Minima -A general coverage transceiver

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The Minima is a simple and easy to operate transceiver for all the HF bands with a crisp receiver, a clean output and component cost of less than $100.

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Two prototypes of the Minima have been built. Both work well, and show that the design is easily replicated.

So, what's this Minima anyway?

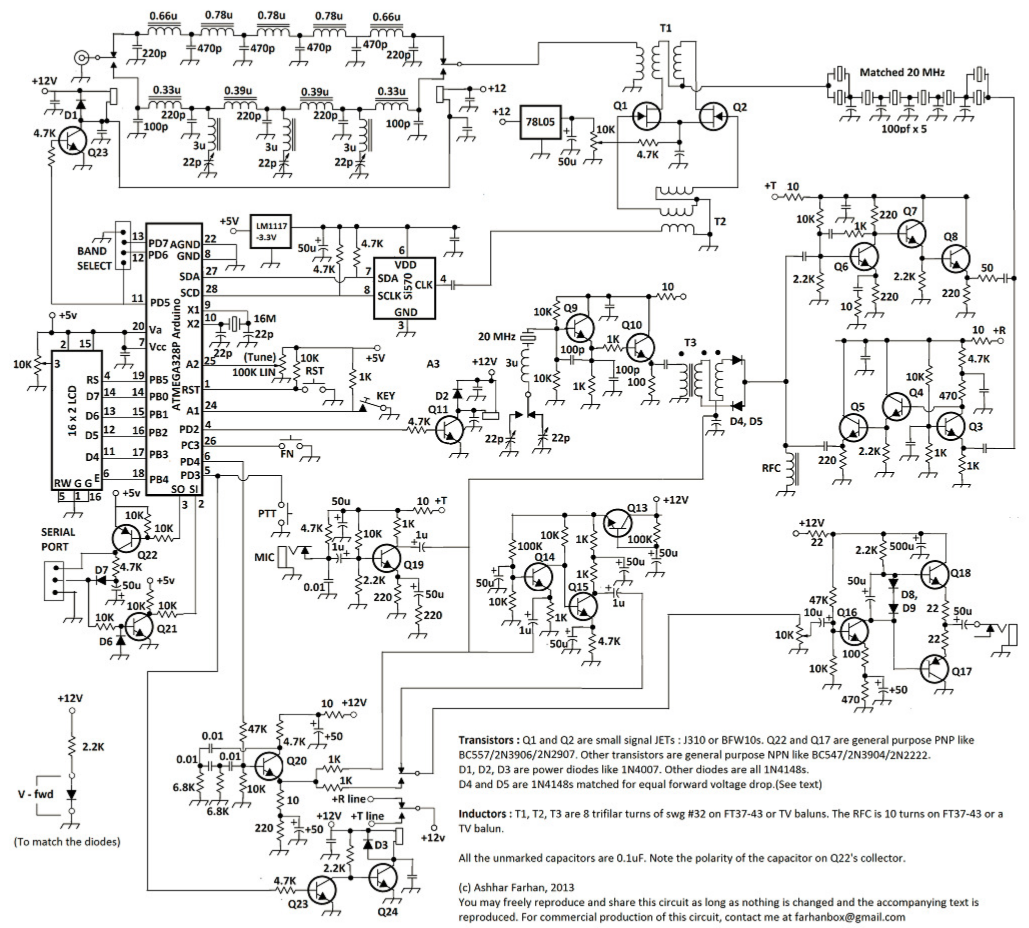
- **Superhet design.** The IF is at 20 MHz.
- **No RF amp before the crystal filter.** As a result, receiver has very low distortion and yet, it's strong enough to deal with the loud signals in today's band conditions.
- **Easy to use.** A single knob tunes the entire HF band. Sideband selection is automatic.
- **One Button.** The single F-button that toggles the RIT and swaps the two VFOs.
- **1 watt output.** Add your own power amplifier to take it to your prefered power level.
- **No tune up.** Just set the BFO frequencies, notch the low pass filters and you're done.
- **Easy to build.** The component count is not much greater than that of the BITX.
- **Arduino based.** The transceiver is controlled with the simple, universally available microcontroller.
- **Hackable.** It is easy to reprogram the Minima, change the circuit and try out new things.

