On Measurement Uncertainty Introduced by Instruments in Frequency Domain Channel Measurement Systems

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***Abstract*—Measurement uncertainty provides a quantitative reference to choose appropriate instruments and measurement methods. This paper focuses on the measurement uncertainty introduced by measurement instruments in frequency domain channel measurement systems. For frequency domain channel measurement, the measurement instrument, Vector Network Analyzer, need to be calibrated before measurement. The uncertainty analysis for various calibration methods is the foundation to make a judicious choice of calibration methods. The uncertainty analysis is based on Monte Carlo method with considering the correlations between S-parameter measurements at different frequencies. This paper illustrates the method of uncertainty analysis and takes the path loss measurement for vehicle-to-vehicle (V2V) channel as an example. The experiments in this paper show that the correlations have a strong influence on the uncertainties of path loss measurements. The uncertainties for different calibration methods are calculated out. Based on the uncertainty analysis, the "response" calibration is suggested for channel measurements.**

***Index Terms*—Channel measurement, uncertainty analysis, path loss, correlations, calibration method**

I. Introduction

It is well known that the design of wireless systems requires a deep understanding of the channel characterization which is operated in. Accurate measurements of propagation channels are important for the simulation, design and performance evaluation of wireless systems. For frequency domain channel measurement, Vector Network Analyzer (VNA) is the main measurement instrument [1]. Before starting a measurement, VNA is first calibrated to correct for the response of the passive elements and electronics used in the measurement. There are several methods of calibration such as "response" calibration and "full 2-port" calibration. Calibration kits, time-consuming, and calibration complexity change with different calibration methods. And different calibration methods result in different measurement uncertainties. The uncertainty analysis is the foundation for the selection of calibration methods.

Uncertainty evaluation is crucial for measurements. As mentioned in [2]: "When reporting the result of a measurement of a physical quantity, it is obligatory that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability". The indication of the quality of the result is the uncertainty. Without the uncertainty, measurement results are not completed. Especially, uncertainty analysis is more important for a specific wireless channel which is produced in a test facility, e.g., reverberation-chamber. The test facility is used for the artificial reproduction of propagation channels. It gives the capacity to test radio communication systems, such as over-the-air testing of wireless devices. To control characteristics in the test facility, the frequency domain channel measurement systems are usually used as an indicator. The indicator is the basis for adjusting the channel characteristics in the test facility [3], [4]. So the importance to analyze the uncertainty of channel measurement comes from the requirements for the controllability and repeatability of channel simulation in the test facility. The research on the measurement uncertainty is very important to develop a reliable test facility that can meet the requirement for testing wireless devices.

In the recent decades, a great number of channel measurements have been conducted, and many channel models have been established based on them [5]–[7]. The channel measurement (i.e., channel sounding) techniques may be classified as direct pulse measurements, spread spectrum sliding correlator channel measurements and frequency domain channel measurements [8]. For the spread spectrum sliding correlator channel measurements, measurement errors are analyzed. The measurements are affected by four different types of systematic errors: commutation, pulse-compression, aliasing, and misinterpretation error. Based on the analysis, guidelines for setting important sounder parameters are provided [9]. For the frequency domain channel measurements, some aspects that contribute to the uncertainty are discussed. These aspects mainly include small-scale fading, measurement system repeatability, off-frequency estimation, controlled-environment reference and systematic measurement-system uncertainties [10]. Measurement system repeatability is a part of the measurement instrument uncertainty. This paper focuses on the measurement uncertainty introduced by measurement instrument and provides a more comprehensive analysis on this uncertainty source. The cables used in channel measurement are also an uncertainty source.

The effect of using co-axial cables in ultra-wideband channel measurement is investigated in [11]. Measurement instruments are one of the most important uncertainty sources for channel measurement. The uncertainty of the measurement instruments propagates to the uncertainty of channel parameters. But, the measurement uncertainty introduced by measurement instruments is not well studied. To our knowledge, this is the first work that addresses the measurement uncertainty introduced by the measurement instruments in frequency domain channel measurements.

This paper presents an investigation into the measurement uncertainty based on Monte Carlo method. This paper illustrates the procedure of uncertainty analysis with path loss measurement for Vehicle-to-vehicle (V2V) channel. Typical approaches to the VNA S-parameter measurement uncertainty analysis do not account for the statistical correlations between S-parameter measurement uncertainties at different frequencies e.g., in [12], [13]. In this paper, the uncertainties are analyzed with considering the correlations. To provide comparison, the uncertainties without considering the correlations are also presented. The comparison shows the correlations have a strong influence on the uncertainties of channel parameters measurements. Based on the uncertainty analysis, some suggestions on instruments and calibration methods are presented.

