# A Measurement-Based Random-Cluster MIMO Channel Model

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## 1 Introduction

We present a novel geometry-based stochastic MIMO channel model based on the concept of multipath clusters. The so-called *Random-Cluster Model (RCM)* represents the channel in a propagation-based stochastic way, in which the geometry enters solely by statistical means. The starting point is the recently published parametric COST 273 MIMO Channel Model [1]. However, instead of using physical parameters (e.g. rooftop height or scatterer distance), our model requires only cluster parameters. As another major feature beyond COST 273, the model can now be *parametrized* directly from measurements. The model presently supports multi-user packet access, i.e. the channel changes completely from one time instant to another. Simple future extensions will incorporate smoothly time-variant channels as well.

We will present the new model in Section 2, and its parameterization in Section 3. The model is validated against MIMO measurement data using two performance metrics in Section 4. Finally we conclude the paper in Section 5.

## 2 Random Cluster Model

The model is structured as follows (Figure 1):

1. The *parametric channel* model (Section 2.2) bases on the concept of *multi-path clusters*. The COST 273 MIMO Channel Model [1] is taken as the conceptual basis but is improved as follows: (i) the number of parameters has been significantly reduced; (ii) the input parameter is a *statistical description* of the cluster parameters.
2. The system model is used to compile the frequency-dependent *channel matrix* from the parametric channel data (Section 2.3). The system parameters are the antenna array configurations, the antenna element patterns, and the system bandwidth.

### 2.1 Model overview

We introduce the concept of clusters in the following way [2]: Clusters are examined from the Tx and the Rx side separately. They show a mean angular positions and spreads when seen from the Tx and Rx, respectively, as well as a mean delay and a delay spread. (The term "spread" always refers to the rms spread values.) One can visualize this as an extension of the double-directional propagation model [3] to clusters. It does not matter for the description of a cluster, which propagation mechanism this cluster stems from (reflection, scattering, diffraction, ...). Clusters are only described by their mean parameters (delay, angles, powers) and their spreads. This makes this approach computationally advantageous.

Mathematically, the cluster-based impulse response can be written as

$$\mathbf{H}(\tau) = \sum_{c=1}^{N_c} \mathbf{H}_c(\underbrace{\gamma_c, \bar{\tau}_c, \bar{\varphi}_{\mathrm{Tx},c}, \bar{\varphi}_{\mathrm{Rx},c}, \sigma_{\tau_c}, \sigma_{\varphi_{\mathrm{Tx},c}}, \sigma_{\varphi_{\mathrm{Rx},c}}}_{\mathbf{\Theta}_c}) \tag{1}$$

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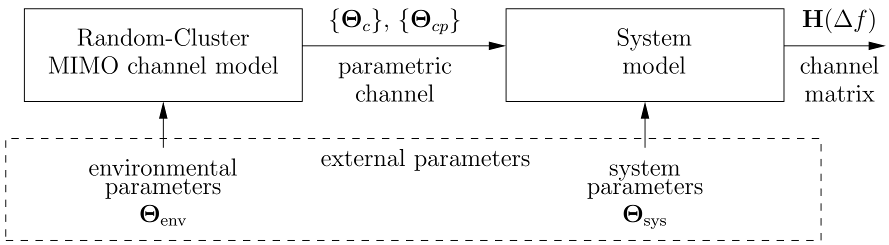



Figure 1: Model structure

where $\mathbf{H}_c(\cdot)$ denotes the cluster impulse response, and $\mathbf{\Theta}_c$ is the $c$th cluster parameter set containing the cluster's power $\gamma_c$, the *cluster position parameters,* i.e. mean delay $\bar{\tau}_c$, mean AoA $\bar{\varphi}_{\text{Rx},c}$, and mean AoD $\bar{\varphi}_{\text{Tx},c}$, the *cluster size parameters,* i.e. the delay spread $\sigma_{\tau_c}$, and the angle spreads $\sigma_{\varphi_{\text{Rx},c}}$ and $\sigma_{\varphi_{\text{Tx},c}}$, the number of paths within the $c$th cluster $N_{p,c}$, and the number of coexisting clusters $N_c$. The cluster impulse response is given as

