SDR-Based Channel Emulator using a Semi-Stochastic Radio Propagation Model

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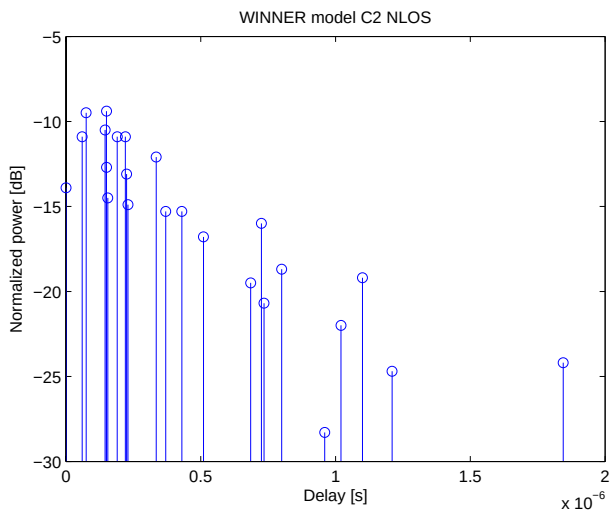
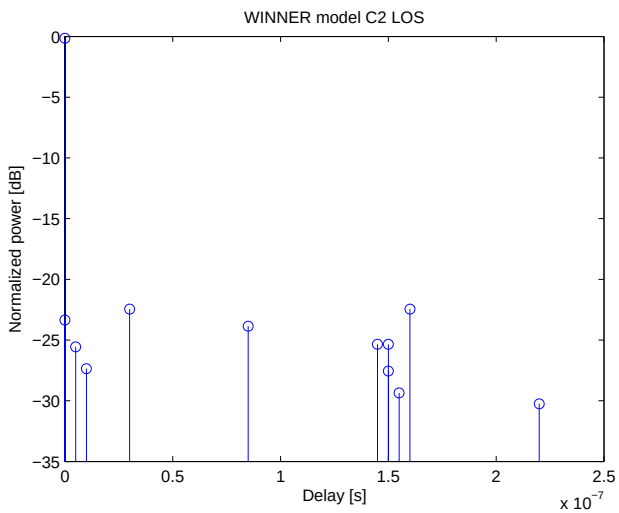
June 12, 2013