The reminder of this paper is organized as follows. In Section II, the uncertainty analysis approach with considering the correlations between S-parameter measurement uncertainties at different frequencies is presented. In Section III, as an example the measurement uncertainty of the path loss for V2V channel is analyzed. Section VI concludes the paper.

II. Measurement Uncertainty Analysis

In the frequency domain measurement systems, wideband frequency responses are measured by VNA. Then the power delay profile (PDP) of the channel is derived by inverse Fourier transform [14]. Most important channel parameters can be obtained from the PDP.

From calibration certificates and specifications for VNA, the uncertainties of frequency responses (S-parameters) can be obtained under a certain calibration method for a certain VNA. From the uncertainties of the S-parameters, the uncertainties of channel parameters are calculated. The method for the calculation is determined by the post-processing algorithm as shown in Fig. 1. As the post-processing is nonlinear, the method based on the Monte Carlo method for calculating uncertainties is used in [15]. The relationship between the measurement procedure and the uncertainty analysis procedure is shown in Fig. 1. In the left part of Fig. 1, the measurement procedure is shown. The "Frequency Response" is measured by VNA. "Data Postprocessing" consists inverse Fourier transform and channel parameters extraction. The left part of Fig. 1 shows the uncertainty analysis procedure.

The detailed procedure of uncertainty analysis for channel parameters measurement is illustrated in Fig. 2. Firstly, the wireless channel is measured with the proposed measurement

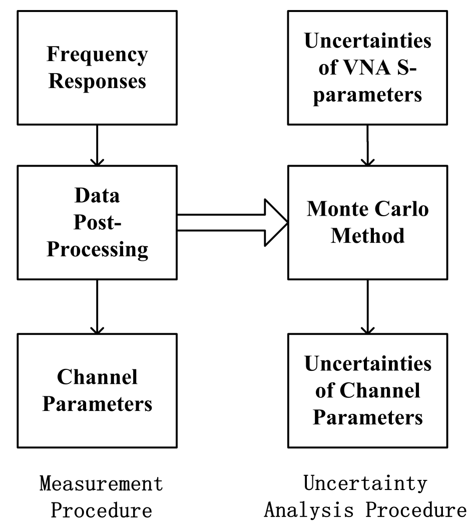


Fig. 1. Relationship between the measurement procedure and the uncertainty analysis procedure

system to obtain the frequency response ($Trial_0$). The measurement results contain a set of S-parameter measurement data. Based on the uncertainties of these measurement data, the probability density functions (PDFs) of S-parameters for each frequency point of the frequency response are obtained. Then N trials are calculated from the PDFs. For Monte Carlo simulation, N is typically more than 50000.

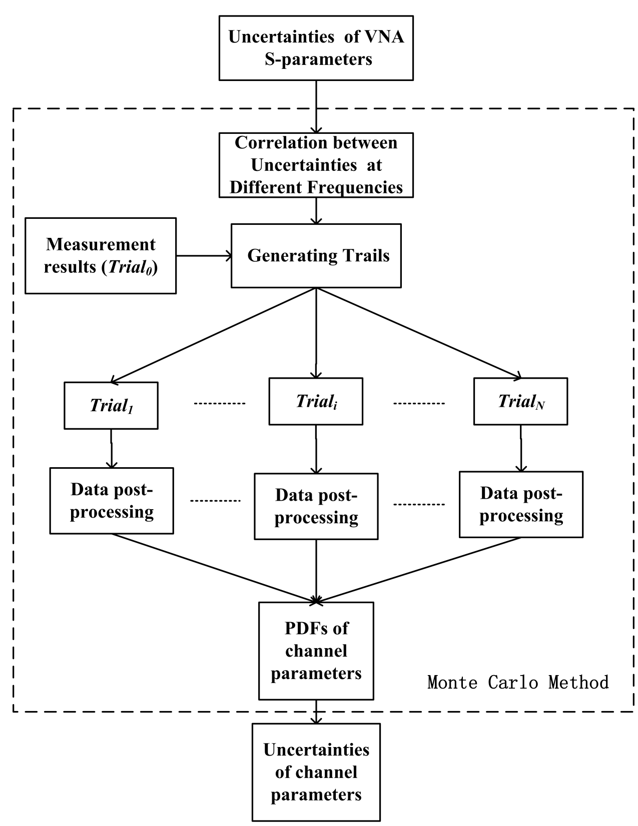


Fig. 2. Flowchart describing uncertainty analysis for channel parameters

It is worth noting that, when generating the N frequency responses, the correlations between S-parameter measurement uncertainties at different frequencies should be considered. With considering the correlation, the i^{th} trial is calculated as

