Measurement-Based Time-Variant MIMO Channel Modelling Using Clusters

***Nicolai Czink*[1,2], *Ernst Bonek*[2], *Juha Ylitalo*[3], *Thomas Zemen*[1]**

[1]Forschungszentrum Telekommunikation Wien (ftw.), Donau-City-Straße 1, A-1220 Wien, Austria
E-Mail: {czink,zemen}@ftw.at
[2]Institut für Nachrichtentechnik und Hochfrequenztechnik, Technische Universität Wien,
Gusshausstraße 25/389, A-1040 Wien, Austria
E-Mail: ernst.bonek@nt.tuwien.ac.at
[3]Elektrobit, Tutkijantie 7, FI-90570 Oulu, Finland
E-Mail: juha.ylitalo@elektrobit.com

Abstract

We present the novel Random-Cluster Model (RCM), a time-variant frequency-selective MIMO channel model. The most significant feature of the RCM is that it is parametrised directly from channel measurements by an automatic procedure. Thus, the RCM is *specific to the environment*, although it retains all advantages of a stochastic model. In this way it closes the gap between channel measurements and channel modelling.

Validation proves that the RCM can render very well channels in the kind of measured ones.

1 Introduction

In this paper, we present the Random-Cluster Model (RCM), a novel double-directional geometry-based stochastic MIMO channel model. The RCM uses multipath clusters to model the time-variant and frequency-selective propagation environment. Clusters allow to characterise the propagation environment in a compact way using only few parameters, which is their primary purpose for being applied in channel modelling. The previously controversial existence of clusters in measurement data was substantiated (independent of the authors' view) in [1].

The RCM is parametrised by clusters identified in measurements. To this purpose, we recently presented a fully automatic algorithm able to identify and track clusters in time-variant MIMO channel measurements [2]. The mere fact that clusters *can* be tracked in measurements demonstrates that clustering makes sense, since they obviously stem from scattering objects.

Currently popular MIMO channel models [3, 4] are well suited for random access communications, where terminals communicate in bursts, during which the channel remains (almost) static, then remain silent for a longer period during which the communication channel is assumed to change completely. In addition to this, the RCM is capable to model channels for continuous transmission in a time-variant environment as well, by creating smoothly time-variant channel realisations.

The RCM is a *stochastic* MIMO channel model, yet it is parametrised directly from measurements. A single multi-variate pdf of the cluster parameters is estimated from double-directional [5] MIMO channel measurements in a specific environment. This *environment pdf* is representative for the wave propagation in this environment. Realisations of the RCM are drawn from this distribution.

2 The Random-Cluster Model

Figure 1 gives an overview of the Random-Cluster Model. It consists of three main parts: (i) The model initialisation, (ii) small-scale updates by cluster movement, and (iii) large-scale updates by a birth/death process. All of these parts require an accurate parametrisation of the environment. In the next paragraphs we will first detail the environment description. Subsequently we will discuss the individual steps of the model.

2.1 Environment description — Multipath clusters

The RCM uses multipath clusters to model the channel. A cluster is described by its parameters $\mathbf{\Theta}_c$ given in Table 1. For the description of the environment we consider the *multivariate distribution* of the cluster parameters [6]. This approach is advantageous over methods using only marginal distributions, which cannot model correlations between the cluster parameters, as discussed in [7].

This multivariate distribution is estimated from measurements: First, a clustering-and-tracking framework is applied to time-variant MIMO measurements, to identify the parameters of all clusters occurring in the measurement. Subsequently, the multivariate distribution of the cluster parameters, $\mathbf{\Theta}_{\text{env}} = f(\mathbf{\Theta}_c)$, is estimated using a kernel density estimator, e.g. [8]. By parametrising the RCM directly from measurements, it becomes very specific to the chosen measurement route.

2.2 Model description

This section discusses the individual steps of the RCM (see Fig. 1).

Initialisation: The initialisation procedure generates the first snapshot of the channel model.

Drawing initial cluster parameters: The environment pdf $\mathbf{\Theta}_{\text{env}}$ provides a description for all kinds of clusters that were identified in the environment. To actually generate a snapshot, first the *intended snapshot power*, and the *number of clusters* needs to be determined.

