Interlaboratory Millimeter-Wave Channel Sounder Verification

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***Abstract*—The channel sounder verification program within the National Institute of Standards and Technology-coordinated 5G mmWave Channel Model Alliance aims to place channel sounders on a sound metrological foundation by using well-established laboratory verification methods coupled with modern waveform metrology tools. To provide comparison-to-reference verification of channel sounder hardware measurements, we begin by measuring deterministic conducted channels, established using a channel sounder verification artifact and temperature control unit. This artifact produces multiple stable and repeatable environments to compare the channel sounders' hardware performance to a reference measurement provided by a vector network analyzer. The reference vector network analyzer measurements have an uncertainty analysis including systematic and random components to verify the channel sounder performance. Due to its portable nature, this artifact has potential use in a robin-robin testing between laboratories. General insights and common problems are provided using measurements of the verification box from a one channel sounder in the Alliance.**

***Index Terms*—5G technology, channel sounder, conducted measurements, measurement verification, millimeter-wave wireless communications, propagation channel, wireless system.**

I. Introduction

The quest for increased capacity and throughput by the wireless communications industry has pushed spectrum usage into millimeter-wave (mmWave) frequencies. In-depth understanding of mmWave channel characteristics is imperative for the design and standardization of mmWave communication systems. MmWave applications such as Internet of Things (IoT) in manufacturing and cellular [1-3] facilities can generate numerous communication channels with scattering and multipath components (MPCs). Designing communications systems to handle potential distortion may involve techniques such as error correction, equalization, and/or new modulation [4] schemes. Understanding the characteristics of mmWave channel is often provided through measurements via a channel sounder.

Successful characterization of a channel depends upon the trustworthiness of the channel sounder's measurements. Obtaining trustworthy measurements requires verification of the channel sounder's hardware and data post-processing performance, combined with accurate measurement best-practices. At mmWave frequencies, verification is vitally important because channel sounder hardware becomes less ideal and non-linear, so calibration and quantification of the hardware-measurement-induced error often becomes critical. As an example, sampling circuits in a channel sounder may introduce distortion when operating at the state-of-the-art sampling speeds. Signal distortion in the measurement may come from every step from signal generation and transmission to signal reception and demodulation. Verification of the channel sounder's hardware and post-processing requires separating measurement errors from the channel variations. Quantification of the signal distortion may be determined using a comparison-to-reference channel sounder verification methodology [5].

The participants of the 5G mmWave Channel Model Alliance [6], formed in July 2015, have different channel sounder architectures, each with unique hardware and data post-processing. While there are multiple verification approaches to determine the performance of the hardware, they provide different levels of channel sounder verification, based upon the needs of the researchers [6].

One straight-forward type of channel sounder verification is known as "in-situ" verification. It leverages propagation environments with "known" or predictable propagation conditions during measurement campaigns [7,8] for easy comparison to simulated models such as a two-ray bounce or free-space propagation. Another type of channel sounder verification uses controlled environments such as anechoic chambers, reverberation chambers, or conducted measurements [9] with comparison to simulated models. The comparison-to-reference method presented here does not rely on a simulation of the RF environment. Rather, it extends the controlled measurement approach by using a temperature-controlled channel sounder verification box [10] (as seen in Fig. 1) with known propagation channel characteristics measured by a reference measurement system.

The value of this approach lies in a direct measurement-to-measurement comparison of a stable and controlled channel. There are no assumptions required about the environment modeling ambiguities such as erroneous dielectric descriptions, misalignment of the antenna position and rotation, and/or improper handling of the boundary conditions in a full-wave simulation. However, this approach does require a channel sounder with a removable antenna to connect to the channel sounder verification box.

The NIST verification box provides multiple repeatable and stable conducted channels with known time delays and

