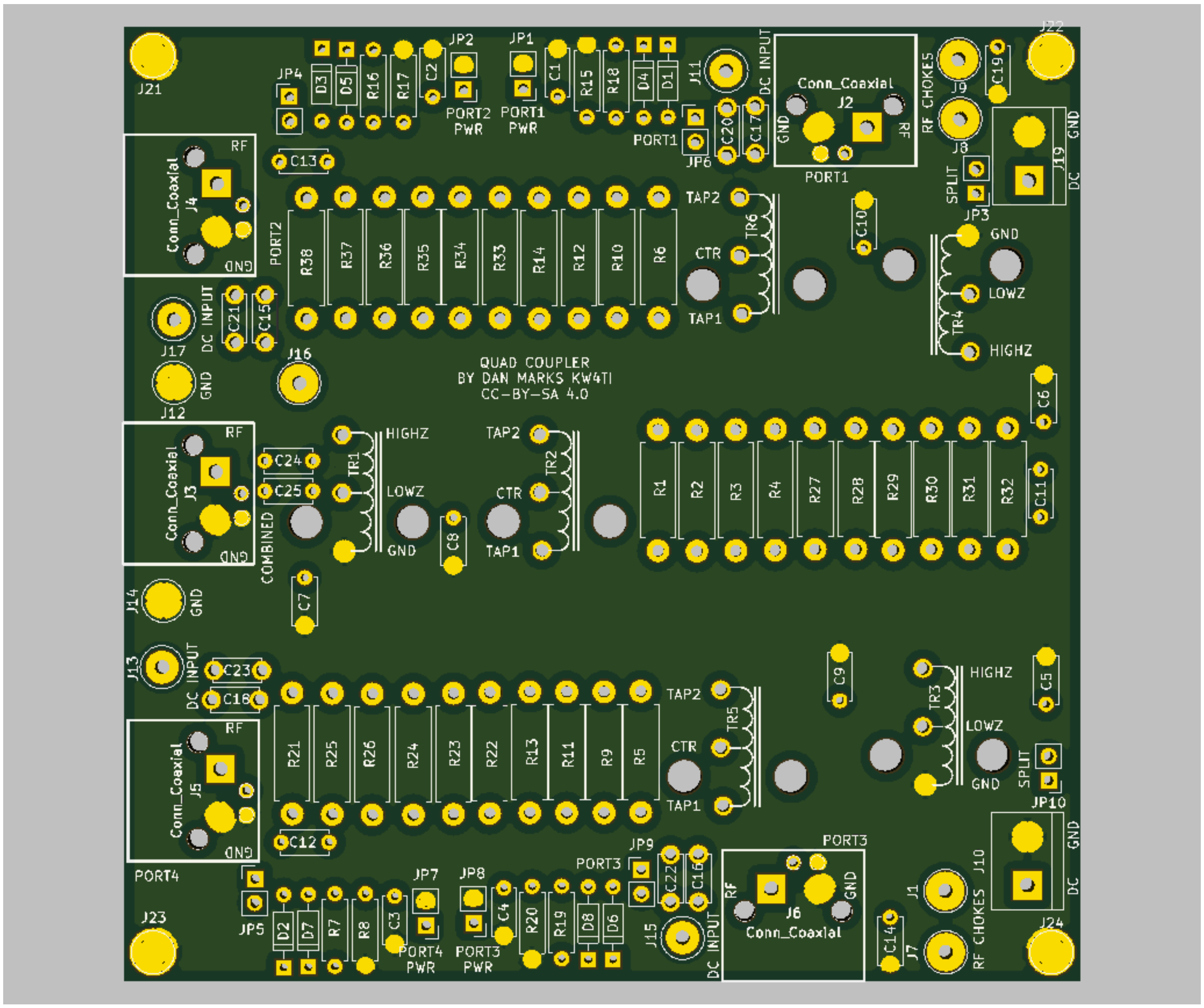


Simplified Schematic

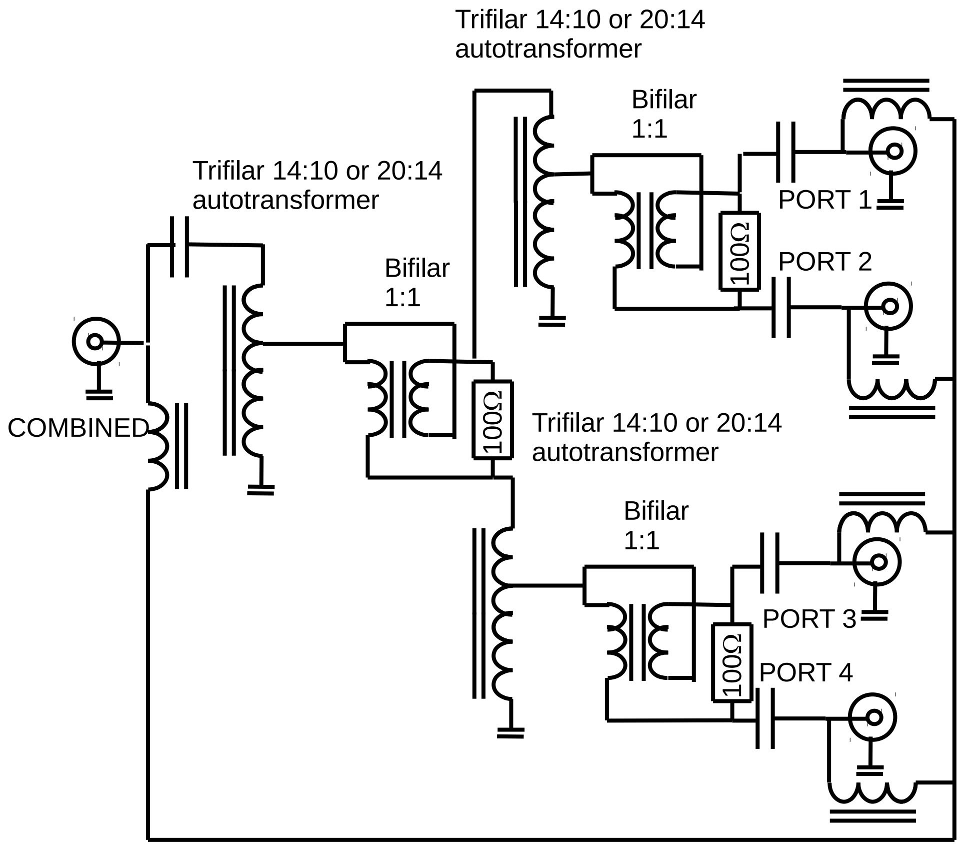


The LittleSwitchBus is similar to the SwitchBus except that it contains the I2C decode circuity and selects one of four rather than one of five relays, and the relays are the “small” relays. Because of this, it has less isolation than the SwitchBus module. The port connects a single port A/B to one or more of five ports PORT A/B 1-4. There are two independent switch multiplexers on the module. It may be used, for example, to select an antenna, so that the ModularTuner system may be used as an antenna selector as well. The two multiplexers on the module may be used together, for example, to place a filter into the signal path, or to form a single 5-by-5 multiplexer by joining ports A and B together. The other ports may be terminated or grounded by placing the appropriate resistor on the normally closed contact of the selection relays. The LittleSwitchBus is useful for selecting taps on a transformer, for example, to change the ratio of an impedance transformation.

