REVERBERATION CHAMBERS FOR TESTING WIRELESS DEVICES AND SYSTEMS

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Signal propagation in realistic environment

\[ \vec{e}_T = \sum_{n=1}^{\infty} \vec{e}_n (t - \tau_n) u(t - \tau_n) \]

\[ u(t - \tau_n) = \begin{cases} 
1 & \text{if } t \geq \tau_n \\
0 & \text{if } t < \tau_n
\end{cases} \]

\[ E = A_{LOS} \cos(2\pi f_c t) + \sum_{n=1}^{N} A_n \cos[2\pi(f_c + f_n)t + \phi_n] \]
Signal propagation in realistic environment

Urban environment

Rural environment

Direct component (LOS)

Scattered component (NLOS)
**Ricean K-factor**

**K-factor:** \( k = \frac{\text{direct component}}{\text{scattered components}} \)  \ or \  \( K = 10 \log(k) \)

- \( K = -\infty \) dB (Rayleigh)
- \( K = 4 \) dB
- \( K = 1 \) dB
- \( K = 10 \) dB
A delay profile in the form of a "tapped delay-line", characterized by a number of taps at fixed positions on a sampling grid. The profile can be further characterized by the r.m.s. delay spread and the maximum delay spanned by the taps.

**Table B.2.1-1 Delay profiles for E-UTRA channel models**

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of channel taps</th>
<th>Delay spread (r.m.s.)</th>
<th>Maximum excess tap delay (span)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended Pedestrian A (EPA)</td>
<td>7</td>
<td>45 ns</td>
<td>410 ns</td>
</tr>
<tr>
<td>Extended Vehicular A model (EVA)</td>
<td>9</td>
<td>357 ns</td>
<td>2510 ns</td>
</tr>
<tr>
<td>Extended Typical Urban model (ETU)</td>
<td>9</td>
<td>991 ns</td>
<td>5000 ns</td>
</tr>
</tbody>
</table>

**Table B.2.1-3 Extended Vehicular A model (EVA)**

<table>
<thead>
<tr>
<th>Excess tap delay [ns]</th>
<th>Relative power [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>-1.5</td>
</tr>
<tr>
<td>150</td>
<td>-1.4</td>
</tr>
<tr>
<td>310</td>
<td>-3.6</td>
</tr>
<tr>
<td>370</td>
<td>-0.6</td>
</tr>
<tr>
<td>710</td>
<td>-9.1</td>
</tr>
<tr>
<td>1090</td>
<td>-7.0</td>
</tr>
<tr>
<td>1730</td>
<td>-12.0</td>
</tr>
<tr>
<td>2510</td>
<td>-16.9</td>
</tr>
</tbody>
</table>
Definition of Reverberation Chamber

A properly operating RC is an electrically large cavity, where the electromagnetic field is statistically uniform, isotropic and randomly polarised within an acceptable and predictable uncertainty and confidence limit.

- Uniformity implies all spatial locations within RC (at sufficient distance from metal surfaces) are equivalent.
- Isotropic implies that at given location in RC electromagnetic energy is same in any direction.
- Random polarization implies that the phase relationships between polarized components are equivalent.
......electrically large cavity...

Frequency Domain

\[
\vec{E} = -\frac{1}{j \omega \varepsilon} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{p=0}^{\infty} \int_{V} \vec{J} \cdot \vec{f}_{mnp} \, dV \quad \vec{f}_{mnp} - j \omega \mu \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{p=0}^{\infty} \left( k_{mnp}^2 - \tilde{k}^2 \right) \int_{V} \left| \vec{e}_{mnp} \right|^2 \, dV \quad \vec{e}_{mnp}
\]

\[
\tilde{k}^2 = k^2 + (-1 + j) \frac{k^2 \omega_m}{Q_m \omega}
\]

Plane \( z = 2 \) m, \( f = 563 \) MHz

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COST IC 1407 Training School - Prague
"Reverberation chambers..."
Field stirring actions

MECHANICAL STIRRING, i.e. boundary condition variations
- Rotating paddles (NIST group, ...)
- Moving walls (Capsalis, ...)
- Vibrating walls (VIRC by Leferink, ...)
- ............

SOURCE STIRRING
- Generator amplitude or phase variation (Hill, ...)
- Frequency variation (frequency stirring) (T. A. Loughry, ...)
- Moving transmitting antenna to change mode coupling (Huang, Carlberg, Kildal, ...)
- ....