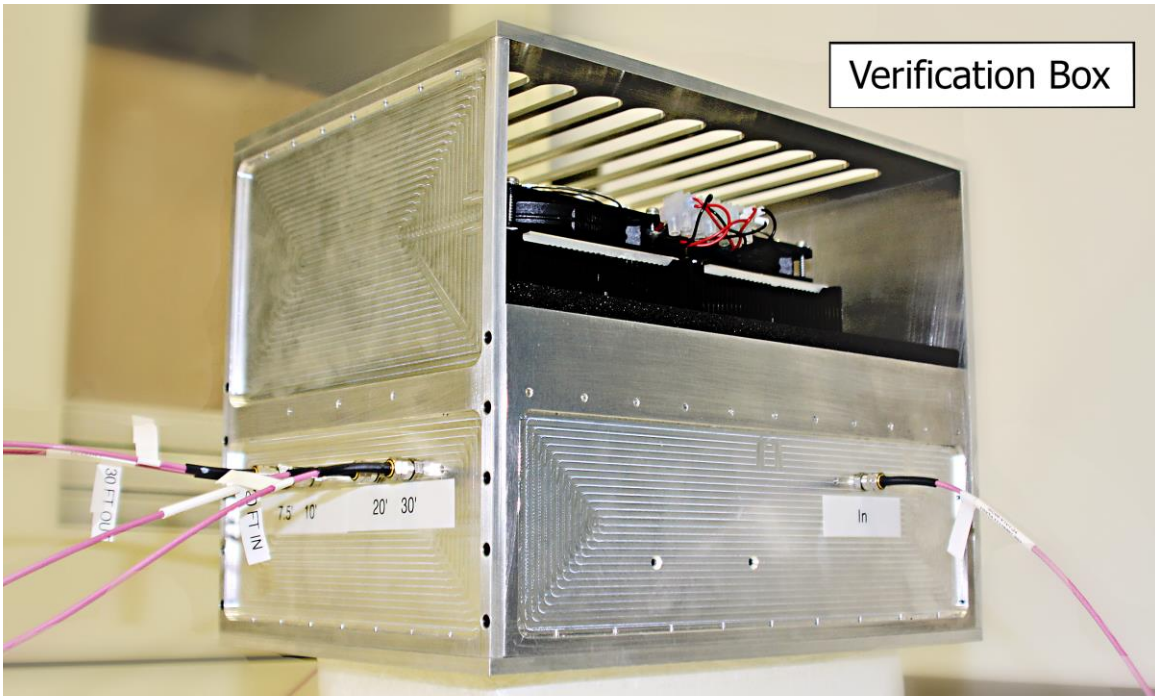

Fig. 1: The temperature-controlled NIST channel sounder verification box. The box dimensions are approximately 210 x 240 x 300 cm^3.

MPC magnitudes with a frequency range from 10 GHz to 62.5 GHz. Using these conducted channels, we can construct Power Delay Profiles (PDPs) of different channel configurations. The PDP is the magnitude squared of the complex impulse response. The verification box is capable of multiple channel configurations including a direct path with a single pulse, single multipath, and double multipath (DM) configurations. Examples of the direct path and double multipath configurations are shown in Fig. 2. The verification box serves as a portable system for round-robin testing across laboratories.

II. Comparison-To-Reference Channel Sounder Verification Methodology

The approach starts with the characterization of the box's channels by a vector network analyzer (VNA) [11, 12]. A requirement for the VNA is a comprehensive error analysis such as the NIST Microwave Uncertainty Framework [13]. During the comparison, if the channel sounder does not have an error analysis associated with its measurements, the comparison provides some confidence toward the trustworthiness of the channel sounder's measurements. If the channel sounder does have an error analysis, overlapping errors bars in the PDPs would indicate agreement between the systems. The channel sounders in this paper demonstrate the adaptability of the verification box to verify hardware and post-processing performance.

Key to enabling the comparison, the channel sounder and NIST reference VNA measurement parameters such as frequency range and frequency spacing are set to identical values. Connector type and use of adapters is particularly important. This is because the VNA is calibrated at the reference plane seen in Fig. 3 (see the green and yellow boxes) to ensure that systematic and random errors such as VNA system drift are captured during the calibration. This allows errors in measurements of the verification box to be

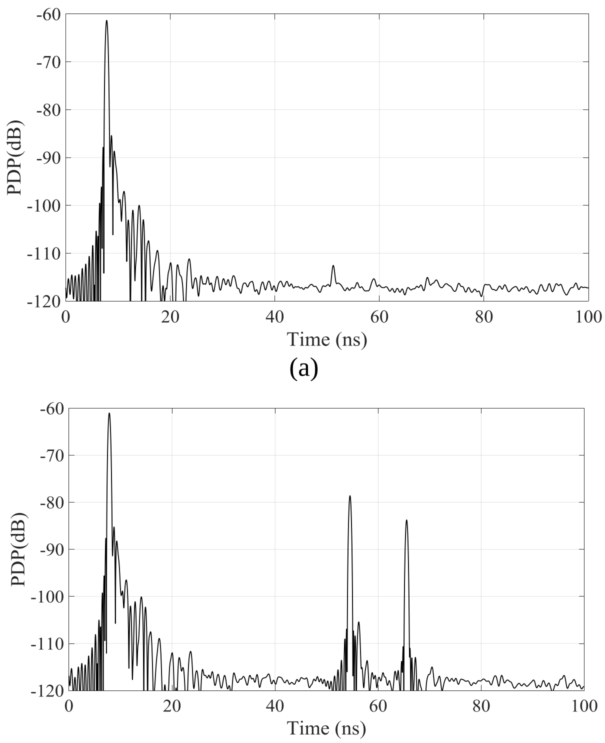

Fig. 2: (a) Power delay profile measured by a vector network analyzer of a direct path configuration. (b) Power delay profile measured by a vector network analyzer of a double multipath configuration of the channel sounder verification box.

