Verifying the Performance of a Correlation-Based Channel Sounder in the 3.5 GHz Band with a Calibrated Vector Network Analyzer

Jeffrey A. Jargon, Jeanne T. Quimby, Kate A. Remley, Amanda A. Koepke, and Dylan F. Williams
National Institute of Standards and Technology
Boulder, CO 80305 USA
Email: jeffrey.jargon@nist.gov

***Abstract* — We verified the performance of a correlation-based channel sounder in the 3550 MHz to 3650 MHz band with a calibrated vector network analyzer (VNA) by comparing measurements in a stable, coaxial environment at the same reference planes. The purpose of this experiment was to focus on the performance of the channel sounder's hardware, as opposed to antenna effects or channel variations. Two conducted propagation channels were utilized – one consisting of a length of cable and an attenuator to simulate a line-of-sight channel, and another with a pair of splitters joined by cables of different lengths to simulate a multipath environment. Performing repeated measurements and estimating the components of uncertainty due to random effects, we found that the channel sounder and VNA measurements agreed to within 0.25 dB for values of path gain, and the peaks in the power delay profile agreed to within 2 dB.**

***Keywords* — comparison, conducted channel, correlation-based channel sounder, measurement, path gain, power delay profile, vector network analyzer, wireless systems.**

I. Introduction

Channel sounding is a method for evaluating the electromagnetic environment for wireless communications. Radio signals propagate between a transmitter and receiver over multiple paths due to natural terrain, manmade obstacles, and environmental conditions [1]. Channel sounders measure characteristics of a radio propagation channel including path gain, decay time, and angular dispersion. Models developed from these measurements are typically the first step in standardizing new wireless technologies. While many models currently exist, applications are constantly under development that necessitate new and improved channel models. For example, in the 3550 MHz to 3650 MHz ("3.5 GHz") band, rules for spectrum-sharing systems are being developed based on specific channel models [2]. Success of the spectrum-sharing systems will, in part, depend on the accuracy of these models.

Recently, researchers at the U.S. National Institute of Standards and Technology (NIST) and the Institute for Telecommunication Sciences (ITS) collaborated to conduct a series of channel-sounder verifications to identify sources of uncertainty due to systematic and random effects in channel-sounder hardware. Three separate channel sounders operating in the 3.5 GHz frequency band, each having significantly different architectures, were studied [3]. Uncertainties in the channel sounders were studied by comparing coaxial measurements made by these systems to measurements performed on a VNA, which included reference-plane translations for direct comparison and a thorough uncertainty analysis.

Conducted-channel measurements were performed to focus on the performance of the channel sounders' hardware, as opposed to antenna effects or channel variations. Two propagation channels were studied – one consisting of a length of coaxial cable and an attenuator to simulate a line-of-sight channel, and another with a pair of splitters joined by coaxial cables of different lengths to simulate a multipath environment.

Here, we focus on the comparison between the VNA and the NIST correlation-based channel sounder using path gain and power delay profile (PDP) as the metrics. Path gain is a measure of attenuation an electromagnetic field experiences as it propagates through space. We have slightly modified this definition to include propagation through a conducted channel. PDP gives the intensity of a signal received through a multipath channel as a function of time delay, which is the difference in travel time between multipath arrivals [4].

Propagation of the VNA's uncertainties to the metrics of interest (path gain and PDP) were performed using NIST's Microwave Uncertainty Framework software [5]. Furthermore, we shifted the VNA reference planes to align directly with the channel sounder's reference planes using characterized switches that connected both systems to the conducted channels. This scheme, illustrated in Figure 1, enabled direct comparisons. We also studied the variability in measurements with respect to various timescales of relevance to channel measurements, including repeated measurements conducted in rapid succession, measurements made on an hour-scale timeframe, and measurements reproduced over several days.

Below, we describe the correlation-based channel sounder, explain how we derived path gain and PDP from VNA measurements, and provide results of our comparison.

II. Correlation-Based Channel Sounder

The channel sounder is a Pseudo-Noise (PN)-sequence correlation-based system [6]. It consists of a transmitter and receiver synchronized with two rubidium clocks. The synchronized clocks ensure that drift between samples is small enough for accurate resolution of the delay spread and allows for measuring the absolute timing between transmitter and receiver.

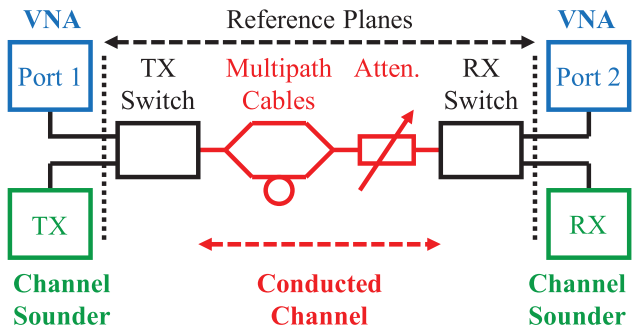

Fig. 1. Measurement setup.