QuadCoupler Module

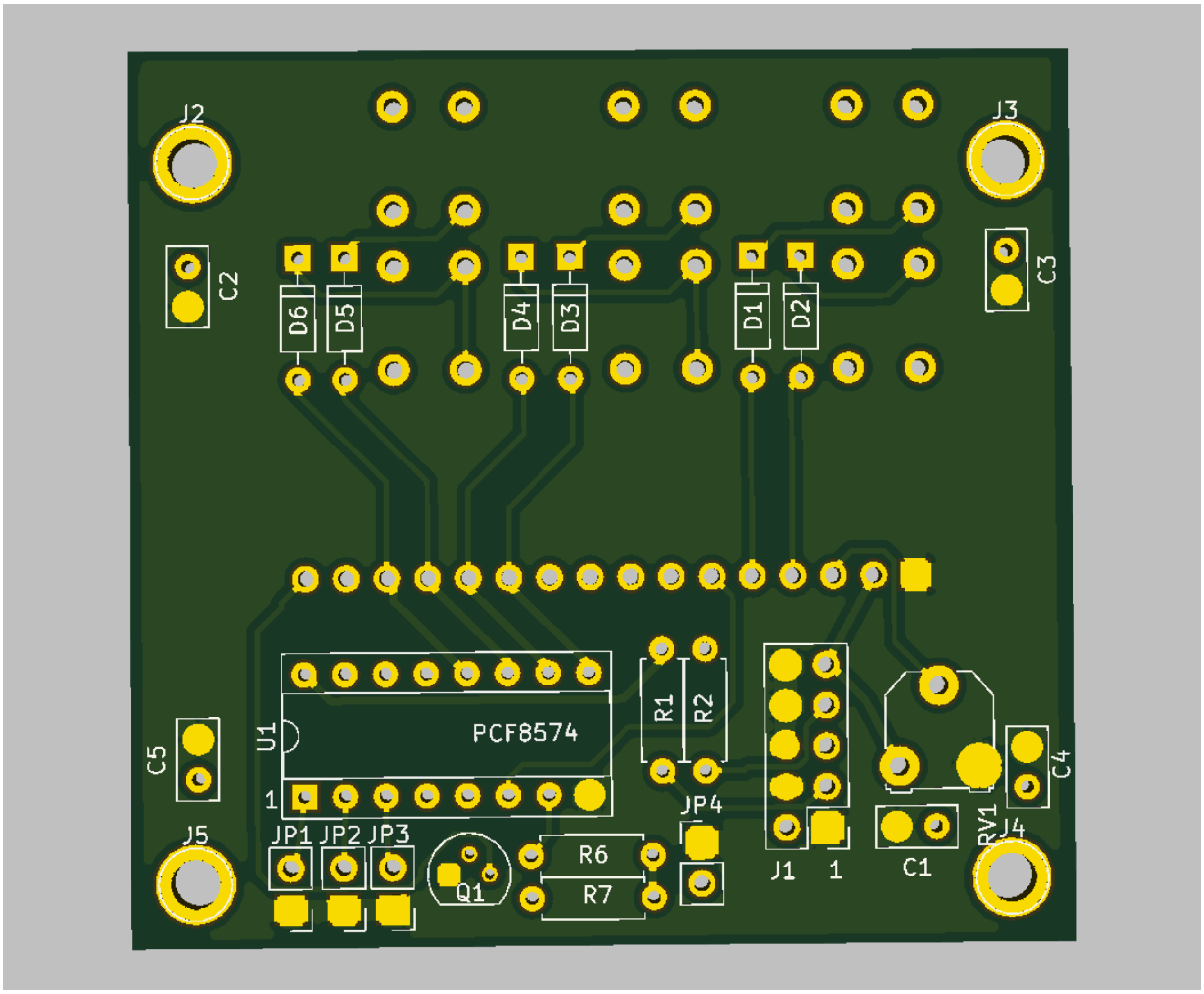


Simplified Schematics



The QuadCoupler contains three Wilkinson dividers that split the incident power nearly equally among four antenna ports. The power is incident at J3 and is divided to J2, J4, J5, and J6. The Wilkinson dividers consist of two transformers, one of which transforms the load impedance from 50 to 25 ohms, and another which divides the 25 ohm impedance over two 50 ohm ports. DC power may be injected using bias-tees into each of the output ports at J11, J13, J15, and J17. DC power may be coupled from the input port J16. There are peak detectors built into the board to measure the voltage at each of the output ports to ensure that the power split is equal. The combined footprints are used so that BNC right-angle PCB connectors or two position screw terminal blocks may be soldered to the board.