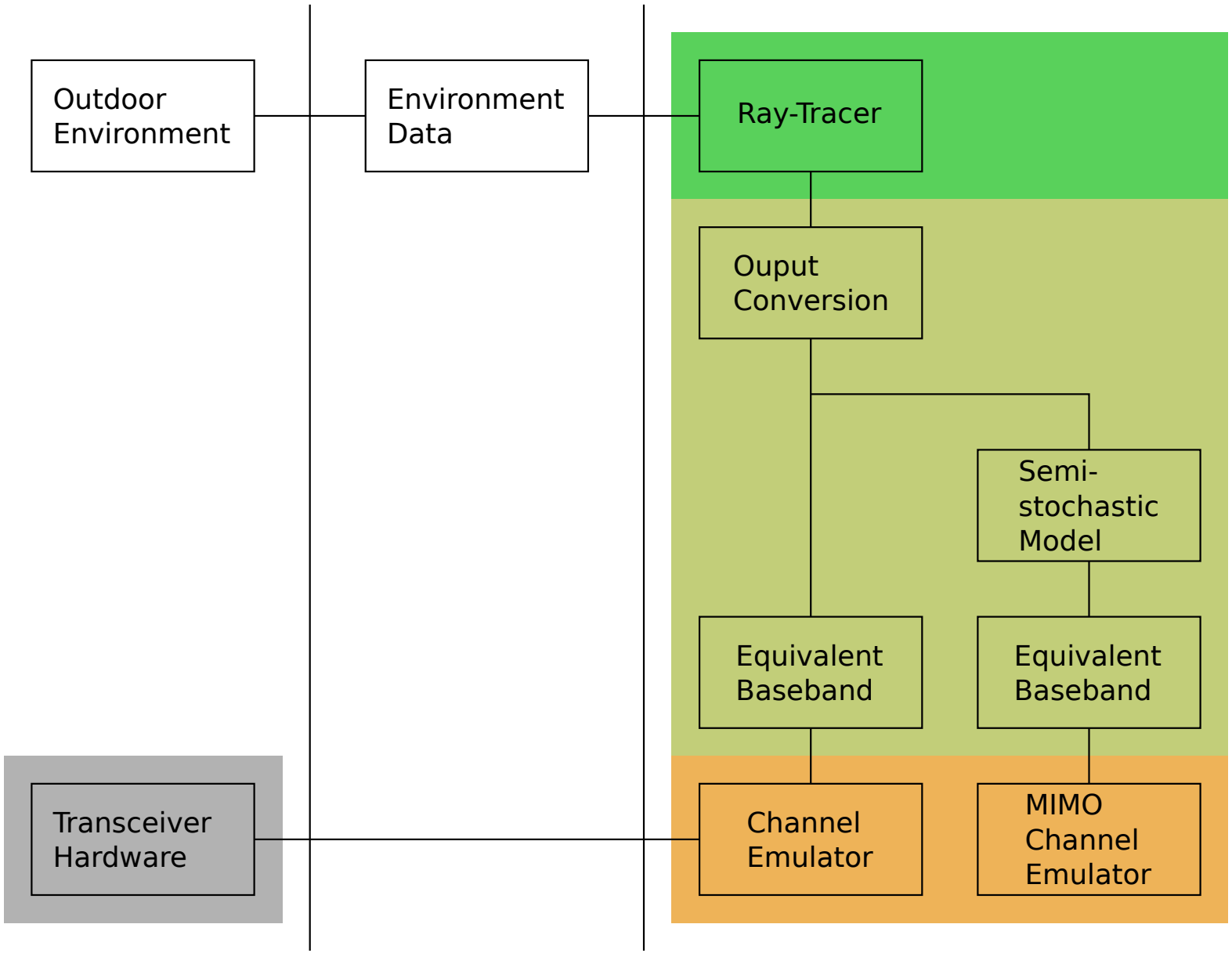
Motivation

- From stochastic channel models to more realistic, site aware models
- Software defined channel emulation
- Hardware in the Loop testing





Workflow Overview

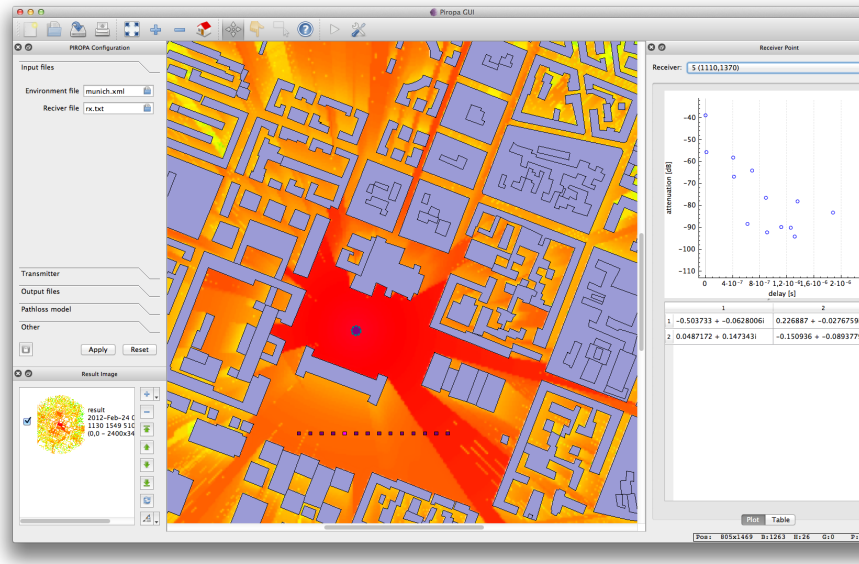


Ray optical path simulation
What is PIROPA?

PIROPA is a non-interactive C++ command line program, a Demonstration GUI facilitates the usage.

Input

- Vector based environment data,
- a transmitter location t, andTo
- receiver locations r_i

