Deep Fading in a Reverberation Chamber for Wireless Device Testing

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Abstract. Reverberation chambers (RCs) are a feasible option as test environment for evaluation of wireless devices with integrated antenna as they inherently emulate a Rayleigh fading channel. In this paper the dependency of deep fading on the frequency and position/orientation of an equipment under test (EUT) antenna is evaluated for different numbers of RC steps and loading conditions. The measured data were applied to an exemplary standard for wireless communication. The measurement results are highly repeatable and independent of frequency or position/orientation of the EUT and loading conditions.

1. Introduction
Reverberation chambers (RCs) are used in various standards as reproducible test environments, e.g. for electromagnetic compatibility testing [1], or mobile phone performance testing [2, 3, 4]. They consist of an electromagnetically shielded volume in which mode stirrers are built in. The latter may be mechanically moving or rotating metal plates or differently designed facilities in order to change the electromagnetic field distribution within the volume. A sequence consisting of a certain number of individual measurements is taken at various mode stirrer conditions (steps). Over a full measurement sequence an equipment under test (EUT) is exposed to a statistically quasi-homogeneous and quasi-isotropic electromagnetic field with a Rayleigh-distributed field strength, i.e., Rayleigh fading [2, 3, 5, 6]. Due to these characteristics a RC is an auspicious test environment for wireless devices with integrated antennas, especially if the mounting orientation and therefore the direction and polarization of the incident electromagnetic field is unknown, such as wireless sensors in industrial environments.

IO-Link Wireless (IOLW) is a new standard for wireless factory automation [7, 8]. The physical layer is based on Bluetooth Low Energy within the 2.4 GHz band [7]. RCs are suggested as test environment for IOLW [9] and thus IOLW is regarded as reference system as already elaborated in [10].

2. Measurement Setup
The measurements were performed in a Bluetest RTS60 RC. The inner dimensions are approx. 1.8 m (height), 1.2 m (depth) and 1.9 m (length). That type of RC utilizes two planar mode stirrers, a turntable for the EUT and three switchable, fixed and orthogonally arranged antennas for excitation (see e.g., [3]). The measurement sequences consist of 300, 600 and 1500 steps (i.e., mode stirrer and fixed antenna combinations). A sleeve reference dipole antenna was used as EUT. The $S$-parameters between the EUT antenna and the fixed antenna arrangement were measured for 1001 frequencies within 2.4 to 2.5 GHz. In order to adapt the power delay profile (PDP) of the RC to a large variety of industrial environments, commercially available
pyramidal and cuboid foam absorbers were placed in the RC (see e.g., [6, 11, 12]). The absorbers were at least one wavelength away from the next point of the EUT. The resulting RMS (root mean square) delay spread $\tau_{\text{RMS}}$ of the power delay profile was about 190 ns, 50 ns and 23 ns, respectively. The EUT antenna was mounted on three radii on the turntable and each three different heights and each three orthogonal orientations (i.e., polarizations: radial, tangential, vertical), as shown in Figure 1. Thus in total 27 measurement sequences were recorded for each number of steps and loading or $\tau_{\text{RMS}}$, respectively.

The measurements confirm that the mean $S_{21}$-parameters over the stirrer combinations for the 27 measurement sequences are within the same order of magnitude and almost flat over the frequency range for each loading case (an example is shown in [10, Figure 1]). Therefore, these mean values can be assumed to be equal in good approximation and in this case it is irrelevant what is averaged over. Figure 2 shows exemplarily the empirical cumulative distribution (eCDF) of fading for the 27 measurement sequences at 2.44 GHz with 300 Steps and $\tau_{\text{RMS}} \approx 50$ ns.

![Figure 1.](image1.png)

**Figure 1.** Measurement points (MPs) on the turntable.

![Figure 2.](image2.png)

**Figure 2.** Fading eCDF for the 27 positions/orientations of the EUT, exemplarily shown for 300 steps and $\tau_{\text{RMS}} \approx 50$ ns.

### 3. Evaluation for a limited Subset of Frequencies

For wireless device evaluation, the probability of fading (below the mean value of the radio channel) is of importance, as these can lead to outages. Thus a constant probability, independent of the frequency and position/orientation of the EUT is a key requirement. In the following sections, the RC is evaluated on a subset of 73 frequencies from 2403 MHz to 2475 MHz with 1 MHz spacing. This corresponds to the IOLW standard.

