FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

BACHELORS'S THESIS

AMPLITUDE PROBABILITY DENSITY TESTING OF A CHANNEL EMULATOR

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ABSTRACT

Rayleigh probability distribution is commonly used to model statistical aspects of multipath fading in wireless communications. Radio channel emulators mimic real-world propagation scenarios. This thesis examines the Rayleigh fading channel model, with a focus on the Amplitude Probability Density (APD), and the goal is to develop a test automation case for evaluating the functionality of Rayleigh fading channel models provided by Keysight PROPSIM radio channel emulator. Verification measurements were conducted using equipment such as the PROPSIM radio channel emulator, a signal generator, and a spectrum analyzer.

Keywords: PROPSIM Radio Channel Emulator, Rayleigh fading channel, Amplitude probability density (APD), Test automation.

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TIIVISTELMÄ

Langattomassa tietoliikenteessä Rayleighin todennäköisyysjakaumaa käytetään yleisesti monitiehäipymisen mallintamisessa. Radiokanavaemulaattorit jäljittelevät todellisia signaalin etenemisskenaarioita. Tässä opinnäytetyössä tarkastellaan Rayleighin-häipyvää kanavamallia keskittyen amplituditodennäköisyystiheyteen (APD) ja tavoitteena on kehittää testiautomaatio Keysight PROPSIM kanavaemulaattorin tarjoamien eri kanavamallien toimivuuden arvioimiseksi. Todentavat mittaukset suoritetaan käyttämällä laitteita, kuten PROPSIM radiokanavaemulaattoria, signaaligeneraattoria ja spektrianalysaattoria.

Avainsanat: PROPSIM-radiokanavaemulaattori, Rayleighin häipyvä kanavamalli, amplitudin todennäköisyystiheys (APD), testiautomaatio.

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PREFACE

This thesis was completed during my internship at Keysight Technologies Oulu R&D. I want to thank my supervisor, Pekka Kyösti, for his valuable guidance. Thanks also to my colleagues at Keysight Oulu PROPSIM R&D, especially Ilmari, Aleksi, and Antti, for their help and support. Their mentorship has been invaluable, and I am grateful for their patience in explaining complex concepts and sharing their expertise.

In Oulu 29.04.2024

Iisa Mäenpää

LIST OF ABBREVIATIONS AND SYMBOLS

APD	Amplitude Probability Density
AWGN	Additive White Gaussian Noise
CI	Continuous Integration
CIR	Channel impulse response
DUT	Device under test
IQ	In-phase and quadrature components
IR	Impulse Response
LOS	Line-of-Sight
PDF	Probability Density Function
R&D	Research and development
RF	Radio frequency
RX	Receiver
SA	Spectrum Analyzer
SG	Signal generator
SNR	Signal to noise ratio
TX	Transmitter

X	Gaussian random variable
π	pi
s	Second
e	Euler's number
σ	Standard deviation
σ^2	Variance
p(x)	Probability density
E[X]	Expected value of random variable
VAR[X]	Variance of random variable

1 INTRODUCTION

Wireless systems, devices, and services have become integral to everyday life. In wireless communications, electromagnetic waves transmit data from a transmitter (TX) to a receiver (RX). Transmitted electromagnetic waves travel through a propagation channel and are typically affected by different propagation phenomena, such as reflection, diffraction, and scattering. Together, the propagation channel, TX, and RX constitute what is known as the radio channel in the context of wireless communication [1].

Understanding the channel through which the signal is transmitted is crucial when researching and developing wireless systems such as smartphones, WLAN devices, and satellite communication systems. Radio channel emulators are commonly used for the design and analysis of these systems and devices, for instance in benchmarking and system performance tests. With a programmable channel emulator, users can select from pre-established channel models or develop custom models derived from real-world channel measurements. One of the most advanced and versatile commercial radio channel emulators is Keysight PROPSIM radio channel emulator. In principle, PROPSIM channel emulator replaces the radio channel between antenna parts. PROPSIM emulates, i.e. models accurately the real-world propagation environment in a laboratory setting [2].

Radio channels are often modelled using statistical analysis to characterize the channel properties [1]. Several types of channel models exist, each representing different characteristics of the propagation environment. One of the commonly used statistical analyses of the propagation phenomenon is the Rayleigh distribution. Rayleigh fading is observed in radio channels when the amplitude and phase of a transmitted signal fluctuate unpredictably, because of multipath propagation [3]. The scope of this thesis is limited to Rayleigh distributed channel models.