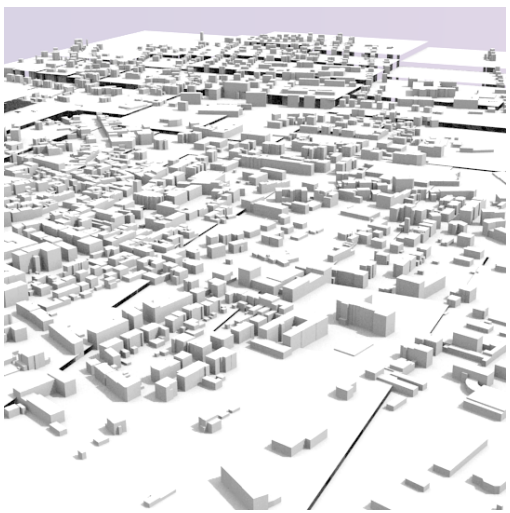


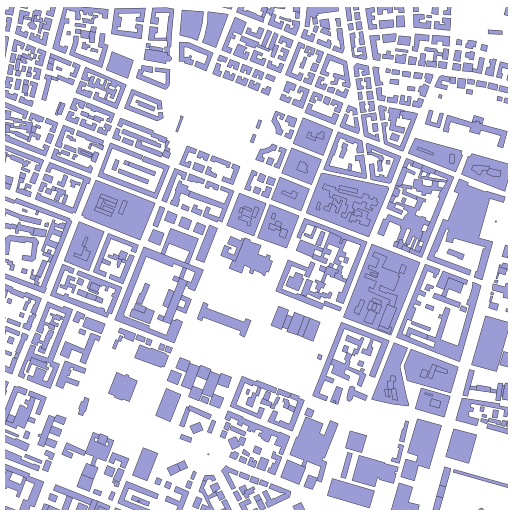
Output

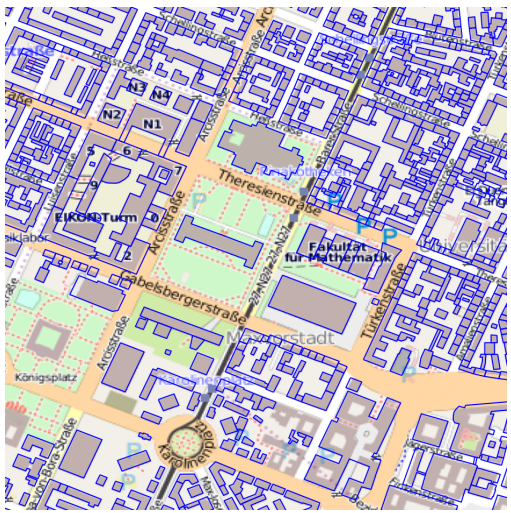
- Sets of paths $\{p|p \text{ is a path from } t \text{ to } r_i\}$, where
- the path p is a sequence $(t, c_1, c_2, \ldots, c_{n-1}, r_i)$ and
- $t, r_i, c_i \in \mathbb{R}^3$ are locations in the environment space.

Ray optical path simulation
Environment data

- Environment data is vector based 2.5D building data
- All walls are upright and roofs are flat
- Data is available from governmental, commercial and non-commercial sources (e.g. OSM)
- Dealing with the data quality, or lack of quality, is a challenge
- There is no unified standard format for such data
- A preprocessing tool creates a custom input format for PIROPA







Basic Path loss model

$$L^{dB}(p) = L_0^{dB}(p) + \sum_{e \in E} \sum_{i=1}^{n_e(p)} L_e^{dB}(\alpha)$$

$$L_0^{dB}(p) = 20 \lg \frac{4\pi}{\lambda_t} - 10 \lg G_t(\phi(r), \psi(r)) + z_A + 10\gamma \lg d(r)$$

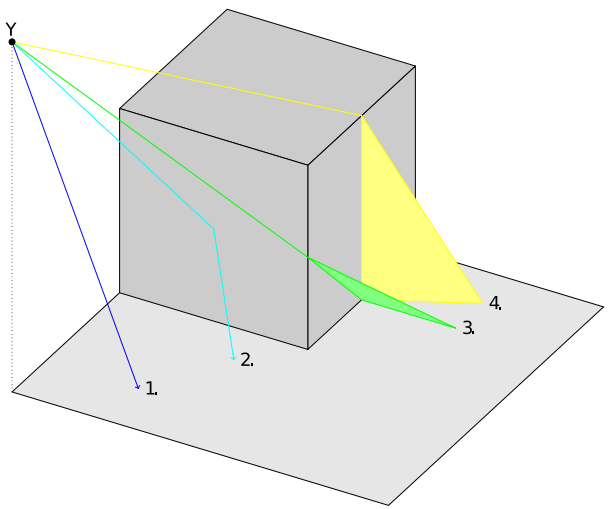
- λ_t signal wavelength
- $G_t(\phi(r), \psi(r))$ antenna gain in the given direction
- z_A calibration coefficient
- γ path loss exponent
- $d(r)$ the passed distance of the path

Ray optical path simulation
From path to color image

Basic Path loss model

$$L^{dB}(p) = L_0^{dB}(p) + \sum_{e \in E} \sum_{i=1}^{n_e(p)} L_e^{dB}(\alpha)$$

- $E = \{\text{Reflection}, \text{Vertical diffraction}, \text{Horizontal diffraction}\}$



- $n_e(p)$ The number of occurrences of an effect $e \in E$

Basic Path loss model

$$L^{dB}(p) = L_0^{dB}(p) + \sum_{e \in E} \sum_{i=1}^{n_e(p)} L_e^{dB}(\alpha)$$

$$L_e^{dB}(\alpha) = \sum_{j=0}^{k} z_{e,j} \alpha_{e,i}^{j}(p)$$

- $\alpha_{e,i}^{j}(p)$ is the angular change at a certain position
- $z_{e,j}$ calibration coefficients for effects