LCDadapter Module

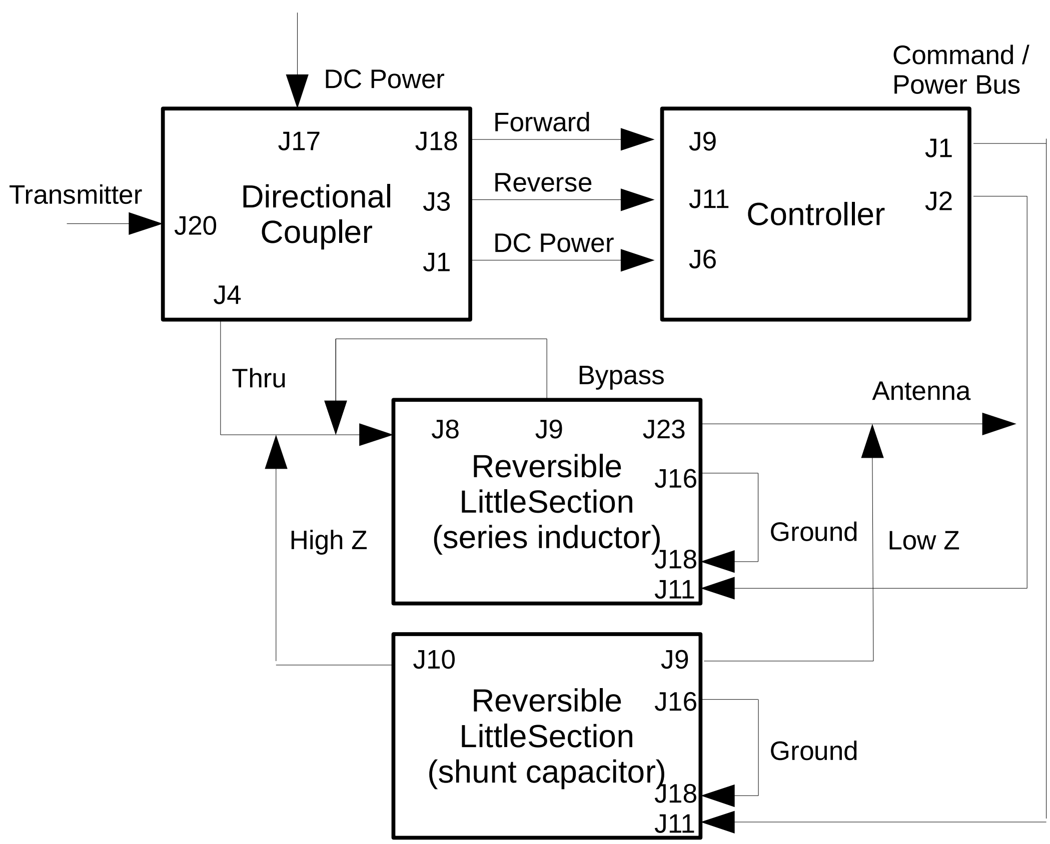


The LCDadapter module is an I2C adapter that is soldered to a HD44780 display. It is modified from the conventional PCF8574 I2C to HD44780 adapters commonly available by adding six push buttons that may be read through I2C that may be used to control the ModularTuner. A conventional PCF8574 adapter may be easily modified to add the six buttons and therefore this module can be made from the commercially available PCF8574 I2C displays. This module is being made available for those who would rather have a predesigned module compatible with the Controller rather than modify a commercial module, and this PCB has the same grounding conventions used by the other modules to best ensure RFI immunity.