The channel sounder's transmitter contains a vector signal generator that generates a PN code sequence and modulates a binary-phase-shift-keying (BPSK) signal since this type of modulation is robust and widely used in long-distance communications [7]. The transmitter then upconverts the BPSK signal to the 3.5 GHz RF carrier frequency. The bandwidth of the channel sounder corresponds to the bandwidth of the BPSK symbols modulated by the PN sequence. The vector signal generator we used is specified to have a maximum output power of +10 dBm with a -161 dBm/Hz noise floor. The waveform corresponding to each PN sequence is oversampled by four times, providing 8188 samples with a 5 nanosecond/symbol sampling rate. Therefore, a single record of 400 PN sequences (or "code words") has a duration of 16.37 milliseconds.

The channel sounder's transmitter repetitively transmits a PN sequence of digital symbols with a maximum sequence length of 2047 (order of 11). The average power transmitted is maintained through the continuous transmission of the signal. The modulated signal is amplified and filtered to reduce harmonics. The signal is transmitted either through an attenuator for a back-to-back measurement or through the pair of splitters joined by coaxial cables of different lengths.

The channel sounder measures a set of raw complex data, which are corrected with a back-to-back measurement to remove hardware effects. The corrected data are then used to estimate path gain and PDP of the measured channel. Further details of this system can be found in Reference [6].

III. Vector Network Analyzer

Channel sounding can be performed in the frequency domain with a VNA, however, this approach is typically too slow in dynamic environments to capture the time-varying nature of a wireless channel across a wide bandwidth. Furthermore, VNAs are problematic for channels where the transmitter and receiver need to be spaced far apart since the VNA requires that the transmit and receive sides must be tethered together for timing synchronization. Other systems, such as the NIST correlation-based channel sounder, are usually preferred since they can make measurements quickly and are equipped with rubidium clocks to provide untethered synchronization.

In the case of stable conducted channels, VNAs are ideal for verification purposes since they have a high dynamic range, can make extremely wideband channel measurements (dependent on the bandwidth of the VNA), and are capable of traceable uncertainties, as explained below.

In this experiment, we made use of a short-open-load-thru (SOLT) calibration kit with Type-N coaxial connectors. Physical models of the calibration standards were developed and validated using a TRL calibration within the NIST Microwave Uncertainty Framework [8]. This software tool utilizes parallel sensitivity and Monte-Carlo analyses, and enables us to capture and propagate the *S*-parameter measurement uncertainties and statistical correlations between them. By identifying and modeling the physical error mechanisms in the calibration standards, we can determine the statistical correlations among the *S*-parameters. These uncertainties, due to systematic effects, can then be propagated to measurements of devices under test. The uncertainties are propagated to the calculated metrics of interest (path gain and PDP) while maintaining correlated uncertainty mechanisms throughout the process.

PDP and path gain may be calculated from *S*-parameter measurements. Prior to computing these metrics, the VNA hardware settings were chosen in consideration of the channel and channel sounder. The IF bandwidth of the VNA was set to 20 Hz to ensure adequate dynamic range (greater than 110 dB). The VNA frequency range was set to 3.3–3.7 GHz, which was the range used by the correlation-based channel sounder. A dwell time of 1 ms was applied to the VNA measurements to ensure proper settling while taking measurements. The number of frequency points, N_{VNA}, taken by the VNA was computed from the spatial resolution of the channel sounder.

We compute the bandwidth-limited, measured impulse response, $\mathrm{h}_{\mathrm{VNA}}(t)$, and power delay profile, $\mathrm{PDP}_{\mathrm{VNA}}(t)$, of the channel by taking an average of the calibrated transmission parameters, S_{12} and S_{21}, assuming the channel is reciprocal:

$$\mathrm{h}_{\mathrm{VNA}}(t) = IFFT\left(\frac{\mathrm{S}_{12}(f)+\mathrm{S}_{21}(f)}{2}\right). \tag{1}$$

$$\mathrm{PDP}_{\mathrm{VNA}}(t) = |\mathrm{h}_{\mathrm{VNA}}(t)|^2. \tag{2}$$

The VNA path gain, G_{VNA}, can be computed by averaging over the frequency-domain data. Note that the path gain in this work does not include antenna gains since the channel included only coaxial cables and attenuators. For a VNA measurement, the path gain may be computed from the calibrated frequency-domain *S*-parameters as:

$$G_{\mathrm{VNA}} = \left(\frac{1}{\mathrm{N}_{\mathrm{VNA}}}\sum_{n=1}^{\mathrm{N}_{\mathrm{VNA}}}\left|\frac{\mathrm{S}_{12}(f)+\mathrm{S}_{21}(f)}{2}\right|^2\right)^{1/2}. \tag{3}$$