We achieve this by a stepwise procedure: First, the marginal pdf of the number of clusters, $f(N_c)$ is evaluated by integrating over the other dimensions, then the actual number of clusters for the first snapshot, $\tilde{N}_c$, is determined by drawing from this pdf. Secondly, the environment pdf is conditioned on $\tilde{N}_c$, and marginalised to the snapshot power. From this marginal distribution $f(\rho|\tilde{N}_c)$, the intended snapshot power, $\tilde{\rho}$, is determined by drawing from this pdf. Finally, the environment pdf is conditioned on both the number of clusters and the intended snapshot power, $f(\mathbf{\Theta}_c|\tilde{N}_c, \tilde{\rho})$. From this distribution, we draw the $\tilde{N}_c$ cluster parameter sets $\tilde{\mathbf{\Theta}}_c$. By these drawn clusters, the multipath structure of the initial snapshot is set.

Symbol	Cluster parameter
$\bar{\tau}$	cluster mean delay
$\bar{\varphi}_{\text{Tx}}$	azimuth cluster position at Tx
$\bar{\varphi}_{\text{Rx}}$	azimuth cluster position at Rx
$\bar{\theta}_{\text{Tx}}$	elevation cluster position at Tx
$\bar{\theta}_{\text{Rx}}$	elevation cluster position at Rx
σ_τ	cluster delay spread
$\sigma_{\varphi_{\text{Tx}}}$	cluster azimuth spreads seen from Tx
$\sigma_{\varphi_{\text{Rx}}}$	cluster azimuth spreads seen from Rx
$\sigma_{\theta_{\text{Tx}}}$	cluster elevation spreads seen from Tx
$\sigma_{\theta_{\text{Rx}}}$	cluster elevation spreads seen from Rx
σ_γ^2	cluster mean power
ρ	total snapshot power
N_c	number of clusters coexisting
N_p	number of paths
$\Delta\sigma^2_{\gamma,c}$	increment of cluster power
$\Delta\bar{\tau}_c$	increment of cluster mean delay
$\Delta\bar{\varphi}_{\text{Rx},c}$	increment of cluster mean AOA
$\Delta\bar{\varphi}_{\text{Tx},c}$	increment of cluster mean AOD
$\Delta\bar{\theta}_{\text{Rx},c}$	increment of cluster mean EOA
$\Delta\bar{\theta}_{\text{Tx},c}$	increment of cluster mean EOD
Λ	cluster lifetime

Table 1: List of cluster parameters, contained in $\mathbf{\Theta}_c$

Placing paths within each cluster: In every cluster c, the corresponding number of paths, $\tilde{N}_{p,c}$ (determined in the previous step), are placed [6]. Every path is described by its complex amplitude (γ), its total delay (τ), and the azimuth and elevation of arrival and departure, respectively, ($\varphi_{\text{Tx/Rx}}$, $\theta_{\text{Tx/Rx}}$). The delay and angular parameters are drawn from a Gaussian distribution, where the mean and variance are determined in the cluster parameters (see Tab. 1). The paths within a cluster show the same amplitude determined by the total cluster power, but a random phase, which is drawn from a uniform distribution.

Generating the channel matrix — System model: Given a certain frequency bin Δf, and antenna array patterns $\mathbf{a}_{\text{Tx/Rx}}(\varphi_{\text{Tx/Rx}}, \theta_{\text{Tx/Rx}})$, the MIMO channel transfer matrix can be calculated as

$$\mathbf{H}(t', \Delta f) = \sum_{c=1}^{\tilde{N}_c} \sum_{p=1}^{\tilde{N}_{p,c}} \gamma_{p,c} \cdot \mathbf{a}_{\text{Rx}}(\varphi_{\text{Rx},p,c}, \theta_{\text{Rx},p,c}) \cdot \mathbf{a}_{\text{Tx}}^{\text{T}}(\varphi_{\text{Tx},p,c}, \theta_{\text{Tx},p,c}) \cdot \mathrm{e}^{-j2\pi\Delta f \tau_{p,c}}, \tag{1}$$

where the subset p, c denotes the pth path in cluster c. In this paper we use a 4×4 MIMO configuration with uniform linear arrays at both link ends, and a centre frequency of 2.55 GHz at a bandwidth of 20 MHz, with a number of 32 frequency bins.

Time bases: The RCM distinguished between two time bases: the *sampling* time base, Δt_s, and the cluster-lifetime time base, Δt_Λ, where $\Delta t_\Lambda = \text{const} \cdot \Delta t_s$. Cluster lifetimes are multiples of Δt_Λ.

Small-scale time variation: On small scale, we implemented time variation by linearly changing the parameters of the propagation paths. In every sampling time instance Δt_s, the increments determined in the cluster parameters are added to the respective path parameters. In this way, clusters are moving in delay (causing Doppler shifts), and in angles, and smoothly change their power.