The related work of this thesis is to develop a test to verify that the channel emulator's Rayleigh fading channel model works according to specified channel model standards. This was achieved by comparing the theoretical Rayleigh distribution with the observed Amplitude Probability Density (APD). This method shows the statistical probability of the occurrence of a certain amplitude.

1.1 MOTIVATION AND BACKGROUND

Testing and verification are crucial in research and development (R&D). Testing aids the development process, whereas verification ensures the quality of the final product. In the context of channel emulator R&D, integration testing involves verification of whether independently developed hardware and software units of the channel emulator function together correctly. The outcomes of the study documented in this thesis could later be added to the channel emulator integration testing environment.

The test method used in this study measures the signal statistics when the fading channel model is applied to the radio frequency (RF) output. Impulse response data (.ir-data) of the emulated channel model and the measurement of the emulation were compared with the theoretical distribution. Different distributions may resemble one another visually, and slight variations in their shape may be challenging to distinguish. Employing automated verification processes that are based on theoretical foundations can prove to be more accurate. Manual amplitude probability testing typically involves laborious and time-consuming procedures, which can slow the development cycles. Automation also aids regression testing, which ensures that the previously developed and tested parts perform as expected after any change.

The first task involved planning of how to conduct the test case. Requirements were set for the test case. Different measurements were conducted with varying sample sizes, and the methods were verified using different data and synthetically distorted emulation files.

The test case was developed using the Python programming language and the Nose unit testing framework, similar to other test cases in the PROPSIM R&D integration testing environment. This ensures that the test case can be used for ongoing testing and aid in future product development processes.

2 THEORY

In radio communication systems, understanding the characteristics of the radio channels is essential for designing and optimizing wireless networks. Theoretically, the behavior of a radio channel could be described using Maxwell's equations, however, in many circumstances, it is too complicated to calculate the exact solutions. One of the methods to model the radio channels is the stochastic method. Stochastic methods use statistical distributions and random variables for the analysis of channel parameters, such as received power or field strength. Stochastic variations in the received power are particularly important for understanding fading phenomena, which can result from interference among multipath components [1]. When attempting to model the statistical characteristics of a channel, there are several probability distributions that can be considered. Some widely used distributions are Rayleigh, Rician, Nakagami and Lognormal distributions [3].

2.1 Rayleigh fading

The Rayleigh probability distribution is the most widely used probability distribution from statistical channel models for the envelope fading of radio signals [4]. The Rayleigh distribution is usually used as a statistical model to describe the propagation phenomena that often occur in densely populated areas, where the direct line-of-sight (LOS) between the transmitter and receiver is obstructed by numerous buildings and objects. This can result in interference, phase shifting, and fading at the receiver due to multipath propagation, resulting in multiple versions of the signal. In Rayleigh fading, the amplitude of the received signal experiences random fluctuations due to the constructive and destructive interference of the multipath components. These signals have different delays, which results also in different phases. Due to the scattering of multiple elements, the signal also loses its gain, which results in different amplitudes of the signal. Figure 1 illustrates a typical Rayleigh fading channel.

Figure 1: Example of Rayleigh fading channel.

In Figure 1, the direct visibility between the transmitter and receiver is obstructed. As the signal scatters from multiple paths to the RX, it experiences random amplitude fluctuation.

There are many scatterers in the channel, and by applying the central limit theorem, the channel real and imaginary (I/Q) channel impulse response (CIR) components become Gaussian. If the process has zero-mean, the envelope of the channel response at any time has a Rayleigh probability distribution [3].