PIROPA Algorithm

1. Shoot rays from the transmitter location into the scene

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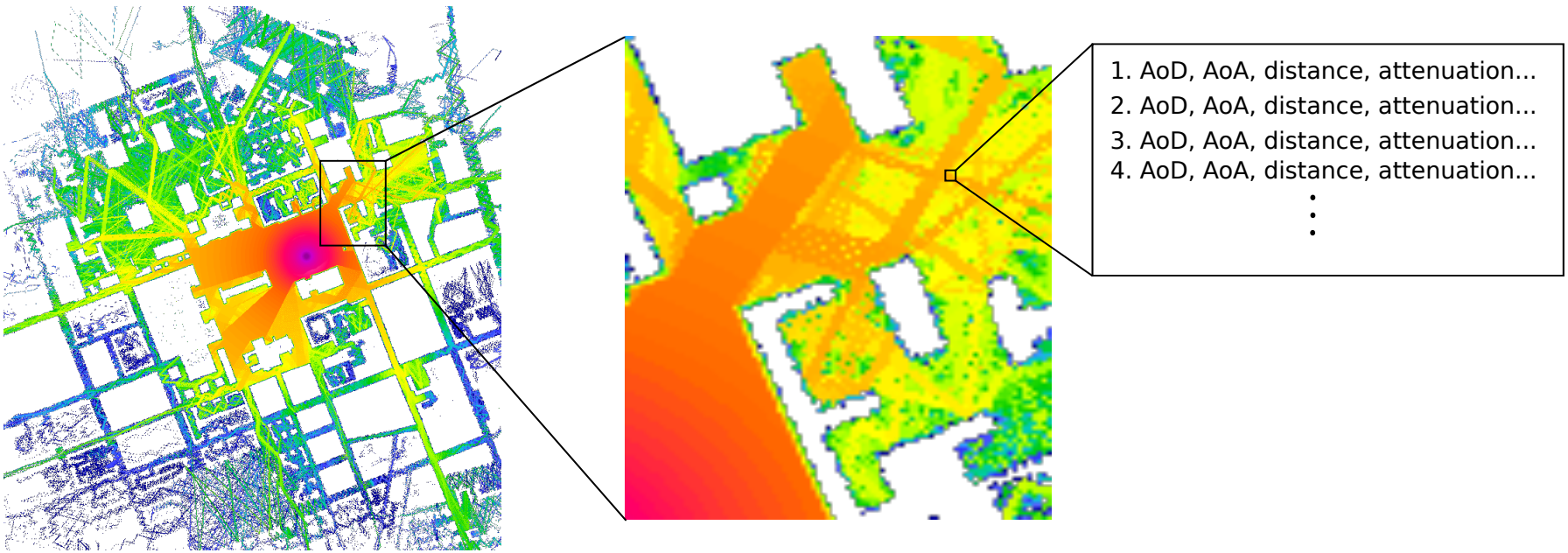
3. Test the found intersection points for occurrences of physical effects
4. Insert a virtual transmitter according to the effect parameter
5. Start over until termination condition is met

Ray optical path simulation
Simulation Performance

- Many Tweaks to increase performance
- Large environment data is partitioned to increase performance on the intersection test and improve memory handling. This is completely transparent to the simulation.
- The typical building structure allows for some assumptions which leads to a faster calculations. A two times 2D calculation instead of a full 3D calculation is performed.
- OpenCL to employ a multitude of heterogeneous computing hardware

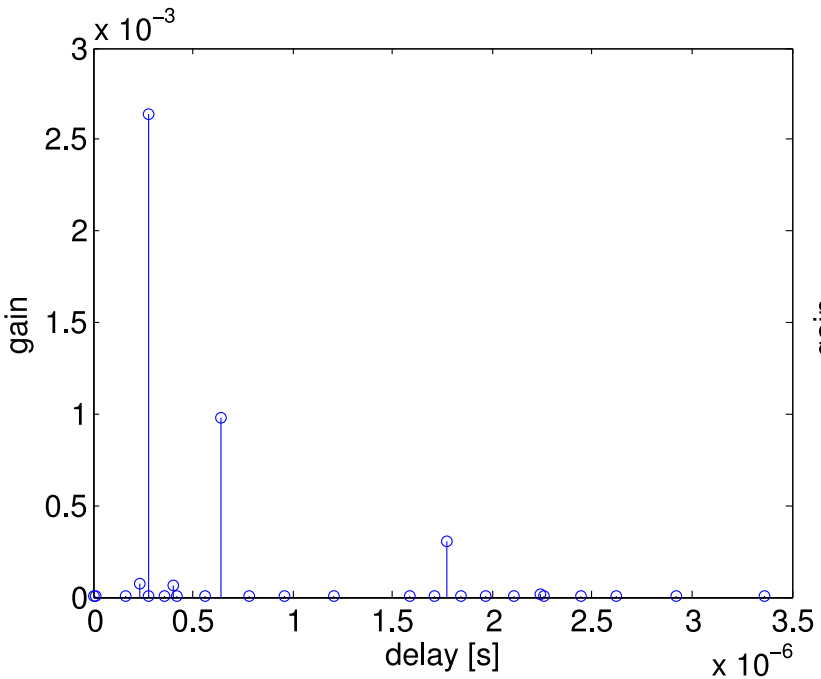
Ray optical path simulation
Output data

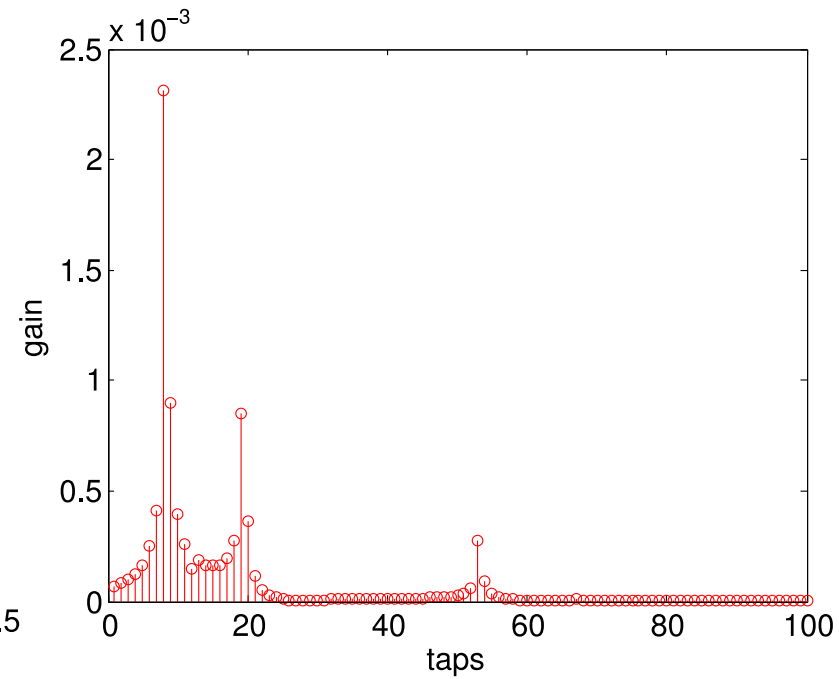
- The output data is a text file or an image representation
- In the image, every pixel is a receiver and the attenuation is displayed by the color
- The text format contains the complete set of information of all paths for a given receiver location
  - extract channel (emulation) data with a conversion tool