If used with the push buttons, the transistor Q1 should be omitted and JP4 should be closed. To make the backlight respond to commands as in the commercial modules, Q1 should be present and JP4 opened.

A simple L-match tuner for 100 watts maximum power

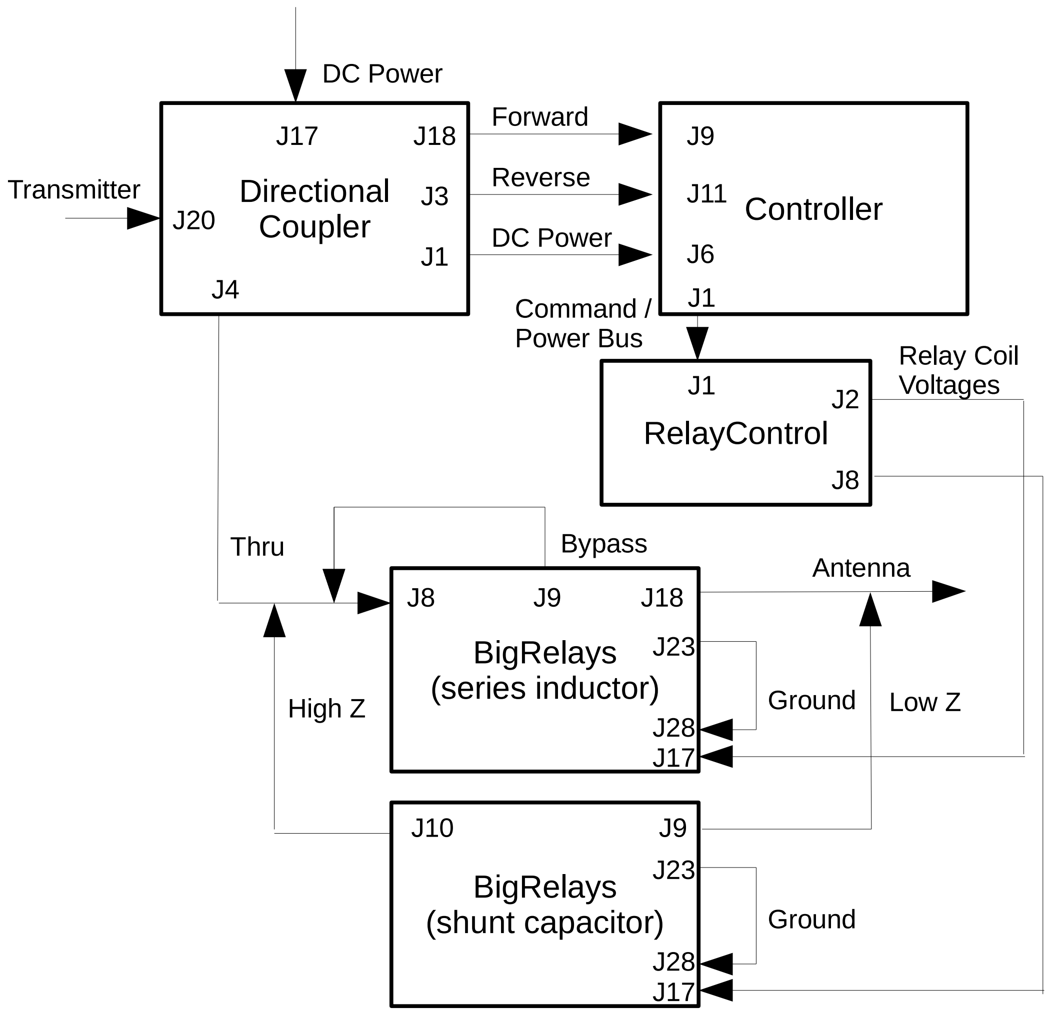
The wiring diagram of a simple L match tuner using four modules is shown below:



The power from the transmitter is incident on the Directional Coupler at the input port J20. The forward power is sampled to port J18 and is connected to port J9 on the controller. Likewise, the reverse power is sampled at port J3 and connected to port J11 on the controller. The DC power is connected from J1 on the DirectionalCoupler to J6 on the Controller.

There are two ReversibleLittleSection modules, one wired as series inductors and another as shunt capacitors. The thru connection of the DirectionalCoupler on J4 is connected to the inductor section at its input port J8. The switchable port relay is connected so that its normally closed port J9 is connected to J8 so that when the tuner is in bypass mode, the inductors are shorted out. The always connected port J23, is connected to the antenna. The other ReversibleLittleSection with shunt capacitors module is connected to either the input or output port of the inductor module, with the normally closed J9 port connected for a low impedance L-matching network, and the normally open port J10 connected for a high impedance L-matching network. On both sections, J16 is connected to J18 to connect the RF ground to the chassis, and there are Command/Power bus connectors connected from the Controller to both modules.