Engineering is all about making choices and deciding what to leave out. So, what's not included in the Minima?

- **No AGC.** A good AGC to match the Minima will add complexity to the transceiver. Preference was given to undistorted audio from an unencumbered signal chain.
- **1 Watt output.** You'll want to add a linear to boost the power level.
- **20 Mhz notch.** The transceiver has a deep notch around 20 Mhz. So, the transceiver works everywhere in the HF bands, except at 20 Mhz.

How the Minima works.

Arduino's code for the Minima is at https://github.com/afarhan/radiono Here's the entire circuit (hi res)



The Minima architecture is slightly different from that of a traditional superhet transceiver.

Choice of 20 MHz Intermediate Frequency

For a general coverage receiver, we'll want to use the highest possible IF so that our image frequency is as away from the receiver passband as is possible. We choose 20 Mhz IF, as it happens to be the highest frequency for which fundamental-mode microprocessor crystals are easily available. The advantage of such a high IF is that the image response of the transceiver is now from 40 to 70 Mhz - safely away from the 0-30 MHz operating range of the Minima.

Front-end filtering

The front-end uses a pair of low pass filters. The first one covers from 0 to 15 MHz and the second covers 15 MHz to 30 MHz. They perform three functions :

1. Operating between 0 and 15 MHz, the local oscillator tunes between 20 and 35 MHz. Though the mixer balance nulls out the local oscillator at the RF port, the first low pass filter with the 15 MHz cut-off is needed for sufficient isolation of the local oscillator from the RF port when operating below 15 MHz.
2. Operating between 15 to 30 MHz, the second low pass filter with 30 MHz cutoff is used. Additionally, the second filter should not allow signals at 20 MHz to pass in either direction. To achieve this, three traps are placed inside the second low pass filter. These are notched to tune out 20 MHz signals.
3. When the transceiver tunes from 0 to 30 Mhz, the the local oscillator tunes from 20 to 50 Mhz, producing the image frequencies from 40 to 70 Mhz. Both the low pass filters suppress these images sufficiently.

The KISS Mixer

The KISS mixer is a little unusual. If you carefully look, the gates of the two JFETs are being driven by the VFO and not the signal! The two transistors Q1 and Q2 are alternatively turned on and off by the VFO signal at their gate. These transistors connect either of T1's primary ends to the ground (Actually to the common bypass capacitor). So, the RF signal appears chopped up at the local oscillator frequency. This is what leads to switching mixer action. Like most switching mixers, the KISS mixerworks in the reverse direction as well.

This is such a simple design that Chris Trask (N7SWY) has called it the "Keep IT Simple, Stupid!' configuration in his paper.

The KISS mixer does two amazing things :

- Unlike a diode mixer, it doesn't behave too badly without a diplexer or a post-mix amp.
- Unlike other passive mixers, the KISS mixers losses are quite low.

These features allow us to directly connect the mixer to the crystal filter. This architecture the reception sparklingly clear and it also eliminates any front-end switching when going from receive to transmit and vice versa!

Oscillator

The Minima uses an Si570 chip from Silicon Labs as the local oscillator. Unlike DDS frequency generators, this chip has remarkably clean phase noise and virtually no spurs. It is an 8 pin package that is easily soldered. The prototypes were built without PCBs over a copper clad board with a regular 25 watts iron using a flat tip.

Crystal Filter

The crystal filter at 20 Mhz is an important part of the Minima. We use slightly larger than normal bandwidth for a much better receiver experience. The filter uses two parallel crystals in the end-points. This helps the filter have very low ripple. The crystal filter is cut for 50 ohms termination.

