

The WA4DSY 56 KILOBAUD RF MODEM

A Major Redesign

By Dale A. Heatherington, WA4DSY

Abstract

In 1987 I designed a 56 kilobaud RF modem which was sold in kit form by GRAPES, the Georgia Radio Amateur Packet Enthusiast Society. This paper describes how the WA4DSY 56 kilobaud RF modem was radically redesigned to lower cost, reduce size, and improve reliability, manufacturability and useability. The reader is referred to the ARRL publication Proceedings of the 6th Computer Network&- Conference, page 68 for details on the original design.

Overview

The original modem was implemented on 3 PC boards. It required both plus and minus 5 volts for the modem and 12 volts for the external transverter. The purchaser of the kit had to fabricate his own enclosure and obtain a suitable power supply. There were no status indicators. Only those hams with above average home brewing skills would attempt to build the unit. However, once built, the modem performance and reliability were quite good. Several high speed networks have been successfully built using these modems.

Unfortunately the large amount of skilled labor required to build a modem kit and to some extent, the cost have limited the wide spread adoption of these modems for high speed networking. I have redesigned the modem to address these issues.

The new design implements the modem on a single 4 layer printed circuit board powered from a 12 volt power supply. The PC board measures about 7 inches on each side. Signals produced by the new design are identical with the original and the new modems will interoperate with the old ones.

Most of the modem functions are implemented digitally in a Xilinx (tm) Field Programmable Gate Array (FPGA). The bandwidth limited MSK signal is generated digitally at 448 kHz to eliminate the need for analog double balanced modulators and a 90 degree phase shifter. This signal is up converted to the 10 meter band at 1 milliwatt. The converter is synthesized over a 2 mhz range (28-30 mhz). An external transverter converts the signal to the 222 or 430 mhz band. The delay between RTS and signal out is quite low, about 20 microseconds or 1 baud interval.

Note that this is a true *modem* which converts data to RF, unlike the G3RUH and K9NG designs which are baseband signal processors and don't do any *modulating* or *demodulating*.

The receiver is implemented with a single chip device and is synthesizer tuned from 28 to 30 MHz. A quadrature detector is used for FM demodulation. The demodulated signal is sliced using a circuit similar to the

one in the original design which automatically adjusts the slicing level. The signal is then fed into the FPGA where clock recovery and data carrier detection are done digitally. The delay between receiving a signal and carrier detect indication is about 3 milliseconds.

The user interface has been greatly improved. Ten LEDs indicate received signal level. Other LEDs indicate *Request To Send*, *Data Carrier Detect* and *Ready*. The data interface is dual mode. A single switch selects CMOS or RS422 modes. The signals are presented on a DB15 connector wired to mate with the Ottawa PI2 Packet Interface Card. Other devices such as TNCs can be connected by wiring an appropriate cable and connectors.

Unlike the original design which allowed the user to reconfigure the modem for different baud rates, the data rate of the new design is fixed. Major changes are required to both the RF and FPGA circuits for use at any other baud rate. Part of the reason is because the first IF of 448 KHz must be 8 (or some power of 2) times the baud rate. Also, the receiver chip is being operated close to its maximum rate at 56KB.

Data Coding

All data coding is done in the FPGA chip. The chip is clocked at 14.3 1818 MHz. The transmit clock is obtained by dividing by 256. The exact baud rate is actually 55.9304 kilobaud, the same as the original design. The transmit clock signal is sent to the user on the RS422 interface. The user's transmit data source is expected to use the rising edge to clock out each bit. The modem samples data bits on the falling edge of the clock.

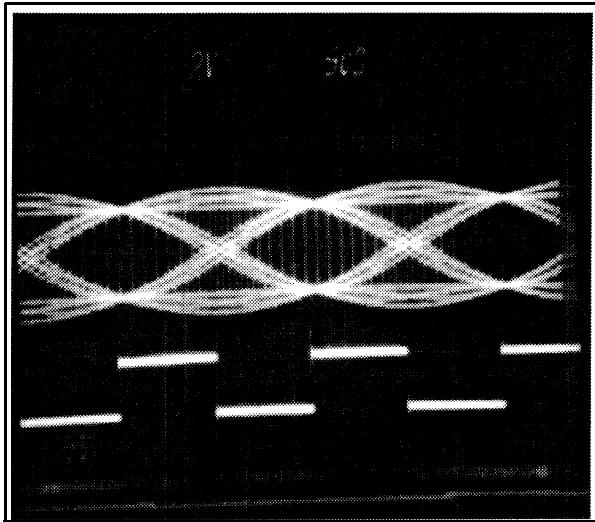
The transmit data stream is scrambled using the same shift register configuration as the original modem, a 17 bit register with feedback taps at stages 5 and 17. This is *not* compatible with KBNG and G3RUH 9600 bps modems. For more details on the scrambling system, see the section titled "Descrambler" below. After scrambling, the data enters the digital state machine where both NRZ to NRZI conversion and RF waveform table lookup operations are performed.

Modulator

This modem has no physical modulator. All RF waveforms are stored in EPROM. A digital state machine fetches the appropriate waveform segment from EPROM in response to the current data bit to be transmitted. 32 samples of the stored digitized waveform segment are read from the EPROM and sent to a Digital to Analog Converter (DAC) during each baud interval. The carrier frequency is exactly 8 times the baud rate to permit the splicing of different waveform segments together without phase discontinuities. The result is a 448 kHz bandwidth limited MSK signal. Unlike the previous version of this modem, there are no modulator related adjustment controls. The signal always has perfect phase shift and deviation characteristics. The signal is identical to the one produced by the original WA4DSY 56 KB modem.

Transmitted signal characteristics

- Modulation is MSK
- Bandwidth is 70 kHz at 26 DB down
- 3.5 DB amplitude variation
- 14 kHz FM Deviation
- 90 degree phase shift per baud



Top trace: Raw TX signal from 8 bit DAC
Lower Trace: 56KB TX Clock

Upconverter and IF

The 448 kHz MSK signal shown in the photo above is first filtered with an 80 kHz wide 3 section LC bandpass filter to remove digital sampling noise. It's

then mixed with 10.245 MHz and converted to 10.693 MHz. The 10.693 MHz signal is passed through two 10.7 MHz (180 kHz BW) ceramic filters to remove the local oscillator and unwanted lower sideband (10.245 and 9.797 MHz). The undesired frequencies are reduced by at least 90 db.

