A "Fool-Resistant" Sequenced Controller and IF Switch for Microwave Transverters

Feeling foolish since you blew up that nice new transverter because the T/R switching wasn't sequenced right? Here's a way to avoid that problem.

By Paul Wade, N1BWT

L ast summer, I suffered the failures of two 10-GHz preamps and one coax relay. Fortunately, none occured at critical times, and I finally rigged up an inconvenient but safer two-switch scheme to prevent further problems. But I did resolve to come up with a better control system this winter. Ideally, it would be fool-proof, but fools are too resourceful for that, so I've tried to make it as fool-resistant as possible.

Discussion

For several years, I've been using variations of a transverter IF switch by KH6CP.[1] This has worked well in

[1]Notes appear on page 00.

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several of my transverters, and I've made various improvements, but it does not adequately sequence various switching functions.

Three sequencing techniques are commonly used. The first is to intercept the PTT line so the transceiver is controlled by the switch box. Often, this requires modification of the transceiver, particularly those that do break-in CW only, transmitting when the key is touched. I want to be able to interchange various transceivers without modification so I can lend spare equipment to willing rovers.

The second approach uses a fixed-sequence switch, usually a series of time delays, which, once started, go through the sequential operations without further safeguards.

The last, and least successful, method is to switch an external relay

directly from a transceiver's PTT line. Often, the current available from the PTT line is inadequate for driving a relay, and I know of several cases where the transceiver has been damaged by this technique.

My preference would be a switch that goes through sequential operations but checks that appropriate conditions are met before proceeding to the next step—in logic design, this is called a *state machine*. As I started to sketch out the sequence of operations I wanted, I realized that ordinary T/R switches, such as relays, don't have an appropriate state to deal with break-in transceivers, which are delivering RF before the switch is ready for it. To deal with this, I use a PIN-diode IF switch and have designed the controller to have a third state, in addition to transmit and receive, in which all

applied RF power is absorbed. I call this third state the *safe* state. Since one of the functions of the IF switch is to attenuate the transmitted power from the IF transceiver, the safe state is implemented by adding two PIN diodes that absorb the power.

Design

The first step in the design process is to sketch out the desired timing for the switching sequence. This evolved to the timing diagram shown in Fig 1, which goes through one cycle from receive to transmit and back to receive. The second step is to synthesize a logical state machine that generates the desired timing. The final step is to actually design a circuit that implements the logical state machine. Following this progression helps to ensure that the final circuit will operate as intended since there is a clear target to work toward.

The desired operation of the state machine sequence is shown in the *state diagram*, Fig 2. The system starts in the inactive receive state. When an activation signal is received, the system moves to the *safe* state, absorbing all RF power. The switching sequence can then continue at whatever speed is required, not releasing the RF power to the transmit circuitry until the system is ready to go to the transmit state. Normally, this would mean removing power from the receive section, then driving the microwave T/R relay, waiting long enough for it to switch (or to sense that the fail-safe contacts closed, if you are fortunate enough to have a relay with this feature) and finally, applying power to the transmit section. When the activation signal is removed, we go from the transmit state to the safe state, reverse the

switching procedure, then return to the receive state.

Since this state machine is intended to be used in several transverters and with various IF transceivers, I added some options to increase flexibility:

1. RF sensing ensures that any RF power applied to the IF port will cause switching to the safe state—even if no control signal is applied—to protect the transverter from damage. Full RF switching may be enabled by setting the J17 jumper, allowing the use of any transceiver, even a hand-held, for the IF.

2. PTT polarity selection is provided since some transceivers ground the PTT output on transmit while others provide a positive voltage. There are separate inputs for these two PTT polarities; each requires low current and has a switching threshold of about 5 V.

3. Single-cable switching supports transceivers that put the dc PTT voltage on the RF output cable. Jumper J3 sets the PTT polarity for the IF cable.

4. A transmit-ready signal can be sensed. Some amplifiers require a warm-up period, so this input must be grounded to indicate that everything is ready to transmit; otherwise, the switching sequence will remain in the safe state and not continue. This input could be automatically or manually switched.

5. Fail-safe sensing detects when the fail-safe contacts on a coax or waveguide relay have closed—and prevents transmitting until they do. I've not yet found a good coax relay with this feature, but my 10-GHz wave-guide relay does have it. Jumper J15 selects between fail-safe operation and time-delay-only sequencing.

6. FET output drivers for the safe

state activate a coax relay, activate dc power switching and drive LED indicators for the operator. I like to have three LEDs: TRANSMIT READY, SAFE, and TRANSMIT.

