Electronic Antenna Switching

Not only is electronic T/R switching faster than using relays, it can be less expensive, too!

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Until recently, the typical amateur station switched the antenna between the receiver input and the transmitter output with a relay. The common T/R, or transmit-receive relay was relatively slow, switching in 10 or 20 milliseconds. Some specialists demanded faster operation, the traditional example being the CW enthusiast who operates "full break-in," or QSK. An effective QSK system operates fast enough that received signals can be heard between dots at code speeds of 30 words per minute, or even faster.

The demand for QSK capability has increased in recent years, largely the result of interest in digital modes that are faster and more automated than CW, the original digital mode. This article explores some methods for nonmechanical switching. Not only are the methods simple, but they are probably less expensive than a good relay.

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The Basic Requirements

The fundamental T/R element, shown in Fig 1A, is a single-pole double-throw switch. This complication may or may not be needed; the simplified SPST topology of Fig 1B is often adequate. The system requirements are:

- There should be a low-loss connection between the transmitter and the antenna when the transmitter is operating.
- The switch should attenuate signals from the transmitter so that there is no damage to the receiver input. Minor receiver overload may be tolerable.
- Antenna signals must *not* be severely attenuated in reaching the receiver input. A few dB loss is generally not a problem on the lower HF bands, but would be intolerable at VHF.
- The transmit path should not introduce distortion to a transmitted SSB signal; requirements are relaxed for CW and most other digital modes.
- Distortion in the receive path should be low enough that there is no compromise in receiver performance.

T/R Switching for QRP Rigs

A very common electronic T/R system example is shown in Fig 2. A 50-Ω antenna will usually reflect a similar load to the power amplifier collector, causing the receiver tap point to *see* 50 Ω so long as the amplifier is not functional. The low impedance drives a small capacitor with a typical reactance of 500 Ω. During receive periods, the diodes do not conduct, allowing the signal to reach the receiver. The

500-Ω inductor resonates with the capacitor to form a moderately low-loss signal path.

Switching action occurs when the two back-to-back diodes are turned on by the transmitter radio frequency energy. With each diode conducting on alternating RF half cycles, the 500-Ω capacitor is essentially grounded. It then becomes part of the low-pass transmitter network. This must, in concept, be taken into account during the design of the low-pass matching network, although it can usually be ignored. This "standard" T/R switch was popularized by W7EL in his "Optimized" transceiver.[1]

[1]Notes appear on page 7.

The maximum current capability of the diodes limits the transmit power that can be used with this scheme. Standard 1N4152 switching diodes can conduct a maximum current of about 100 mA. They are adequate for 5-W rigs in a 50-Ω system, or up to about 25 W in a 12-Ω environment. Higher powers can be accommodated with the methods presented below.

There are several performance parameters that we might measure (or calculate) in this simple circuit. The first is receive-path insertion loss. This is usually under 1 dB with typical (X=500 Ω) components, a small price (at HF) for the convenience of electronic T/R.

Next we ask how well the receiver is protected. Specifically, how much transmitter power is available at the receiver antenna terminal? My measurements show an available power of −10 dBm, at least 20 dB below the level that would cause damage, but still a very "loud" signal. Effective receiver muting circuitry is needed for smooth station operation. The power available at the receiver does not depend strongly on the transmitter power being used.

The T/R circuit is in the receiver signal path and should be evaluated for IMD performance. Less than ideal performance might compromise receiver dynamic range. This is rarely of concern in low-power portable stations used on quiet bands. It can become a major concern to a 40-meter operator in Europe or even on the east coast of North America.[2]

A 20-meter version of the circuit of Fig 2 was built and evaluated for insertion loss and 3rd-order input intercept. This band was picked because measurement equipment was available. The T/R series-tuned circuit used a small trimmer capacitor (22 pF) and a 5-µH inductor wound on a T50-2 toroid. The measured input intercept was −3 dBm. This is low enough to compromise the performance of *modern* receivers, including many direct conversion circuits using diode-ring-mixer front ends.