#### 3.1. Rayleigh Fading Validation

In [4, Appendix C] a procedure for Rayleigh fading evaluation based on a $\chi^2$-test is described. This procedure was performed for each loading, each EUT position/orientation, each stirring sequence and each frequency used by IOLW. (According to [4], here 11 vector network analyzer (VNA) frequency steps were used for the frequency averaging, which corresponds to presumed 1.1 MHz signal bandwidth.) The Rayleigh fading hypothesis was never rejected for the unloaded RC. The rejection probability increases for a loaded RC, but remained below 1%, even in the worst case of the heaviest loaded RC. Nevertheless, the described procedure in [4] uses 15 bins, whereby the bin which includes the samples with the lowest received power covers $-\infty$ dB to $-11.6$ dB (relative to the mean). Therefore all samples which represents deep fading are covered only by that single bin. In the following, the deep fading range is examined in more detail, since a fading of $-10$ dB can often be handled by the system without errors, but typically much deeper fading cannot.
3.2. Dependence of Fading on the Frequency

The empirical probability of measured $S_{21}$-values whose magnitudes are at least -10 dB, -20 dB, and -30 dB relative to the mean $S_{21}$-value as a function of frequency are calculated. Figure 3 show the mean, minimum, maximum and the (normalized) estimated standard deviation (SD) according to [1] over the $N = 27$ positions/orientations of the EUT antenna of the $S_{21}$-parameters exemplarily for 300 and 600 steps and $\tau_{\text{RMS}} \approx 50$ ns.

The mean over the 27 positions/orientations is almost frequency flat and in accordance with theory of Rayleigh fading. The SD increased with deeper fading. Additionally, for some frequencies there is at least one position/orientation, at which no fading of more than 20 dB below the mean value is observed. Table 1 lists the SDs (as shown in Fig. 3) averaged over the 73 frequencies and normalized to the mean value over the frequencies and positions/orientations for -10 dB, -20 dB, and -30 dB and each, 300, 600 and 1500 steps, respectively. This normalized SD values decreases with a higher number of steps, but is almost independent of $\tau_{\text{RMS}}$.

![Figure 3. Empirical probability of fading as a function of frequency for 300 (left) and 600 (right) steps (both for $\tau_{\text{RMS}} \approx 50$ ns).](image)

3.3. Dependence of Fading on the Position or Orientation

The dependency of the fading as a function of the position/orientation of the EUT antenna is evaluated in this section. Figure 4 shows the mean, minimum, maximum and the SD of the 73 frequencies for each position/orientation exemplarily for $\tau_{\text{RMS}} \approx 50$ ns and both, 300 and 600 steps. The results are similar to the previous ones. The SDs (as shown in Fig. 4) averaged over the positions/orientations and normalized to the total mean value over the frequencies and positions/orientations are listed in Table 1. The normalized SD values averaged over the positions/orientations are the same as the ones which are averaged over the frequencies. The mean values over all frequencies and positions/orientations for the specific number of steps and loading fit very well with the theory of Rayleigh fading.

![Figure 4. Empirical probability of fading as a function of position/orientation for 300 (left) and 600 (right) steps (both for $\tau_{\text{RMS}} \approx 50$ ns).](image)

4. Summary

The measurements show that the averaged empirical probability of fading is independent of frequency or the position/orientation of the EUT and also independent of loading or $\tau_{\text{RMS}}$, respectively. However, for some individual combinations of position and frequency, very deep fading did not occur. As the SD generally decreases with increasing number of (independent) steps, the number of this outliers can be reduced. Overall, the RC is a reproducible test environment for wireless device performance under Rayleigh fading conditions.
Figure 4. Empirical probability of fading as a function of position and orientation of the EUT for 300 (left) and 600 (right) steps (both for $\tau_{RMS} \approx 50$ ns).

Table 1. Mean values and SD for different fading levels, steps and $\tau_{RMS}$. The theoretical values from Rayleigh fading for the mean are given in italics.

| Fading depth | $\tau_{RMS}$ | 300 Steps | 600 Steps | 1500 Steps |
|--------------|--------------|-----------|-----------|------------|
|              | 190 ns | 50 ns | 23 ns | 190 ns | 50 ns | 23 ns | 190 ns | 50 ns | 23 ns |
| -10 dB Mean | 0.0948 | 0.0958 | 0.0968 | 0.0947 | 0.0959 | 0.0978 | 0.0949 | 0.0956 | 0.0973 |
| -10 dB SD Pos./Or. | 0.18 | 0.18 | 0.19 | 0.13 | 0.14 | 0.14 | 0.08 | 0.10 | 0.11 |
| -20 dB Mean | 0.0100 | 0.0103 | 0.0100 | 0.0098 | 0.0101 | 0.0103 | 0.0099 | 0.0100 | 0.0101 |
| -20 dB SD Freq. | 0.56 | 0.58 | 0.56 | 0.41 | 0.41 | 0.40 | 0.25 | 0.26 | 0.27 |
| -20 dB SD Pos./Or. | 0.57 | 0.58 | 0.56 | 0.41 | 0.41 | 0.40 | 0.25 | 0.26 | 0.26 |
| -30 dB Mean | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0011 | 0.0010 | 0.0010 | 0.0010 |
| -30 dB SD Freq. | 1.80 | 1.79 | 1.77 | 1.25 | 1.28 | 1.23 | 0.80 | 0.82 | 0.80 |
| -30 dB SD Pos./Or. | 1.83 | 1.83 | 1.79 | 1.25 | 1.29 | 1.24 | 0.81 | 0.82 | 0.80 |

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