7. A DPDT relay may be jumpered to be switched by any of the FET drivers
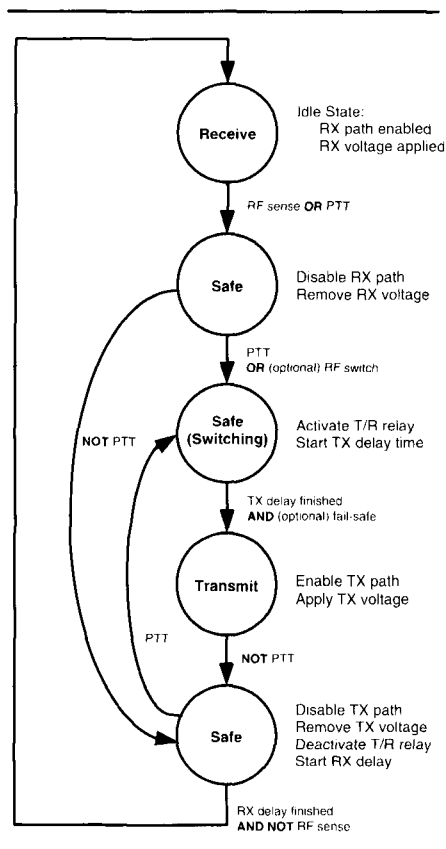

Fig 2—Sequencer state diagram. The circles show the individual states, while the text to the right of each circle shows the actions performed upon entering the state. The text next to each connecting line shows the conditions necessary to advance to the state the line goes to.
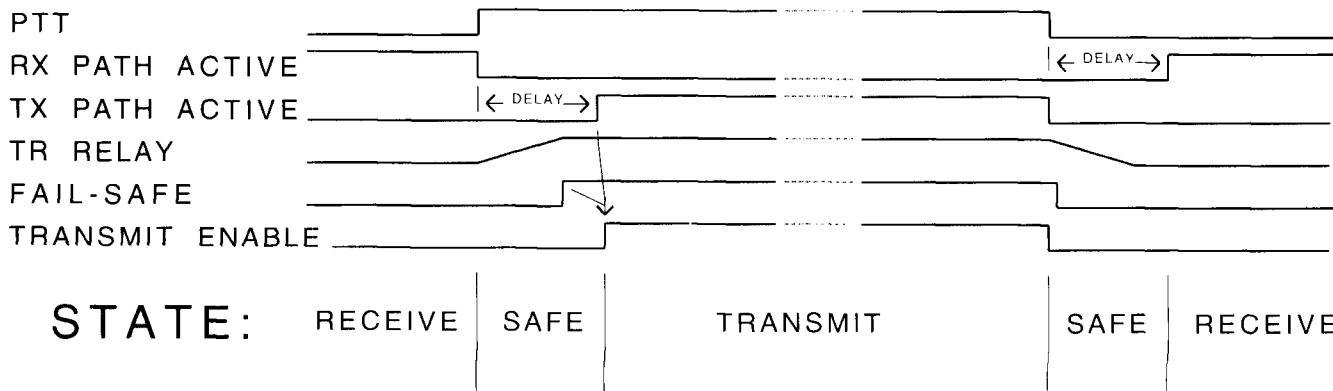

Fig 1—Sequencer timing diagram.

to operate at the desired point in the desired sequence.

The components for each of these options are indicated on the schematic diagram, Fig 3, and may be populated as desired.

Circuit Description

Some have suggested using a small microprocessor to implement switch sequencing. The flexibility and programmability of this approach would be great, but I am very cautious about putting microprocessors in high-intensity RF fields. Since my intent is
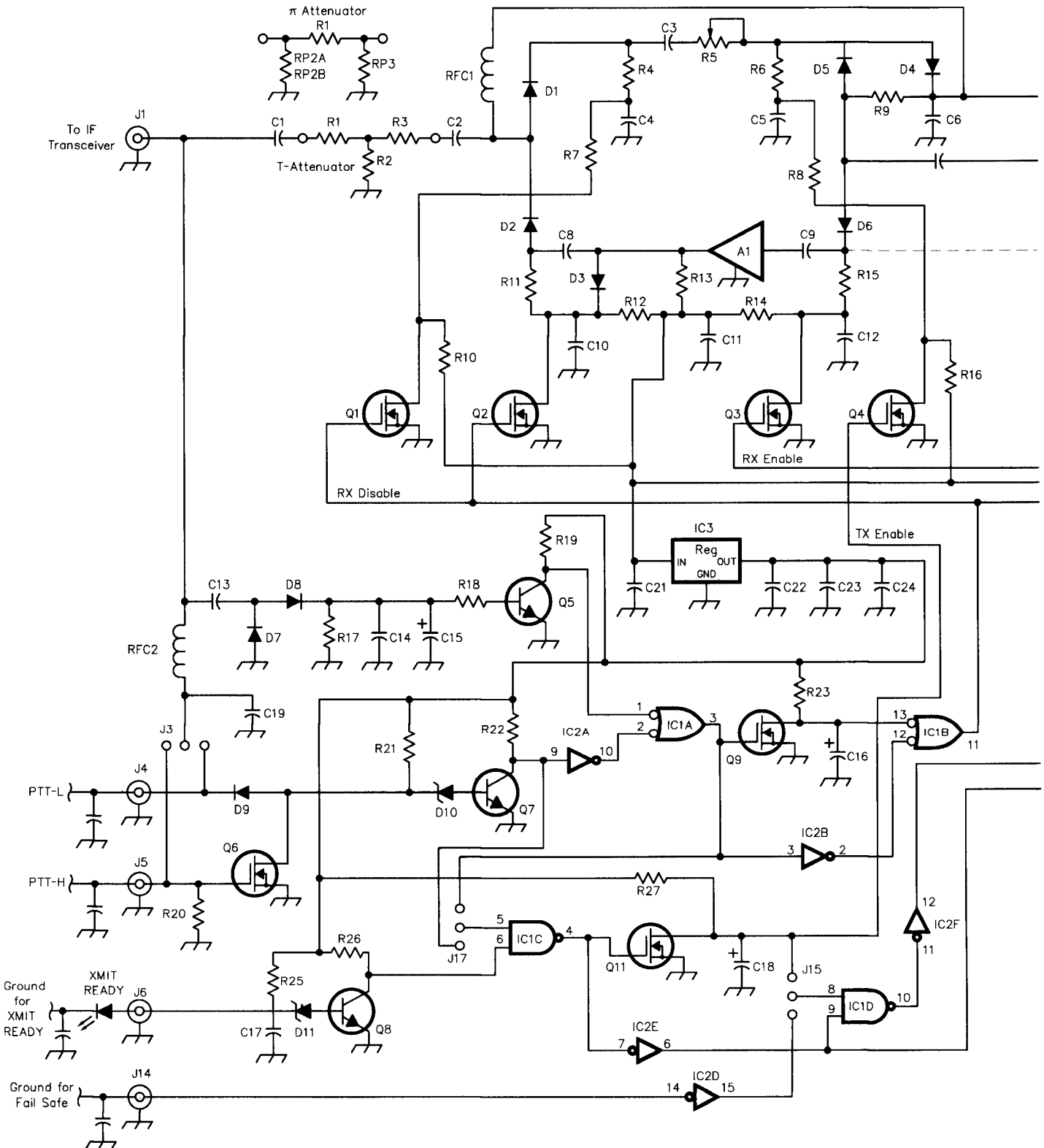
to include both the PIN-diode switch and the controlling state machine in a small metal box, there may be a significant amount of RF in the box. Therefore, I chose to design using components that are cheap, proven and readily available, and are also slow enough not to respond to RF. And wherever possible, I use these components in circuits I have used before and know to work well.