Channel Emulator
Equivalent Baseband Conversion

- RWP Simulation outputs discrete "impulse response"/power delay profile (after conversion)
- Pulses not on a uniform sampling grid
- Equivalent baseband conversion is necessary to obtain filter coefficients
- We use an FFT filter design method for the interpolation





Channel Emulator

Equivalent Baseband Conversion

$$h(t) = \sum_m \alpha_m \delta(t - \tau_m T_s) \qquad \tau_m \in \mathbb{R}$$

$$H(f) = \sum_m \alpha_m e^{-j2\pi f \tau_m T_s}$$

$$H_k = \sum_m \alpha_m e^{-j2\pi k f_s \tau_m T_s} \qquad f_s = \frac{1}{N T_s}$$

$$= \sum_m \alpha_m e^{-j2\pi \frac{k}{N} \tau_m}$$

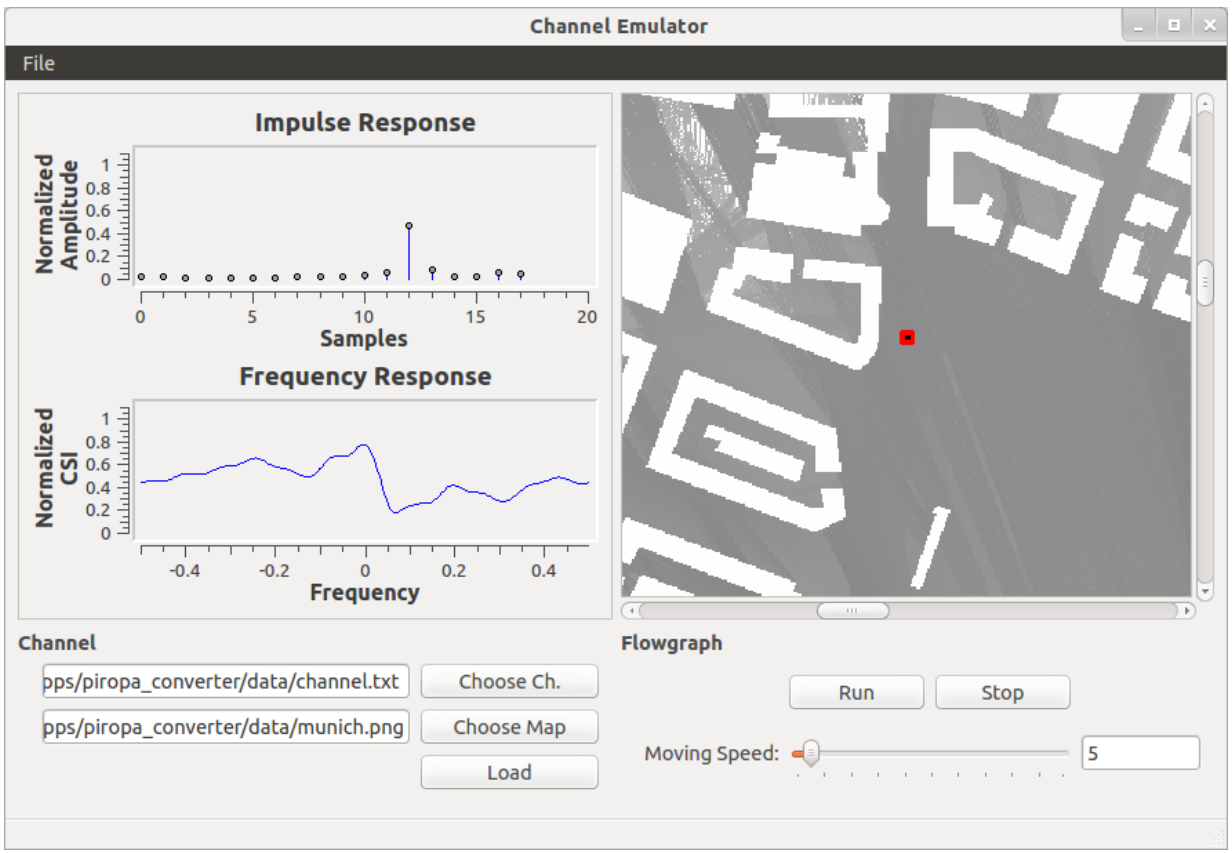
$$h_n = \sum_{k=0}^{N-1} H_k e^{j2\pi \frac{k}{N} n}$$