Each diode was replaced with a series connection of two diodes, increasing the measured input intercept to +7 dBm. The same circuit with three diodes in each leg produced an $IP3_{in}$ of +13.5 dBm. This performance approaches that needed for use with wide-dynamic-range receivers.

A 2-W transmitter using this T/R circuit was evaluated for receiver protection with multiple diodes. The available power at the receiver antenna terminal was −10 dBm with one diode per leg, −4 dBm with two diodes per leg, and −1 dBm with three diodes per leg. While adding diodes reduces the protection, the power available to the receiver is still well below the damage level.

The QRP scheme can be extended to higher powers with a single switch element (Fig 3) where the back-to-back diodes are replaced by a shunt PIN diode. The bias must now be controlled with the key or VOX. A bipolar transistor has also been used, although I've seen no performance reports. A suitable reverse bias is required during receive periods when a single diode is used. This is required

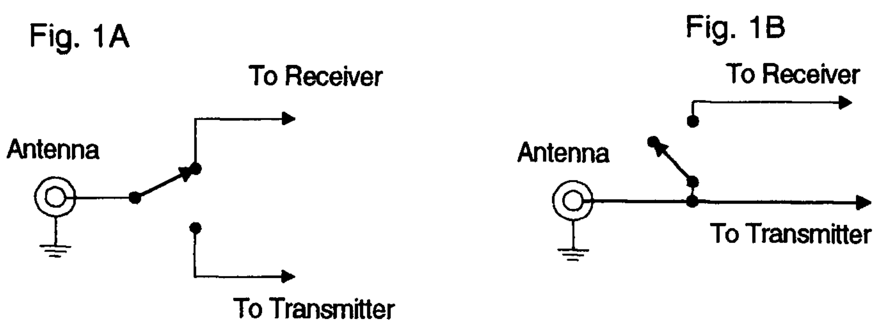

Fig 1—Basic SPDT antenna switch is shown at A. The configuration in B is suitable if a direct connection between transmitter and antenna does not cause problems during receive periods.

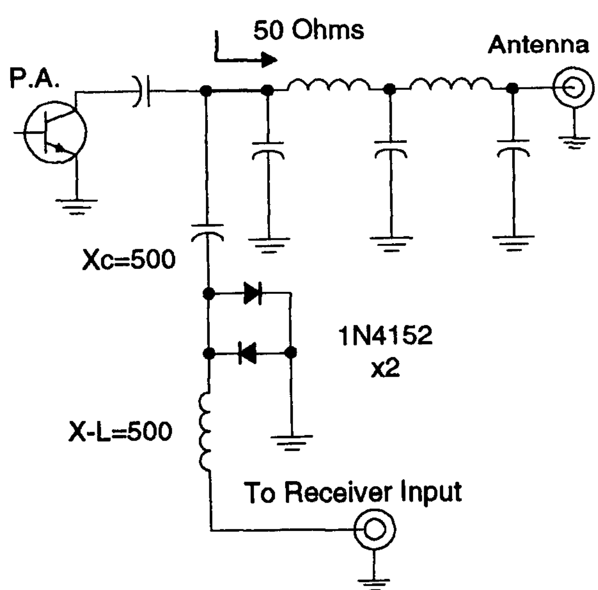

Fig 2—Simple T/R system for use with QRP transmitters. This scheme is suitable for powers up to 25 W or more. See text.

owing to the capacitance of the PIN diodes with zero bias. PIN diodes will be discussed more below.

Shown in Fig 4A is a scheme that I have used at the 100-W level with an amplifier operating from a 12-V supply. This scheme is still safe at the 100-W level because the L-C circuit in the T/R system was changed to keep the peak current at or below 100 mA in the 1N4152 diodes. Generally, with a N:1 turns ratio transformer from a single transistor power amplifier, the peak diode current will be

$$I_{peak} = \frac{N \cdot C \cdot F \cdot V_{cc}}{159.2}$$

where C is in pF, V_{cc} is in volts, F is in MHz, and I is in mA. N is doubled if a push-pull amplifier is used. In the example, the transformer is 1 center-tapped turn to 4 turns, so N becomes 8. At 7 MHz, a 17-pF capacitor with V_{cc}=12 yields a peak diode current of 72 mA, still a safe level with the 1N4152. The inductor used in this instance was 30 µH, the series combination of two 15 µH RF chokes. The Q for these chokes was about 50, which produced an insertion loss of about 2 dB; this level was acceptable at 7 MHz.