Let's take a quick tour of the schematic diagram, Fig 3. The IF transceiver connects to J1, and its transmit power is reduced by the attenuator, R1, R2 and R3. The values shown provide about 14 dB of attenuation. Since low-inductance power resistors are becoming hard to locate, it may be necessary to adjust the attenuator design to fit the available component values. I described how to do this using a computer program, PAD.EXE, in *QEX*.[2] The program, which calculates resistor values and power ratings for attenuators, is available from the *QEX* web site, **http://www.arrl. org/files/ qex/** in file qexpad.zip. The input attenuator used here is designed for the 2 to 3-W output available from small portable transceivers.

The attenuator is followed by the PIN-diode switch. A PIN diode acts as an RF conductor when dc is flowing through it, but acts as an RF open circuit when reverse-biased. Each PIN diode in this circuit is supplied with +6 V at one end, so the other end may be switched between +12 V and ground to reverse the bias. D1 and D2 select the transmit or receive path on the IF side, while D5 and D6 select the path on the transverter side. The transmit path goes through an adjustable attenuator that can be adjusted for 20 to 38 dB of total transmit attenuation. This is needed because most mixers require around 1 mW or less of power. The receive side uses an MMIC amplifier stage, A1, to overcome the loss of the input attenuator—the MAR6 provides enough gain to end up with 6 dB of net gain ahead of the transceiver, with a noise figure better than that of most transceivers.

The safe state is provided by PIN diode D4, which shorts the output end of the attenuator. Turning off FET Q4 causes current to flow through D4, making it an RF conductor, and causes D5 to be reverse-biased, making it an open circuit for RF. Thus, RF flowing into the transmit path has no output path and must be dissipated in the attenuators. The reflected power must pass through the attenuator twice, for a total loss of 60 dB, so essentially no reflected power is seen by the IF transceiver.

An additional safety feature is provided by D3, which is turned on by FET Q2. D3 shorts out any transmit energy that leaks through D2 (when it's off) and also disables MMIC amplifier A1 by reducing the dc voltage supplied to it.

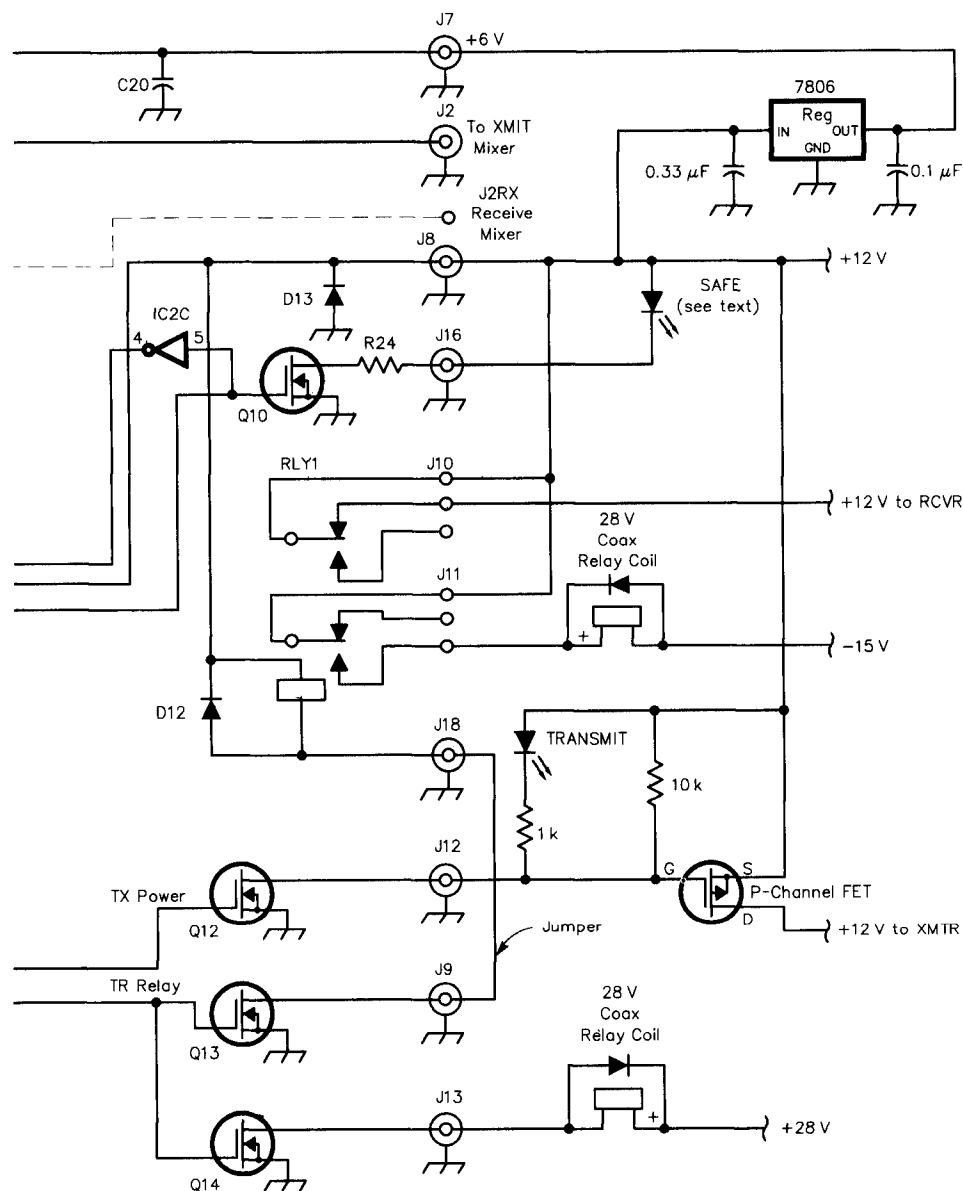The switching states for the PIN-

Fig 3—Schematic diagram of the IF switch and sequencer. (See Table 2 for parts list.)