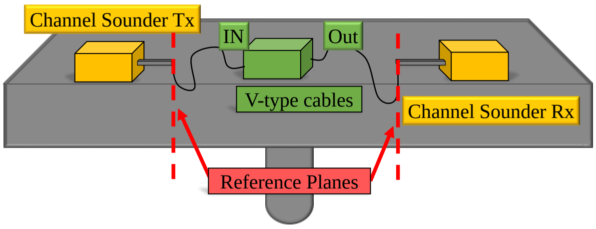

Fig. 3: Channel sounder verification box reference planes.

propagated into the channel metrics during the VNA post-processing.

Prior to use, the box is warmed up for approximately 1 hour prior to connecting to the channel sounder. The channel sounder measures the verification box at the same reference plane as the VNA. A channel sounder from the Alliance and a NIST reference VNA comparison of the PDP, delay window and RMS delay spread [14] are shown later in a Table III.

A. *Reference Vector Network Analzyer Description*

The reference VNA is vital for the comparison-to-reference channel sounder verification. The VNA measures the complex scattering-parameter (S-parameter) response of the artifact. The VNA S-parameter measurements are post-processed using the same parameters as the channel sounder to emulate the system response of the artifact including filter type, center frequency, bandwidth, slope and phase dispersion. During the post-processing of the VNA data, we propagate random and systematic uncertainties to channel metrics of interest. The VNA's parameters are provided in Table I for channel sounder verification shown here.

Table I: Reference vector network analyzer measurement parameters.

Vector Network Analyzer Settings for comparison with the Communications Research Centre Canada channel sounder		
Center Frequency (GHz)	26	38
Bandwidth (MHz)	1250	1000
IF Bandwidth (Hz)	10	10
Number of points	1601	1601
Output power (dBm)	-5	-5

B. *VNA-Based Channel Sounder*

As an example of the comparison-to-reference technique, we used a VNA-based channel sounder as shown in Fig. 4. This channel sounder records complex scattering parameters such as S21 data across seven frequency bands. The VNA is connected to custom-developed TX and RX units via coaxial cables for a maximum link distance of 50 m. To prevent excessive signal attenuation over the long cables, frequency up- and down-converters are used for the higher bands (26, 38 and 61 GHz). A common 10-MHz reference signal generated at the VNA is distributed to the TX and RX units via separate coaxial cables. This serves to phase-lock the frequency converters. In order to suppress out-of-band interference, separate bandpass filters (BPFs) and low-noise amplifiers (LNAs) are used.

The measured transmission gains are compensated for the complex frequency response of the measurement system


Fig. 4: VNA-based multiband channel sounder.

itself, determined from back-to-back measurements [15] that bypass the antennas with a precisely characterized cable. This provides the complex channel transfer functions (including antenna gains, estimated separately) for each band. The system can be configured with different transmit power levels and IF bandwidths, and to perform coherent averaging over multiple channel transfer functions, for example, when measuring at locations with very high propagation loss. The block diagram of the channel sounding system is shown in Fig. 5.

Dual-polarized horn antennas, mounted on top of tripods and mechanically steered by pan-tilt units (PTUs), shown in Fig. 5 are controlled by software run on the host computer. These provide directional fully customized scanning capabilities to the system in terms of angle, frequency and polarization, and displays the corresponding channel estimates in the frequency and time domains. Table II shows the frequency bands available to this channel sounder. It also provides the gains, half power beam widths (HPBWs) and cross-polarization discriminations (XPDs) of the horn antennas as they were measured in the configuration shown in the photograph. The XPDs listed are the minimum off-axis values determined over the 6-dB beam widths and averaged over both ports.