2.1.1 Rayleigh random variable

Based on the central limit theorem, adding many random variables will eventually become Gaussian probability density. If two independent and identically distributed variables are normally distributed with zero mean and variance σ^2, then a Rayleigh random variable can be represented as, [3]:

$$X = \sqrt{X_1^2 + X_2^2}\ , \tag{1}$$

where X is the Rayleigh random variable and, X_1 and X_2 are independent zero-mean Gaussian variables, with standard deviation sigma. The probability density function (PDF) of the Rayleigh random variable is as follows, [5]:

$$p(x) = \begin{cases} \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}} & x > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Where x is the envelope amplitude of the signal, σ^2 the mean power of the received signal and $x^2/2$ is the instantaneous signal power. The mean is calculated as, [5]

$$E[X] = \sigma\sqrt{\frac{\pi}{2}} \tag{3}$$

And variance as, [5]:

$$VAR[X] = \left(2 - \frac{\pi}{2}\right)\sigma^2 \tag{4}$$

The variance depends on the received power due to shadowing and path loss. Under Rayleigh fading, the channel coefficients are complex Gaussian, the envelope is Rayleigh, and power is X^2. Rayleigh refers to the signal envelope [1]. The probability density function (PDF) the Rayleigh distribution with different variances is illustrated below.

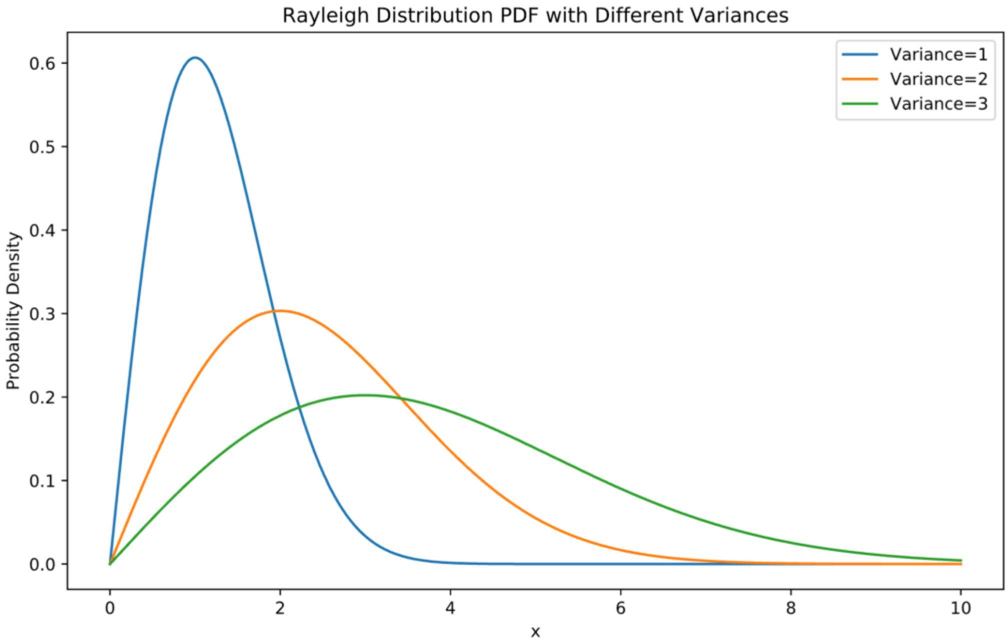

Figure 3: Rayleigh probability density function (PDF) with different variance values.

From the figure, it can be observed that the distribution flattens with larger variance values. The randomness of the variable is usually represented by a PDF graph, showing the likelihood of receiving a certain value. In the case of a Rayleigh fading channel, the PDF shows the likelihood of the received amplitude power. The theoretical model of the Rayleigh distribution was used as a reference in this test case, and all the data were evaluated based on the theoretical formula.

3 MEASUREMENT SETUP

Running the test case requires specific measurement instruments. For this test case a signal generator (SG), a radio channel emulator and a spectrum analyzer (SA) are required. In short, the signal generator simulates the transmitter, the channel emulator replaces the radio channel, and the spectrum analyzer can be viewed as a receiver. The study was conducted using Keysight's measurement instruments, as shown in Figure 2.