diode switch are straightforward: in the receive state, FET Q3 is turned on, which causes D6 to turn on. FETs Q1, Q2 and Q4 are turned off, so D2 and D4 are on while D1, D3 and D5 are off—only the receive path is active. The next state is the safe state, reached by turning on FETs Q1 and Q2 and turning off Q3; this turns on D1 and D3 while turning off D2 and D6, so the IF input is switched to the transmit side but the output side is not connected and D4 shorts the attenuator output. Finally, the transmit state is reached by turning on Q4, which turns off D4 and turns on D5, completing the transmit path.

With the resistor values shown, the PIN-diode currents are adequate for an input power level of about $1/8$ W, so the input attenuator should reduce the IF power to this level or lower. For higher powers, it would be necessary to increase the on current through the diodes, particularly D1. However, it shouldn't be necessary to switch much power, since the RF output to the mixer input should be milliwatts or less.

All the FETs used in this circuit are N-channel enhancement-mode MOSFETs used as switches. The sources are all grounded and the gate is the control element. When the gate voltage is close to the source voltage, or ground, the FET is turned off, and no current flows from drain to source. To turn the FET on, the gate voltage must be several volts more positive than the source voltage, allowing current to flow from drain to source with only a few ohms of resistance. For practical purposes, we may consider the drain to be shorted to ground when the FET is on and open circuited when the FET is off. Since these are insulated-gate FETs, no gate current is possible and no dc power is required for switching. The gate voltage required to switch the smaller FETs is roughly 2.5 to 3 volts, but larger power FETs such as Q14 require a somewhat higher voltage, so the whole switching circuit operates at 8 V, provided by the three-terminal regulator, IC3.

The rest of the schematic describes the control logic. The RF-detect section, from C13 to Q5, drives IC1A to force the system to the safe state as soon as RF input is detected. The PTT section, from Q6 and D9 to Q7, is a DTL (diode-transistor logic) gate with a switching threshold set by Zener diode D10. The PTT output is inverted by IC2A to also drive IC1A and force the safe state. Note that IC1A is drawn as an OR gate, with inversion bubbles on the inputs to show that they are as-serted low; thus the output of IC1A is asserted when either input is in the low, or asserted, state. The output of IC1A is inverted by IC2B which activates OR gate IC1B, thus driving the *RX Disable* signal to turn FETs Q1 and Q2 on and put the PIN-diode switch in the safe state. The output of IC1B is also inverted by IC2C to drive the *RX Enable* signal. This turns FET Q3 off when Q1 and Q2 are turned on, and vice-versa. Finally, IC1B also drives
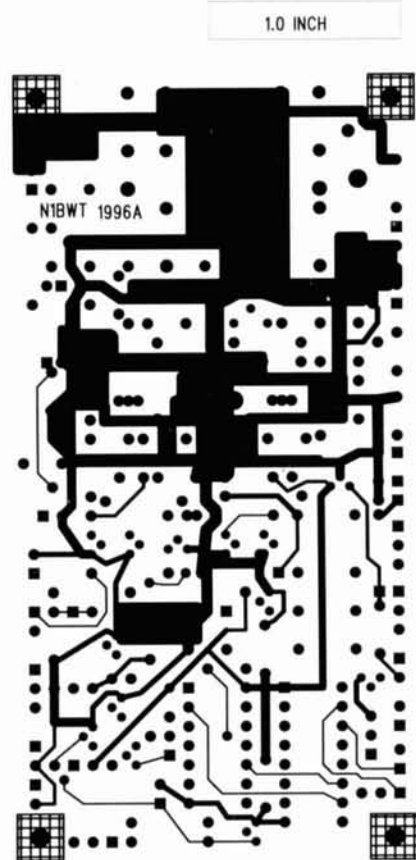

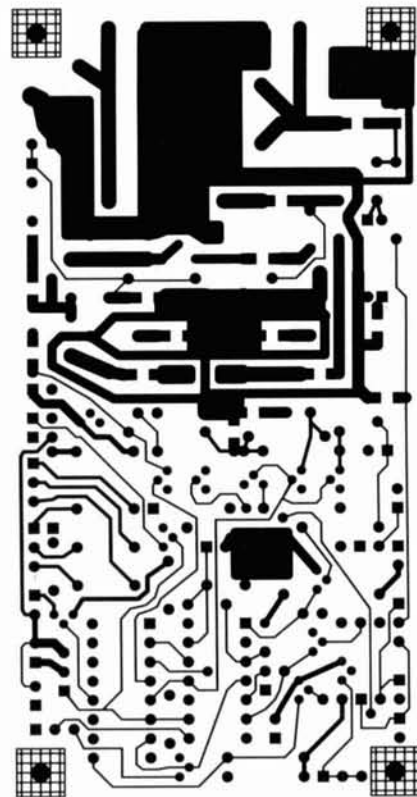Fig 4—Top-layer printed-circuit board pattern.