IF amp

During reception, the signals suffer 10 db of losses in the LPF, the mixer and the crystal filter before entering the RX IF amp. It must, therefore, have a very low noise figure to preserve the receiver sensitivity. A common-base amplifier of Q3 with 0.5mA emitter current has low noise and 50 ohms input impedance.

The Q4 and Q5 transform the 470 ohms collector load into a low impedance drive for the modulator. A requirement for the crystal filter to exhibit low ripple in the passband.

The transmit IF amplifier uses a standard feedback amplifier with higher current as it needs to handle the stronger signals from the modulator side. Both these amplifier are derived from Kopski and Hayward's work on BITX amplifiers.

Crystal oscillator, (de)modulator

The crystal oscillator uses a single crystal in a VXO. An Arduino controlled relay switches either of the two trimmers that pull the carrier frequency for lower or upper side-band.

Diode modulators usually have a carrier null adjustment. This adjustment is often critical and insufficient. The Minima dispenses with the that adjustment by using pre-matched diodes. The diode matching scheme is shown at the left-bottom of the Minima's circuit diagram. Using that circuit, test out a couple of diodes and select a pair with best matched forward voltage drop across them.

The overall carrier suppression can easily exceed -50 dbc with carefully selected diodes, tightly wound T3 and the steep slope of the crystal filter.

Receiver audio chain

Up to the audio chain, the receiver gain has been carefully kept down just enough to preserve sufficient noise figure up to the detector. As a result, almost all of the Minima's gain is at audio frequencies. This makes building Minima non-critical.

The audio amplification chain is entirely built with discrete transistors to provide high fidelity and low distortion in keeping with the rest of the receiver's performance.

Transmission

During voice transmission, the following happens:

- The PTT is pressed. It energizes the T/R relay, powering up the mic amplifier and the TX IF amp while powering down the RX IF amp.
- The Arduino detects the PTT line going down and switches to the TX frequent (if the RIT is on).
- The other pole of the T/R relay mutes the audio by disconnecting the RX audio pre-amp from the audio power amp.

CW is generated by Injecting an audio tone of 700 Hz into the modulator. During the CW transmission the following happens:

- The key press is detected by the Arduino, it pulls the PTT line down and switches the T/R relay on. It also shifts the TX frequency if required (only on RIT)
- The T/R relay powers up the TX IF amp, powers down the RX IF amp and shifts the audio amplifier input from the RX audio pre-amp to the tone generator.
- The tone generator is keyed by the Arduino to modulate the carrier as well as provide the side-tone to on the audio amplifier.
- The Arduino moves back to receive mode after a timeout on the key line.

Power Amplifier

The output RF power has been kept down to 1 watt. This allows it to drive a higher power amplifier of builder's choice. The power chain has extensive feedback in all stages to keep the gain within the range across the HF spectrum. It uses the inexpensive 2N2219s.

Arduino

Arduino is a very popular and easy to use microcontroller system. It is based on a specially programmed ATMEGA328P chip and PC based development environment. The PC based environment allows one to program it in simple C language (instead of assembly language). It is downloaded to the chip through a serial port without requiring programmer.

The Arduino handles a number of functions:

- Controls the Si570's frequency with the I2C interface and Wire library.
- Interfaces to the 16x2 LCD display with a 5 wire interface.
- Tuning with RIT and two VFOs.
- Automatic switching of low-pass filters, sidebands.
- Transmit/Receive switching.
- CW keying.

The Arduino's code are called 'sketches'. The Minima sketch is available for download from https://github.com/afarhan/radiono

Building and Operating the Minima

Now, remember :

- Use the only the CMOS version of Si570.
- I knew you'd forget it, so I am telling you again, only the CMOS version of the Si570 works.
- There is no carrier null control.The modulator diodes are matched for equal forward voltage drop.