Large-scale time variation: To introduce large-scale changes in the propagation conditions, we included a cluster birth/death process. In every cluster lifetime interval, t_Λ, the lifetime of each cluster is decreased. Dying clusters are fading out during the next cluster lifetime interval. New clusters are drawn in the same way as described in the initialisation procedure.

3 Model validation

We validated the RCM against MIMO channel measurements carried out with an Elektrobit Propsound CS^{TM} wideband channel sounder at a center frequency of 2.55 GHz [7]. In this paper we present validation results for a particularly interesting measurement route in an office scenario, *without* line of sight between transmitter and receiver. The Tx was moved through the room while the Rx was at a fixed position in a corridor. The validation of more scenarios can be found in [9, Chap. 4].

Validation procedure: We used the following procedure to quantify the model's fit to measurement: (i) estimate propagation paths from the measurements using a high-resolution parameter estimation algorithm [10], (ii) identify clusters of propagation paths from the measurements as described in [2], (iii) parametrise the environment parameter pdf $\mathbf{\Theta}_{\text{env}}$ as described in Section 2.1, (iv) use the RCM to generate new realisations of the channel, (v) use the same system model on the identified paths from measurement (*reference channels*) and in the RCM (*modelled channels*), (vi) compare the reference channel with the modelled channels using different validation metrics.

Validation results: In this paper we applied two different validation metrics, mutual information (MI) [11], and the Environment Characterisation Metric (ECM) [12]. More validation metrics are used in [9, Chap. 4].

Mutual information: We used MI as first validation metric to provide results comparable with other publications. MI validates the *local fading* around the stations. However, it is no good metric to judge on the multipath structure of the channel [9, Sec. 3.2.1]. We evaluated the mutual information after normalising the channels to constant transmit power at 10 dB average (per-antenna) Rx SNR by

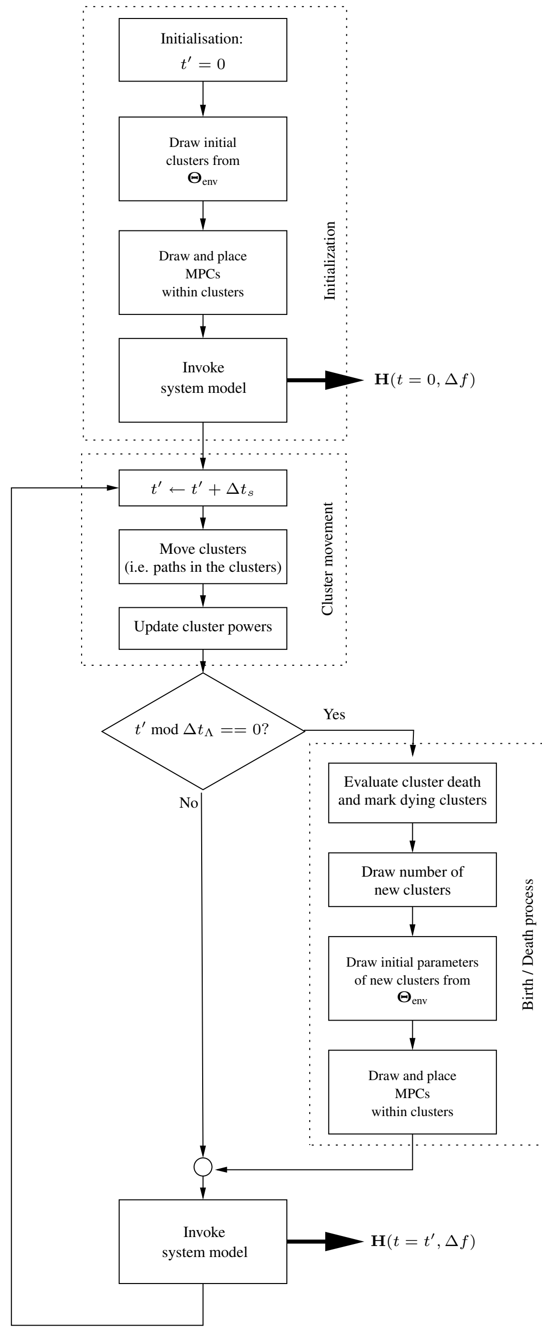
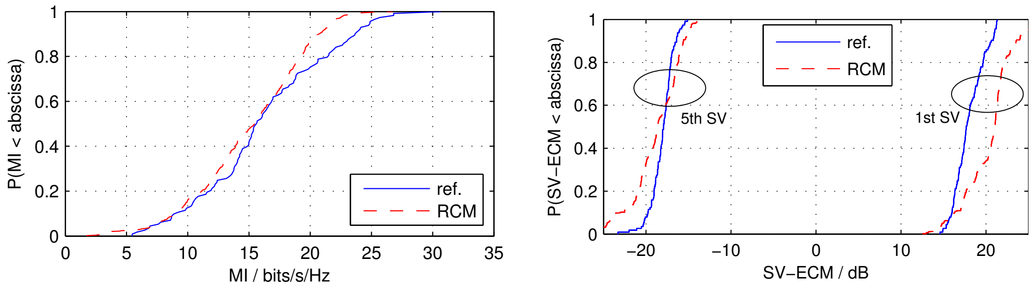