Fig 5—Bottom-layer printed-circuit board pattern. (Note: Board requires plated-through holes.)
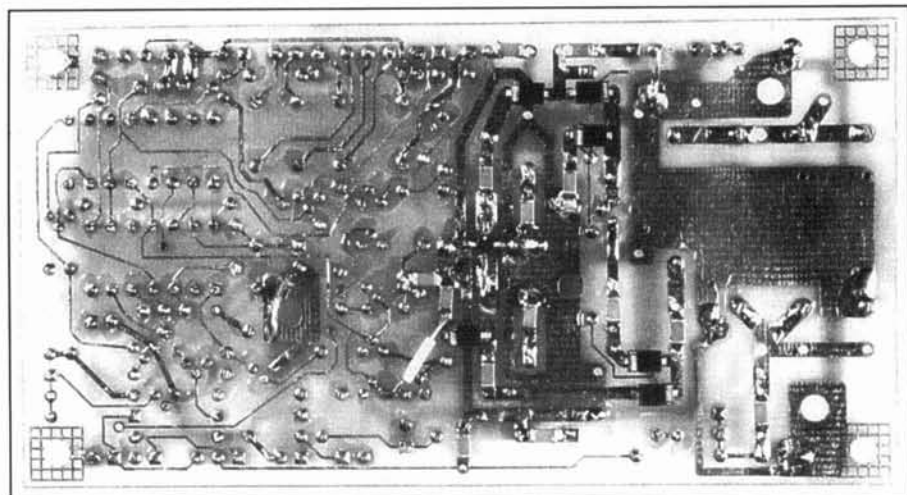

Fig 6—The bottom side of the PC board, showing PIN diode and chip capacitor replacement.

FET Q10, which is turned on in the safe and transmit states so it may be used as a signal to control the voltage supplied to receive stages and preamps.

The PTT section has two inputs, PTT-L on J4 and PTT-H on J5. PTT-L must be grounded, or asserted low, to activate, while PTT-H requires a positive voltage, or high assertion. Both inputs have an operating threshold in the 2 to 5-V range, so any input voltage below the threshold is considered low and any input above the threshold is considered high. The high threshold provides considerable tolerance for different rigs, dirty contacts, etc. The PTT section can also be activated through the IF cable input on J1—any dc voltage on J1 is delivered to the logic circuit through RFC2. Jumper J3 selects the polarity for the IF input; the right-hand position selects PTT-L and the left-hand position selects PTT-H.

The transmit-ready section, from J6 to Q8, is another DTL gate. Its output drives IC1C, which is drawn as a NAND gate; both inputs must be asserted high for the output to be asserted low. The other input to IC1C is selected by jumper J17; in the lower position, it is the output from the PTT circuit. Thus the IC1C logic function requires both transmit ready and PTT to be asserted. The upper jumper position takes the output from IC1A, which also includes the RF detection, making the logic require both transmit ready and either PTT or RF detect. This allows switching using only RF detection. Capacitor C15 sets the hang time for RF switching. With the values shown, switching time seems fast for SSB or for slow CW, so a bit of experimentation might be needed to find a time that feels right.

The output of IC1C is inverted by IC2E (note the inversion bubble on the input, to match the output of IC1C which is asserted low) to drive FETs Q13 and Q14, one of which should be used to enable the T/R relay. The IC1C output also drives FET Q11, which is an inverter with a time delay set by R28 and C18. Q11 drives the *TX Enable* signal, so completion of the time delay turns on FET Q4 to allow the transmit power to flow through J2. When jumper J15 is in the upper position, the completion of the time delay will also allow IC1D to switch, driving Q12 and enabling the transmit state. The lower position of the jumper forces IC1D to wait until J14 is grounded by the fail-safe contacts on the T/R relay.

When PTT is released and no RF is detected, the output of IC1A is deasserted. This voltage transition passes through FET Q9, an inverter with a time delay set by R24 and C16. Until the time delay completes, pin 13 of OR gate IC1B remains asserted, keeping the PIN-diode switch in the safe state while all the other switches are released. Since the safe state prevents any RF from getting through, sequencing of the switches isn't critical in this direction.

Finally, IC3 regulates the logic voltage to 8 V to maintain constant time delays. The R and C values specified yield time delays of 200 to 300 milliseconds, but the delay can be increased or decreased by changing the values. For instance, increasing C16 from 10 μF to 16 μF would increase the time delay by about 60%. Alternatively, increasing R24 from 33 kΩ to 51 kΩ would have the same effect.

Relay RLY1 may be driven by Q13 to operate at the same time as the T/R relay, during the safe state, or driven by Q12 to operate when entering the transmit state. Notice diode D12 across the relay coil. This serves to protect the FET from the reverse voltage spike caused by removing the current from the relay coil. All relay coils should have a diode to protect the driving circuitry; even a relay driving another relay can suffer contact damage from the switching spike.

Construction

I decided that this circuit is complex enough to justify layout of a printed-circuit board since my intent is to use copies in several transceivers. All the components between the two vertical rows of jacks on the schematic diagram, Fig 3, fit on the PC board. A double-sided board with plated-through holes was needed for full interconnection; the top-layer pattern is shown in Fig 4, and the bottom layer is in Fig 5. Boards are available from Down East Microwave.[3]