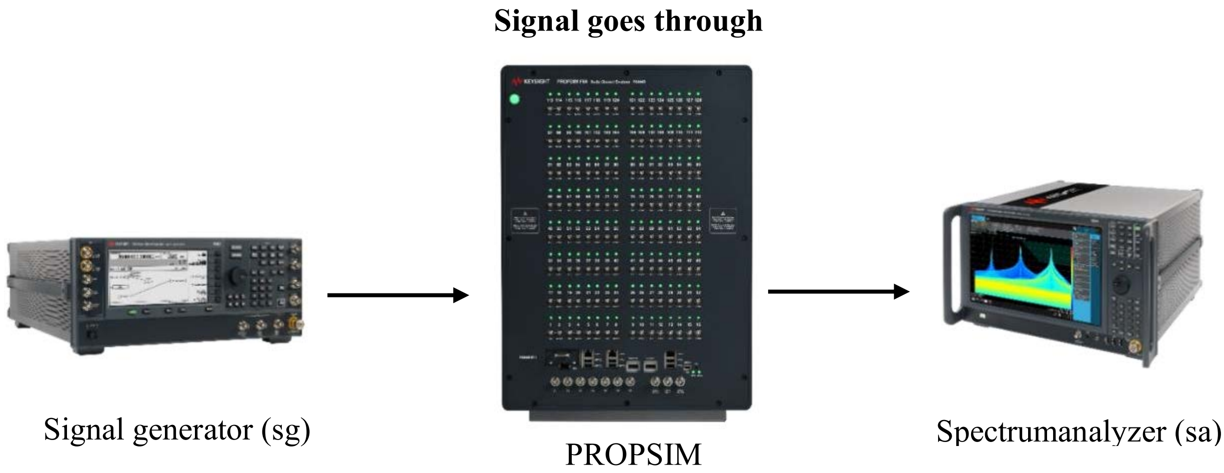

Figure 2: Devices used for the integration test.

The signal generator was set to provide a non-distorted continuous wave (CW) signal, which was then transmitted to the PROPSIM channel emulator in the middle of the figure. The fading channels can be defined as a software generated impulse response (.ir-files), which were also tested against the theoretical model. The PROPSIM channel emulator receives the signal and uses a previously defined emulation file and emulates the signal with the defined channel model.

The emulator output is then connected to the Spectrum Analyzer. The Spectrum Analyzer measures the power per frequency component of the emulated signal and displays a spectrum of the signal amplitudes. Python programming language was used to control the measurement instruments and define settings. Some of the parameters used for the measurement equipment are shown in Table 1.

Table 2: Parameters and their values

Parameters for SA	**Value**
Sweep Points	1001
Center Frequency	2200 MHz
Sweep Time	0.2 s
Number of samples (generated)	20020000
Number of samples (.ir)	499999
Parameters for SG	
Center Frequency	2200 MHz

The accuracy of the verification depended on the number of samples collected as the probability density function calculation would become inaccurate with small sample sizes. Before constructing a test case, the measurement was first tried manually. After understanding the measurement, the automation design of the test case could begin.

4 ANALYSIS AND VERIFICATION METHOD

Test automation in terms of Amplitude Probability Density (APD) testing offers several advantages. The program sets the settings automatically for each device under testing and performs the measurement. This process could take more time when performed manually. Analysis of results is simplified with predefined requirements. Also, testing can be conducted continuously without the need for human presence, allowing for testing at any time of day. The test takes about 10 minutes to operate, depending on the decided sample size. In the following chapters, the test process is explained in more detail.

4.1 Test automation

If a test case has pre-defined requirements for the software and hardware it is called functional test. Integration testing is part of functional testing [6]. The purpose of integration testing is to ensure that independently developed hardware and software work together as a cohesive unit. A good test case has a clear objective or goal, which is aligned with the requirements or specifications for the device under test (DUT).

The aim of this study is to develop a test case that verifies the Amplitude probability density (APD) of a channel model, emulated with a radio channel emulator. A test case should also have the expected outcome or result of the test, which is in this study the expectation that the channel is Rayleigh distributed after an emulation. Designed tests should be such that they are independent and do not rely on other test cases. However, the test should be reusable across different test scenarios and emulations. It should also be suitable for automation, especially for repetitive or regression testing. PROPSIM integration tests usually have a common structure in terms of folder structure, naming and code structure. Key software tools and paradigms used in the PROPSIM integration testing are as follows:

- Python: A high-level programming language.
- Nose: Unit testing framework module extending Python's built-in unit test classes.
- Object-Oriented Programming (OOP): OOP principles are employed to design modular and maintainable test scripts. By organizing code into classes and objects, code is more reusable and scalable.
- Matplotlib and NumPy: 3rd party Python libraries that are utilized for data visualization and numerical computations.
- Git: Version control system that is used for storing test cases, managing code changes, and collaborating with team members.
- Jenkins: open-source Continuous Integration (CI) server software that automates the integration process.