L-match tuner for greater than 100 watts power



The L-match using the BigRelays modules requires one RelayControl module which can drive two BigRelays modules. The connection of the tuning elements of the L-match are the same as the ReversibleLittleRelays version, with the normally closed port on the BigRelays inductor module used to short the inductors out in the bypass configuration, and the normally open/normally closed ports on the BigRelays capacitor module used to select the Low Z and High Z configurations.

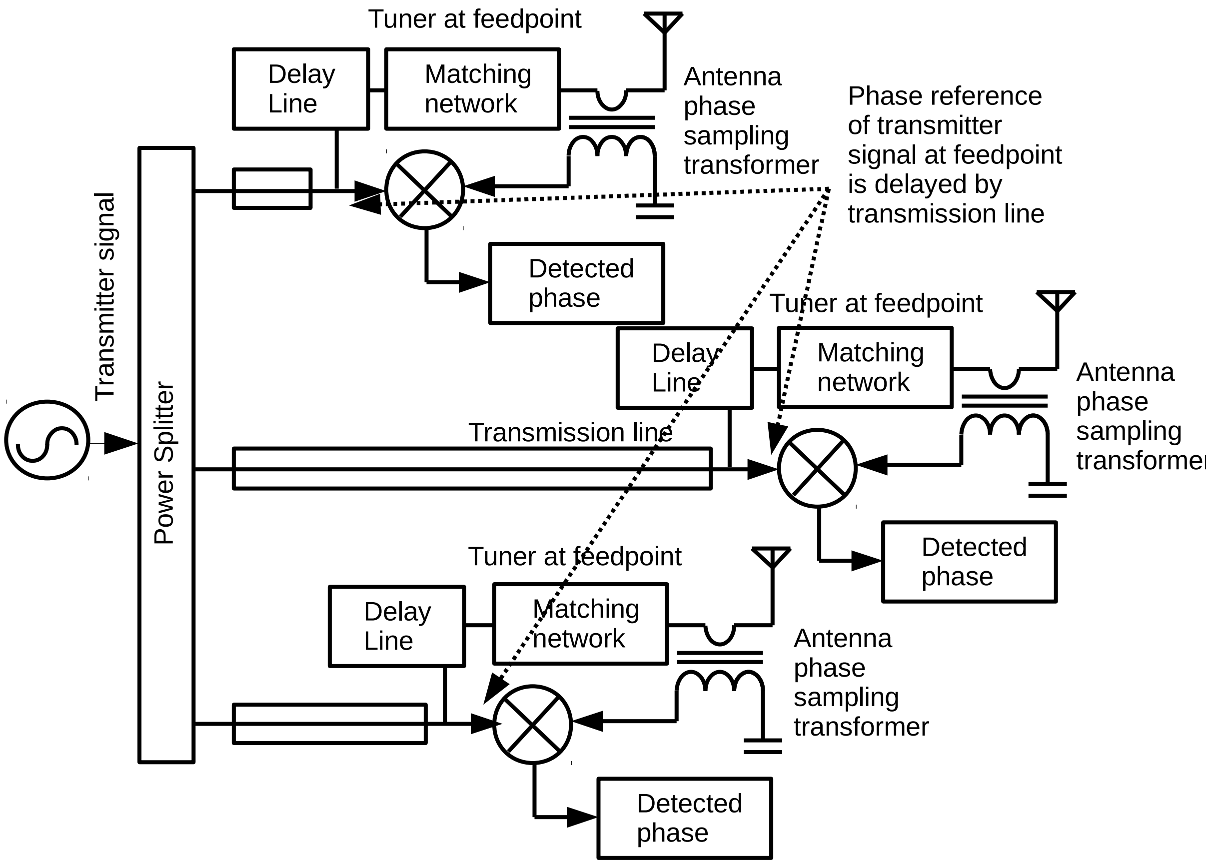
Balanced vs. unbalanced tuners

The L-match configurations shown are for unbalanced transmission lines such as coaxial cable and vertical antennas with the outer conductor of the cable at a fixed potential. Balanced transmission lines such as ladder line or open wire feedline require opposite potentials on the two conductors. There are two approaches to modifying a tuner to feed a balanced transmission line.

One approach is to design a network that is symmetric. For example, a L-network may be modified by inserting two identical inductances in series with both conductors of the transmission line. While in principle this works, in practice it is difficult to achieve good balance. Not only must be inductances be matched, other asymmetric effects such as stray capacitances must also be identical for the two conductors. Furthermore, this method adds cost and complication over alternative methods.

A second approach is to put a common-mode choke balun on the output of an unbalanced L-network. The common-mode choke balun forces the currents in the two conductors to be equal. For high power, a high voltage is developed across the because of the high impedance of the balun multiplies any common mode current. The choke should be placed on a short coaxial cable less than a meter from the tuner in a well-insulated plastic box. The choke can be constructed from 10-15 turns of coaxial cable on one or two FT240-31 or FT240-43 stacked toroidal ferrite cores depending on the power levels used. Terminals for the open wire feedline can be joined to the coaxial cable after passing through the balun. This approach is simple, and the cost of two FT240-43 is often less than constructing another relay module. The only disadvantage of this approach is that there are high voltages developed across the balun so that the balun should be kept away from sensitive equipment.