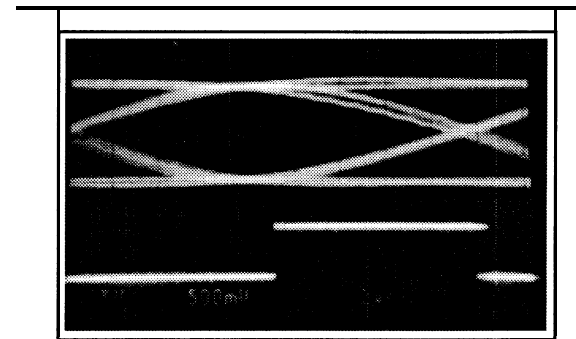
The desired 10.693 MHz signal is then mixed with a VCO signal in the 39 MHz range. The lower sideband of the mixer output (28-30 MHz) is selected with a two section LC bandpass filter. Both conversions are done with NE602 frequency converter chips.

The 29 MHz signal is amplified 30 db by an MMIC chip and sent out to the users transverter on a BNC connector. The output level is adjustable from -10 DBM to +5 DBM.

The local oscillators are running at all times to assure instant response to the user's "Request to Send" control signal. The total delay is less than 20 microseconds from RTS to RF data signal out. Contrast this to the original design which required up to 6 milliseconds to start the transmitter.

Receiver

The receiver uses a Motorola MC 13 135 chip for all RF signal processing. The received signal in the 28-30 MHz range from the user supplied transverter is filtered by a two section bandpass filter before entering the receiver chip. The first local oscillator is a VCO in the 39-41 MHz range controlled by a synthesizer. The signal is mixed with the VCO to convert it down to 10.693



Receiver Eye pattern

MHz. The signal is bandpass filtered with a single 180 kHz wide ceramic filter before being mixed with 10.245 MHz and converted down to 448 kHz. A 60 kHz wide LC bandpass filter provides both selectivity and deemphasis. Frequency modulation is recovered with a quadrature detector.

Frequency Synthesizer

I used a Motorola MC 145 162 synthesizer chip for this design. It is programmed serially with a three wire interface. It has completely separate reference counters and divide by N counters for transmit and receive. The

reference oscillator running at 10.245 MHz also drives both the receive down-converter and the transmit up-converter.

The VCOs are designed to cover 39 to 41 MHz, 10.693 MHz above the 29 MHz IF frequencies. The receive VCO is included in the MC13135 receiver chip. The transmit VCO is a Colpits transistor oscillator with an emitter follower output buffer.

Since there is no microprocessor in this modem, I needed a way to generate the data to program the synthesizer. I had the good fortune of having extra space in the EPROM; so I put the frequency data there. Up to 8 different bit patterns for independent TX and RX frequencies can be stored in the EPROM. The first thing the FPGA does after loading its configuration data is read one of the selected frequency bit strings into the synthesizer chip. Three switches code for the 8 frequencies. Any 8 frequencies can be programmed into the EPROM using a simple program written in C. The program will be supplied with the modem. If the user wants a custom set of frequencies, he must have access to an EPROM programmer or order a custom EPROM from the dealer. Still, this is superior to the original design which used custom crystals often requiring a 6 to 8 week wait and costing 10 to 15 dollars each.

Gated Tracking Data Slicer

Before the recovered signal can be used it must be processed to determine the state of the received bit, 1 or 0. This is done with an analog comparator chip. Its threshold is set exactly halfway between the voltage level of a "1" and a "0". It outputs a "1" if the input is higher than the threshold and a "0" if it's lower. There is a problem when the carrier frequency of the incoming signal changes. The voltage levels of the ones and zeros change so the threshold is no longer exactly half way between them. This causes an increase in errors. One common solution, which doesn't work very well, is to AC couple the output of the demodulator to the detector. This is fine if the short and long term average of the number of ones and zeros is equal. This ideal condition cannot be guaranteed even if a scrambler is used. A much better solution is to put some intelligence in the detector so that it averages the voltage level of the ones separately from the average of the zeros and then subtracts the two averages to obtain the ideal threshold level. This circuit doesn't care about the ratio of ones to zeros as long as there is a reasonable number of each. A scrambler is used to make sure there is a reasonable number of both ones and zeros. The circuit will compute the correct threshold if the input signal carrier frequency is anywhere within the expected range of the ones and zeros, in this case plus or minus 14 kHz. The data slicer used in this implementation is gated with the recovered clock. It only sees voltage levels near the center of a baud interval. A leaky sample and hold technique is used to grab the middle 1 microsecond of each bit. There is little variation in the peak levels from bit to bit thus reducing unwanted fluctuations in the slicer level.

Clock Recovery

Clock recovery is done digitally in the FPGA. There are no adjustments such as VCO center frequency as in the original design. The phase of a 3 modulus counter is compared with the data zero crossing times. The counter is driven by a 3.579545 MHz clock. The baud rate for each modulus is listed below.

	<u>Modulus</u>	<u>Baud Rate</u>
•	63	56.818 (fast)
0	64	55.930 (on time)
0	65	55.069 (slow)

The counter can divide by 63, 64 or 65. The divide by 64 setting produces a 56 kHz clock. If the zero crossing was late relative to the counter's terminal count then the counter is counting too fast. The counter modulus is set higher so it will be earlier next time. If the zero crossing is early the modulus is set lower so it will be later next time. If no zero crossing is detected the modulus is set to "on time" so the clock won't drift during strings of ones or zeros. This scheme only introduces about 0.5 microseconds of clock jitter (3%).