III. RESULTS

Comparison of the channel sounder's measurements of the verification box against the NIST reference VNA has led to insightful information about the channel sounder. The

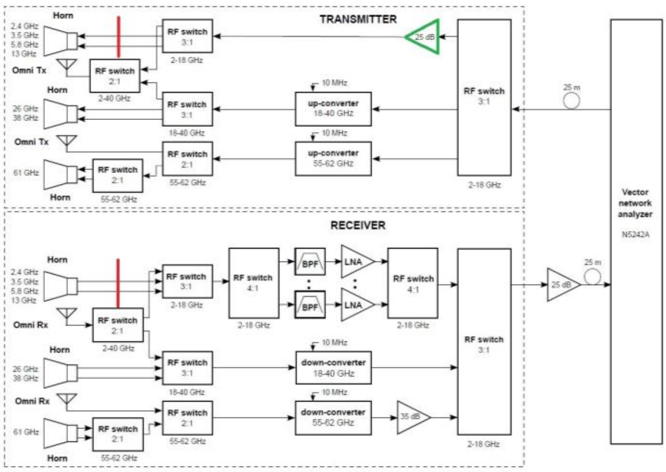

Fig. 5: Block diagram of the VNA-based channel sounder. Red lines indicate channel sounder reference planes. Green triangle indicates power amplifier.

Table II: Properties of the channel sounder.

Parameter	Value							
Center frequency (GHz)	Band	2.4	3.5	5.8	13	26	38	61
	Start	2.4	3.4	5.725	12.75	25.25	37.50	61
	End	2.5	3.475	5.875	13.25	26.50	38.50	61.5
Bandwidth (MHz)		100	75	150	500	1250	1000	500
Gain (dBi)	Horn	8.7	10.6	12.8	18.4	16.7	18.8	19.4
	Omni Tx	3.6	3.9	0.7	4.8	5.6	4.5	6.6
	Omni Rx	4.0	4.0	1.6	4.0	5.8	5.6	3.5
HPBW (degrees)	E-Plane	58	38	36	17	22	17	20
	H-plane	68	53	33	15	20	14	20

representative results provided here relate to common problems encountered across many channel sounder architectures, post-processing techniques, and measurement set-up parameters. During the post-processing of the data, a Blackman filter and maximum scaling was applied to the NIST data.

A. Power Amplifier Input Setting

A power amplifier is commonly used in a channel sounder to increase the transmitted power and extend the physical range between transmitter and receiver. Determining the appropriate input power setting without affecting the channel measurement is a challenge facing many researchers. For example, if the power setting is too high, the power amplifier may create a false artifact. As an example of this is shown by the arrow in the PDP in Fig. 6(a). When the channel sounder input power was set to a high-power setting, the false artifact power was -86 dB near 11 ns but at a low-power setting, the false artifact power was -92 dB. This is a 6 dB difference in the power while the channel sounder was operating at a center frequency of 38 GHz. Next, the channel sounder center frequency was changed from 38 GHz to 26 GHz. Near 11 ns in Fig. 6(b), the artifact shown by the arrow is independent of the input power into the power amplifier. This difference in behavior is due to the channel sounder frequency of operation. It is important to note that the power amplifier was operated within its operational specifications.

B. Channel Sounder Dynamic Range

The verification box direct path configuration compares the power level of the NIST reference VNA to the channel sounder versus time for a known channel without any MPCs. As seen in Fig. 7, the channel sounder dynamic range between the main peak and the power level at 457 ns is approximately 57 dB while the NIST reference power level is 80 dB ± 5 dB. This is a difference of 22 dB. This particular box configuration of the verification box provides an independent view of the actual channel sounder. It also enables researchers to assess if the system's dynamic range meets their needs for their measurement campaigns.

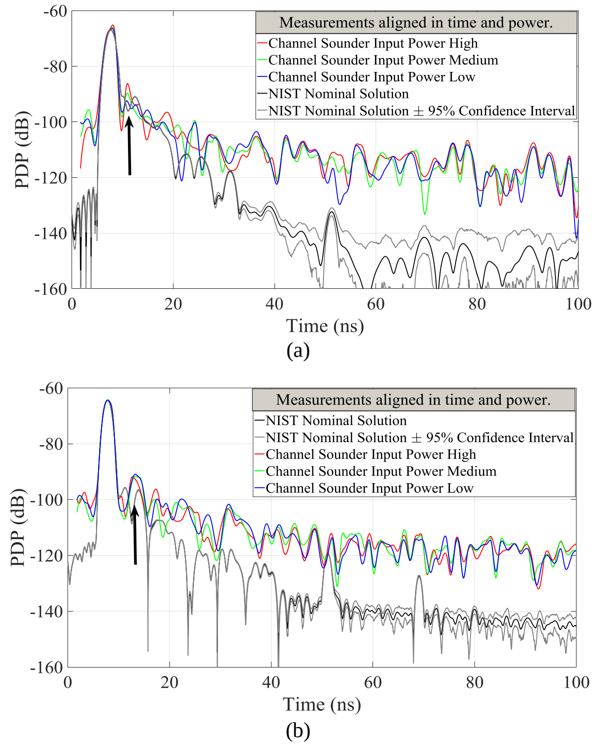

Fig. 6: (a) Channel sounder measurements at a center frequency of 38 GHz, (b) Channel sounder measurements at a center frequency of 26 GHz. Channel sounder data aligned to NIST nominal solution in time and power. The same power amplifier was used for both figures.