Minima is very easy to build. Considerable effort of a few months has gone into refining the Minima to be a very easy to duplicate transceiver. The prototypes have been made on copper sheets and unetched PCBs. One could even make it on a perf board!

- Only three trifilar transformers are used
- No front-end tuning required. The 20 Mhz notch is easily tuned by tuning to 20 Mhz and setting the trimmers to minimum noise.
- Frequency stability is easily achieved with the Si570 and Arduino.
- Apart from the Si570, no special parts are required.

There are many ways to build a transceiver. We recommend building the separate modules of Minima on small copper clad boards and interconnecting them through shielded cables.

We have built two prototypes. Pictures of both are at the end of this article.

The User Interface of the Minima reflects a personal preference for clean, simple controls. It doesn't have 5000 memories, and variable bandwidth settings etc.

- To transmit voice, press the PTT.
- Disconnect the mic and press the key to transmit CW.
- The Minima uses shuttle tuning. Keep the tuning knob at 12 o'clock position at all times. Slight clockwise rotation starts tuning up the band slowly.
- Anti-clockwise starts tuning down the band.
- Rotating the knob to the end position changes the frequency at 100 Khz per step. There is no band switch. Just tune over to any frequency in the 30 Mhz spectrum.
- Tapping the F-button toggles the RIT control.
- Minima has two VFOs. Double tap the F-button to swap the VFOs
- Push and hold the F-button to set both the VFOs to the current frequency.
- While scanning the band (with the knob away from the center position), pressing the F-button stops the knob. Use this to stop at an interesting signal.
- The appropriate sideband is automatically selected.

Conclusion

The Minima is one of the simplest transceivers to make. It can be constructed in almost any way. Nothing is very critical. It also lends itself to variations. One can easily add a linrad backend, provide separate band-pass filters for each of the ham bands under Arduino control, etc. You can hack it in various ways.

The Minima is an immensely enjoyable rig. It has a great tuning system that takes a little getting used to. Over the last few months it has been a travel companion, a bench receiver, and the evening ragchewer. In all these 'modes' it performs very well.

Design Notes for the Minima transceiver

Introduction

These notes are in addition to the main article that describes the Minima transceiver. They are not required for building and operating the Minima - that information is (hopefully) all in the original article. These are for the curious who will want to hack the Minima.

A number of circuit blocks have been borrowed from other works. These are mentioned with the source. You might find it interesting to read them up.

A number of references are made to other projects on this web site. A popular transceiver, the BITX is frequently mentioned as the source for some generic building blocks. The BITX details are available at http://www.phonestack.com/farhan/bitx.html.

History in ten parts

This is a long capture of how the Minima came about. It includes references on the web that might interest those treading a similar path.

Part 1 - Sweeperino Woes

In 2012, I had completed a computer controlled Si570 based digital sweeper called the Sweeperino. You can see the project at http://www.youtube.com/watch?v=qRNOp1F81i8. It allowed me to generate a signal between 0 and 60 Mhz and in the VHF range with a 1 Hz accuracy. This signal would be fed to any circuit like a filter, amplifier, etc. and the output measured with great accuracy and range with an AD8307 based W7ZOI's power meter.

As my video shows, the sweeperino had a challenge : The harmonic content of the signal generator produced ghost responses in filters. To overcome them, I was contemplating replacing the open AD8307 with a superhet receiver front-end that would filter out these harmonic responses. I started looking around for a front-end for the sweeper that would match the 90db logarithmic range of the AD8307.

Part 2 - Mixed thoughts about Mixers

Around that time, Chris Trask N7ZWY performed some experiments on diode mixers and H-mode mixers that promised a very high input intercept. He posted his findings on EMRFD's Yahoo! group in a paper called Mixer Musings. The elegance and the simplicity of was quite enticing and I started digging around for more information on H-mode mixers and other forms of passive FET mixers.

