Update on the TAPR VNA Project

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The paper reports on the status of the TAPR Vector Network Analyzer project, a 200 KHz to 100 MHz USB-based vector network analyzer. Changes since the project was published in the July/August 2004 issue of QEX magazine[1] include a beta test, lessons learned during the beta test, and suggestions for further improvements.

Kitting and Assembly

TAPR assembled a beta test team of 10 people to build kits and test the VNA as the precursor to a possible kit. The beta project used a revision-2 printed circuit board (implementing the R1.1 schematic) that addressed some of the problems in the R1 unit. The fine-lead-pitch integrated circuit parts were soldered to the 10 boards by Steve Bible, N7HPR before they were mailed to the beta testers. The remainder of the parts (discrete resistors, inductors, capacitors, and connectors) were soldered to the board by each beta test team member. The discrete parts were 0805 sized surface-mount (SMT) parts. By and large even though many of the team had never assembled an SMT project, no one had any particular difficulty with either the discrete parts or the through-hole connectors.

Connectors

The BNC connectors on the original unit were changed to SMA connectors. This is due to two reasons: the BNC connectors had poor RF construction: the connection was via two leads out the rear of the connector bent at a 90-degree angle. These proved to present a measurable impedance bump at 100 MHz. The BNC connectors were meant to be swaged into the circuit board, but this mechanical connection was found to be unreliable. The SMA connectors were right-angle type; they proved to have a good impedance match, and soldering them to the circuit board proved to be much more solid mechanically.

Reworks

The R2 PCB corrected the design errors in the R1 unit. However some new problems cropped up in the R2 board: the buffer amplifier (new to the R2 layout, an add-on to the R1 board) oscillated in the GHz range, and the AD8302 detectors were detecting about -40 dBm signals that could not be observed on the input leads with a 100 MHz oscilloscope. The buffer amplifier problem was traced to excessive emitter inductance. The emitter traces on the circuit board were approximately 0.15 inches long, and this was enough to allow the buffer amplifier to oscillate. It was quickly reworked using copper foil tape to establish an improved emitter ground connection.

The detector problem was far more difficult to find. It had manifested itself on the R1 circuit board, but was assumed due to millivolt-level potential differences along the solid copper ground plane. It was reworked on the R1 board with twisted-pair traces that brought the ground-return signal along with the desired signal to the reference inputs on the AD8302. The

R2 circuit board was laid out with this coupling mechanism in mind. It turned out that this was not the coupling mechanism, and thus the R2 board had the same problem as the R1 board.

The problem instead appears to be coupling form the +3.3 VDC plane to both the (+) and (-) differential inputs of the AD8302. Such coupling should normally be common-mode and thus rejected. However, the AD3802 provides a low-impedance drive to the (-) input to establish the DC-reference level for the cascaded limiting amplifier stages. Thus, the common-mode noise is converted to differential mode noise on the die of the AD8302 itself. The rework applied to the R2 board involved lifting the traces up away from the +3.3V power plane, and instead connecting with a twisted pair from the connector to the AD8302 (on the Rx connector) and from the reflection video amplifier to the AD8302 (on the Tx connector). Although the rework does not alter the schematic, it reduces the coupling from the +3.3V plane to the detector inputs.

Calibration Improvements

With this rework, the S21 dynamic range was improved to about 52 dB best case at 50 MHz on one of the units. This involved some additional +3.3V plane decoupling as well. The S11 range is about 25-35 dB depending on frequency. The AD8302 detectors are capable of about 57-58 dB dynamic range. We have found that the detectors start to saturate near 0 dBm. An additional amplitude calibration step was implemented to measure the detector output for 1 dB input steps near the saturation level.

This was accomplished by adding new code (R1.1) to the target device (USB processor on the VNA) to program the transmit output level with 1 dB resolution. Then the transmit level is stepped down in 1 dB steps while the detector output is measured. This is stored in a table that is saved for that particular VNA unit, and saved independently for the Tx and Rx detectors. These values are also recorded at about 20 frequencies throughout the sweep range. This improved amplitude calibration table is used by a 2-dimensional interpolation routine to improve the accuracy of the amplitude measurements across the sweep range.