$$Mag_i = Mag_0 + \rho \cdot \zeta_i^{Mag} \cdot e + (1-\rho) \cdot \xi_i^{Mag} \quad (1)$$

$$Phase_i = Phase_0 + \rho \cdot \zeta_i^{Phase} \cdot e + (1-\rho) \cdot \xi_i^{Phase} \quad (2)$$

where:

Mag_0: $Mag_0 = [Mag_0(f_1)...Mag_0(f_j)...Mag_0(f_M)]$, a 1-by-$M$ vector represents magnitude components of the measurement results, M is the number of swept frequencies.

Mag_i: $Mag_i = [Mag_i(f_1)...Mag_i(f_j)...Mag_i(f_M)]$, a 1-by-$M$ vector represents magnitude components of the i^{th} trial for the Monte Carlo simulation.

$Phase_0$: $Phase_0 = [Phase_0(f_1)...Phase_0(f_j)...Phase_0(f_M)]$, a 1-by-$M$ vector represents phase components of the measurement results.

$Phase_i$: $Phase_i = [Phase_i(f_1)...Phase_i(f_j)...Phase_i(f_M)]$, a 1-by-$M$ vector represents phase components of the i^{th} trial for the Monte Carlo simulation.

ρ: correlation coefficient between S-parameter measurement uncertainties at different frequencies.

e: 1-by-M vector of all ones.

ζ_i^{Mag}: a scalar random variable, its probability density function is obtained from the uncertainty of magnitude measurement in VNA.

ζ_i^{Phase}: a scalar random variable, its probability density function is obtained from the uncertainty of phase measurement in VNA. $\rho \cdot \zeta_i^{Mag} \cdot e$ and $\rho \cdot \zeta_i^{Phase} \cdot e$ represent the correlation section of the VNA S-parameter measurement uncertainty for the i^{th} trial.

ξ_i^{Mag}: $\xi_i^{Mag} = [\zeta_{i,1}^{Mag}, ..., \zeta_{i,M}^{Mag}]$, a 1-by-M vector of randam. The PDFs of $\zeta_{i,1}^{Mag}, ..., \zeta_{i,M}^{Mag}$ are obtained from the uncertainty of magnitude measurement in VNA.

ξ_i^{Phase}: $\xi_i^{Phase} = [\zeta_{i,1}^{Phase}, ..., \zeta_{i,M}^{Phase}]$, a 1-by-M vector of randam. The PDFs of $\zeta_{i,1}^{Phase}, ..., \zeta_{i,M}^{Phase}$ are obtained from the uncertainty of phase measurement in VNA. $(1-\rho) \cdot \xi_i^{Mag}$ and $(1-\rho) \cdot \xi_i^{Phase}$ represent the uncorrelation section of the VNA S-parameter measurement uncertainty for the i^{th} trial.

For each trial, the post-processing procedure is performed. This paper illustrates the procedure with path loss. Path loss for $Trial_i$ (PL_i, quantities expressed in decibels) can be calculated as [16], [17]

$$PL_i = -10log_{10}[\frac{1}{M}\sum_{j=1}^{M}|Mag_i(f_j)|^2] \quad (3)$$

In this way N results of path loss are calculated from (3). Then the PDF of path loss is achieved. Finally, through numerical analysis, the uncertainty of path loss is achieved [18].

