An Antenna Remote-Control Tuning System

The authors describe an automatic antenna tuning system using a bias tee that includes a bi-directional 2.4 GHz port.

Nelson Sollenberger, KA2C, and Jeff Addleman, W3ADD

Bias tees power remote devices via coax shared with RF signals. For ham radio use, one bias tee is normally located in the shack to connect an RF signal and dc power to a common coaxial cable. A second bias tee is located with the remote equipment to separate the RF signal and dc power from the shared coax. A bias tee normally has two RF ports and one dc port. In this article, we describe a bias tee with four ports. It includes a 2.4 GHz Internet of Things (IoT) control port and a dc power port capable of 2.5 A, and it can handle HF RF power up to 1.5 kW.

All of the necessary documents for this project (schematics, Gerber files, software, etc.) can be found at **www.arrl.org/qst-in-depth**. These files can be used

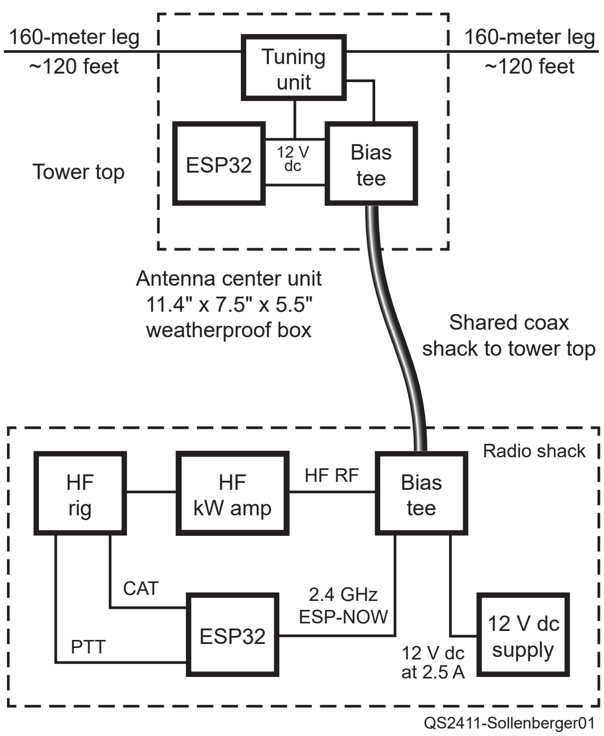

Figure 1 — Remote-control tuning system using a bias tee with a 2.4 GHz port.

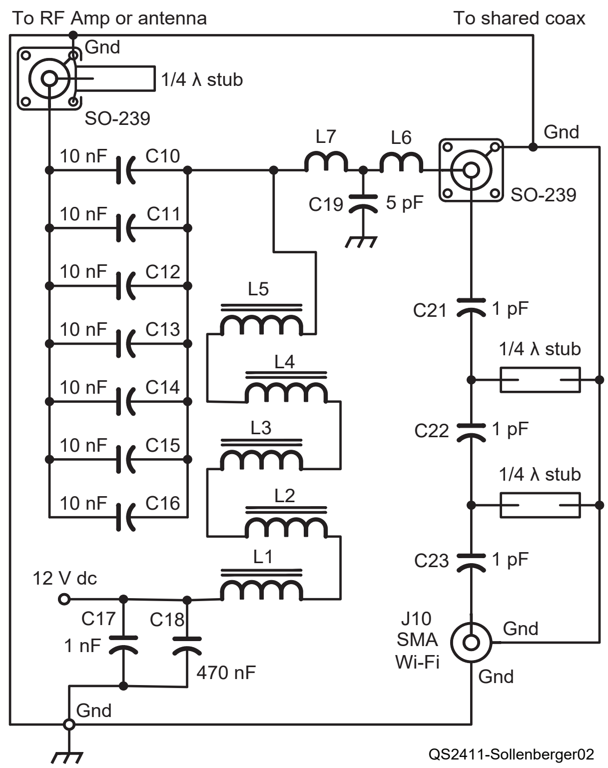

Figure 2 — Four-port bias tee schematic.

with the free *DipTrace* schematic and printed circuit board (PCB) tools at **www.diptrace.com**.