$$\mathbf{H}_c(\tau, \mathbf{\Theta}_c) = \sum_{p=1}^{N_{p,c}} \mathbf{H}_{cp}(\underbrace{\gamma_{cp}, \tau_{cp}, \varphi_{\text{Tx},cp}, \varphi_{\text{Rx},cp}}_{\mathbf{\Theta}_{cp}}), \tag{2}$$

where $\mathbf{H}_{cp}$ denotes the contribution of the $p$th path in the $c$th cluster to the impulse response, where each path is described by the path parameter set $\mathbf{\Theta}_{cp}$ containing the path power $\gamma_{cp}$, delay $\tau_{cp}$, AoA $\varphi_{\text{Rx},cp}$, and AoD $\varphi_{\text{Tx},cp}$.

#### 2.1.1 Contribution

The essential task of a *parametric* channel model is to create the cluster- and path parameter sets ($\mathbf{\Theta}_c$ and $\mathbf{\Theta}_{cp}$) from the environment parameters $\mathbf{\Theta}_{\text{env}}$. The *system* model then creates a channel matrix from these parameters.

Our novel approach to model the environment is the following: the environment parameter $\mathbf{\Theta}_{\text{env}}$ is the multi-dimensional probability density function (pdf) of the joint distribution of all cluster parameters, hence,

$$\begin{aligned}\mathbf{\Theta}_{\text{env}} &= P_{\mathbf{\Theta}_c}(\mathbf{\Theta}_c) \\ &= P_{\bar{\tau},\bar{\varphi}_{\text{Tx}},\bar{\varphi}_{\text{Rx}},\sigma^2_{\bar{\gamma}},\sigma_\tau,\sigma_{\varphi_{\text{Tx}}},\sigma_{\varphi_{\text{Rx}}},N_c,N_p}(\bar{\tau}, \bar{\varphi}_{\text{Tx}}, \bar{\varphi}_{\text{Rx}}, \sigma^2_{\bar{\gamma}}, \sigma_\tau, \sigma_{\varphi_{\text{Tx}}}, \sigma_{\varphi_{\text{Rx}}}, N_c, N_p).\end{aligned} \tag{3}$$

This approach enables to easily create new clusters by drawing new samples from this pdf. In the following we describe how to create new channel realizations using the individual blocks of the model.

### 2.2 Applying the parametric channel model

The parametric channel model creates cluster parameter sets $\mathbf{\Theta}_c$ and path parameter sets $\mathbf{\Theta}_{cp}$ from the environment pdf $\mathbf{\Theta}_{\text{env}}$.

#### 2.2.1 Obtaining the cluster parameter sets $\mathbf{\Theta}_c$

The multi-dimensional environment pdf $\mathbf{\Theta}_{\text{env}}$ in (3) provides a representation of all possible kinds of clusters in a scenario. To model one realization of a scenario, we first have to fix the number of clusters. To do so we draw the *current* number of clusters $\tilde{N}_c$ from $\mathbf{\Theta}_{\text{env}}$.[1] Then we reduce the environment pdf given the number of clusters $\tilde{N}_c$ by conditioning as

$$\mathbf{\Theta}_{\text{env}}^{(\tilde{N}_c)} = P_{\mathbf{\Theta}_c|N_c}(\mathbf{\Theta}_c|N_c = \tilde{N}_c). \tag{4}$$

Finally, we create a number of $\tilde{N}_c$ *new clusters* by drawing cluster parameter sets $\mathbf{\Theta}_c$ from this reduced distribution.

[1] Mathematically this is done by integrating over all dimensions except for $N_c$, then drawing $\tilde{N}_c$ from this marginal distribution.