Part B of Fig 4 shows another refinement. The single L-C circuit and diode pair has been doubled, but with capacitors that are now half the original value. This reduces the current in each diode by two, allowing the transmitter power to increase by four.

Toward Higher Power T/R Systems

Although the systems presented above can be extended to higher power, they have problems. First, they are single-band designs. Second, the scheme only works well with power amplifiers that are biased off during receive periods. An amplifier biased on will generate noise, with much of it available to the receiver input where it can mask signals. It is often desirable to bias high power amplifiers on, even when used in digital modes, owing to improved stability.[3]

The answer to the T/R problem has been available for many years in the form of high-power PIN diodes. A PIN diode is a structure with the usual P and N semiconductor regions found in most junction diodes, but with an intervening region of *intrinsic* silicon. The intrinsic material has no doping that would cause one conductor type to dominate over another. The PIN diode has the useful property that it can conduct an RF current that is much larger than the dc current that biases the diode on. The intrinsic region also serves the purpose of increasing the breakdown voltage of the structure when it is reverse biased. PIN diodes, specified for RF applications and suitable for high power T/R switching, are available from Microsemi Corp of Watertown, MA, and are discussed in the literature.[4]

Although I have used inexpensive high-voltage rectifier diodes as PIN diode substitutes for RF switching applications, I had never tried to use them to switch large RF currents.[5] The project was "on the list," but still untried. Then I had one of those experiences that are becoming all too rare in Amateur Radio, an on-the-air contact that evolved into a meaningful technical exchange. A CQ on 20-m CW produced a reply from Jim, K5CX. Jim's full break-in, high-power, solid-state transmitter included diode T/R switching *with inexpensive diodes*! The information exchanged in the contact and in later correspondence provided the basis for the antenna switch to be described.

A test circuit is required to evaluate diodes; this is shown in Fig 5. RF chokes and high-voltage ceramic capacitors isolate biasing circuitry from the RF switch. The components shown are suitable for 7- to 14-MHz operation. The diode to be tested is placed in the circuit, bias is attached, and RF is applied. The "on" performance is first

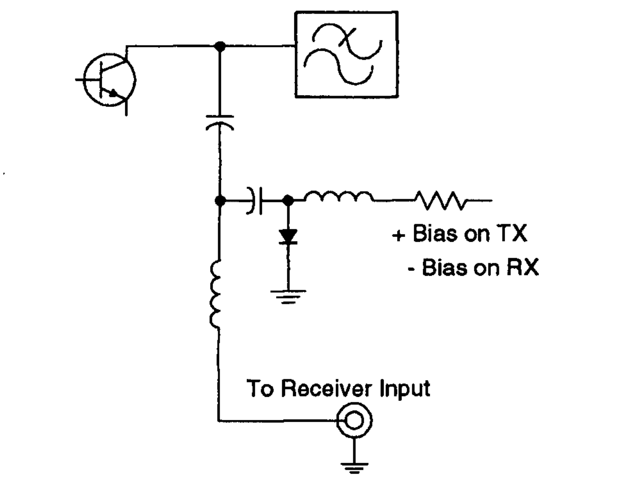

Fig 3—A single shunt diode serves the T/R function if the bias is controlled from external circuitry.