The block diagram in Figure 1 shows the four-port bias tee that connects the control signal to a 160-meter inverted **V** with integrated tuning at the antenna center unit. The bias tee's fourth port allows high-speed control and monitoring using a two-way 2.4 GHz IoT signal multiplexed on the shared coax. This provides a fixed, low-attenuation path without fading and interference. Low-latency and high-reliability two-way data transfer is supported using an ESP-NOW IoT protocol on ESP32 devices. ESP32 modules with a Wi-Fi or ESP-NOW 2.4 GHz I-PEX connector are available for about $11 as of press time (product number ESP32-DEVKITC-VIE). These modules support many general-purpose input/output (GPIO) pins that can be configured for a variety

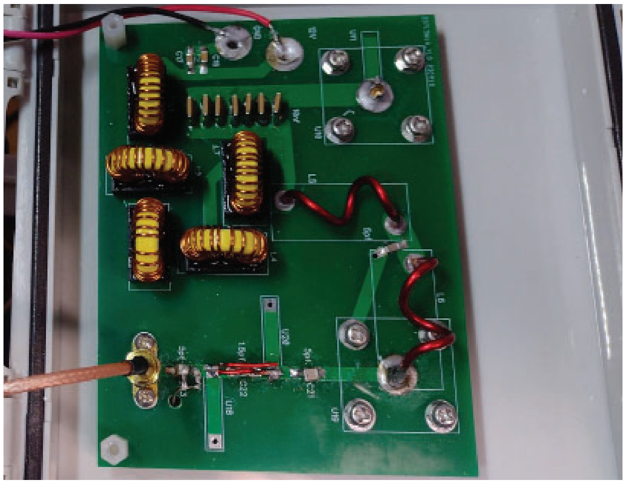

Figure 3 — The completed bias tee.

of uses, including general-purpose digital input/output, serial ports for I2C, universal asynchronous receiver/transmitter and other protocols, and analog-to-digital converter/digital-to-analog converter functions.

A Bias Tee Design with a 2.4 GHz Port

Figure 2 is the schematic of the four-port bias tee, and Figure 3 is a picture of the completed PCB. The bias tee fits on a 4.25-inch × 3.25-inch × 1.6-millimeter-thick two-sided FR4 PCB.

Seven parallel 0.01 µF 2 kV surface-mount device (SMD) capacitors isolate the dc from the RF signal. Each capacitor carries about 0.8 A RF at 1500 W. The measured loss of the bias tee below 60 MHz is typically less than 0.1 dB.

The dc power is coupled into the combined signal path through five Murata 32330C 33 µH 2.5 A toroid inductors in series. These inductors provide adequate blocking of a 1.5 kW RF signal. While the self-resonant frequency is about 28 MHz for each inductor, the reactance is still high at 60 MHz. There are dc bypass capacitors of 0.01 µF and 0.47 µF placed at the dc power connection to provide additional RF isolation. From 3 to 60 MHz, the high-power RF signal suppression on the dc path is 70 – 80 dB. On 160 meters, there is 60 – 65 dB of suppression.

Figure 4 — The control unit front panel.

The combined high-power RF signal and dc power are coupled to the shared SO-239 output through a two-stage filter, which blocks the 2.4 GHz control signal. This filter consists of two inductors in series, each two turns of ½-inch diameter × 1-inch-long #12 AWG solid copper wire. There is also a 5 pF shunt capacitor between the inductors. A ¼ λ 2.4 GHz open stub is placed on the high-power HF SO-239 connector; this stub shorts any leakage of the 2.4 GHz control signal, and it helps isolate the 2.4 GHz signal in the coax to the remote equipment. The 2.4 GHz open stub and 2.4 GHz blocking filter also block any 2.4 GHz noise from the rig or from the antenna to the shared coax, eliminating any possible interference with the control signals.

The 2.4 GHz control signal passes through three 1 pF 2 kV SMD capacitors in series, which blocks HF signals and dc power higher than 80 dB while passing 2.4 GHz signals with some modest attenuation. Two shorted ¼ λ 2.4 GHz stubs further block any HF at the 2.4 GHz port. Attenuation is more than 90 dB for signals less than 60 MHz, and it varies from 10 to 20 dB for signals that are more than 1 GHz. The 2.4 GHz attenuation is modest relative to the high path loss allowable for the control signal with ESP-NOW. An additional 20 dB of attenuation was added on this path using three SMD resistors at the SMA connector to give an overall 2.4 GHz path loss of about 80 dB; this results in about a –60 dBm signal level at the receiver. As the ESP32 device outputs +20 dBm at 2.4 GHz, and the ESP-NOW receiver sensitivity is about –97 dBm, the –60 dBm signal will support relatively long shared coaxial paths depending on the type of coax used. The dc voltage drop in the coax may be more limiting than the 2.4 GHz signal loss, though modern small form factor relays used for antenna switching and tuning typically require less than 50 mA.