Data Carrier Detector

The data carrier detector is also implemented digitally in the FPGA. There are no adjustments. Two gates are used to separate data zero crossings which fall within plus or minus 12 1/2% (in sync) of the terminal count of the 3 modulus counter described above from the zero crossings which fall outside this range (out of sync). If the clock recovery circuit is phase locked, all zero crossings should fall within the 25% "in sync" window. This is true even at low signal to noise ratios. The "in sync" zero crossings cause a 5 bit counter to increment. The "out of sync" zero crossings cause the counter to decrement. The "carrier detected" flip flop is set when the counter reaches maximum count (31). The flip flop is reset when the counter reaches minimum count (0). The counter is designed not to overflow. It has "stops" at count 0 and 31. Carrier detect occurs when the clock recovery circuit has acquired phase lock and 31 more "in sync" zero crossings have occurred relative to "out of sync" zero crossings. This takes about 3 milliseconds or about half the time of the original 56KB modem with less falsing. Measurements show solid carrier detect even when the bit error rate is as high as 6%. Random noise can't assert carrier detect because the zero crossings have random timings and will occur with equal probability at any point in the baud interval. Since 75% of this interval is devoted to decrementing the 5 bit counter, it will quickly go to zero and reset the carrier detect flip flop. Periodic waveforms that are harmonically related to the 56 kHz clock frequency will trigger carrier detect if the clock recovery circuit phase locks to it.

NRZI to NRZ conversion

NRZ is a data signaling format in which zeros are represented by a certain voltage level and ones by another. NRZI is a signaling format in which zeros are represented by a change in voltage level while ones are

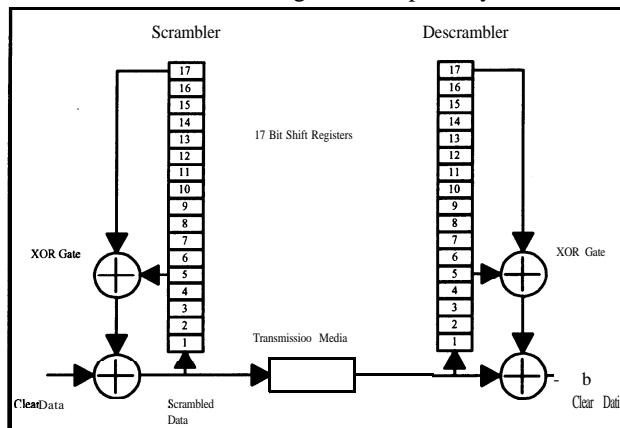
indicated by no change. NRZI coded data is not affected by inverting the data voltage levels or the mark/space frequencies in the case of FSK. This modem converts the incoming NRZI data to NRZ data with a simple circuit consisting of a “D” Flip Flop and XOR gate. These components are in the FPGA chip.

Descrambler

A self synchronizing data scrambler was used in this modem for two reasons. First, it makes the data stream look like a random stream of ones and zeros regardless of the data being transmitted. This characteristic makes the tracking data slicer and clock recovery circuits work better. Second, it makes the RF spectrum look and sound like band limited white noise. In other words, the RF energy is spread evenly over the modems bandwidth and shows no single frequency lines regardless of the data being transmitted. Any potential interference to neighboring channels is limited to an increase in the noise floor instead of squeaks, squawks, and other obnoxious noises. This type of scrambling is also commonly used in high speed synchronous modems for telephone use.

The hardware to implement the scrambler and descrambler is very simple. It consists of a 17 bit shift register and two XOR gates, also known as a *Linear Feedback shift Register (LFSR)*. Each transmitted bit is the result of the exclusive ORing of the current data bit with the bits transmitted 5 and 17 bits times before. To descramble the data, it is only necessary to exclusive OR the current received bit with the previous 5th and 17th bits. If the data consist of all ones, the scrambler will produce a pseudorandom sequence of bits that will repeat after 13 1071 clock pulses or every 2.34 seconds at 56 kilobaud.

This linear feedback shift register scrambling scheme does not violate the FCC prohibition against codes and ciphers because its purpose is to “facilitate communication” and the algorithm is publicly available.



Scrambler Block Diagram

Note: G3RUH and K9NG scramblers use 17 bit shift registers tapped at stages 17 and 12. The sequence produced is not maximum length.

8 Bit FIFO and Bit Repeater Mode

To allow this modem to be used as a full duplex bit repeater I have included a first in-first out (FIFO) buffer and logic circuitry to route the received data bits back to the transmitter. When repeater mode is enabled, the data carrier detect signal will assert request to send. A 2 second watchdog timer prevents transmitter lockup. The FIFO buffer is 8 bits long. To allow for both plus and minus “bit slip”, the FIFO does not start sending data until it’s half full. The transmitter then pulls bits out of the FIFO at it’s fixed clock rate while the receiver inserts bits into the FIFO at the receiver clock rate. The FIFO is reset when data carrier detect (DCD) drops. With a data rate difference between incoming and outgoing data of 0.01% a packet of 40,000 bits (5000 bytes) can be retransmitted before the FIFO buffer overflows. Since this is much larger than typical AX25 packets, I don’t think this restriction will be a problem. Keep in mind that DCD must drop between packets to reset the FIFO.

A single internal switch enables the bit repeater mode. The external data I/O connector remains active to allow communication with a local computer.

Watchdog Timer

A 2 second watchdog timer is built in and may be bypassed with a switch setting. The timer is reset when RTS is false and begins timing when RTS is true. PTT will be turned off if RTS is not removed after about 2 seconds. A resistor and capacitor set the time-out value. This is the only analog timing circuit in the modem.

Remote Control

Computers used in amateur packet networks are often located with the TNCs, modems and radios in inaccessible places such as mountain tops. When the computer software crashes, which it often does, the control operator doesn’t want to have to go to the distant site to push the reset button. A remote control reset function is built into this modem.

Normally open relay contacts are available for whatever use may come to mind. The contacts close when the modem decodes several milliseconds of a pseudorandom bit pattern sent to it from another modem in convenient reach of the control operator. A push button on the rear panel causes the modem to send the special sequence.

The sequence generator is an 8 bit linear feedback shift register with user specified taps. The tap locations are specified along with the frequency data in the EPROM. Each RX/TX frequency pair may have a different code assigned. Each set of taps produces a unique code. The receiving modem must see at least 256 bits of

the pattern before it will start to close the relay. ‘The sequence must continue for another several milliseconds to allow the relay to close. A single incorrect bit in the sequence will reset the decoder so that another correct sequence of 256 bits are needed to cause relay closure. The front panel “ready” LED will change from green to red when the code is being received.

Signal Level Display

Ten LEDs on the front panel indicate relative signal strength. The RSSI signal from the MC 13 135 receiver chip drives an LM3914 linear bar graph display controller chip. I have found this a most welcome feature. I’ve used it to map signal coverage areas by first setting my station to “ping” the local 56KB packet switch every 2 seconds; then with only a modem, transverter and antenna in the car, I can get a good idea of how well the packet switch covers various areas by watching the signal level LEDs and the DCD LED (and the road).