III. Example and Discussion: Uncertainty Analysis for V2V Channel Measurement

V2V communications have recently received much attention due to some new applications [19], [20]. A measurement system for penetration loss of vehicle is developed. The results are valuable for path loss modeling and involvement of extra loss in network planning [19], [21]. A V2V measurement was carried out in a 10-meter semi-anechoic chamber in National Institute of Metrology (NIM), Beijing, P. R. China, as shown in Fig. 3. The chamber was used to produce a static channel for the measurement system. For the measurements reported here, the proposed measurement system was set up with the following parameters. Points (1024) were recorded in the frequency band which was from 5.85 GHz to 5.86 GHz, with a frequency spacing of 9.8 kHz. Intermediate-frequency averaging bandwidth was set to 1 kHz. Two Identical horn antennas were used at transmit and receive sites. All antenna heights were approximately 1.5 m above the ground. The distance between the two antennas was 6.4 m. The two antennas were pointed at each other's direction and a typical minibus was located perpendicularly to the TX-RX boresight. Fig. 4 shows the measurement results in frequency domain and Fig. 5 shows the PDP in time domain derived by the inverse Fourier transform.

In such a frequency band, the typical correlation coefficients between S-parameter measurement uncertainties at different frequencies are generally large. Hence, the correlation coefficients (ρ) in this study are assumed to be 0.9 [22]. Based on Monte Carlo method, the PDF for path loss is calculated. Fig. 6(a) shows the PDF for path loss, when the uncertainty of magnitude measurement is 0.6 dB and the uncertainty of phase measurement is 4.3 degree, which derived from "full 2-port" calibration [23]. Then, an uncertainty U_{PL-VNA} of 0.52 dB ($k = 2$)[1] is obtained. U_{PL-VNA} is the uncertainty in an estimate of path loss introduced by the VNA. Fig. 6(b) shows the PDF for path loss, when the uncertainty of magnitude measurement is 0.9 dB and the uncertainty of phase measurement is 6.3 degree, which is derived from the "response" calibration i.e., the time saving calibration method [23]. Then, an uncertainty U_{PL-VNA} of 0.76 dB ($k = 2$) is obtained. To illustrate the importance of considering the correlation, the uncertainties without considering the correlation ($\rho = 0$) are calculated. The U_{PL-VNA} is 0.03 dB ($k = 2$) with "full 2-port" calibration and the U_{PL-VNA} is 0.05 dB ($k = 2$) with "response" calibration.

The uncertainties of path loss measurement introduced by VNA are shown in Table I. Following findings can be summarized:

1. The typical uncertainties of path loss introduced by VNA in frequency domain measurement systems are from 0.52 dB to 0.76 dB. The uncertainties represent the measurement reliability. The uncertainties define a confidence interval about the result of a path loss measurement. The uncertainty analysis are important to develop a reliable test facility that can meet the requirement of repeatability for testing wireless devices.

2. The results show that the correlations on uncertainties have a strong influence on the uncertainties of path loss.

[1] k is the coverage factor. The coverage interval for k = 2 contains 95% of the distribution.

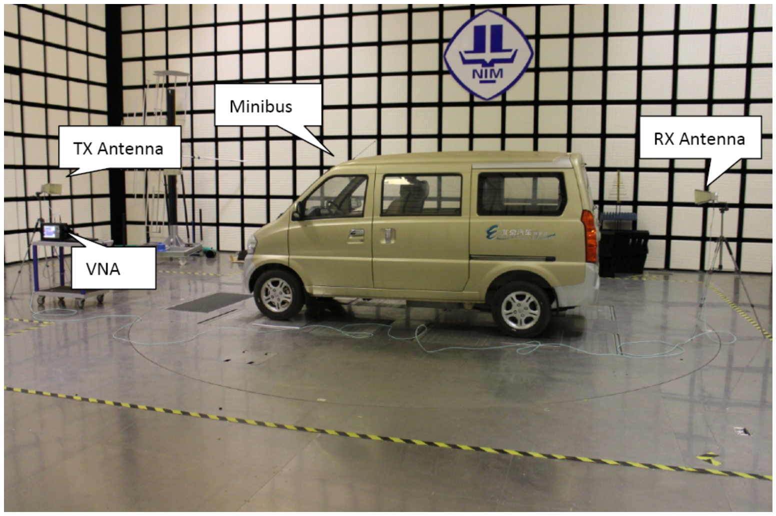
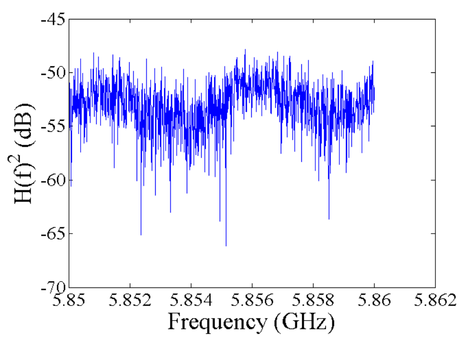
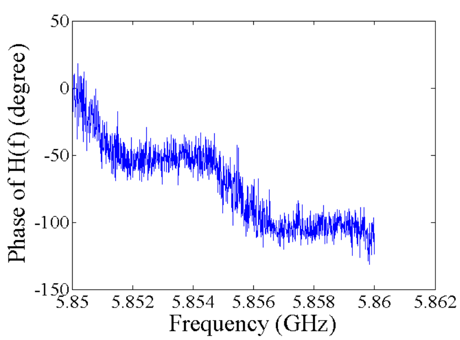