ESP-NOW Control Signaling Using ESP32 Processor Modules

ESP32 modules can be programmed with the *Arduino IDE* software. The *Arduino IDE* version 1.8.19 was used with an Espressif Systems ESP32 version 1.0.4 board software package for the ESP32 hardware. Typically, one ESP32 module is placed in a control box in the radio shack with the 2.4 GHz control signal interfaced to the four-port bias tee. A second ESP32

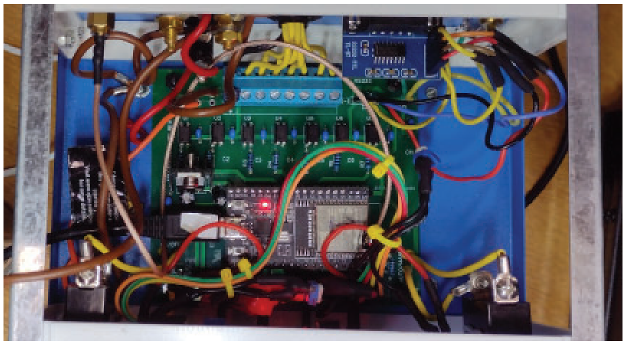

Figure 5 — The control unit interior.

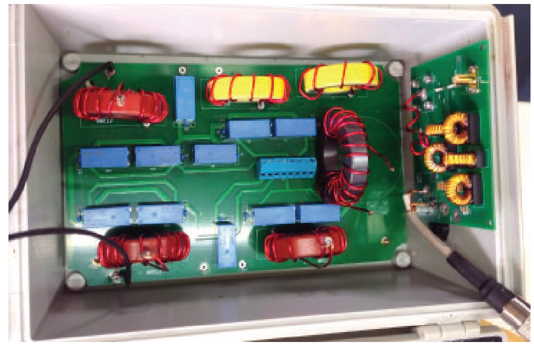

Figure 6 — Part of the 160-meter center unit.

module is located in a remote unit also connected to a four-port bias tee. The control unit includes a user interface with pushbuttons, switches, LCD and LED indicators, a push-to-talk (PTT) connection, and an RS-232 interface for a CAT connection to the rig. The remote unit includes GPIO connections to opto-isolator drivers and relays.

This architecture can be easily expanded. The ESP32 remote processor can output up to 64 control signals by adding I2C serial-to-parallel ICs and relay drivers. Multi-band and multiple antenna operation can be supported by placing antenna switching and antenna tuning relays with the remote equipment. It is also possible for a single ESP32 controller in the radio shack to be interfaced to multiple bias tees and coaxial cables with a 2.4 GHz RF splitter, which allows control of multiple ESP32 remote processors and antenna systems using ESP-NOW in a star network arrangement.

A Remote-Tuned 160-Meter Inverted V

A 160-meter inverted **V** with integrated step tuning was built with relay switchable loading inductors placed in the antenna center unit. The system uses the rig's frequency CAT interface to control the antenna tuning based on pre-configured software tables in the control unit. The tuning tables were programmed during antenna construction and testing. PTT information prevents hot-switching of the tuner. Figures 4 and 5 show the front panel and interior of the control unit, respectively. Figure 6 is the partially assembled antenna center unit showing the tuning PCB and the bias tee PCB. Figure 7 shows the fully assembled antenna center unit.

Three different PCB designs are used: the four-port bias tee used at both ends of the shared coax, a single PCB design used for both the ESP32 control unit and the ESP32 remote unit, and a tuning PCB used in the antenna center unit.

The remote ESP32 outputs five GPIO control signals to opto-isolator relay drivers that control the relays for the 160-meter antenna step tuning system. The 7 µH, 3.5 µH, 1.75 µH, 0.88 µH, and 0.44 µH toroidal inductors in the center unit tuning PCB provide step tuning in a binary coded arrangement, with 32 steps to achieve finely spaced antenna resonant frequencies. The antenna resonates just below 2.0 MHz without any inductive loading. With all inductors inserted, the frequency is lowered to about 1.8 MHz. Two inductors are placed on one leg of the antenna, and three inductors are placed on the other antenna leg. It is not necessary to balance the loading exactly, as the antenna impedance changes slowly for small changes in the feed position with a center-fed antenna.

For the 160-meter inverted **V**, 11 frequency segments were selected to tune the antenna across the 160-meter band in test mode. That information was input to the tuning table in the control unit software. With the center of the inverted **V** at about 40 feet in height, the antenna's resistive impedance was about 20 Ω. An RF transformer on the tuning PCB, consisting of an FT240-43 toroid with an interleaved 8T primary and 5T secondary, provides impedance matching. This resulted in a standing wave ratio (SWR) of less than 1.5:1 across the band. However, depending on your antenna's particular characteristics, you may need to change the RF transformer.

ESP32 Software

The ESP32 control unit runs in three modes: **AUTOMATIC**, **MANUAL**, and **TEST**. The remote unit runs in just one mode. The **TEST** mode for the control unit is selected by holding in the **SELECT** button during power **ON**. A toggle switch can select **AUTOMATIC** or **MANUAL** mode.