Phase measurement, phasing the array, and the antenna current sense transformer



One of the unique aspects of this antenna tuner design is the ability to sense the phase of the antenna current. This enables feedback so that the phase of the antenna current may be adjusted by a switched delay line to achieve a desired radiated phase. The relative phase between the forward signal and the current is measured as the forward signal phase is independent of any reflections or imperfect matching of the antenna. The forward signal at the tuner serves as a phase reference for both the antenna current and the reflected signal phases. Because the forward signal originates at the transmitter, the delay of the signal originating at the transmitter propagating to each tuner must be characterized if the phase relationship between the signals at the antenna tuners is to be known. For example, equal cable lengths between the transceiver and the tuners may be used so that the delays to each antenna tuner are equal and therefore the phases are the same at all frequencies. However, this is not necessary if a switched delay line is used such as the DelayLine module, as the phase can be adjusted at the feedpoint to compensate both for unequal delays to the tuners as well as orient the radiation in a desired direction.

The phased array arrangement that is implemented by the ModularTuner is somewhat unusual. Typically, the power must be divided between the antennas and the correct phasing applied to compensate for any mutual impedance or coupling between the antennas as to achieve the greatest gain. Because of this, most phased arrays work only for a limited number of bands and produce a limited number of radiation patterns. It is desired to use the ModularTuner to experiment with arrangements of phased arrays that take advantage of impedance matching at the feedpoints of each antenna as well as the dynamic phase adjustment of each antenna. Because the ModularTuner at present has no modules to adjust the power balance between the antennas, the gain must be optimized with equal power radiated from all antennas. This in general does not produce as high of gain as if the power could be arbitrarily allocated between antennas.

Due to the mutual impedance between the antennas, the radiation resistance of an antenna can be significantly reduced or even be negative in extreme cases. One of the advantages of having adjustable tuning elements at the feedpoint is that within a certain range of impedances, the impedance matching network can compensate for the variations in the radiation resistance of an antenna caused by its interactions with other antennas. To minimize this problem, the antennas in the array may be placed such that they are separated by distances at least the length of the antenna elements themselves.

If the antennas can be impedance matched such that they radiate equal amounts of power, the delay can be adjusted independently of the impedance transformation as the delay is applied between the transmitter and the antenna matching network by adding variable amounts of coaxial cable to the signal path. Then the antenna current sense transformer can be used to determine the phase of the radiated current given the applied delay.

If the delays to all of the antennas have been calibrated, then by using the known phase of the forward signal at the antenna feedpoint, the phase can be set such that all of the antennas have a known relative phase relationship. However, in practice, one is often trying to direct a beam towards a particular station. In this case, this station can serve as the reference signal to adjust the antenna phases and accurate phase calibration of the array is not required. By adjusting the delays at each antenna to maximize the signal strength from the station, the array forms a beam directed towards that station. If the direction to the station is known, the phases used to direct the beam to the station may be recorded and reused when one wishes to direct the beam back in the same direction at the same frequency. When trying to reach a distant station, it may be more useful to optimize the phase to receive the greatest signal so that the transmitted signal likewise has additional gain. While such an arrangement may not achieve the best gain over an antenna array designed to radiate in particular fixed directions for a particular band, it may be much more useful in practice to achieve a moderate amount of gain in any direction on many different bands.

Another advantage of this method is that an exact arrangement of the antennas is not required, and so antennas in the phased array may be placed in a staggered or irregular pattern as long as they are sufficiently separated. Furthermore, having impedance matching for each antenna in the array enables a heterogeneous set of radiators to be used, so that wires may be placed of varying lengths or perhaps even metallic objects in the environment can be used as radiators. The agility of such a system may be more useful in practice.

Another possibility to be explored in the future is to derive a known phase signal from a GPS disciplined oscillator (GPSDO) at each feedpoint. The phase of the forward wave may be measured relative to the common phase of the GPSDO at each feedpoint and this phase may be used to calibrate the delay to the feedpoint. There is a port for a NEO7M GPS module on the Controller that can be used to find the position of the antenna feedpoint as well as derive a frequency that is a multiple of 1 Hz with an edge synchronized to the beginning of each second.

The antenna current sense transformer is typically constructed from 15 secondary turns around a FT50-43 ferrite toroid. The wire or coaxial cable carrying the antenna current should be inserted through the toroid and is the one primary turn. It is important to insert the wire through the center of the toroid so that it does not pass near the secondary and capacitively couple to it. If a coaxial cable is used, it should be grounded at only one end to act as a Faraday shield. The secondary should be connected to the Controller board and is terminated by a 50 ohm resistor. The wires connected to the Controller should be twisted together to minimize the loop area. If there is still excessive capacitive coupling between the primary and secondary of the antenna current sense transformer, a the connection to the Controller can be wrapped several times around a ferrite toroid as a common-mode choke. This may be necessary for high power as even a small amount of capacitive coupling may result in excess common-mode signal.

