Potential of Coefficient Reduction in Delay, Space and Time based on Measurements

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***Abstract*— Measurement results demonstrating the great potential of reducing estimated channel coefficients in mobile communication systems are presented.**
The core of the RAKE philosophy is the assumption, that the energy occurs concentrated in the dimensions of the signal space. Suppressing non-energy-carrying dimensions in the impulse responses cuts also the noise in the corresponding dimensions of the signal space. This document addresses the degree of energy concentration in the channel domains delay, space and time by help of MIMO measurements.
After reviewing the concept of reducing impulse responses in delay, space and time we show measurement results in terms of eigenvalue distributions reflecting the correlations and energy concentrations in the three domains.
The data considered here was recorded during a campaign conducted in Vienna in November 2001 in urban, rural/suburban and indoor environments.
All occurring correlations and energy concentration are observed to be much higher than expected. On one hand this leads to less diversity, but on the other hand this allows for simpler receiver structures and more stable channel estimation by coefficient reduction.

I. Introduction

ONE of the basic properties of mobile communication systems is the time-varying nature of the mobile channel. As a key consequence, for reliable connections the channel has to be tracked. In order to maintain spectral efficiency, the energy exclusively used for channel estimation has to be kept small [1], i.e. the trainings sequences have limited length.
When using antenna arrays, in general knowledge about the time-variant impulse responses on the antenna elements is needed. Considering an array on one side of the transmission chain only, the mobile channel has three domains: delay, space (antennas) and observation time. The quality of the impulse response estimates is strongly related to the system performance [1][2]. Long training sequences improve the estimates, but decrease spectral efficiency. In addition, their length is limited by the time-variation.
Another possibility is, to reduce the number of coefficients in the impulse responses to be estimated by exploiting long-term properties of the channel like power delay profile, temporal correlations [3] and spatial correlations [4]. Suppressing non-energy-carrying dimensions is equivalent to excluding noise from the estimates of the channel impulse response, which improves the system performance.
In the delay domain, this ends up in the original RAKE structure [5]. Beamforming is the counterpart in the space domain [6]. A similar technique can be applied to the observation time domain [1][7] which often is described by a velocity and the JAKES doppler spectrum [8].
The degree of reduction and herewith the achievable quality of the estimates solely depends on the long-term structure of the channel. Therefore, this work evaluates a measurement campaign conducted in Vienna with respect to the coefficient reduction in delay, space and time.
Section II reviews the concept of reducing estimates of coefficients which exhibit energy concentrations and/or correlations. Furthermore, its application to time- and space-variant channel impulse responses is given and the quasi wide sense stationarity assumption is recalled. The measurement setup and the considered environments are described in sections III and IV. The results in terms of cumulative distribution functions of eigenvalues are demonstrated in section V. Section VI draws some conclusion for future channel modelling.

II. Reduction of Coefficients

We will start with a more abstract review of reducing estimated coefficient vectors with arbitrary correlation matrix. In section C we will apply the derived concept to time- and space-variant channel impulse responses.
Let us assume, that we want to estimate random parameter vectors $\vec{x} \in \mathcal{C}^N$ with arbitrary correlation matrix

$$\mathbf{R}_{xx} = \mathbf{E}\left\{\vec{x} \cdot \vec{x}^H\right\}. \quad (1)$$

An estimation process, e.g. a correlation with a training sequence, gives us noisy estimates of the desired vector

$$\hat{\vec{x}} = \vec{x} + \vec{n} \quad (2)$$

where $\vec{n}$ is a noise process which we assume to be white and independent from the variable $\vec{x}$.

$$\mathbf{R}_{nn} = \mathbf{E}\left\{\vec{n} \cdot \vec{n}^H\right\} = \sigma_N^2 \cdot \mathbf{I}_N \quad (3)$$

A. Uncorrelated Coefficients

Let us first consider the case, where $\vec{x}$ is uncorrelated, i.e. $\mathbf{R}_{xx}$ is a diagonal

$$\mathbf{R}_{xx} = \mathrm{diag}\left\{\lambda_1, \lambda_2, ..., \lambda_N\right\}. \quad (4)$$

It is well-known since [5], that we can improve the quality of the estimate $\hat{\vec{x}}$ in terms of e.g. mean squared error or bit error rate by setting components in $\hat{\vec{x}}$ corresponding to small λ_i-values to zero. This effect is the core of the RAKE philosophy and is quantified in [9] for the delay and space domain. This operation can be written as

$$\hat{\vec{x}}_R = \mathbf{J} \cdot \hat{\vec{x}} \quad (5)$$

where $\mathbf{J}$ is a selection matrix, which is simply the identity matrix $\mathbf{I}_N$ with the diagonal entries j_{ii} corresponding to weak λ_i-values being replaced by zero.