In **MANUAL** mode, the user can select the antenna tuning settings from the pre-programmed table called **THREE_BAND_LOOKUP_TABLE_H**. This table is intended to support antenna tuning for up to three

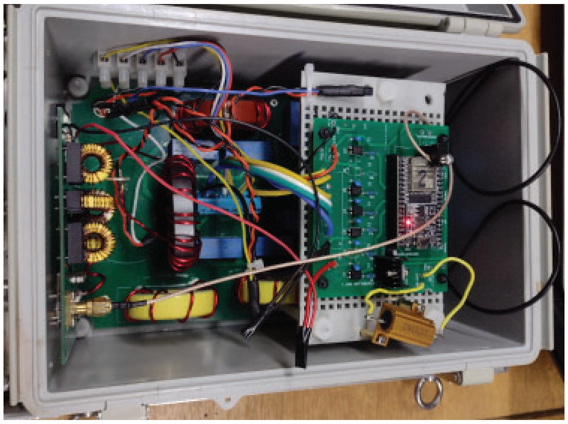

Figure 7 — The complete center unit.

frequency bands. The user can step through the pre-programmed table with pushbuttons on the front panel of the control unit. The pre-programmed table contains a set of frequencies and corresponding relay settings for the remote unit. When a relay change is needed, the control unit sends a command to the remote unit using ESP-NOW over the shared coax.

In **AUTOMATIC** mode, the control unit monitors the rig's frequency using a CAT RS-232 interface, and it uses the pre-programmed table to determine when antenna tuning relay changes are needed. In both **AUTOMATIC** and **MANUAL** modes, the PTT signal is monitored by the control unit, and relay changes are blocked when PTT is active.

In **TEST** mode, the user can step through all possible antenna tuning relay settings using the pushbuttons on the front panel of the control unit. This mode is used during initial system setup to determine a table of frequencies and tuning relay settings for the **MANUAL** and **AUTOMATIC** modes. A good target is to add a new entry to the tuning table when the SWR reaches about 1.5. Once frequency and relay settings are determined in **TEST** mode, that table is transferred manually to the software table. The control unit code is then rebuilt with that table and downloaded into the control unit hardware.

The remote unit has only one mode in this example, and it is fairly simple. ESP-NOW continuously monitors for any incoming messages. When a change in relay information arrives, it is sent to the appropriate GPIOs with low delay. The remote unit also replies to incoming messages with an acknowledgment, so the control unit can detect any loss in the connection. If a loss of ESP-NOW communication occurs, the auto/manual LED will blink and the condition will be sent to the LCD. The remote ESP32 is lightly loaded in this example, and adding functions such as SWR monitoring and/or automatic tuning is possible.

Conclusion

A shared coax from the radio shack to an antenna system that supports up to 1.5 kW transmit power for the HF bands, 12 V dc (or higher) up to 2.5 A, and control signaling at 2.4 GHz using IoT devices is attractive. A high-performance, low-cost four-port bias tee can be built and used at both ends of the shared coax to multiplex and de-multiplex the signals. ESP32 devices were used to build control and remote units for a 160-meter inverted **V** with antenna-integrated tuning. ESP-NOW IoT protocol at 1 Mbps provides two-way data and supports low delay. The control unit monitors the rig's frequency and PTT to control the antenna tuning relays and prevent relay changes during transmit periods.

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✓ Schematics, Gerber files, software, and other documents necessary for this project

All photos provided by the authors.

Nelson Sollenberger, KA2C, was licensed in 1970 as WN3PKU, and he has held the call sign KA2C since 1980. He received his BSEE from Messiah College in 1979 and his MSEE from Cornell University in 1981. He worked in cellular radio technology with AT&T, Bellcore, and Broadcom from 1979 to 2016. Nelson is an IEEE Fellow, an AT&T Fellow, and a Broadcom Fellow. He enjoys CW, casual DXing and contesting, and ARRL Field Day. Nelson also enjoys restoring boat anchors and doing ham radio construction projects. He has been an ARRL member since 1970, and he is a member of the Antietam Radio Association. Visit Nelson's website at **www.ka2c.com** for more information about antennas. He can be reached at **nelsonsollen@gmail.com**.

Jeff Addleman, W3ADD, was first licensed in 2021 as KC3RIJ. He received a BSME from Penn State in 1974. He was employed by several construction equipment manufacturers during his career as a registered Professional Engineer. Jeff has many hobbies, including ham radio activities, Arduino programming, woodworking, electronic projects, skiing, walking, and playing with computers. Jeff enjoys ham radio construction projects that include electrical and mechanical design and real-time firmware applications. He has been an ARRL member since 2021, and he is a member of the Antietam Radio Association. He can be reached at **addy165@comcast.net**.

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