Appendices

Commands for the antenna tuner

The commands that may be issued over the USB serial interface or the Wireless interface when in remote control mode are documented here.

`HELP`

Display the list of commands and their arguments.

`READSTATE <state number>`

Read the configuration from the memory <state number>. There are currently four locations numbered 1 to 4 to store configurations.

`WRITESTATE <state number>`

Write the current to from the memory <state number>. There are currently four locations numbered 1 to 4 to store configurations.

`SAVECACHE <frequency khz>`

Write the current state of the relays 1 to 3 to the tuning state cache with an entry at the frequency given by <frequency khz>.

`RECALLCACHE <frequency khz>`

Read the state of the relays 1 to 3 from the tuning state cache with an entry at the frequency given by <frequency khz> and change the relays to this state.

`SHOWCACHE`

Show the tuning parameters of all entries in the tuning state cache in the order of most recently used entry to least recently used entry.

`CLEARCACHE`

Erase all entries in the tuning state cache. Any subsequent tuning cycles require an exhaustive tune to find a match at the target reflection magnitude and will be stored in the cache once found.

`TUNER?`

Show the state of the tuning configuration. A list of entries and their corresponding values are displayed in the form `<entry name>=<entry value>`.

`SETTUNER <entry name>=<entry value>`

Change an entry in the tuning configuration. For example, to change the maximum reflection permitted for a tune to 0.3, use the the command “`SETTUNER MAXREFLECTION=0.3`”. These changes are not saved immediately. They can be committed to flash using the WRITESTATE command or will be automatically saved after five minutes. The same format is used for `<entry name>=<entry value>` as is displayed by the `TUNER?` command.

`TESTRELAY <relay #> <is switch?> <relay/switch number> <setting>`

Manually turn on/off a relay on a RelayModule to test its function. The relay module number is given by <relay #>, a number from 1 to 8. <is switch?> is equal to 1 for testing one of the port selection switch relays, and 0 for testing one of the component selector relays. <relay/switch number> is the number of the component selector or port selection switch relay. Currently the switch number is either 1 or 2, and the number of component selector relays can be up to 16. Finally <setting> is zero or one, 0 being an open relay and 1 being a closed relay. For example, to set component relay 3 on relay number 2 to the closed state, use “`TESTRELAY 2 0 3 1`”.

`SETRLY <relay #> <relay value> <method>`

Set the relay module <relay #> to be tuned to the value <relay value>. method=0 for choosing the closest available value to the desired value, method=1 chooses the closest available value strictly less than the desired value, and method=2 chooses the closest available value strictly greater than the desired value. For example, if relay module 1 is an inductor relay module, and one wishes to set its value to 1234 nH or the closest available value, use “`SETRLY 1 1234 0`”.

`RLYDEF <relay #> <default number #>`

Set the entry for a relay module numbered <relay #> to a default configuration. This is how a new relay entry is activated. The following default configurations are available:

0 = blank an entry and disable the relay module
1 = BigRelays/LittleRelays module set up for series inductors
2 = BigRelays/LittleRelays module set up for parallel capacitors
3 = DelayLine module
4 = ReversibleBigSection/ReversibleLittleSection module set up for series inductors
5 = ReversibleBigSection/ReversibleLittleSection module set up for parallel capacitors
6 = LittleDelayLine module

It is likely necessary that the values of the components need to be changed from the default values.

`RELAY?`

Print out the configuration information of all the relays in the form `<entry name>=<entry value>`.

`SETRELAY  <relay #> <entry name>=<entry value>`

Set the entry labeled <entry name> on relay module <relay #> to the given <entry value>. The format of `<entry name>=<entry value>` the is the same as shown in the `RELAY?` command.

`TUNE  <tuning state>`

Set the tuning state to <tuning state>. <tuning state>=0 corresponds to standby mode, which will retune only if excessive reflections are detected. <tuning state>=1 corresponds to "force tune" mode, which will always tune the next time the amount of power is not too low or too high for acceptable tuning. If rig control is enabled, the force tune attempts to send a signal to the rig to send power to tune immediately. <tuning state>=2 is disable tuning if excessive reflections are detected, but does not change the current state of the relays.

`STATUS`

Display status of tuner, including tuning state, frequency of last tune, SWR, and estimated load impedance.

`DEBUG <debug mode>`

Turns on debug messages. <debug mode>=0 is debug messages disabled, <debug mode>=1 is debug messages enabled.

`BYPASS`

Place the tuner into bypass mode. If the tuning state is not set to disable tuning, when excessive reflections are detected, the tuner will initiate a tuning cycle.

`REMOTE <remote state>`

Turn the remote control over wireless on or off. <remote state>=1 is enable the remote control over wireless, and the command interface is available over wireless. <remote state>=0 is disable the remote control over wireless, and the remote reverts back to the packet interface.

Tuner configuration entries

The entries that configure the Controller tuner configuration are documented here. They are changed by means of the “SETTUNER” command, and may be saved in flash using the “WRITESTATE” command.

`LABEL=<label>`

A text label up to 15 characters describing the configuration.

`POWERCALIB=<power calib>`

A number used to calibrate power in watts from the analog-to-digital measurements of the forward and reverse power.