IV. MEASUREMENT COMPARISON

Despite the VNA and the correlation-based channel sounder sharing the same conducted channel, imperfections in the switches and differences in cable lengths used by the VNA and channel sounder meant that the two instruments were connected to slightly different channels. To overcome this, the reference planes of the VNA measurement were shifted to those of the channel sounder in post-processing. Having characterized the *S*-parameters of the switches, de-embedding and embedding procedures were used to shift the reference planes of the VNA to the channel sounder's reference planes, thus enabling a direct comparison of the two instruments [9].

Table 1 lists the correlation-based channel sounder and the VNA path gains for both the direct and multipath channels. A variable attenuator was switched among three values (approximately 18 dB, 28 dB, and 38 dB) for each channel. The standard uncertainties accompanying the VNA measurements include components due to both systematic and random effects, while the standard uncertainties for the correlation-based channel sounder only include components due to random effects. The nominal values and standard uncertainties were calculated from five repeated sets of five measurements taken in rapid succession each day for a duration of five days. For comparison purposes, the differences are also tabulated in column 3, as are the root-sum-of-squares (RSS) of the uncertainties. The data show the differences are within 0.25 dB for all cases, and the path gains measured by the VNA are always slightly lower. The uncertainties for the differences are always less than or equal to the actual differences, which is likely because the standard uncertainties for the correlation-based channel sounder do not include components due to systematic effects, such as impedance mismatches between components, and frequency-dependent distortions in the transmitter and receiver.

Figure 2 illustrates the PDPs of the correlation-based channel sounder and VNA for multipath channel 1. The peaks at 49 ns and 104 ns are aligned to within 2 dB. Additionally, the noise floor of the channel sounder is considerably higher than that of the VNA.

V. CONCLUSIONS

We verified the performance of a correlation-based channel sounder in the 3.5 GHz band with a calibrated vector network analyzer by comparing measurements in two conducted propagation channels at the same reference planes. We estimated the components of uncertainty due to systematic effects of the VNA and random effects of both systems and found that the channel sounder and VNA measurements agreed to within 0.25 dB for values of path gain, and the peaks were aligned to within 2 dB for values of PDP.

Table 1. Comparisons of path gain between the correlation-based channel sounder and the VNA.

Direct Channel		Path Gain ± Std. Unc. (dB)	Difference ± Unc. (dB)
1	VNA	-53.52 ± 0.13	0.14 ± 0.14
	Channel Sounder	-53.38 ± 0.05	
2	VNA	-63.38 ± 0.03	0.25 ± 0.08
	Channel Sounder	-63.13 ± 0.07	
3	VNA	-73.43 ± 0.09	0.16 ± 0.10
	Channel Sounder	-73.27 ± 0.05	
Multipath Channel		**Path Gain ± Std. Unc. (dB)**	**Difference ± Unc. (dB)**
1	VNA	-60.63 ± 0.12	0.24 ± 0.14
	Channel Sounder	-60.39 ± 0.07	
2	VNA	-70.56 ± 0.07	0.14 ± 0.11
	Channel Sounder	-70.42 ± 0.09	
3	VNA	-80.58 ± 0.11	0.25 ± 0.15
	Channel Sounder	-80.33 ± 0.10	

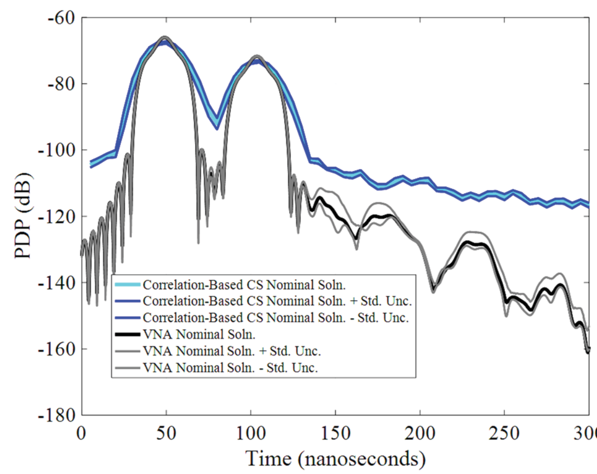

Fig. 2. Comparison of power delay profiles of the correlation-based channel sounder and VNA for multipath channel 1.

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