Tune-up and Test Aids

Since only half the EPROM storage was used for the main FPGA configuration code, state and waveform tables, I provided a switch which allows the modem to “boot up” using the other half of the EPROM. In the other half is an FPGA configuration for a direct digital frequency synthesizer which is used to sweep the modems tuned circuits. It sweeps a 200 KHz range centered on 448 KHz. A square wave is also generated on the receive clock output line for scope sync. The rising edge coincides with the 448 KHz center frequency. Adjustment of the filters for proper response shape requires only a 30 MHz dual trace scope. The scope must be adjusted so the rising edge of the “receive clock” square wave is centered and exactly one complete cycle is displayed. The other channel can then be used to probe various points in the modem to observe the frequency response envelope calibrated to 20 KHz per horizontal division. The receive filter can be checked if the an attenuator is placed between the TX and RX BNC connectors. The transmitter becomes the sweep generator.

A push button on the rear panel will activate the transmitter and send scrambled marks. The 2 second watchdog timer is automatically bypassed to allow transverter tune-up or power measurement.

Interfaces

Transverter: Power and PTT (Push To Talk) transverter signals are provided on a 5 pin DIN connector. The remote control relay contacts are also on this connector. BNC connectors are provided for the 29 MHz transverter IF signals. Pin assignments are as follows:

1. PTT
2. Relay contact
- 3 Ground
4. Relay contact
5. +12volts@2Amps

Power: The power input connector is a common 2.1 mm round DC power jack used in many other consumer electronic devices. Positive voltage is supplied on the center pin. A 12 volt 2.5 amp external switching power supply runs the modem and transverter.

Data: A female DB 15 connector is used for the data interface. The pin assignments are the same as the Ottawa PI2 card. A single switch on the PC board changes the electrical standard from balanced RS422 to unbalanced CMOS. The RS422 interface is based on the 26LS32 and 26LS31 chips. The CMOS interface uses a 74HC244 chip.

Pin assignments

RS422

1. No connection
2. + Receive Clock (O^{ut})
3. + Receive Data (O^{ut})
4. + Transmit Clock (O^{ut})
5. + Carrier detect (out, low true)
6. + Transmit Data w
7. + Request to Send (in, low true)
8. Mode Select (Not Used)
9. Ground
10. - Receive Clock (out)
11. - Receive Data (O^{ut})
12. - Transmit Clock (O^{ut})
13. - Carrier Detect (out, high true)
14. - Transmit Data w
15. - Request to Send (in, high true)

CMOS

1. No connection
 2. Receive Clock (O^{ut})
 3. Receive Data (t^{out})
 4. Transmit Clock (@ut)
 5. Carrier detect (out, low true)
 6. Transmit Data w-0
 7. Request to Send (in, low true)
 8. Mode Select (Not Used)
 9. Ground
 - 10.. 15 No connection
-

Internal Option Switch Functions

<u>Switch Off</u>	<u>On</u>
1. RS422	CMOS
2. Normal	RX Mute Disable
3. Normal	Repeater Enable
4. Normal	Scrambler Disable
5. Normal	Key Transmitter
6. Normal	Tune up
7. Normal	Watchdog Disable
8. Frequency Select 2	
9. Frequency Select 1	
10. Frequency Select 0	

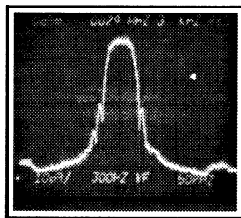
Performance

Due to deadline and other time constraints, I was unable to do a bit error rate test on the latest PC board revision. The previous version needed about 2 db more signal to achieve the same bit error rate as the original WA4DSY 56KB modem. This was a receiver problem related to excessive wideband digital noise getting into the receiver RF stages. This will be resolved before production.

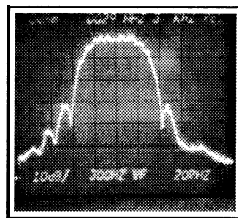
Performance with off frequency signals seems to be at least as good as the original design, degrading only about 1 db with a 5 KHz frequency offset.

The response time from RTS to DCD has been measured at about 3 milliseconds. I'm using a TXDELAY value in NOS of 5 ms and haven't encountered any problems. This is much faster than the original design which required a TXDELAY setting of 15 ms.

The transmitter spectral bandwidth is about the same as the original design.



Transmitted spectrum
Horizontal: 50 KHz/division
Vertical: 10 DB/division



Transmitted spectrum
Horizontal: 20 KHz/division
Vertical: 10 DB/division

Applications

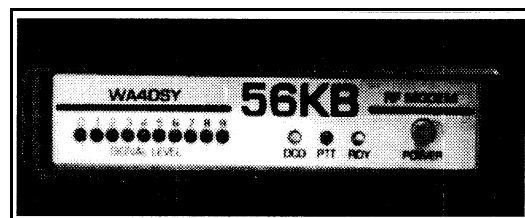
This modem can find uses in several areas. When the original modem was introduced in 1987, the computing power available to the average ham was quite limited and had problems keeping up with 56KB data. Today (1995) the average ham can afford a 66 MHz 486 machine. Multitasking operating systems such as OS/2 and Linux running on these machines allow hams to set up their own TCP/IP Web sites on the air. Applications such as a Web server are useless at 1200 baud. For this reason, I believe this modem has as much potential for use as a user LAN modem as it does for point-to-point links. Assuming the built in full duplex bit repeater works as expected, I hope to see many 56KB FDX user LANs spring up around the world. They would work just like an FM voice repeater except for the 70 KHz bandwidth requirement. There is one such LAN in Ottawa, Ontario, Canada.

We plan to put up a full duplex 56KB Metropolitan Area Network on 222.400 (input) and 223.85 MHz (output) here in the Atlanta, Georgia area using a 56KB modem, a receive converter, transverter and a Sinclair duplexer. Users, of course, only need a modem and transverter.