This study was conducted using these tools and protocols as well, as the test could be later part of PROPSIM integration test suite. The structure of the test case developed for this study is presented in Figure 3.

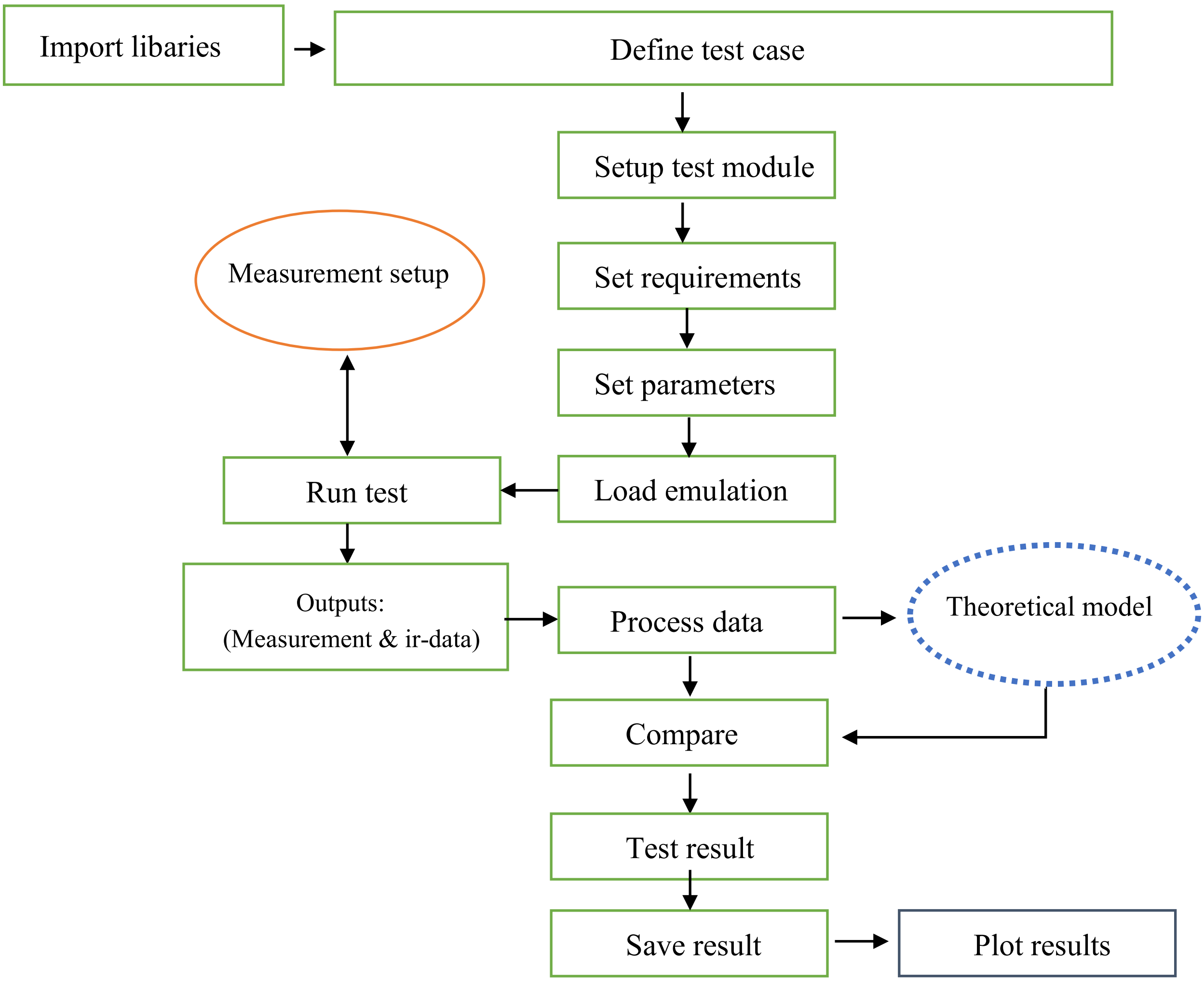

Figure 3: Structure of the test case

First, the necessary libraries were imported, the measurement instruments were initialized, and the requirements were set. In this test case, the requirements were a specific deviation limit and sample points. Finally, the emulation is loaded into PROPSIM, adjusting inputs, outputs, and setting measurement instruments, and routing signals to PROPSIM channels with an external routing device.