`MINTUNINGPOWER=<min power>`

The minimum amount of power needed to initiate a tuning cycle in watts.

`MAXTUNINGPOWER=<max power>`

The maximum amount of power allowed during a tuning cycle in watts. This is to prevent hot switching with excessive power.

`MAXREFLECTION=<reflection coefficient>`

The maximum reflection coefficient, between 0.0 and 1.0, allowed before the tuning cycle is successfully completed.

`RETUNETHRESHOLD=<reflection coefficient>`

The threshold over which the reflection from the antenna must exceed before automatic tuning is initiated. This number is between 0.0 and 1.0.

`SEARCHRELAXATION=<relaxation constant>`

A number for the search algorithm that determines how greedy the algorithm is. <relaxation constant>=1.0 is the most greedy. The default is 1.05. The number may be increased if tunes can not be found at the expense of more lengthy tuning cycles.

`REMOTECHANNELNO=<channel no>`

The channel number to assign to the remote wireless radio on startup.

`SEARCHKHZSPACING=<khz #>`

The maximum difference in frequency between a desired frequency and the frequency of a tuning cache entry to match the entry. The default is 10 kHz.

```
RIGCONTROL=<rig control>
```

Turn on rig control. Currently the value rig control numbers are <rig control>=0 for no rig control, or <rig control>=1 for ICOM. This only takes effect after resetting the tuner.

```
SWITCHBYPASS=<relay #>,<switch #>,<state>,<relay #>,<switch
#>,<state>, ...
```

Specify the state of the switches on the relay modules that place the tuner into the bypass state. The format of these are triads of numbers indicating the relay module number, switch number on the relay module, and the state of either 0 for open or 1 for closed. For example, if switch #2 on relay #1 should be open, and switch #1 on relay #3 should be closed, this would be "`SWITCHBYPASS=1,2,0,3,1,1`". All unused entries should be zero.

```
SWITCHSTATE1-6=<relay #>,<switch #>,<state>,<relay #>,<switch
#>,<state>, …
```

During a tuning cycle, the switches are set to the states given by SWITCHSTATE1, SWITCHSTATE2, SWITCHSTATE3, SWITCHSTATE4, SWITCHSTATE5, SWITCHSTATE6 in that order. These states encode, for example, high and low Z configurations of a L match tuner, but would configure the switches for other network topologies for more complicated tuning networks. The format of these are triads of numbers indicating the relay module number, switch number on the relay module, and the state of either 0 for open or 1 for closed. See the example in SWITCHBYPASS.

Relay configuration entries

The entries that configure the Controller relay modules such as the BigRelays/LittleRelays/DelayLine/ReversibleBigSection/ReversibleLittleSection/LittleDelayLine modules are documented here. They are changed by means of the “SETRELAY” command, and may be saved in flash using the “WRITESTATE” command.

```
MODULETYPE=<moduletype>
```

Configures the module type. <moduletype>=0 is module disabled, <moduletype>=1 is series inductor module, <moduletype>=2 is parallel capacitor module, and <moduletype>=3 is delay module.

```
NORELAYPORTS=<number of relays>
```

Number of digital outputs on the board dedicated to selecting components. Some digital outputs control two relays.

```
NOSWITCHES=<number of switches>
```

Number of digital outputs on the board dedicated to switching between ports. Some digital outputs control two relays.

```
MCP23017=<state>
```

Chooses whether the module contains a MCP23008 or MCP23017. <state>=0 for a MCP23008 and <state>=1 for a MCP23017.

```
I2CADDR=<hex address>
```

Configures the I2C address of the relay module. This number is specified in hexadecimal.

```
AUTOTUNE=<autotune state>
```

Chooses whether this relay module should be automatically adjusted during a tuning cycle. <autotune state>=0 indicates the relay module should not be changed, and <autotune state>=1 indicates the relay module should be automatically adjusted.

```
OFFSETVAL=<offset value>
```

The amount of inductance, capacitance, or delay in the relay module when all of the adjustable components are turned off. This is to compensate for a minimum parasitic inductance, capacitance, or delay.

```
SETTLETIME=<time in ms>
```

This sets the amount of time after the relay change state command is issued over I2C that the tuner should wait for the state change to mechanically occur.

```
COMPVALUE=<component value 1>,<component value 2>,… <component value 16>
```

Set the values of the components at each relay. This is typically in nF for inductors, pF for capacitors, or 0.1 ns increments for delays. These values are separated by commas. Unused entries should be zero.

```
PORTBITS=<relay bit mask 1>,<relay bit mask 2>, …  <relay bit mask 16>
```

Sets the bit masks corresponding to each relay for each component as specified in COMPVALUE. The values are in hexadecimal. Each bit mask should have only one nonzero bit. Unused entries should be zero. Generally the default values for the particular boards suffice and do not need to be changed.

```
SWITCHBITS=<switch bit mask 1>,<switch bit mask 2>
```

Sets the bit masks corresponding to the two switches. The bit masks are in hexadecimal. Generally the default values for the particular boards suffice and do not need to be changed.