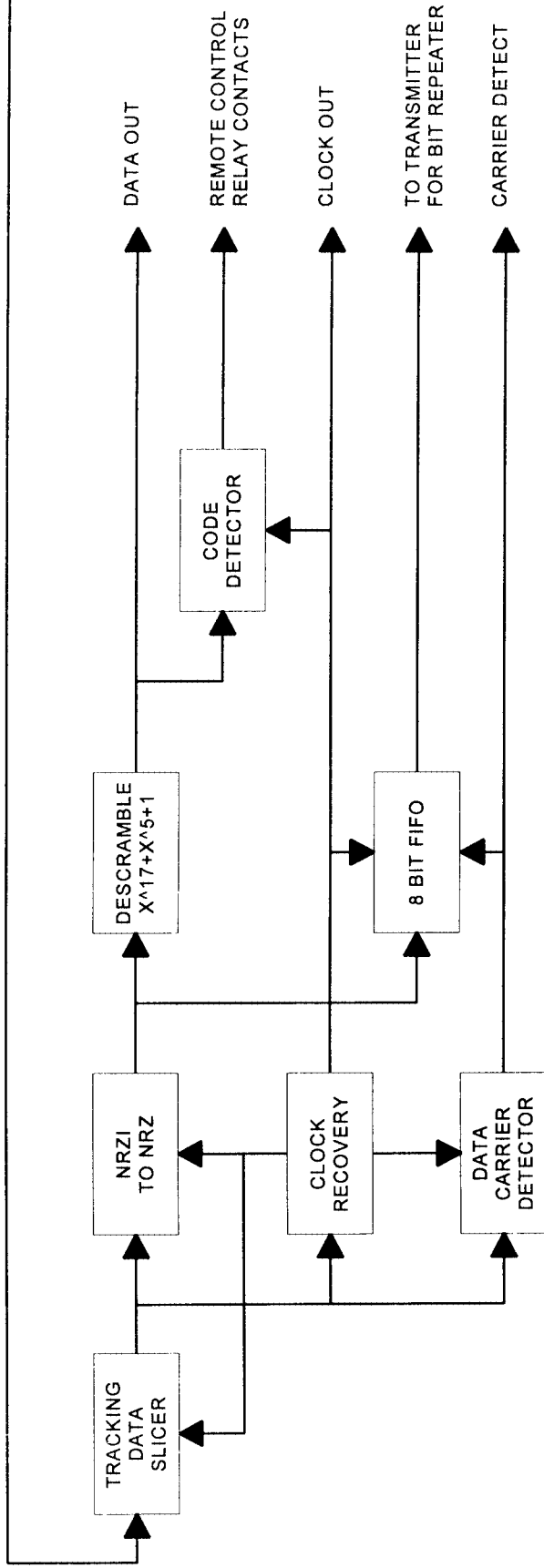
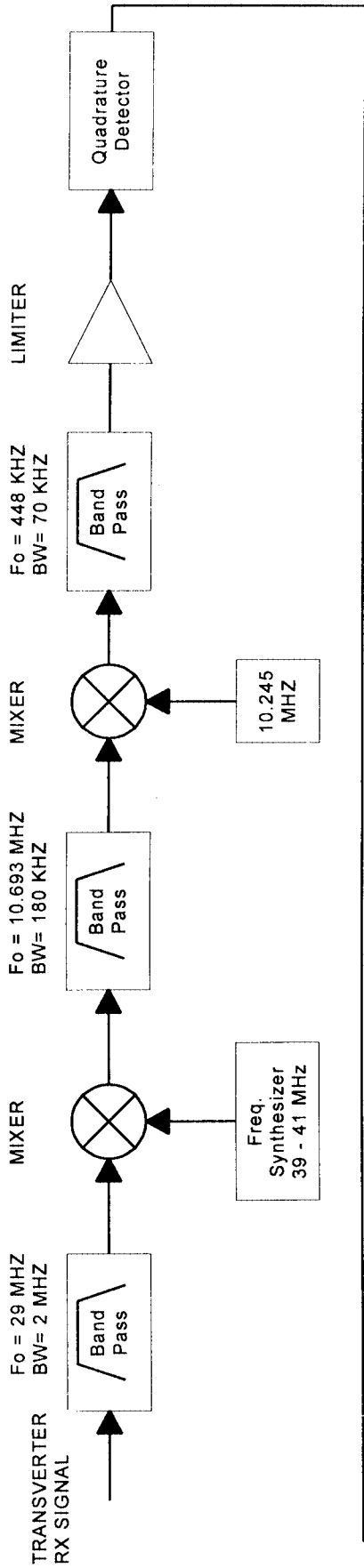
The U.S. now has a 1 MHz wide band (219 to 220 MHz) for "point-to-point fixed digital message forwarding". The band is divided into ten 100 KHz channels. This modem is ideal for that service.