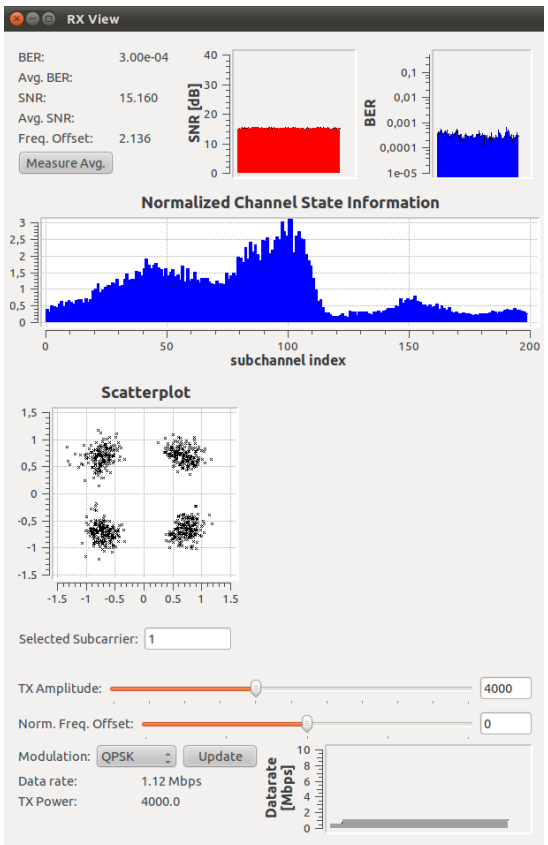
$$\vdots$$

$$= \sum_m \alpha_m e^{-j\frac{\pi}{N}(n+(N-1)\tau_m)} \frac{\sin(\pi\tau_m)}{\sin(\frac{\pi}{N}(\tau_m - n))}$$