Fig. 3. NIM semi-anechoic chamber with the channel measurement system



(a)Transfer function measurements in V2V band for magnitude



(b)Transfer function measurements in V2V band for phase

Fig. 4. Propagation-channel transfer function measurements in V2V band for magnitude and phase

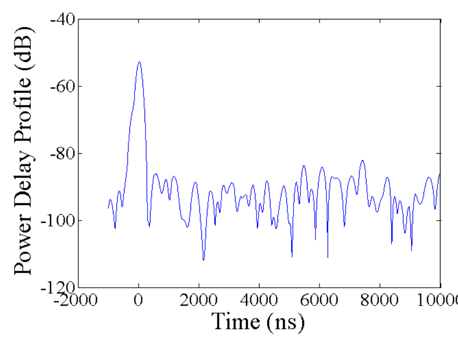


Fig. 5. Power delay profile for V2V channel measurement in semi-anechoic chamber

TABLE I
UNCERTAINTIES FOR PATH LOSS MEASUREMENT IN THE V2V CHANNEL MEASUREMENT

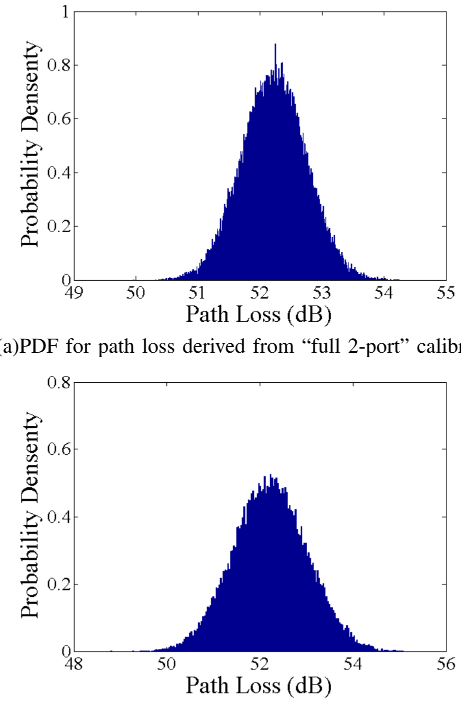
Calibration method	Uncertainty ($\rho = 0$)	Uncertainty ($\rho = 0.9$)
$Full\ 2-Port$	0.03 dB	0.52 dB
$Response$	0.05 dB	0.76 dB

The uncertainty of path loss increases with the increase of correlation. Without considering correlations, the uncertainty will be underestimated.

3. The uncertainty analysis shows that the difference of the uncertainties of path loss between the two calibration methods is 0.24 dB. Comparing to some other uncertainty components, the difference is relatively very small [11]. So, the "response" calibration is suggested based on the quantitative analysis.

IV. CONCLUSION

This paper investigates uncertainties in channel measurement. The uncertainties of VNA propagate to the uncertainties of channel parameters. In frequency domain channel measurement systems, the uncertainty for channel measurement is associated with the VNA S-parameter measurement uncertainties and the statistical correlations between S-parameter measurement uncertainties. The uncertainty analysis shows that different VNA calibration methods have no significant influence on the uncertainties of channel parameters. Therefore, in engineering implementations, the time saving calibration method e.g., "response" calibration is suggested. This is useful for measurement system design. In this paper, uncertainty



(a)PDF for path loss derived from “full 2-port” calibration

(b)PDF for path loss derived from “response” calibration

Fig. 6. The PDFs of Path loss for V2V channel measurement

analysis for path loss is demonstrated. The same method can be used for other channel parameters. Uncertainty analysis presented in this paper can be helpful to build a reliable system for channel measurement.

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