Sales and Marketing

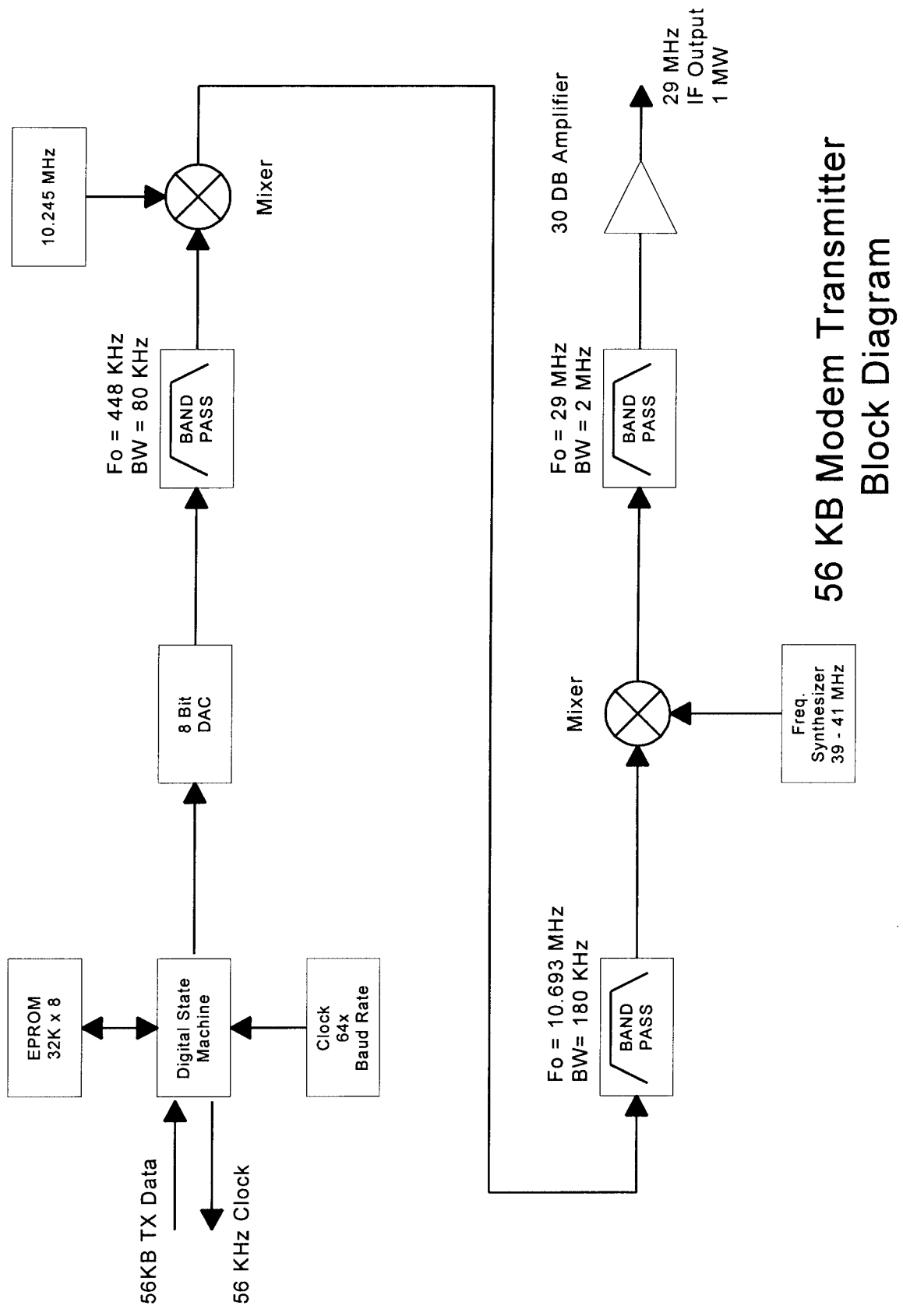
By now you're probably wondering how to get one of these modems. You can't, at least not right now. The modem is still in development. However, I'm negotiating with a well known manufacturer of packet radio equipment to produce and sell this modem. I hope to see them advertised for sale late in 1995 or early 1996. GRAPES will also be involved in modem sales.