C. Power Delay Profile Metrics

A channel sounder user's ability to distinguish actual multipath components from false artifacts due to reflections from non-ideal hardware is very important. The channel sounder verification box double multipath configuration provides a known channel with MPCs at 51 and 68 ns, as seen in Fig. 8 (the box can be configured to an alternative double multipath configuration with MPCs at 55 and 65 ns). The channel sounder PDP results above -100 dB falls within the error bars of the NIST reference VNA results.

A comparison of the arrival time of the main peak delay window, RMS delay spread, and number of MPCs is shown in Table III for this configuration of the box. The multipath threshold was set to -30 dB and the percent of energy in the delay of 90% for calculation of the channel metrics. Note that

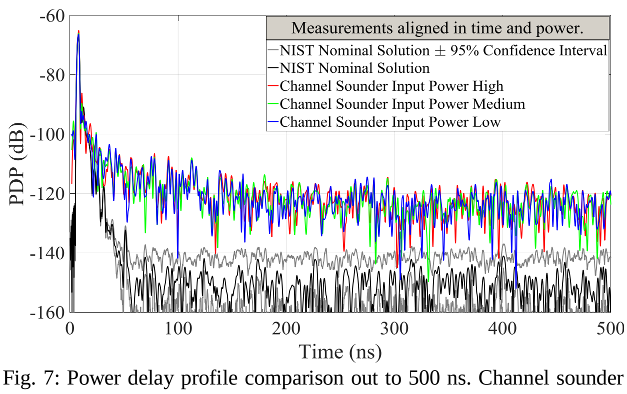

Fig. 7: Power delay profile comparison out to 500 ns. Channel sounder data aligned to NIST nominal solution in time and power.

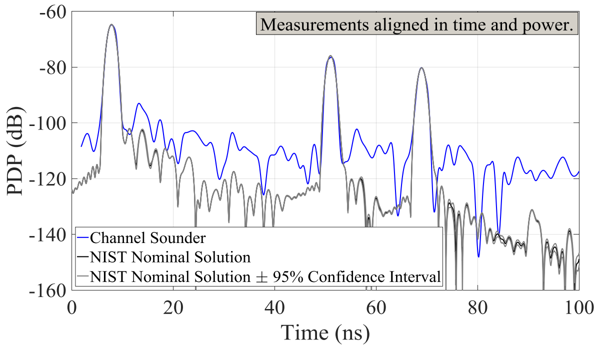

Fig. 8: Comparison of a double multipath configuration with time alignment. Channel sounder data aligned to NIST nominal solution in time and power.

Table III: Comparison of channel metrics [14].

	Arrival Time (ns)	**Delay Window (ns)**	**RMS Delay Spread (ns)**	**Number of MPCs**
NIST Reference VNA	7.81	44.25 ± 0.001	14.1 ± 0.01	3
Channel Sounder	6.4	44.2	20.5	3

the channel sounder results were time-aligned to the NIST nominal solution in Fig. 8 but the initial time of arrival is provided in the table.

D. PDP Post-Processing

In the channel sounder, the received signal must be post-processed to recover the PDP of the channel. Even small errors in, or incorrect configuration of, the post-processing software can result in spurious responses, distortion and reduced dynamic range [16]. For VNA-based channel sounders, the choice and correct implementation of the windowing function and IFFT routines are critical. For correlation-based channel sounders, the choice and correct implementation of the correlation routine are critical. The verification box provides a convenient method for identifying deficiencies in the post-processing software that would otherwise be very difficult to detect.

IV. Conclusions

We illustrated a comparison-to-reference channel sounder verification technique by use of a known and stable channel artifact. We illustrated a comparison between a channel sounder and a NIST reference VNA, which provided insightful understanding of the channel sounder hardware, post-processing and important channel metrics. The calculation of the reference channel metrics with uncertainties such as PDP and RMS delay spread helps to establish the accuracy of the channel sounder's performance.

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