All the chip capacitors are mounted on the bottom of the board, as shown in the photograph of Fig 6, and I chose to
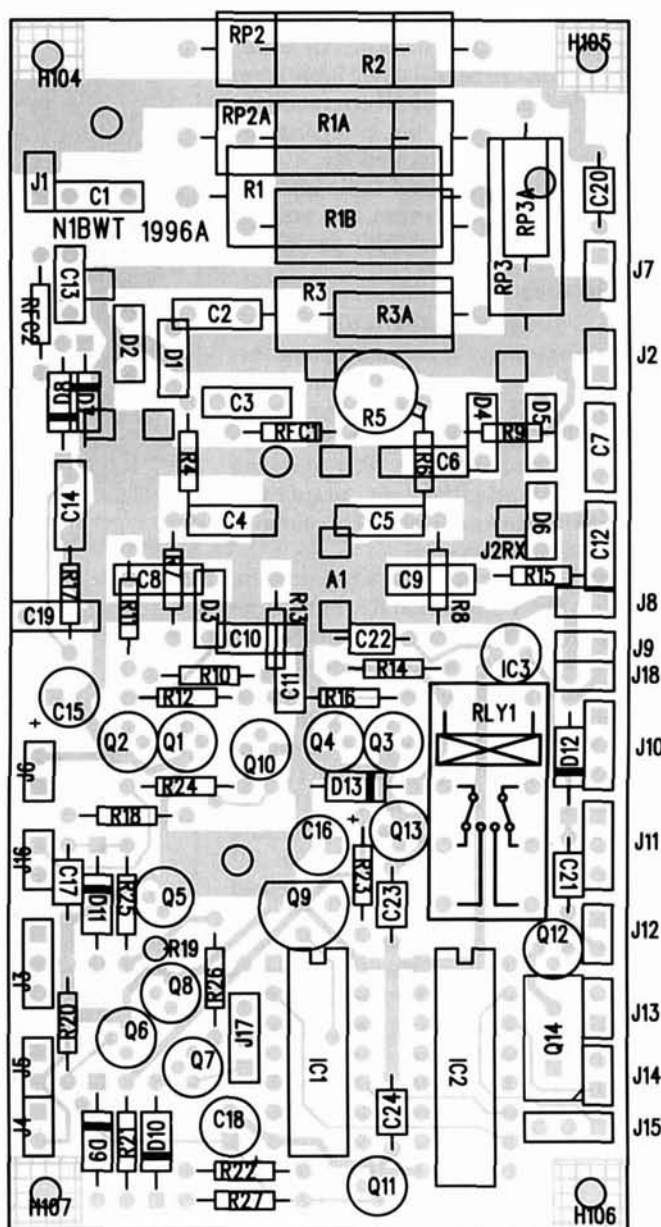

Fig 7—Parts-placement diagram for the printed-circuit board.

put the PIN diodes on the bottom also to keep lead lengths short in the RF path. All of the other components are on the top side of the board, as shown in Figs 7 and 8. Note that the smaller power FETs, such as Q1, have inconsistent pin-outs that vary with part number and manufacturer. Check the data sheet, and make sure that the source lead connects to ground, which is the wide trace running all over the top of the board. The gate lead connects to the middle pad of each footprint, leaving the drain at the far end.

Component values are not critical. I've tried to calculate optimum values, but any resistor or capacitor value could be changed to the next higher or lower standard value without significant effect. The RF diodes are stocked by Down East Microwave. All other components are readily available from Digi-Key.[4] The cost of all components totals less than $15, not counting the enclosure box and connectors.

The PC board is sized to fit inside a small die-cast aluminum box since a shielding enclosure is highly desirable.

Application

There is enough flexibility in this circuit that using it requires some decisions; on the other hand, it should be possible to fit it to your system needs rather than forcing the system design to match the controller. The portions of the schematic diagram outside the two vertical rows of jacks show some of the possible functions.

The first decision is whether the transverter uses a single mixer, as shown in Fig 9, or separate mixers for transmit and receive, as shown in Fig 10. A single mixer would connect to J2; otherwise, the transmit mixer connects to J2 and the receive mixer connects to J2RX, which is a hole in the PC board next to C9. In this case, D6 and R15 must be removed, and Q3, C12 and R14 may be removed or used for another switching function, as described below.

The next decision involves the control signals. I usually provide inputs for both polarities of PTT using different connector styles (RCA phono for PTT-H, subminiature phone for PTT-L). The transmit-ready and fail-safe inputs can go to connectors if they are used. Otherwise, they should be jumpered to ground to avoid floating inputs. Finally, jumpers J3, J15 and J17 must be installed as described in the circuit description. The switch will not operate without these jumpers.

Finally, we must decide how to use

the control outputs. I chose to only provide outputs grounded by FET switches, except for the floating relay contacts, to keep unwanted voltages off the board. The signals that drive the FET switches are labeled on the schematic to indicate function. Some possibilities that I have used are shown in the right-hand side of the schematic. The internal relay, RLY1, can be driven by jumpering J18 either to J9, timed to switch a coax relay, or to J12, timed at the transmit state of the sequence. An external coax or waveguide relay usually requires 28 V for operation, which can be provided from a

+28-V supply and switched with the larger power FET Q14, or connected between +12 V and a –15-V supply and switched with the internal relay contacts since many transverters already generate a negative voltage internally.

Power for the transmit stages may be switched with the internal relay contacts or with a solid-state switch using a P-channel power FET like the IRF-9130 or IRF-9530, which can switch several amperes with a small voltage drop. Note that the P-channel FET is used "upside-down," with the positive voltage connected to the source, as shown in the schematic,
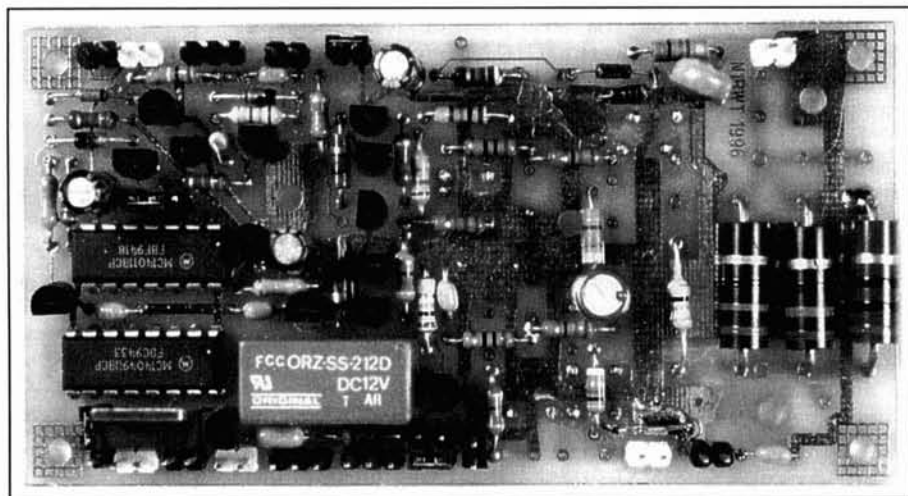