Example of mechanical stirring

Ensemble average, mean value (\langle X \rangle_N)
Maximum value
Max/Mean ratio
Statistical distributions: PDF and CDF.
Example of mechanical stirring

Ensemble average, mean value (\( <X>_N \))
Maximum value
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...electrically large cavity...

Time Domain

\[ \vec{e}_T = \sum_{n=1}^{\infty} \vec{e}_n(t - \tau_n)u(t - \tau_n) \]

\[ u(t - \tau_n) = \begin{cases} 
1 & \text{if } t \geq \tau_n \\
0 & \text{if } t < \tau_n 
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\end{cases} \]
Statistical distributions in an ideal RC

\[ E_x = E_{xr} + iE_{xi}, \quad E_y = E_{yr} + iE_{yi}, \quad E_z = E_{zr} + iE_{zi} \]

\[ < E_{xr} > = < E_{xi} > = < E_{yr} > = < E_{yi} > = < E_{zr} > = < E_{zi} > = 0 \]

\[ f(E_{xr}) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{E_{xr}^2}{2\sigma^2} \right] \]

CHI-2DOF (\( \chi_2 \))

\[ f(|E_x|) = \frac{|E_x|}{\sigma^2} \exp \left[ -\frac{|E_x|^2}{2\sigma^2} \right] \]
Distribution of the received power $P_R$ or of $|E_i|^2$

$$\chi^2_{2\text{-DOF}}$$

$$f(|E_x|^2) = \frac{1}{2\sigma^2} \exp\left[-\frac{|E_x|^2}{2\sigma^2}\right]$$

[Probability Density Function: Chi-Squared]

[ Cumulative Distribution Function: Chi-Squared]
Statistical distribution of the total E-field

CHI-6DOF $\chi_6$

$$f(|E|) = \frac{|E|^5}{8\sigma^6} \exp \left[ -\frac{|E|^2}{2\sigma^2} \right]$$
Example of received power statistics

Chamber dimensions 6 x 4 x 2.5 m
\( f_0 = 45 \text{ MHz} \)

Stirring ratio 42 dB

\[
CDF \left\{ \chi_2^2(s) \right\} = 1 - \exp\{-s\}
\]

\( s = \) mean normalised received power
We have to move toward a non-ideal RC to create a realistic propagation channel

\[ f(E_x) = \frac{E_x}{\sigma_x^2} \cdot e^{-\frac{E_x^2}{2\sigma_x^2}} \]

\[ K = \frac{\nu^2}{2\sigma^2} \]

\[ f(x \mid \nu, \sigma) = \frac{x}{\sigma^2} \exp\left(\frac{-(x^2 + \nu^2)}{2\sigma^2}\right) I_0 \left(\frac{x\nu}{\sigma^2}\right) \]
Chamber Set-up for Rician Environment

Antenna positioning away from the DUT

Antenna positioning toward the DUT

By varying the characteristics of the reverberation chamber and/or the antenna configurations in the chamber, any desired Rician K-factor can be obtained.
Reverberation Chamber Ricean Environment

\[ K = \frac{3}{2} \frac{V}{\lambda Q} \frac{D}{r^2} \]

• We see that \( K \) is proportional to \( D \). This suggests that if an antenna with a well defined antenna pattern is used, it can be rotated with respect to the DUT, thereby changing the \( K \)-factor.

• Secondly, we see that if \( r \) is large, \( K \) is small (approaching a Rayleigh environment); if \( r \) is small, \( K \) is large. This suggests that if the separation distance between the antenna and the DUT is varied, then the \( K \)-factor can also be changed to some desired value.

• Next we see that by varying \( Q \) (the chamber quality factor), the \( K \)-factor can be changed to some desired value. The \( Q \) of the chamber can easily be varied by simply loading the chamber with lossy materials.