Figure 1: Flow diagram of the Random-Cluster model

$$I(\mathbf{H}) = \log\det\left[\mathbf{I} + \text{SNR}\cdot\mathbf{H}\mathbf{H}^{\text{H}}\right],$$

where this MI is evaluated for all time instants and frequencies, for both reference channels and modelled channels. Fig. 2a shows the cumulative distribution function (cdf) of the MI of the reference channels (solid line) and the modelled channels (dashed line). We observe that the MI of the modelled channels fits the one of the reference channels very well.

Environment characterisation metric: The recently introduced ECM [12] is directly applied to the path parameters



(a) (b)

Figure 2: Validation results: (a) mutual information, (b) environment characterisation metric

rather than to the channel matrix. The singular values of the ECM (SV-ECM) reflect the spreading of the paths in the parameter space and are thus suitable to genuinely reflect the spatial multipath structure of the channel.

Fig. 2b illustrates the first and fifth SV-ECM of the reference channels (solid) and the modelled channels (dashed), reflecting the strongest and smallest dispersion in the path parameters, respectively. The good fit between the solid and the dashed curves indicates the ability of the RCM to reflect the spatial structure of the parametrised environment well.

4 Conclusions

The Random-Cluster Model is a novel frequency-selective MIMO channel model that is based on multipath clusters. The main focus of the RCM is to reflect the spatial structure of measured MIMO channels, and their time-variant behaviour, thus closing the gap between channel measurements and channel modelling.

We validated the RCM using both mutual information and the novel environment characterisation metric. It turned out that the modelled channels fit very well to the measured ones, which demonstrates that the RCM satisfies its focus.

References

[1] H. Xiao, A. G. Burr, L. Hentilä, and P. Kyösti, “Statistical technique to identify clusters from multi-dimensional measurement data,” in *EuCAP*, Edinburgh, UK, November 2007.

[2] N. Czink, R. Tian, S. Wyne, F. Tufvesson, J.-P. Nuutinen, J. Ylitalo, E. Bonek, and A. F. Molisch, “Tracking time-variant cluster parameters in MIMO channel measurements,” in *ChinaCom 2007*, Shanghai, China, August 2007.

[3] V. Erceg *et al.*, “TGn Channel Models,” IEEE P802.11 Wireless LANs, Tech. Rep., May 2004.

[4] G. Calcev *et al.*, “A wideband spatial channel model for system-wide simulations,” *IEEE Trans. Vehicular Technology*, vol. 56, no. 2, pp. 389–403, March 2007.

[5] 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.

[6] N. Czink, E. Bonek, L. Hentilä, J.-P. Nuutinen, and J. Ylitalo, “A measurement-based random-cluster MIMO channel model,” in *IEEE APS 2007*, Honolulu, USA, June 2007.

[7] N. Czink, E. Bonek, and J. Ylitalo, “Parameterizing geometry-based stochastic MIMO channel models from measurements using correlated clusters,” in *ITG/IEEE Workshop on Smart Antennas*, Vienna, Austria, February 2007.

[8] A. Ihler, “Kernel density estimation toolbox for Matlab,” July 2007. [Online]. Available: http://ttic.uchicago.edu/˜ihler/code/

[9] N. Czink, “The random-cluster model — a stochastic MIMO channel model for broadband wireless communication systems of the 3rd generation and beyond,” Ph.D. dissertation, Technische Universität Wien, 2007.

[10] B. H. Fleury, M. Tschudin, R. Heddergott, D. Dahlhaus, and K. I. Pedersen, “Channel parameter estimation in mobile radio environments using the SAGE algorithm,” *IEEE JSAC*, no. 3, pp. 434–450, 17 1999.

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

[12] N. Czink, G. D. Galdo, X. Yin, E. Bonek, and J. Ylitalo, “A novel environment characterization metric for clustered MIMO channels used to validate a SAGE parameter estimator,” *Wireless Personal Communications*, 2007, in press.