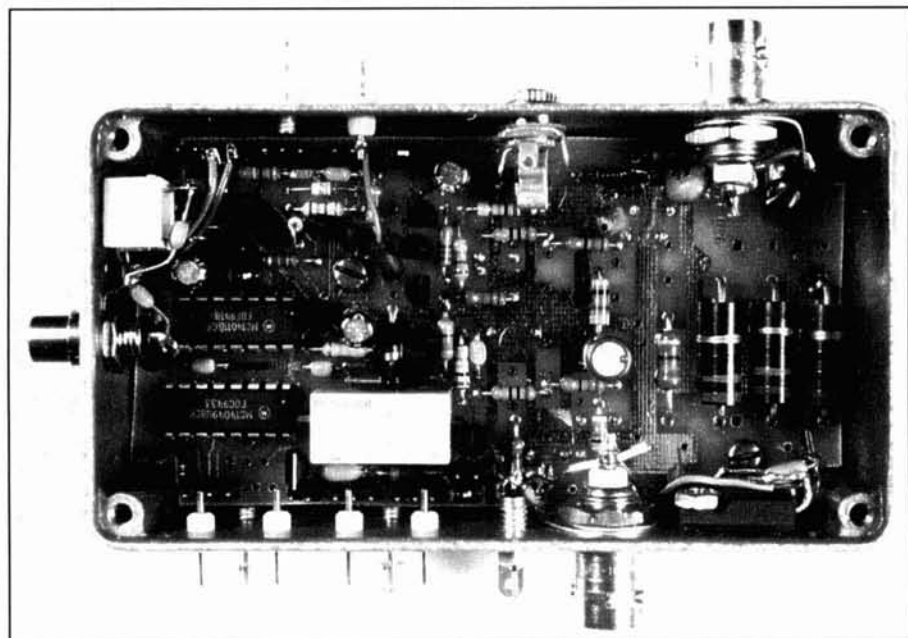Fig 8—The top side of the PC board. The small power FETs are Motorola BS170.

Fig 9—A completed unit, built for use with a single-mixer transverter. The small power FETs are Siliconix VN2222.

since a P-channel FET operates using voltages opposite those of the N-channel FETs described above.

Receive stages and preamps may be switched in several ways. The schematic shows the simplest, using the internal relay to disconnect the voltage at the same time that the T/R relay operates. A more robust sequence would be to remove power when entering the safe state; FET Q10 would be the appropriate driver, with R24 replaced with a jumper so the connection is directly to J16. FET Q10 is turned off during receive and on in all other states. If the receive voltage is set by a variable three-terminal voltage regulator, connecting the adjust pin of the regulator to Q10 would turn off the regulator output. Another alternative, for transverters with separate mixers for transmit and receive, would be to use FET Q3, which turns on during receive and off in all other states, the inverse of Q10. In the two-mixer configuration described above, Q3 is not needed, and R14 and R15 are removed so their pads are available as connection points.

Of course, one needn't be constrained by the printed wiring. If one of the FET switches is not used for the function shown, it can be used for a different function by connecting its gate to the appropriate switching line. All it takes is a hobby knife to cut the trace and a soldering iron to add a wire.

LED indicators may be driven by any output and can be driven by the same FET that drives a relay since the additional current is small. The schematic shows a TRANSMIT READY LED in series with J6, so grounding the transmit-ready line draws enough current to light the LED. If there is no LED in this line, R25 could be much larger to reduce current drain.

The PIN-diode switch requires +6 V to operate, which may be obtained from a three-terminal regulator if not otherwise available. This regulator easily fits inside the die-cast box, as can be seen in Figs 9 and 10.

Finally, all lines entering and leaving the box should be properly filtered. I strongly recommend a bypass capacitor on the inside of the box and a ferrite bead on the wire between the capacitor and the PC board, plus a ground wire from box to board for each connection. I've seen equipment lacking these components unable to operate properly in the high-intensity RF environments found at many mountaintop sites. Listening to TV sync buzz all day is no fun!

The RF connections at J1 and J2 must have closely coupled grounds from box to board; twisted-pair or coax is preferred. The mounting standoffs do not provide an adequate ground path for RF.

Performance

I have built five of these switches and made RF measurements on three of them over the range of frequencies normally used for transverter IFs, with the trimpot set for 30 dB of transmit attenuation at 144 MHz. The results shown in Table 1 are typical.

Clearly, the PIN-diode switch works well at up to 222 MHz, with more than 50 dB of attenuation in the safe state and about 6 dB of gain in the receive state. The trimpot range for setting total transmit attenuation was from 20 to 38 dB at 144 MHz. The switch is still usable at 432 MHz as long as the voltage supply to the transmit amplifiers is sequenced to augment the reduced attenuation in the safe state.

The RF-detect circuit operates reliably with the output from an IC202 transceiver, roughly 2 to 3 W, switching smoothly and ignoring glitches like double-clicking the mike button by remaining in the safe state. I added attenuation between the IC202 and the switch to reduce power. The RF-detect circuit continued to operate with 15 dB of attenuation, at a power level of about 100 mW, but not with 21 dB of attenuation, or roughly 25 mW. This should be adequate margin for safe operation.