Channel Emulator
Software

- Speed of receiver movement defines channel coherence time

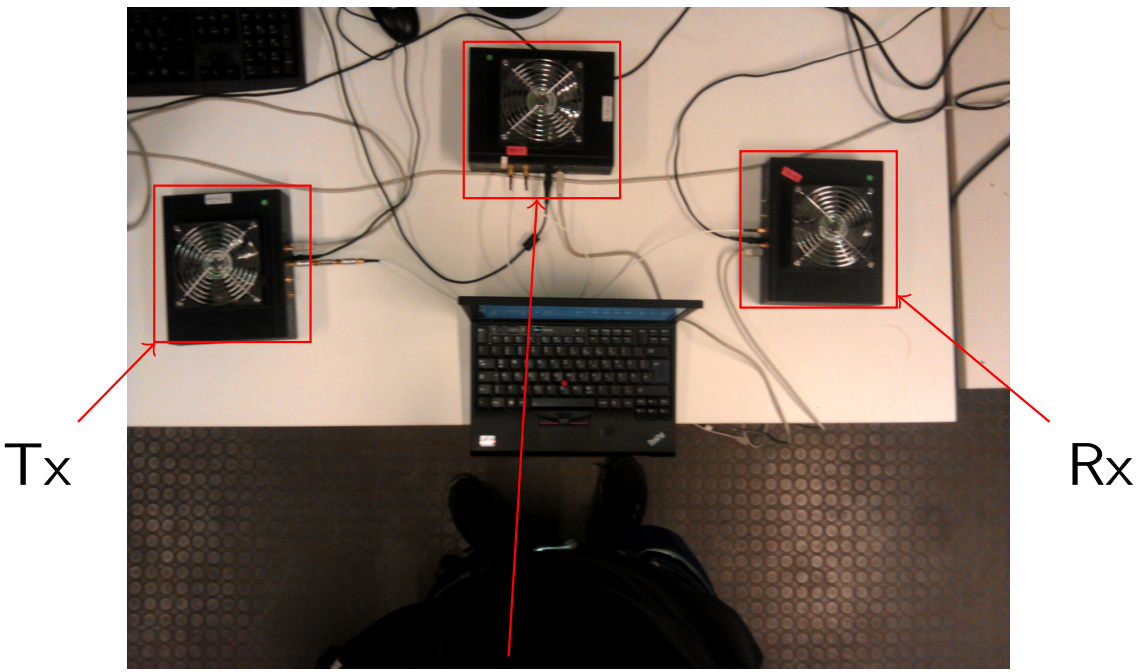




Channel Emulator

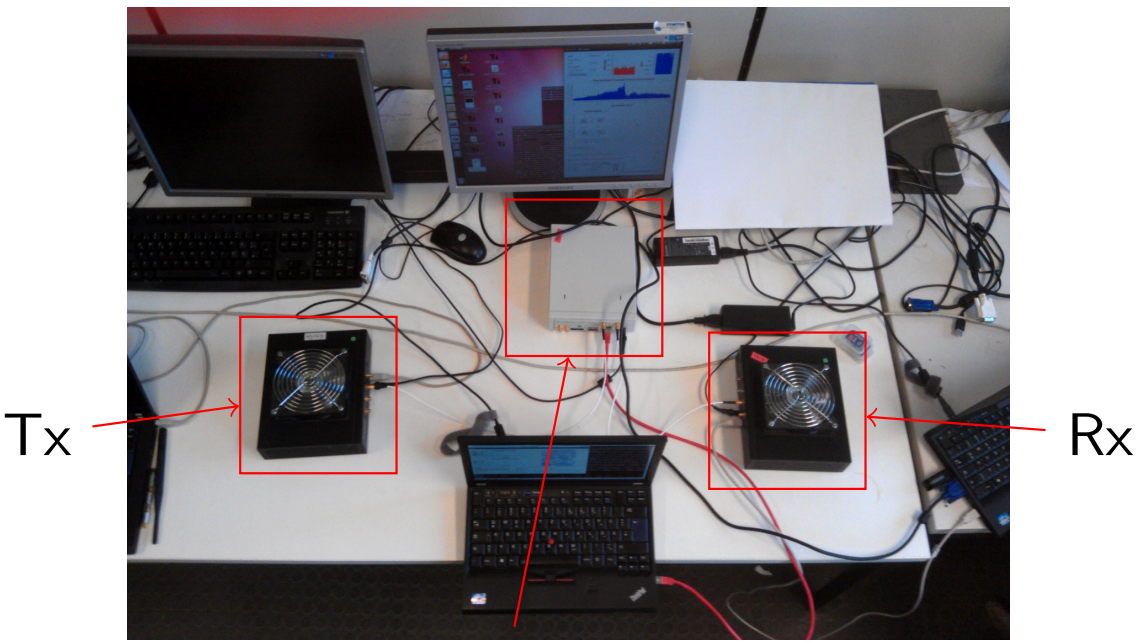
Hardware Testing Configuration

- some testing
- problems with coupling of signals, we used different frequencies for input and output
- problems with additional filtering effect of USRP1, halfband filters etc.

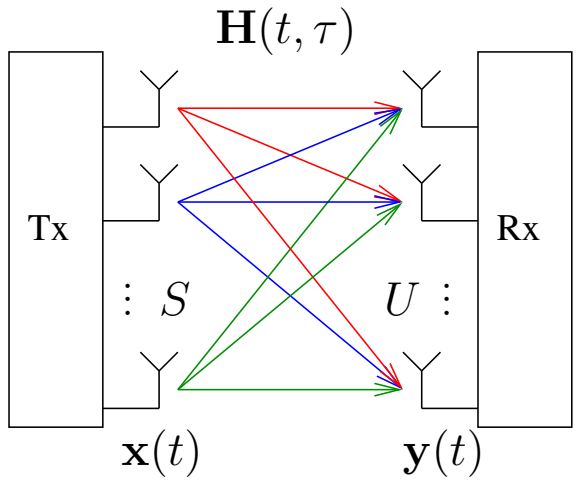


Channel Emulator
Hardware Testing Configuration

- some testing
- problems with coupling of signals, we used different frequencies for input and output
- problems with additional filtering effect of USRP1, halfband filters etc.
- USRP2 works much better



MIMO system model



Received signal:

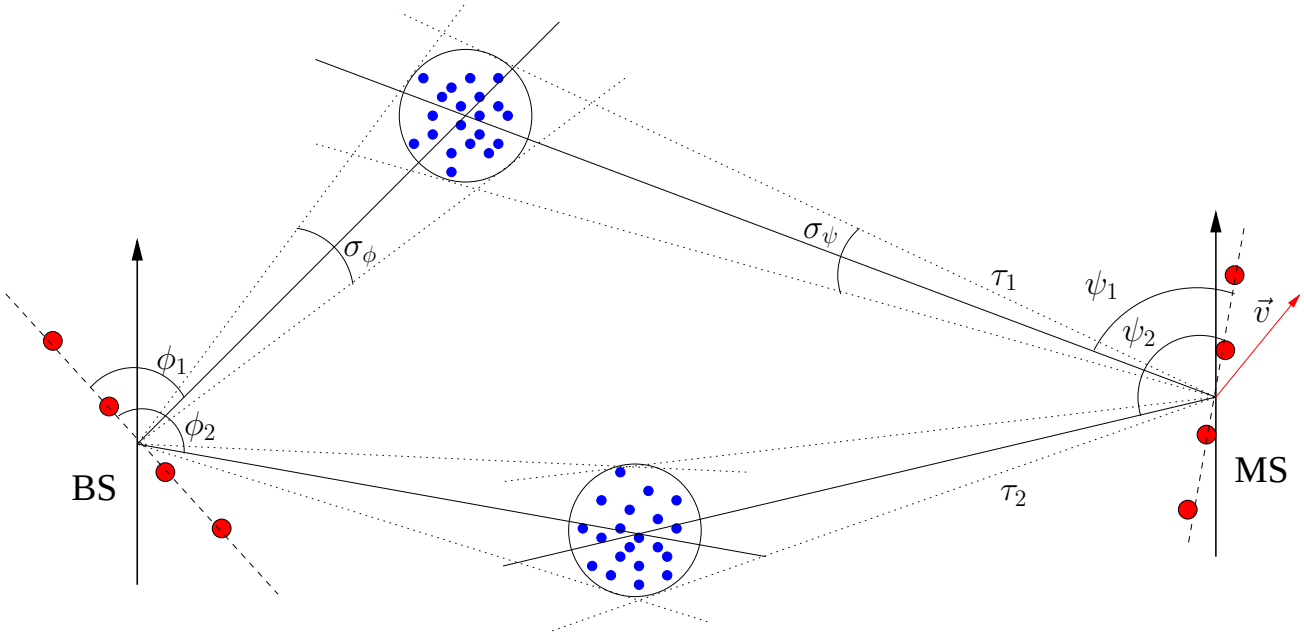
$$\mathbf{y}(t) = \int_{\tau} \mathbf{H}(t;\tau)\mathbf{x}(t-\tau)\mathrm{d}\tau + \mathbf{w}(t)$$