How can we generate a Rician environment?

\[ K = \frac{3}{2} \frac{V}{\lambda Q} \frac{D}{r^2} \]

\[ K = \frac{|\langle S_{21} \rangle|^2}{|S_{21} - \langle S_{21} \rangle|^2} \]
Parameters of interest for the channel emulation

Impulse Responses and Power Delay Profiles

\[ PDP(t) = \left< |h(t)|^2 \right>_N, \ h(t) = IFT[S_{21}] \]

\[ \tau_{\text{RMS}} = \frac{\sqrt{\int_0^\infty (t-\tau_{\text{ave}})^2 PDP(t) dt}}{\int_0^\infty PDP(t) dt} \]

\[ \tau_{\text{ave}} = \frac{\int_0^\infty t PDP(t) dt}{\int_0^\infty PDP(t) dt} \]

One characteristic of the PDP that has been shown to be particularly important in wireless systems that use digital modulation is the \textit{rms} delay spread of the PDP
Insertion of absorbing material to tune the PDP
PDP of an oil refinery

By NIST
Living room (St)  Laboratory

\[ \tau_{\text{RMS}} = 20.64 \text{ ns} \]
\[ \tau_{\text{RMS}} = 22.54 \text{ ns} \]
\[ \tau_{\text{RMS}} = 30.46 \text{ ns} \]
\[ \tau_{\text{RMS}} = 34.25 \text{ ns} \]

\( \tau_{\text{RMS}} = 20.64 \text{ ns} \)
\( \tau_{\text{RMS}} = 22.54 \text{ ns} \)
\( \tau_{\text{RMS}} = 30.46 \text{ ns} \)
\( \tau_{\text{RMS}} = 34.25 \text{ ns} \)
Absorber positioning

8x VHP-8-NRL + 4x VHP-18-NRL + 4x ANW-77

RMS time delay spread

<table>
<thead>
<tr>
<th>SIDE</th>
<th>CENTER</th>
<th>PERIODIC</th>
<th>BARRIER</th>
</tr>
</thead>
<tbody>
<tr>
<td>125.86 ns</td>
<td>78.46 ns</td>
<td>72.04 ns</td>
<td>70.06 ns</td>
</tr>
</tbody>
</table>

ITU-R P.1238-7
Indoor residential
$\tau_{RMS} = 70$ ns

ITU-R M.2135-1
Suburban macro
$\tau_{RMS} = 75$ ns

“Reverberation chambers..."
The chamber coherence bandwidth

Average modal bandwidth

\[ B_m = \frac{f_c}{Q_{av}} \]

Coherence bandwidth

\[ B_{c,\rho} = \frac{f_c}{Q_{av}} \sqrt{1 - |\rho|^2} \]

Channel band

Subcarriers, \( \Delta f = 15 \text{ kHz} \)
Over-The-Air tests in RC of a real Base Station

“Nokia Solutions and Networks” Flexi Multiradio 10 BTS

- 3 sectors RF modules;
- Maximum 80 W x antenna connector;
- Band 20 (800 MHz) and band 3 (1.8 GHz);

6 x 4 x 2.5 m reverberation chamber
Example of a transmission quality test

- **Reference signal received power (RSRP):** is the average of the power of resource elements that carry cell-specific reference signals.

- **Reference signal received quality (RSRQ):** is based on the ratio of RSRP and RSSI (total wideband received power).

- **PDSCH net throughput:** is the throughput measured at physical layer at the client in the data downlink channel, removing the re-transmissions of negatively acknowledged TBs.

- **Signal to interference and noise ratio (SINR):** is the ratio between the wanted part of the signal and the sum of interference and noise.
Modulation and Coding Scheme (MCS) distribution

MCS 22-28
Modulation 64QAM for PDSCH

Robustness

Transport block size (for 50 PRBs)

TP >70Mbps

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Carrier aggregation

<table>
<thead>
<tr>
<th>Cell</th>
<th>Physical Cell ID</th>
<th>EARFCN UL</th>
<th>EARFCN DL</th>
<th>E-UTRA operating band</th>
<th>Bandwidth (MHz)</th>
<th>Center frequency UL (MHz)</th>
<th>Center frequency DL (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell # 1</td>
<td>3</td>
<td>19450</td>
<td>1450</td>
<td>3</td>
<td>20</td>
<td>1735</td>
<td>1830</td>
</tr>
<tr>
<td>Cell # 2</td>
<td>4</td>
<td>24300</td>
<td>6300</td>
<td>20</td>
<td>10</td>
<td>847</td>
<td>806</td>
</tr>
</tbody>
</table>

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"Reverberation chambers..."
Uplink in presence of interference and noise

- Maximum Ratio Combining (MRI)
- Interference Rejection Combining (IRC)
- Coordinated MultiPoint (CoMP)
Uplink in presence of interference and noise