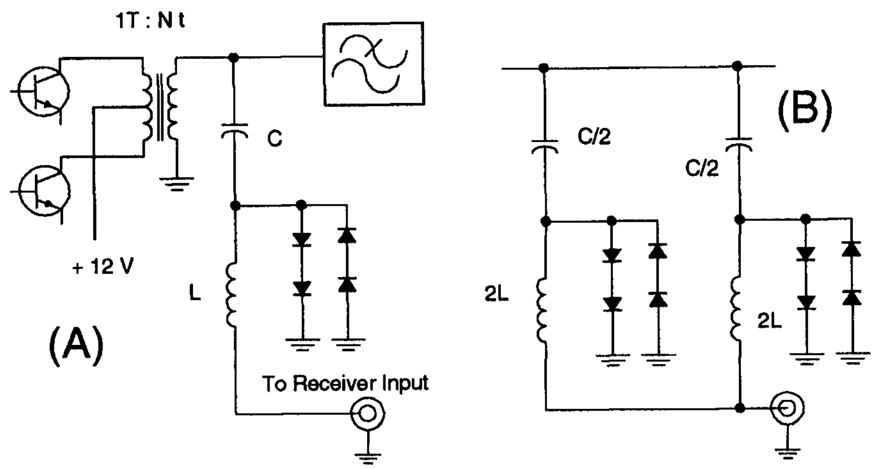

Fig 4—Some variations of the resonant T/R system are shown. A transformer coupled amplifier is used at A. The system in B uses extra parallel reactances, reducing the current in the diodes.

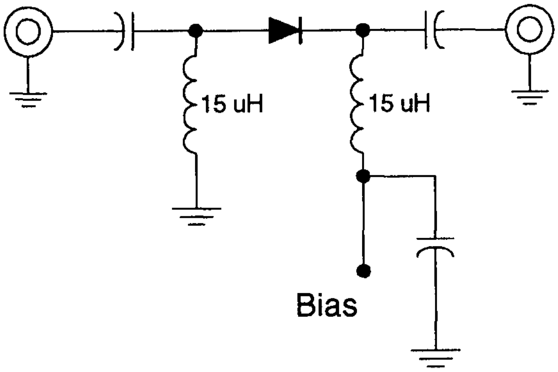

Fig 5—Simple SPST PIN switch. The inductors are molded chokes. All capacitors are 0.02 μF, 1 kV ceramic. There is no difference between input and output for this circuit.

evaluated with an available QRP transmitter. The switch is bypassed and the transmitter output is measured with an oscilloscope and a suitable 50-Ω termination. The RF voltage is measured with as much resolution as possible, for we are looking for small changes. After this calibration, the switch is inserted in the coax line to the termination and the measurement is repeated. The switch performance can be studied as a function of the forward dc current applied to the diode.

After the initial low-power measurements, the process can be repeated with higher power. A high-power termination is required for this measurement.