with

$$\mathbf{H}(t;\tau) = \begin{pmatrix} h_{1,1}(t;\tau) & h_{1,2}(t;\tau) & \dots & h_{1,S}(t;\tau) \\ h_{2,1}(t;\tau) & h_{2,2}(t;\tau) & \dots & h_{2,S}(t;\tau) \\ \vdots & \vdots & \ddots & \dots \\ h_{U,1}(t;\tau) & h_{U,2}(t;\tau) & \dots & h_{U,S}(t;\tau) \end{pmatrix}$$

Geometry-based stochastic channel model

Clusterized MIMO channel:



Double directional radio channel:

$$h_{u,s}(t;\tau) = \int_{\phi}\int_{\psi} g_{u,s}(t,\tau,\phi,\psi)\cdot \sqrt{G_{\mathrm{Tx},s}(\phi)}\sqrt{G_{\mathrm{Rx},u}(\psi)}\mathrm{d}\phi\mathrm{d}\psi$$

Output of deterministic step

From Ray-Tracing algorithm:

Parameters	Description
n, N	Path index, total number of paths (clusters)
G_n	Per path gain $\in [0, 1)$
d_n	Propagation distance
ϕ_n, ψ_n	Path AoD and AoA

Normalized power:

$$P_n = \frac{G_n}{\sum_{n=1}^{N} G_n}$$

Delay:

$$\tau_n = d_n / c$$

Generation of clusters

- The N Propagation paths from ray launching algorithm are regarded as representatives of clusters for MIMO channel model
- Generate M rays for each cluster

Parameters	Description
m, M	Ray index, number of rays per cluster
c_{AoA}	Cluster-wise RMS azimuth spread
α_m	Ray offset angles
$\vec{k}_{\mathrm{Tx},n,m}, \vec{k}_{\mathrm{Rx},n,m}$	Ray direction vectors
$\Phi_{n,m}$	Random initial phase $\in [0, 2\pi)$
$\vec{d}_{\mathrm{Tx},s}, \vec{d}_{\mathrm{Rx},u}$	Antenna element position vectors
v, θ	Speed and direction of mobile station

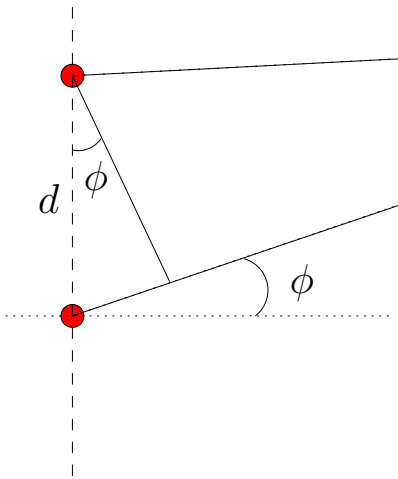
Angle of arrival:

$$\psi_{n,m} = \psi_n + c_{\mathrm{AoA}}\alpha_m$$

Channel coefficients

Channel coefficients based on clusters:

$$h_{u,s}(t,\tau) = \sqrt{\frac{P_n}{M}} \sum_{n=1}^{N} \sum_{m=1}^{M} \sqrt{G_{\mathrm{Tx},s}(\phi_{n,m})} \sqrt{G_{\mathrm{Rx},u}(\psi_{n,m})}$$



$$\exp\left(\jmath\left[\frac{2\pi}{\lambda}\vec{k}_{\mathrm{Tx},n,m}\cdot\vec{d}_{\mathrm{Tx},s}+\Phi_{n,m}\right]\right)$$

$$\exp\left(\jmath\frac{2\pi}{\lambda}\vec{k}_{\mathrm{Rx},n,m}\cdot\vec{d}_{\mathrm{Rx},u}\right)$$

$$\exp\left(\jmath\frac{2\pi}{\lambda}v_{n,m}t\right)\delta(\tau-\tau_{n,m})$$

Doppler frequency component:

$$v_{n,m} = \|v\|\cos(\psi_{n,m}-\theta)$$

Conclusion

- Next: Implement MIMO model into Channel Emulator
- Extensive Testing with 2x2 MIMO OFDM
- Take effects of the hardware into account

Finish

Thank You! Questions?