### 2.2.2 Obtaining the path parameter sets $\mathbf{\Theta}_{cp}$

Using the cluster parameter sets $\mathbf{\Theta}_{\rm c}$, $c = 1 \ldots \tilde{N}_c$, we *create new paths* by drawing the $N_{p,c}$ path parameters for each cluster $c$ from following distributions:

$$\tau_{cp} \sim \mathcal{N}(\bar{\tau}_c, \sigma^2_{\tau,c}),\ \varphi_{\mathrm{Rx},cp} \sim \mathcal{N}(\bar{\varphi}_{\mathrm{Rx},c}, \sigma^2_{\varphi_{\mathrm{Rx},c}}),\ \varphi_{\mathrm{Tx},cp} \sim \mathcal{N}(\bar{\varphi}_{\mathrm{Tx},c}, \sigma^2_{\varphi_{\mathrm{Tx},c}}),$$
$$\mathrm{abs}(\gamma_{cp}) = \sqrt{\bar{\gamma}^2_c / N_{p,c}},\ \arg(\gamma_{cp}) \sim \mathcal{U}(\ [-\pi \ldots \pi)\ ),$$

where $\mathcal{N}$ and $\mathcal{U}$ denote the Gaussian and uniform distribution, respectively.

## 2.3 Applying the system model

The system model creates the frequency-dependent MIMO channel matrix from the double-directional propagation paths.

$$\mathbf{H}(t, \Delta f) = \sum_{c=1}^{N_c} \sum_{p=1}^{N_{p,c}} \gamma_{cp} \cdot \mathbf{a}_{\mathrm{Rx}}(\varphi_{\mathrm{Rx},cp})\, \mathbf{a}^{\mathrm{T}}_{\mathrm{Tx}}(\varphi_{\mathrm{Tx},cp}) \cdot \mathrm{e}^{-j2\pi\, \Delta f\, \tau_{cp}}, \tag{5}$$

where $\mathbf{a}_{(\cdot)}$ denotes the (complex-valued) antenna array response, and $\mathbf{H}(t, \Delta f)$ denotes the time- and frequency-selective MIMO channel matrix with dimensions $N_{\mathrm{Rx}} \times N_{\mathrm{Tx}}$. For simplicity, we use the system model in frequency domain, the delay response can be directly obtained using an inverse Fourier transform.

In this paper, we model a $4 \times 4$ MIMO channel with uniform linear arrays using omni-directional antenna elements spaced 0.55 wavelengths at both Rx and Tx, and a system bandwidth of 20 MHz.

# 3 Parameterization

To construct the environment pdf, cluster parameters are needed. Using the framework introduced in [4], the algorithm identified the cluster parameters from measurements automatically. Subsequently, the environment pdf $\mathbf{\Theta}_{\mathrm{env}}$ is constructed using a kernel density estimator, that supports marginalization and conditioning (e.g. [5]).

# 4 Model validation

We validate the model against MIMO channel measurements carried out with an Elektrobit PropSound CS$^{\mathrm{TM}}$ wideband channel sounder at a center frequency of 2.55 GHz. The measured environment was a non-stationary, non-line-of-sight scenario in a student laboratory at the University of Oulu. The Tx was moved throughout the room, but the receiver was fixed outside the room. See [4] for a description of the measurements.

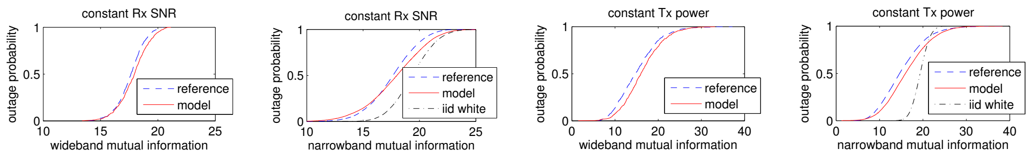
We used the following procedure to quantify the model's fit to the measurements: (i) identify clusters of propagation paths in measurements as described in [4], (ii) parameterize the environment parameter pdf $\mathbf{\Theta}_{\mathrm{env}}$ as described in Section 3, (iii) use the RCM to generate new channel realisations (see Section 2), (iv) use the system model together with the propagation paths from measurements to generate *reference* channels, (v) compare the channels modelled by the RCM to the reference channels by means of validation metrics.