The measurement captured real-valued amplitudes over time, this could be described by the function h(t), where "t" represents time and h(t) belongs to the set of real numbers. Also, the .ir-data were read, and the amplitude values were saved. Before testing .ir-data was converted to decibels and then both the measurement and the .ir-data were normalized by subtracting the maximum of both data sets. Then both datasets were converted from decibels to linear values so that the theoretical probability could be computed. The amplitude values obtained were categorized into corresponding amplitude ranges (bins).

Finally, the difference between the theoretical and measured distributions, as well as the .ir-data distribution was computed. An assert statement was used to check if the delta of both sets of data was within the limits. An assert statement checks if the set condition is true or false and returns, a passed or failed result in the test case [7]. Finally, the relevant data and results were saved for the plot file.

4.1.1 Defining requirements

The hypothesis of this test is that measured and the .ir-data amplitudes were correctly Rayleigh distributed. This hypothesis is always tested after some changes within the PROPSIM development. This makes it a regression test. The test should be able to recognize any abnormality in the amplitude distribution.

Calculating the difference between an expected result and a measured result is a useful method to visualize interpreted results within test automation. A successful test outcome was determined when the maximum delta fell within the specified threshold, indicating a close alignment between the measured data and theoretical expectations. The delta (Δ) is set as follows:

$$\Delta\,(x) = p_{theoretical}(x) - p_{observed}(x)\,, \tag{5}$$

where the delta (Δ) is the difference between the theoretical probability density and the observed amplitudes probability density.

In idealized test case, if a test result were successful and there were not any nonidealities from the measurement and bins, the theoretical curve would be perfectly aligned with the data, and therefore the delta would be 0, and simply a flat line inside the threshold limits. On the other hand, if there were any distortions in the signal, there would be a difference between the distribution shapes, thus the delta would also show as spike that exceeds the threshold.

In practical settings, data handling and measurements are subject to various factors that can impact the accuracy of the data, making it unlikely that the data would exactly adhere to theoretical curve. In the test case, it was determined that the shape of the desired PDF was sufficiently accurate when the maximum difference from the theoretical distribution was set to $\pm$ 0.3 on a linear scale. This limit was determined by visual observation and applying synthetic errors, which determined how well the data were under the theoretical curve. It is noted that the $\pm$ 0.3 difference limit is rather tight, and it is sensitive to small changes in the measurement methodology, which are not necessarily related to the functionality of the channel model. For example, when smaller sample sizes affect the accuracy of the histogram.

4.2 Results

After running the test, it returned whether the test had passed or failed, i.e., the delta was within limits. A plot file of the test was saved for further visual examination. The plot shows the histogram of results and delta between the threshold limits. The histogram of the amplitudes shows the proportion of the amplitude values within a specific amplitude range. The probability of an amplitude falling within a range can be calculated by multiplying the height of the histogram bar by its width of successful results from the test are shown in Figures 4 and 5.