The next measurement is an evalu-

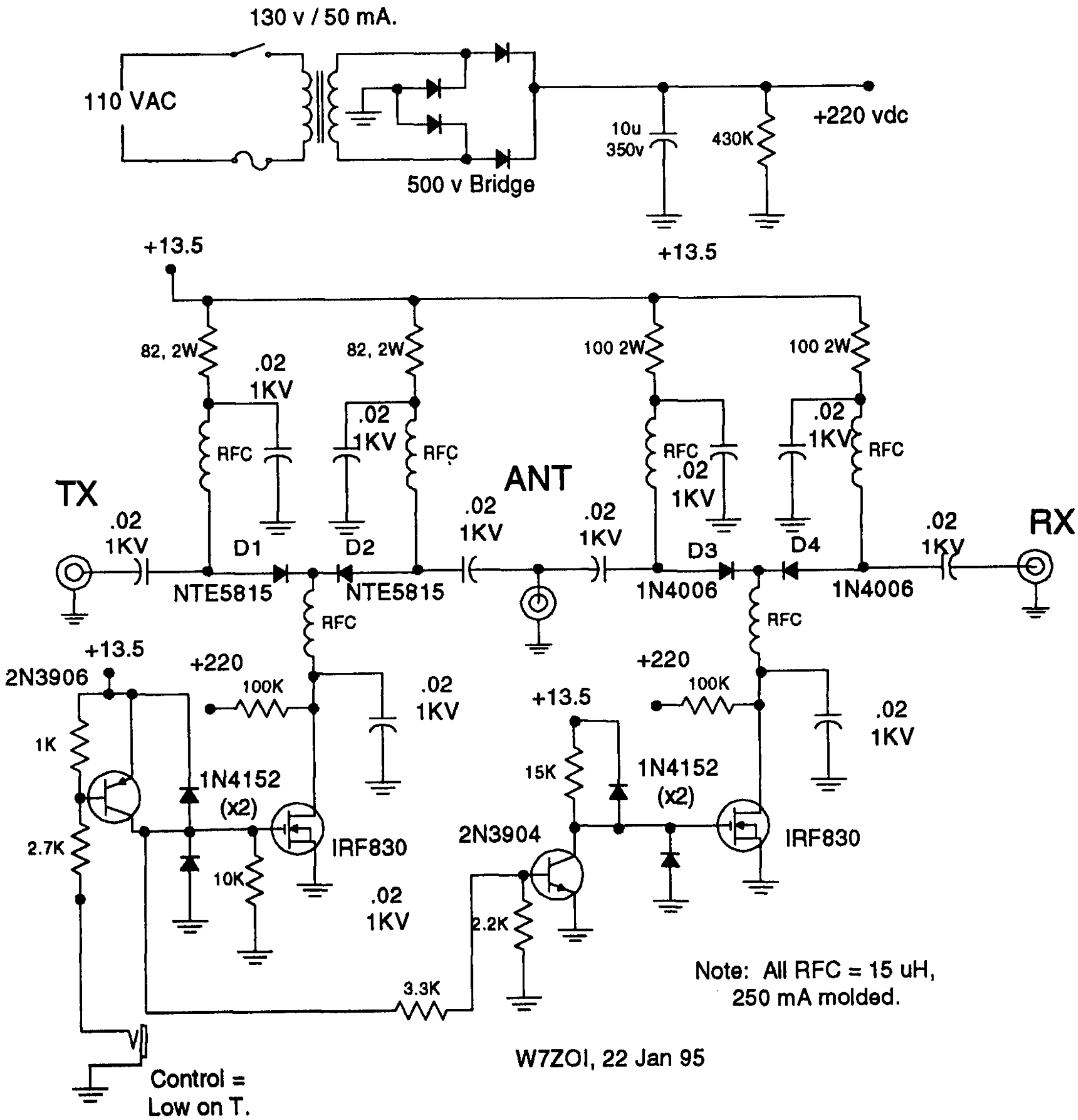

Fig 6—A T/R system suitable for 100-W HF transmitters.

ation of the "off" performance. This is done at low signal levels. A signal generator can be used to provide RF from a well defined source impedance. Alternatively, the QRP transmitter can be used with an attenuator (approximately 10 dB) in its output. I measured output voltage either with a spectrum analyzer or with a 50-Ω terminated HP3400A ac voltmeter.

The switching diodes are characterized by a small resistance when operating with forward bias and by a capacitance when operating with reverse bias. I was not able to measure any forward resistance in any of the diodes I tested; the losses were too low, even at the 100-W level. Also, no temperature rise could be detected in the diodes, even with 100 W flowing.

The series capacitance is related to the insertion loss by

$$C(farad) = \frac{1}{4 \cdot \pi \cdot F \cdot R} \cdot \sqrt{\frac{P}{1-P}}$$

where F is frequency in Hz, R is the source and termination resistance, usually 50 Ω, and P is the power ratio,

$$P = 10^{-IL(dB)/10}$$

P is less than unity.

The diode type recommended by K5CX was the Motorola 6A6. This is a power rectifier specified for I=6 A and reverse voltage of 600 V. The DigiKey catalog lists this diode and several similar devices as manufactured by Diodes, Inc. Jim commented that virtually any of these diodes will provide the needed low on resistance so long as the dc bias current is adequate. I've found that a current of 100 to 200 mA is more than enough for 7-MHz operation at the 100-W level in a 50-Ω system.