As metrics we use the well-known mutual information (MI) [6], and the diversity order metric introduced in [7].

## 4.1 Mutual information

We chose to evaluate the wideband and narrowband MI for either constant Rx SNR of 10 dB (corresponding to optimum automatic gain control at the Tx) or constant Tx power (varying instantaneous SNR at the Rx with an average of 10 dB). The resulting cdfs are detailed in Figure 2.

The results for constant Rx SNR, shown in Figures 2a-b, detail how well the model represents the *multipath structure* of the room. The RCM channels fit the measured ones quite well,




(a) (b) (c) (d)

Figure 2: Validation by mutual information metric

the slope is only slightly different. The comparison to — hypothetical — Gaussian white iid. MIMO channels shows a significant difference. In Figure 2c we investigate the wideband mutual information for constant Tx power of the model, which tells how well the *local variations in power* connected to the spatial structure are modelled. We again observe a good fit to the reference channels. Most importantly, the slopes are almost equal. Figure 2d compares the narrowband MI for constant Tx power. The model fits the reference channels very well, both in mean and slope. Again note the significant difference to the mutual information of Gaussian white iid. MIMO channels.

### 4.2 Diversity metric

Additionally, we used the diversity order metric introduced in [7] providing the theoretical degree of diversity present in the MIMO channel. The metric is given by $\Psi(\mathbf{R}) = (\mathrm{tr}(\mathbf{R})/\|\mathbf{R}\|_\mathrm{F})^2$, with $\mathbf{R}$ denoting the full (short-term) channel correlation matrix $\mathbf{R} = \mathrm{E}\{\mathrm{vec}(\mathbf{H})\mathrm{vec}(\mathbf{H})^\mathrm{H}\}$, where the $\mathrm{vec}(\cdot)$ operator stacks the columns of a matrix into a vector.

We find the average diversity order of the reference channels as 2.3, and the average diversity order of the modelled channels as 2.9, which is a very close fit. For comparison, the Gaussian white iid. channels show a diversity order of 15. The large difference between the iid. channels on the one hand and both the reference channels and modelled channels on the other is attributed to the lack of diffuse components in the channel.

## 5 Conclusions

The presented *random-cluster MIMO channel model* (RCM) uses a statistical description of the scenario to place clusters containing propagation paths in the scenario. The model can be parameterized directly from MIMO channel measurements, which makes it applicable for real-world system testing applications. We are able to model both the spatial structure of the environment and the power variations in the scenario correctly.

Future extensions of the RCM include Doppler shifts of the paths, continuously time-varying scenarios, and diffuse components.

## References

[1] L. Correia, Ed., *Mobile Broadband Multimedia Networks*. Academic Press, 2006.

[2] H. Hofstetter, N. Czink, and A. F. Molisch, "A twin-cluster mimo channel model," in *EUCAP 2006*, Nice, France, 2006.

[3] M. Steinbauer, A. Molisch, and E. Bonek, "The double-directional radio channel," *IEEE Antennas and Propagation Magazine*, vol. 43, no. 4, pp. 51 – 63, Aug. 2001.

[4] N. Czink, E. Bonek, L. Hentilä, J.-P. Nuutinen, and J. Ylitalo, "Cluster-based MIMO channel model parameters extracted from indoor time-variant measurements," in *IEEE GlobeCom 2006*, Nov. 2006.

[5] A. Ihler, "Kernel density estimation toolbox for Matlab." [Online]. Available: http://ssg.mit.edu/~ihler/code/kde.shtml

[6] I. E. Telatar, "Capacity of multi-antenna gaussian channels," AT&T Bell Laboratories, Tech. Rep. BL0112170-950615-07TM, 1995.

[7] M.T. Ivrlac and J.A. Nossek, "Quantifying Diversity and Correlation of Rayleigh Fading MIMO Channels," in *IEEE ISSPIT'03*, Darmstadt, Germany, December 2003.