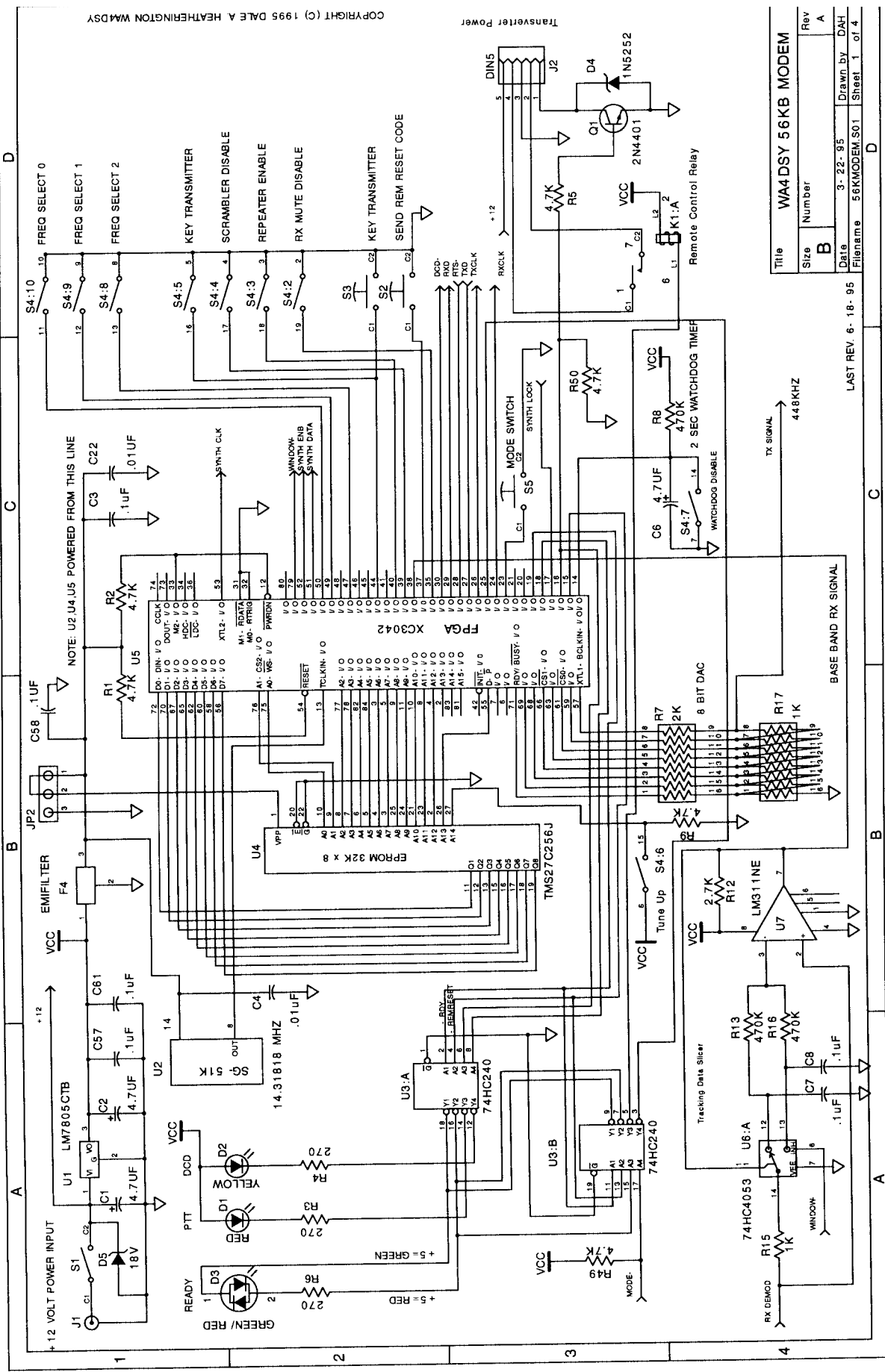


A Prototype Modem



56 KB Modem Receiver Block Diagram

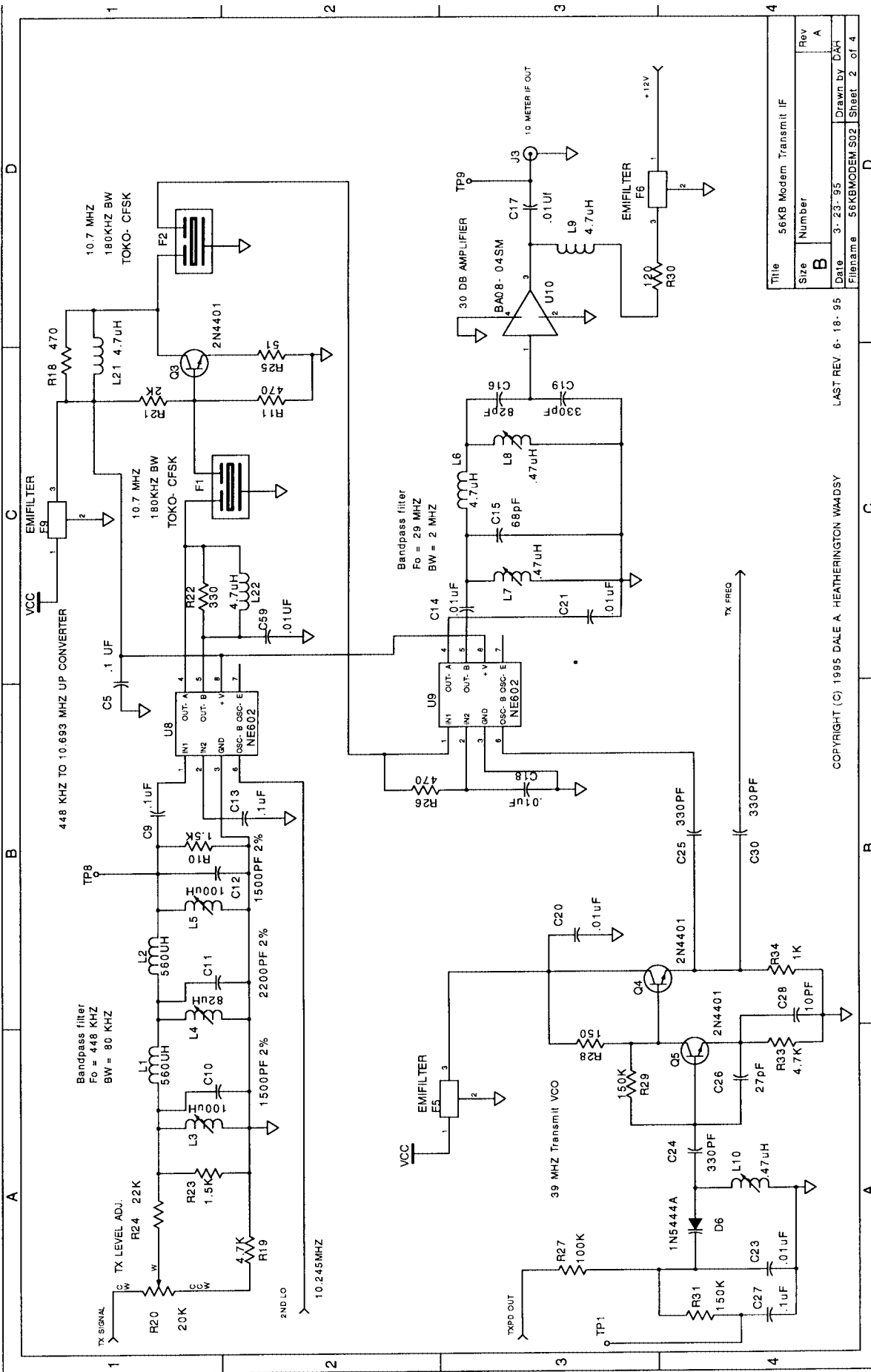




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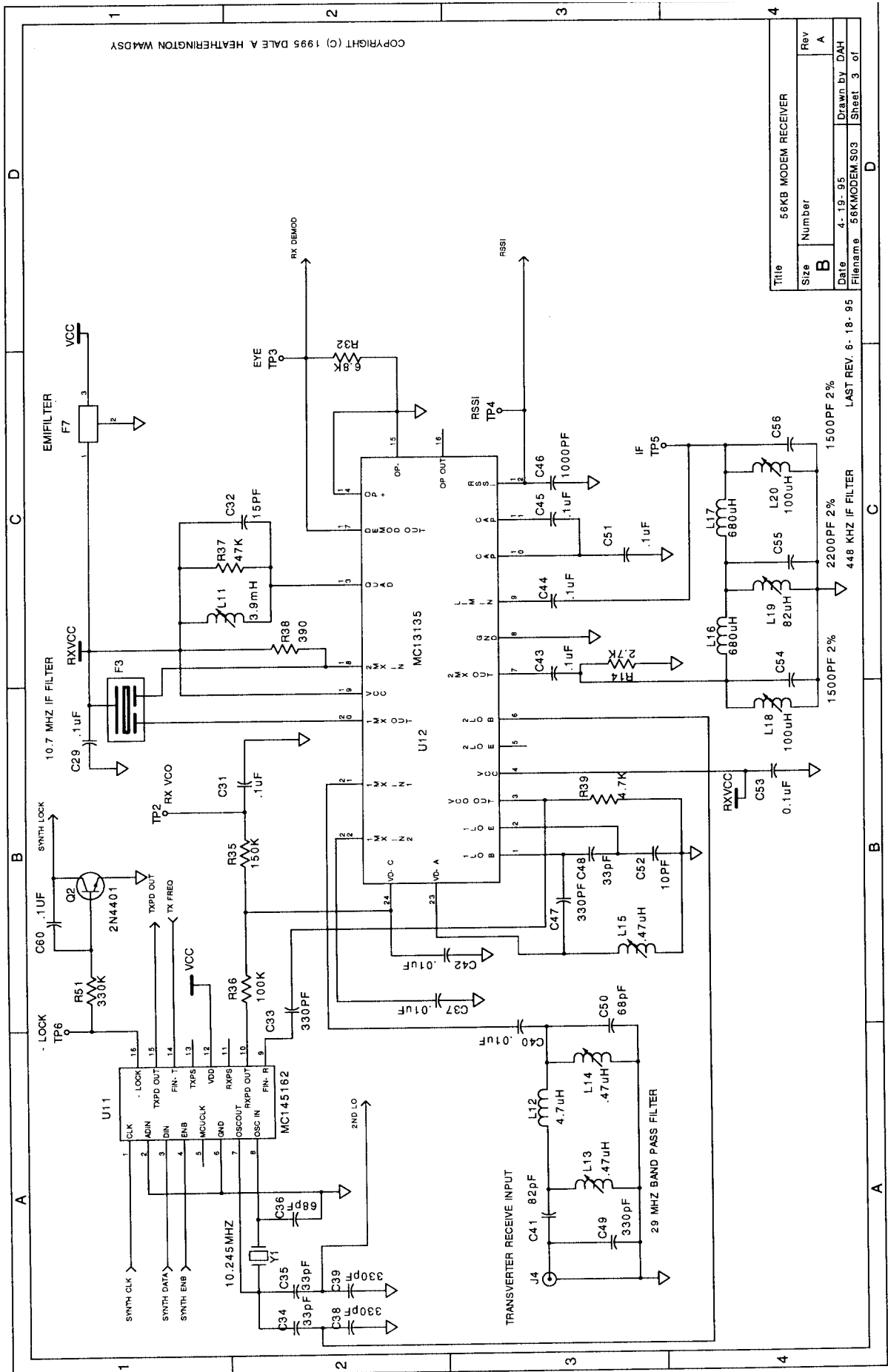
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LAST REV 6-18-95