<table>
<thead>
<tr>
<th>Frequency (50 PRBs)</th>
<th>Subcarriers = 6 PRBs, 1.08 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>TIME (2 slots = 1 TTI = 1 ms = 14 OFDMA symbols) - this is 1st TTI in 10 ms multiframe</td>
<td></td>
</tr>
<tr>
<td>RS</td>
<td>DTX</td>
</tr>
<tr>
<td>DTX</td>
<td>DTX</td>
</tr>
<tr>
<td>RS</td>
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</tr>
<tr>
<td>DTX</td>
<td>DTX</td>
</tr>
</tbody>
</table>

resource elements for PHICH, PCFICH (these could be boosted via parameters) and PDCCH (control channel)

<table>
<thead>
<tr>
<th>Frequency (50 PRBs)</th>
<th>Subcarriers = 180 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>

resource elements for RS (Reference Signals)

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<th>Frequency (50 PRBs)</th>
<th>Subcarriers = 180 KHz</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>

resource elements for broadcast channel (PBCH)

<table>
<thead>
<tr>
<th>Frequency (50 PRBs)</th>
<th>Subcarriers = 180 KHz</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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</tbody>
</table>

resource elements for primary synchronization (PSS)

<table>
<thead>
<tr>
<th>Frequency (50 PRBs)</th>
<th>Subcarriers = 180 KHz</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

resource elements for secondary synchronization (SSS)

<table>
<thead>
<tr>
<th>Frequency (50 PRBs)</th>
<th>Subcarriers = 180 KHz</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
</tbody>
</table>

resource elements for PDSCH (traffic channel)

Pulse duration (μs) | 70 | 100 | 250
Pulse frequency (Hz) | 500 | 1000 | 2000

<table>
<thead>
<tr>
<th>Attenuation on Interfering Ue (dB)</th>
<th>Throughput (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>500 Hz</td>
</tr>
<tr>
<td>65</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>70</td>
<td>2000 Hz</td>
</tr>
</tbody>
</table>

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MIMO 4x4 configuration

Antennas transmitting useful signal (S) 2 panels x-pol

Logperiodic noise antenna

1800 MHz LTE eNB transmitters

R&S Attenuator array

RANK 1

RANK 2

RANK 3

RANK 4

Modulation utilization %

SINR MIMO 4x4 [dB]

Rank utilization %

SINR MIMO 4x4 [dB]

Duty cycle

Noise generator

RC

QXDM

1800 MHz

LTE eNB transmitters

R&S Attenuator array

Antennas transmitting useful signal (S) 2 panels x-pol

Logperiodic noise antenna

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"Reverberation chambers..."
High speed trains: effect of Doppler shift and fading on Throughput and Success rate

(a): same SISO cell

(b): two different SISO cells
Improving signal orthogonality preservation by the so-called PRACH of a restricted set of cyclic shifts in the random access procedure.

After the RC lab. testing, the benefit of using a larger separation between sequences was verified in the Northern Italy High Speed Rail Line between Bologna and Piacenza.
5G Base Stations: a new challenge for the RC testing

- Higher frequency range (e.g. 28 GHz)
- Higher channel bandwidth (200 MHz-400 MHz)
- Beam forming
- Beam steering
- Reduced beam width (6 deg.)
- Very compact equipment: base band electronics, MW electronics, and antennas highly integrated.
- The whole eN inside the RC: power supply, ventilation, safety, .....

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"Reverberation chambers..."
References

• IEC 61000-4-21, “Electromagnetic compatibility (EMC) - Part 4-21: Testing and measurement techniques – Reverberation chamber test methods”.


• Stephen J. BoyesYi Huang, “Reverberation Chambers: Theory and Applications to EMC and Antenna Measurements”, 2015, John Wiley & Sons, Ltd.


• F. Leferink, “High Field Strength in a Large Volume: The Intrinsic Reverberation Chamber”, IEEE EMC 1998, Denver, CO, USA


• GPP, “Universal mobile telecommunications system (umts); lte; universal terrestrial radio access (utra) and evolved utra (e-utra); user equipment (ue) over the air (ota) performance; conformance testing,” ETSI, Sophia Antipolis Cedex, France, 3GPP Technical Specification TS37.544, V14.1.0, Apr. 2017.
References, cont.


• *Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz*, International Telecommunication Union - ITU Recommendation P.1238-7, Feb. 2012.
References, cont.


References, cont.


Many, many others .. sorry for missing.

Dedicated sessions at Conferences

• EMC Europe 2019, INTERNATIONAL SYMPOSIUM AND EXHIBITION ON ELECTROMAGNETIC COMPATIBILITY, 2-6 SEPT. 2019, BARCELONA, SPAIN.