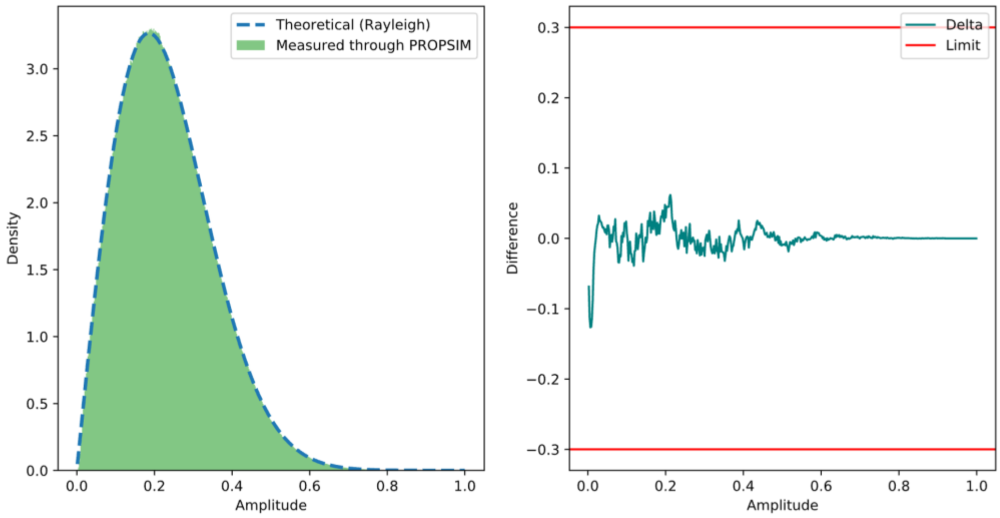

Figure 4: Histogram of measured data with theoretical distribution and a delta plot between the measured and theoretical model. Passed test result.

In the tested Rayleigh fading channel model the measured amplitude distribution closely resembled the theoretical Rayleigh Probability Density Function (PDF) as seen in Figure 4. The discrepancy between the measured distribution and the theoretical Rayleigh PDF is quantified as the "delta," which indicates the level of inaccuracy present in the measurements. In this specific example, the maximum delta observed between the measured fading channel model and the theoretical Rayleigh distribution falls within the acceptable range. This suggests that the measured fading channel model is functioning correctly and accurately representing the expected behavior of the channel model. However, after more detailed inspection, some of the histogram bins exhibit deviations from the theoretical model. These deviations can arise due to factors such as limited sample size and measurement non-idealities. Despite these deviations, the overall accuracy of the histogram remains satisfactory for the intended purpose of the test.

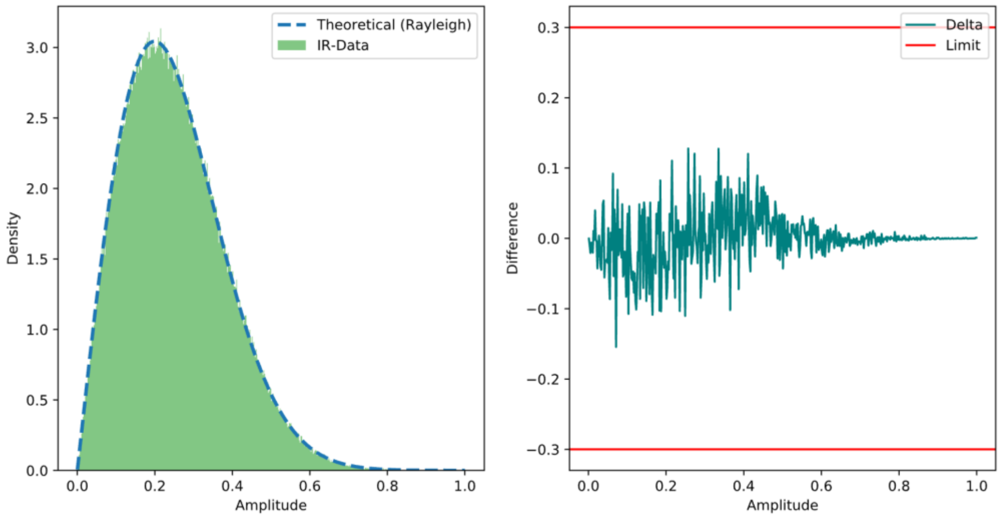

Figure 5: Histogram of IR data with theoretical distribution and a delta plot between the IR data and theoretical model. Passed test result.

The analysis was extended to include the ".ir-data" dataset, revealing that the delta consistently remains below the $\pm$ 0.3 threshold as presented in Figure 5. The .ir-data remains consistent regardless of the specific measurement parameters employed. However, the delta has slightly more error than the measured delta, this is because the .ir-data had less samples than the measured, and it leads to more inaccuracy within the histogram. Based on these results, it was concluded that the PROPSIM software operates correctly in generating the impulse response data (.ir-data) and emulating it.

4.3 Verification

The test case was designed to detect potentially incorrect functionality within PROPSIM. The test method was validated by synthesizing errors within the emulation file. This was achieved by creating Additive White Gaussian Noise (AWGN) to the emulation. When AWGN with a fixed power is added, the resulting amplitude, denoted as $h'(t)$, becomes noisier as expressed by equation 6 :

$$h'(t) = h(t) + n(t), \tag{6}$$

where $h(t)$ is the original amplitude and $n(t)$ is added zero-mean normally distributed noise. This noise level distorts the amplitudes captured. As some of the amplitude values are distorted due to the noise, it also leads to abnormalities within the APD shape. The results of this synthetic error scenario in APD form are depicted in Figure 8.