Title	56KB Modem Transmitter IF
Size	Number
Rev	A
Date	3-23-95
Filename	56KBMODEM.S02
Sheet	2 of 4

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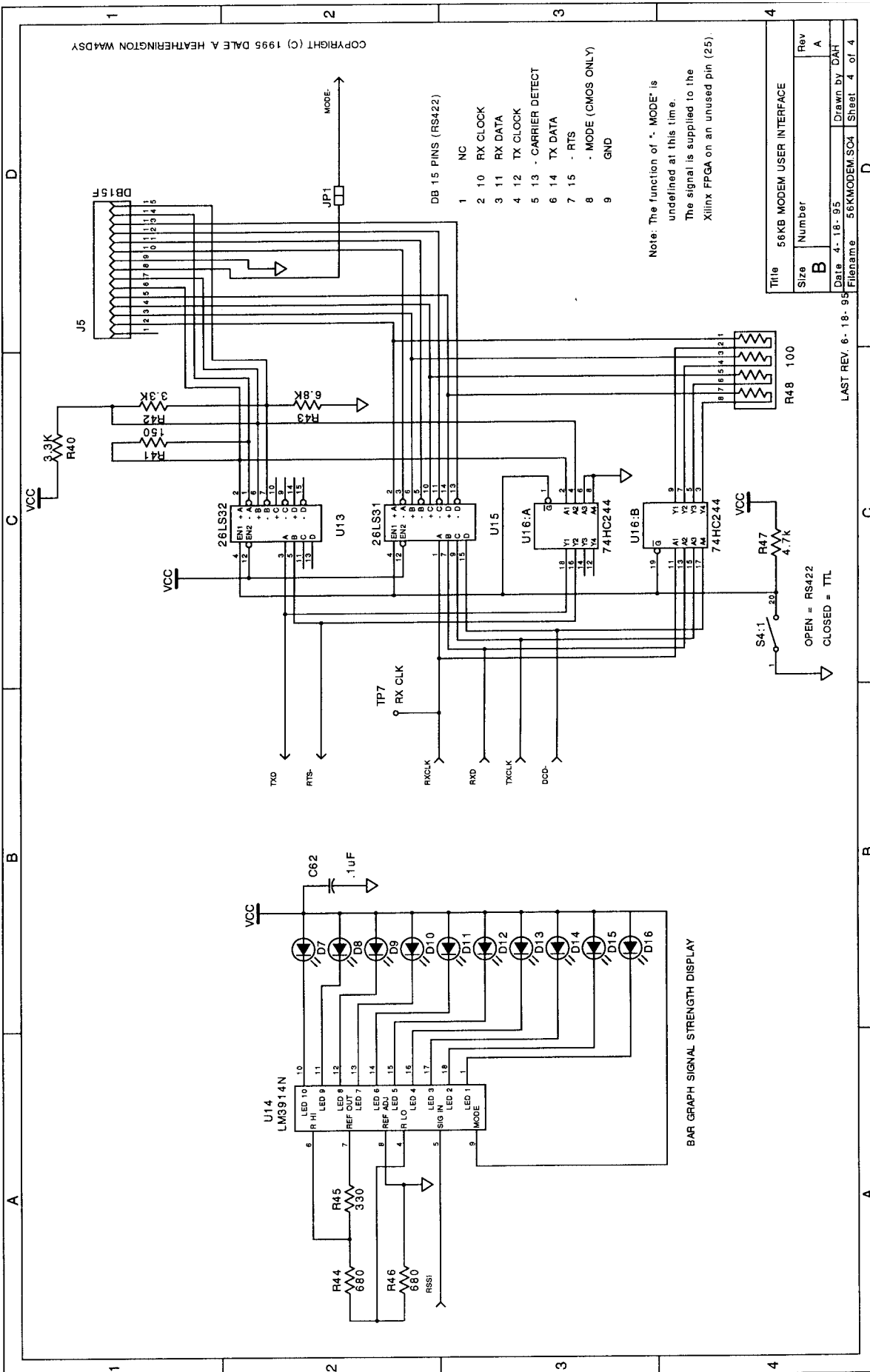


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Size	Number	Rev	A
Date	4-19-95	Drawn by	DAH
Filename	56KMODEM.S03	Sheet	3 of 3

LAST REV. 6-18-95

1500PF 2%
2200PF 2%
448 KHZ IF FILTER



Title 56KB MODEM USER INTERFACE		
Size B	Number	Rev A
Date 4-18-95	Drawn by DAH	
Filename 56KMODEM.S04	Sheet 4 of 4	

LAST REV. 6-18-95

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