Use of FETs as passive switches in mixers has a long history. A recently uncovered a paper by Rick Campbell on his university website details some of it. Campbell refers to earlier work of Wes Hayward and Steven Mass, unfortunately, the paper's reference section was missing. Gain (I7SWX) sent in his paper in a private email. Gain's Mixer was built, tested and documented by Martein, PA3AKE. Martein's site is an awesome resource for anyone who wants to explore high end receivers.

Part 3 - The Front-end begins

A couple of FSA3157s were ordered online and a mixer made with them. An Si570, under Arduino control was used as local oscillator. With an antenna directly connected to the mixer, and its output was fed to the FT-817, tuning up the bands only got grief. The FT-817 was full of noise. Upon probing around, I discovered substantial local oscillator leak into the the IF and RF ports. The local oscillator was probably desensing the receiver.

It was decided to filter out the local oscillator from the IF port. The QER crystal filter described in teh 2012 ARRL Handbook was quite interesting. A quick calculation in the lab notebook created a filter for 12 MHz SSB bandwidth. With the filter added between the IF port of the KISS mixer and the FT-817 antenna socket, the setup was powered up. The stations were weak but remarkably clear.

A single stage of the hybrid cascode IF amplifier by Kopski and Hayward was added to bring up the gain and the noise figure. This is an excellent IF subsystem. The article is available at Roger Hayward's site. Apart from the nominal front-end filtering provided by the Antenna Tuner, no front-end filtering was used. This was just an experiment to try out the KISS mixer.

A second version of the KISS mixer made with discrete 2N7000s failed to impress. It was quite noisy. Probably due to the reverse protection diodes used between the drain and source of 2N7000.

Part 4 - A simple back-end

here. The BFO design was borrowed from the BITX. A 14 MHz, three section, band pass filter was added in the front-end. The receiver was alive.

After an evening of listening to twenty meters, it was clear that this topology was far better than any other receiver tried out at VU2ESE. The reception had the clarity of a high end, phasing type direct conversion receiver.

Part 5 - 20 MHz IF

While visiting a local components store, by chance, I enquired about higher frequency crystals and carried a pack of 20 MHz microprocessor crystals. The hunch proved right, these were indeed 20 MHz fundamental mode crystals. The 40 Mhz crystals proved to be third overtone and they oscillated at 13.333 Mhz when plugged into an RC coupled crystal oscillator.

These were characterized using the G3UUR method. Then, using the sweeperino, they were measured again for 3 db bandwidth and both the methods agreed with 10%. The lab notes read as follows:

Date : 4/9/2013
Freq Shift ~ 4 Kz @ 20 MHz Fc
Cm = 22p x 2 x 4/20,000 = 0.008pF = 8 fF
LM = 7923 uH = 0.008H

A QER filter was quickly designed with the parameters given by Dr.Gordon in the ARRL Handbook (Sec.11.23, 2011 ed.)

C = (Fo . Cm) / (Bw * K23),
Order = 8, q = 1.2532, K12 = 0.7394, K23 = 0.5346

It recommended a termination impedance of 70 ohms. The crystal filter's sweep brought out a beautiful picture.

Part 6 - Going 'General Coverage'

With a 20 Mhz IF, the image response (at 40 MHz and above) moves away sufficiently for us to strip it out with a 30 MHz low pass filter. An elliptical, four section low pass filter was added. to the front-end.

At times, when some devices or computers were switched in the shack, one could hear strong carrier(s) in the IF pass-band. These would be fixed and untunable. These were clearly coming from 20 MHz oscillators in various equipment.

Recollecting a W7ZOI paper on constructing a deep notch filter to measure an oscillator phase noise, a similar approach was tried by adding crystals in parallel to the capacitors of the low pass filters. Though it created a deep notch, it was not at the crystal filter's pass band. This was then substituted by three traps that you now see in the circuit.

Part 7 - Transmission

The microphone amplifier was borrowed from BITX is to amplify the voice. Bob Kopski and Wes Hayward have produced better feedback amplifiers for BITX a few years ago. This circuit was used as the IF amplifier amplifying the signal towards from the modulator to the crystal filter. It has strong 50 ohms output impedance that drives the crystal filter properly.