Conclusion

The IF switch described here is sequenced to provide fool-resistant operation and is flexible enough for most transverter applications. This combination should make microwave operation more reliable and successful and
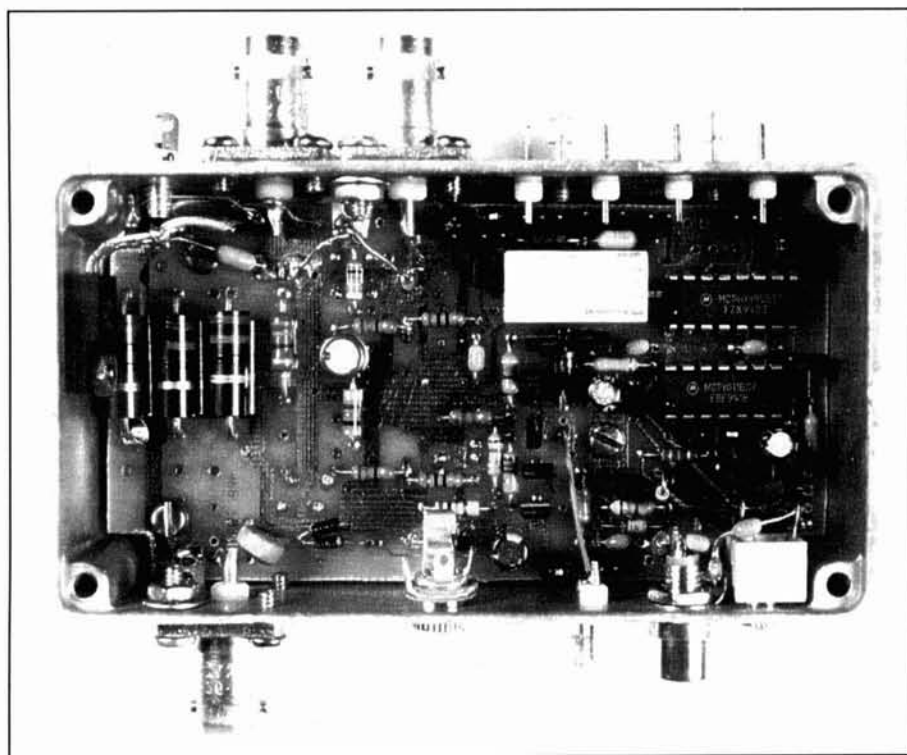

Fig 10—A completed unit, built for use with separate transmit and receive mixers. The small power FETs are Zetex BS170.

Table 1—Measured Performance

Frequency	Receive Gain	Safe-mode gain	Transmit gain
30 MHz	5.5 dB	−60 dB	−31 dB
50 MHz	5.5 dB	−63 dB	−31 dB
144 MHz	6.0 dB	−59 dB	−30 dB
222 MHz	6.5 dB	−50 dB	−29 dB
432 MHz	7.0 dB	−35 dB	−26 dB

Table 2—Parts List

A1	MAR-6 MMIC
C1,2,3,4,5,6,7,8,9,10,11,12,14,15, 19	470 to 2000-pF chip capacitor
C13	2.2-pF disc capacitor (at 50-432 MHz)
C15	22-µf electrolytic capacitor
C16,18	10-µf electrolytic capacitor
C17,20,22,23,24	0.1-µf capacitor
C21	0.33-µf capacitor
D1,2,3,4,5,6	1SS103 PIN diode
D7,D8	1N5711, 1N5712 or HP5082-2035 hot-carrier diode
D9	1N914 or 1N4148 small-signal diode
D10,11	5.1 or 5.6-V Zener diode (1N751, 1N752, 1N5231 or 1N5232)
D12,13	1N4001 rectifier diode
IC1	CA4011 or MC14011
IC2	CA4049 or MC14049
IC3	78L08 8-V regulator
Q1,2,3,4,6,9,10,11,12,13	BS170, VN2222 or VN10 small power switch FET (pinout varies—see text)
Q5	MPSA13 Darlington pair
Q7,8	2N3904, 2N2222, etc BJT
Q14	IRF841, IRF820, IRF830, etc N-channel power FET
T Attenuator	
R1	33-Ω, 2-W carbon resistor (two parallel 68-Ω, 1-W carbon resistors)
R2	22-Ω, 1-W carbon resistor
R3	33-Ω, ¼ or ½-W carbon resistor
π Attenuator:	*add jumper in place of R3*
R1	120-Ω, 1-W carbon resistor
RP2	75-Ω, 2 W carbon resistor (two parallel 150-Ω, 1-W carbon resistors)
RP3	120-Ω, ¼ or ½-W carbon resistor
R4,R6	68-Ω, ¼-W carbon resistor
R5	500-Ω small trimpot
R7,R8	10-Ω, ¼-W resistor
R9	300-Ω, ¼-W resistor
R10	5.6-kΩ, ¼-W resistor
R11,14	10-kΩ, ¼-W resistor
R12	2.7-kΩ, ¼-W resistor
R13	560-Ω, ¼-W resistor
R15	360-Ω, ¼-W resistor
R16	430-Ω, ¼-W resistor
R17	47-kΩ, ¼-W resistor
R18	8.2-kΩ, ¼-W resistor
R19	4.7-kΩ, ¼-W resistor
R20	100-kΩ, ¼-W resistor
R21,22,26	6.8-kΩ, ¼-W resistor
R23,27	33-kΩ, ¼-W resistor
R24	with LED: 1-kΩ, ¼-W resistor; without LED: 0-Ω jumper (wire)
R25	with LED: 680-Ω, ¼-W, resistor; without LED: 10-kΩ, ¼-W resistor
RFC1,2	1-µH RF choke, molded
RLY1	DPDT relay, Radio Shack #275-249
Enclosure	Bud CU-124 or Hammond 1590B die-cast box

help protect the environment by reducing the amount of smoke being released from our equipment.

Notes

[1]Lau, Z., KH6CP, "A VHF/UHF/Microwave Transverter IF Switch," *QEX*, August 1988, pp 3-4.

[2]Wade, P., N1BWT, "Building VHF Power Attenuators," *QEX*, April 1994, pp 28-29.

[3]Down East Microwave, 954 Rt 519, Frenchtown, NJ 08825, tel: 908-996-3584, fax: 908-946-3072.

[4]Digi-Key Corporation, 701 Brooks Ave S, PO Box 677, Thief River Falls, MN 56701-0677, tel: 800-344-4539 (800-DIGI-KEY), fax: 218-681-3380. Also on the World Wide Web at **http://www.digikey.com/**.