Software Interface Enhancements

Improvements in the scale marking were added so that left- and right- scales are displayed and they change with the scale factor and trace offsets. The left scale always displays S21 and S11 magnitude units in dB, compensated for reference level and Tx level changes as well as scale factor. The right scale is selectable for time, SWR, or phase in degrees, and can be user selected. An SWR trace display mode was added that computes and displays SWR based on the magnitude of S11. The original (R1.0 software) had a group delay aperture equal to one sample. The modified software allows selecting the aperture up to 64 samples (which smoothes out the noisiness of group delay measurements).

Markers were added, and they can be dropped and dragged with the mouse. The markers can display parametric values on the left side of the screen, and marker numbers on top of the markers. The marker parameters are color-coded to the traces on the scope display.

A cursor-measurement pop-up was added that allows displaying the coordinates of the cursor in whatever units make sense for the current measurement display. In rectangular mode these are frequency, amplitude, and SWR. In polar mode these are magnitude and phase of the reflection vector, S11, SWR, and the impedance in R+jX format.

A fast measurement mode was added to the R1.1 code. This provides about 2.5 full sweeps per second (S11 plus S21 in the 100 point mode) depending on the speed of the host PC. It is fast enough to permit tuning of filters in real-time (very useful!).

The ability to add or clear a title for the plots (and the printouts) was added to help keep track of a large number of measurements. The print function was tested with a LaserJet2 printer, and the GNU public domain PDFCreator printer driver available from SourceForge[2]. Direct PDF writing has been tested from the application.

Mike Dishop, N8WFF, and John Ackermann, N8UR provided a lot of input for improvements to the PC based user interface.

Further Work

The dynamic range limitation of the S21 measurements is inconvenient. The range is limited in the R2 unit by a transmit level of 0 dBm, and a minimum receive level of -60 dBm. This could be overcome with additional gain on the Rx channel. While the AD8302 has only 60 dB of range, it is possible to boost the weakest signals with an amplifier, but then attenuate the transmit signal level (an ability added to the R1.1 code) by 30 dB. Two sweeps through the S21 passband, one at the high transmit level (0 dBm) for high attenuation and one at a low transmit signal level (-30 dBm) for low attenuation could allow splicing together the two measurements to achieve theoretically ~90 dB of dynamic range. Back-of-the-envelope calculations show that the noise floor of the 100 MHz Rx buffer amplifier would be about:

$$noise\ power = kTB + NF_1 \qquad (1)$$

Where k is Boltzmann's constant, T is the temperature in Kelvins, B is the bandwidth in Hertz, and NF is the noise figure of the amplifier in dB. The selected amplifier has a noise figure of 6 dB and a gain of 16 dB, thus a two stage amplifier will be used. The total noise figure of two amplifiers combined is about 6.5 dB, and the gain about 32 dB., resulting in a thermal noise power of -87.5 dBm, and thus an equivalent dynamic range. Experiments are currently being conducted on this circuitry, and it will be included in the R3 artwork if successful.

Software

The updated software (version R1.1) source and target code and the R1.1 (board version R2) schematic is available on the ARRL QEX download site[3]. More recent software updates beyond R1.1, including a Windows binary executable setup file is available from the TAPR ftp site[4].

The setup was migrated over to the Microsoft setup utility provided with the .NET compiler package. This allows automatic dependency testing of the target PC platform to make sure it has the required installer and the required .NET 1.1 framework. The installer automatically launches Internet Explorer to the proper web page to download the .NET framework if it is not present. However the option to download and install the framework requires affirmative selection by the user.

The beta test team verified the proper operation of the USB interface and .NET software on Windows 98 through Windows XP. No particular problems were encountered.

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[1] "Low-cost 100 MHz Vector Network Analyzer with USB Interface", Tom McDermott, N5EG, and Karl Ireland, July/August 2004 QEX, pp 3-14.

[2] The SourceForge GNU GPL PDFCreator driver is available for download from: http://sector7g.wurzel6.de/pdfcreator/index_en.htm

[3] http://www.arrl.org/qex/files Listed as VNA.zip

[4] ftp://ftp.tapr.org/pub/n5eg Numerous files.