Part 8 - Power Amplifier

The JBOT, described at http://www.phonestack.com/farhan/jbot.html is a 5 watt QRP amplifier made by paralleling a number of ordinary, non-RF transistors. The output from the Minima was not enough to drive the JBOT to full power. An additional stage was used to boost the output at the LPF to the 0 dbm (1 mW) needed to drive the JBOT.

Part 9 - CW

Morse Code is the mode of choice for QRP operators. It was important that the Minima should support CW. An easy way to produce CW is by injecting audio sine wave into the SSB transmitter.

The Arduino is capable of producing square wave audio tones. This is a harsh sounding tone. Extensive filtering resulted in a better sounding note. But such a filter was getting more complex than a simple single transistor phase shift oscillator.

A single transistor audio phase shift tone generator was built to produce a 700 Hz tone. The bias was provided by Arduino to key the tone generator on and off. The audio tone is routed through the audio muting relay such that during transmission, the audio power amplifier's input is connected to the tone generator instead of the receiver audio preamplifier.

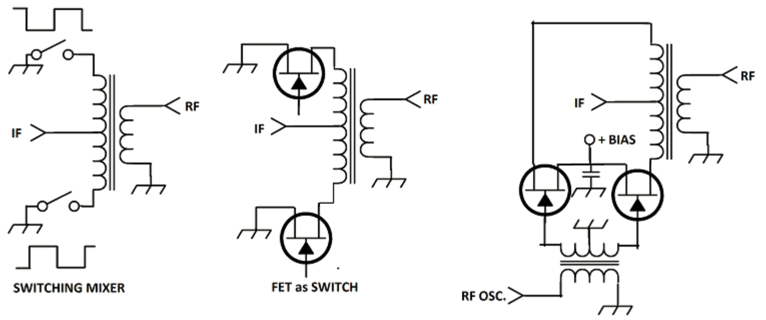
Part 10 - New Audio

Tom Gayle of www.qrp.pops.net fame, said "With so little RF gain in your receiver, it's a shame to see an LM386". After such an affront (*grin*) the LM386 was replaced with a discrete audio amplifier.

What's this KISS mixer anyway?

The mixer used in the Minima has been dubbed the "KISS Mixer" by Chris Trask in his paper. The way it works is very simple.

Consider the transformer in the left diagram of the circuit below. When the lower switch is turned on the lower part of the left side winding of the transformer will become the secondary. The signal at the IF port will follow the RF signal.



However, when the lower switch is turned off and the upper switch is turned on, then the upper part of the left side winding will become the secondary, though in opposite phase. The output at the IF port will now be inverted RF signal.

Why is the KISS mixer better than the diode mixers?

The diode mixers work by using diodes as switches. To turn on a diode, current has to flow through the diode. When a diode is acting as a switch, the signal current as well as the oscillator current are flowing through it simultaneously. For best action, the diodes switches have to be quickly driven to saturation.

A diode mixer works well if all the output at the IF port is absorbed by the next stage's input impedance. For instance a diode mixer works well with a 50 ohms resistor as the IF load. However, when a diode mixer is connected to a crystal filter, only the energy within the crystal's passband is absorbed and the rest is reflected back into the diode mixer. This reflected energy, coming in at a different phase will further mix with the local oscillator, incoming RF signal etc and create more spurious outputs.

As opposed to a diode mixer, the JFET channel does not carry the oscillator currents nor is the channel non-linear like a diode. It is more suitable if we wish to directly drive a crystal filter.

In our mixer, the JFET is out of the signal path as it only shorts the transformer to the ground. This makes the receiver very resilient to loud and out of channel signals.

References

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5. H-Mode mixer Frontend, Bakker Martein, PA3AKE
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7. DC-40 Receiver
8. Controlling the Si570

Some more pictures