The diodes I evaluated included a so-called "equivalent" device, the NTE5815, an industrial rectifier specified at 600 V and 6 A. The 1N4006 diode was also investigated, a device specified at 1 A and 800 V. The NTE5815 appears to be like the 6A6, although it is difficult to tell without more detailed specifications. The best procedure is to test whatever diode is to be used.

The NTE5815 had a capacitance of over 30 pF with a reverse bias of 80 V, with little change in going up to 200 V. The 1N4006, however, had C=3.6 pF. Owing to the small size of the 1N4006 when compared with the monstrous NTE5815, the 1N4006 is only used in the receive path. (In spite of these recommendations, I've encountered no diode failures with 100 W through the 1N4006 diodes I tested. They were surplus without a well-defined manufacturer.)

A friend, K6OLG, sent a few Motorola 1N4007 diodes. These devices, rated at 1 A and 600 V, had a measured C of 2.1 pF at –80 V.

A T/R System for 100-W Transmitters

The final result of these experiments is shown in Fig 6. Owing to the high series capacitance of the NTE5815 diodes, a configuration using two series-connected diodes per switch leg was chosen for the final circuit. All of the components were found in the junk box except for the diodes, and they were inexpensive. High-voltage HEX FETs were used for the dc control. The 1N4152 diodes are included to protect the HEXFETs against transient gate voltages. A junk box power transformer provided a high reverse bias for diodes in the "off" position. If a suitable replacement cannot be found, a pair of back-to-back identical filament transformers could be used. The reverse bias of 220 V is more than enough to keep the diode capacitances low. A forward current of about 150 mA is used to bias the "on" diodes, with the current being "stolen" from the transmitter power supply.

The T/R switch of Fig 6 is normally in the receive mode. It is switched to the TX mode when the control line input is short circuited to ground. The signal to realize this comes from timing circuitry built into the exciter that drives the power amplifier. The same control signal formerly activated a relay.

Several measurements were done with the finished switch. The system provides an isolation of 56 dB between the TX and RX ports when the ANT port is terminated in 50 Ω. If greater isolation was required, a shunt switch at the receive port could be added; this additional diode would be forward biased during transmit periods. The 56-dB value is entirely adequate for the present application, a 100-W transmitter at 7 MHz.

The next measurement was an evaluation of intermodulation distortion in the receive path. No intercept number could be established, for the only IMD observed was attributed to the instrumentation used for the measurement. The measurement did put a lower limit on the switch intercept at +40 dBm. This is beyond the performance of even the best receivers in routine amateur application. It would have been interesting to evaluate the 3rd-order IMD in the transmit path. This was not possible owing to inadequacies in measurement equipment.

RX port isolation will degrade at higher frequencies, encouraging the builder to include the shunt switch mentioned earlier. The RF chokes used are suitable for 7 MHz, but not much lower. The builder interested in the 80- and 160-meter bands should increase the inductance accordingly. L values that become too large may compromise the higher bands through self-resonance effects, so measurements are definitely in order.

Acknowledgments

As mentioned, the basic work that led to the higher power circuits presented was all performed by Jim Miles, K5CX. Many thanks to Jim for sharing his results with us. Thanks also go to Bill Carver, K6OLG/7, for his interests in the circuitry and the methods.

Notes

[1]Lewallen, Roy, W7EL, "An Optimized QRP Transceiver," *QST*, August, 1980.

[2]Personal correspondence, Dave Newkirk, ARRL.

[3]Dye, Norm and Granberg, Helge, *Radio Frequency Transistors: Principles and Practical Applications*, Butterworth-Heinemann, Boston, 1993.

[4]Doherty and Joos, "PIN Diodes Offer High-Power HF-Band Switching," *Microwaves and RF*, December, 1993.

[5]Hayward, Wes, W7ZOI, "Beyond the Dipper," *QST*, May, 1986. A 1N647 was used for band switching in the signal generator described.