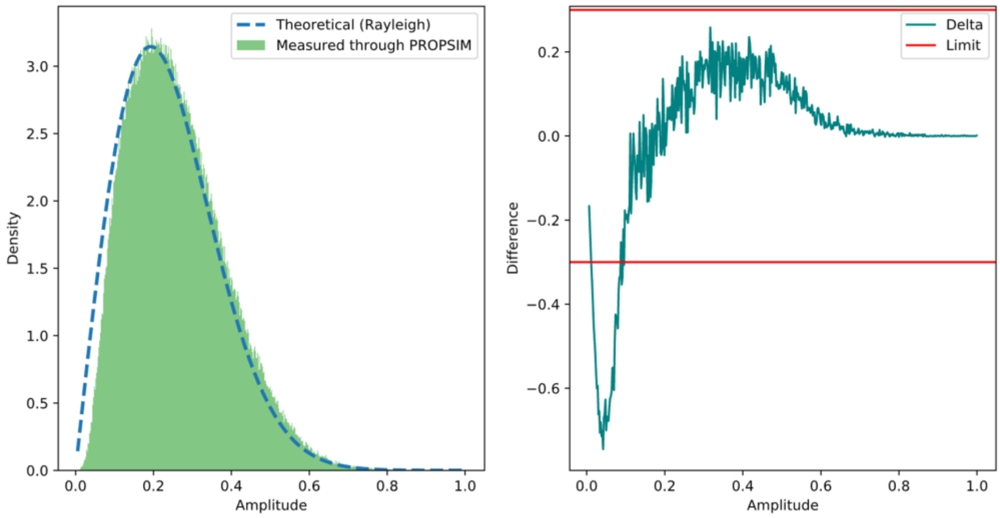

Figure 8: Synthetically created error situation with AWGN. Failed test result.

Figure 8 illustrates the synthetic error situation with AWGN, resulting in a failed test outcome. The distribution shape deviates slightly from the expected theoretical Rayleigh distribution. Additionally, the delta plot reveals an uneven distribution of error accumulation around the zero-mean.

4.4 Discussion

The results of the test were accurate, and the test case worked as expected by identifying the functional and distorted APD shapes. However, further discussion and work is needed to determine the criteria for the best acceptance criteria. When the shape is too distorted and what determines if the distribution is exactly Rayleigh, could be further studied. It is noted that the current measurement method is simply the difference. This difference is always small at the beginning and end of the curve when the values are small. Another option could be the relative error, for example in percentage. There should be a detailed examination of the exact requirements for the channel model, and further development of test methods based on these requirements. Other channel models and their parameters should be considered.

Additionally, further development of the test could include verification of the phase and Doppler spectrum of the channel model through (I/Q) data, which refers to a discrete time series representing a complex baseband signal. This will help assess the channel model's performance and reliability and make the test case more adaptable.

5 CONCLUSION

This thesis was conducted during the internship at Keysight Technologies in Oulu R&D. The motivation behind this study was to automate the verification of the channel model functionality with the (APD) method. For this thesis the scope of the automation was limited to Rayleigh distributed channel models

The development of the integration test involved a theoretical study to comprehend fundamental concepts such as Rayleigh distribution and fading channel models. The probability density functions and histograms were examined. This theoretical understanding served as the basis for creating probability density functions from the measurements.

Practical aspects included conducting measurements using devices such as the signal analyzer, PROPSIM radio channel emulator, and spectrum analyzer. Learning to operate these devices was an integral part of the study, and the correct parameters were determined through experimentation.

The test case was designed as part of the PROPSIM integration testing framework and followed a general PROPSIM integration test structure. Limits for the test were established through experimentation under various scenarios. The thesis introduced the devices used for measurements and described the parameters set for these measurements. The architecture of the test case was explained, along with the methodology for setting hypotheses.

The results of the test were presented and analyzed, indicating that the PROPSIM radio channel model functioned correctly, and the applied test methodology was accurate and functional. Finally, some further developments for the test were suggested. The outcome of this study could serve as an integration test in PROPSIM research and development.

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