B. Correlated Coefficients

In the case, where $\vec{x}$ has arbitrary correlations, i.e. $\mathbf{R}_{xx}$ is non-diagonal, we can decorrelate the variable $\vec{x}$ by help of transform $\mathbf{W}^H$ [10] and get the uncorrelated variable

$$\vec{x}_T = \mathbf{W}^H \cdot \vec{x} \quad (6)$$

where the columns of $\mathbf{W}$ are the eigenvectors of $\mathbf{R}_{xx}$. The covariance matrix of the transformed variable is

$$\mathbf{R}_{xx}^{(T)} = \mathbf{E}\left\{\vec{x}_T \cdot \vec{x}_T^H\right\} = \text{diag}\left\{\lambda_1, \lambda_2, ..., \lambda_N\right\} \quad (7)$$

where λ_i are the eigenvalues of $\mathbf{R}_{xx}$. Applying the transform to the estimates (2) yields

$$\hat{\vec{x}}_T = \mathbf{W}^H \cdot \hat{\vec{x}} = \vec{x}_T + \vec{n}_T \quad (8)$$

where all statistical properties of $\vec{n}_T$ are the same as of $\vec{n}$, since the eigenvectors $\mathbf{W}$ can be chosen to be orthogonal and $\vec{n}$ was assumed to be white (3). We now base the reduction described in the previous section on the eigenvalues λ_i of $\mathbf{R}_{xx}$. Back transformation into the original space finally leads to the reduced estimates

$$\hat{\vec{x}}_R = \mathbf{W} \cdot \mathbf{J} \cdot \mathbf{W}^H \cdot \hat{\vec{x}}. \quad (9)$$

This method is similar to that suggested in [11] and which was called *channel signal subspace projection* in [12]. However, in both references, the parameter vector was assumed deterministic instead of random.

C. Application to Delay, Space and Time

As already mentioned the impulse responses occurring in multiple antenna mobile communications have three domains, namely delay, space and time. In discrete notation, we write (cf. e.g. [4])

$$h(l\tau_o, m, jt_0) \quad (10)$$

where τ_0 is the sampling interval in the delay domain and $l = 1..L$ the corresponding index, $m = 1..M$ is the antenna index of an M-element uniform linear array[1] and $j = -\infty..\infty$ is the observation time index with the sample spacing t_0.
In general we have correlations in all domains and therefore apply the reduction to all of them.
In *delay* domain, we write the $L\times L$ covariance matrix as

$$\mathbf{R}_{xx}^{delay}(m, jt_0) = \mathbf{E}\left\{\vec{h}_d(m, jt_0) \cdot \vec{h}_d^H(m, jt_0)\right\} \quad (11)$$

where $\vec{h}_d(m, jt_0) = [h(1\tau_o, m, jt_0)...h(L\tau_o, m, jt_0)]^T$, i.e. the delay axis is stacked into a vector.
A consequence of the wide sense stationarity uncorrelated scattering (WSSUS) assumption [3] is, that $\mathbf{R}_{xx}^{delay}(m, jt_0)$ is independent from m and j, i.e. $\mathbf{R}_{xx}^{delay}(m, jt_0) = \mathbf{R}_{xx}^{delay}$, and that it is close to a diagonal.
Pulse shaping filters with finite bandwidth smear the discrete and continuous channel delays over several values of the sampled impulse response generating correlations among neighboring taps. However, these correlations decrease rapidly maintaining the diagonal trend of the correlation matrix.
Therefore, most implementations restrict to the main diagonal diag$\left\{\mathbf{R}_{xx}^{delay}\right\}$, which is also called the *power delay profile*. In the case of perfectly diagonal structure, the values of the PDP are also the eigenvalues of $\mathbf{R}_{xx}^{delay}$.

The *spatial* correlations, i.e. between the antenna impulse responses, depend on the array topology. With element spacings less or equal than half of the wavelength, we have the typical beamforming case. The $M\times M$ spatial covariance matrix [13] is

$$\mathbf{R}_{xx}^{space}(l\tau_0, jt_0) = \mathbf{E}\left\{\vec{h}_s(l\tau_0, jt_0) \cdot \vec{h}_s^H(l\tau_0, jt_0)\right\} \quad (12)$$

where $\vec{h}_s(l\tau_0, jt_0) = [h(l\tau_o, 1, jt_0)...h(l\tau_o, M, jt_0)]^T$.
With the WSSUS assumption, it is constant over the observation time j, but not over the delay l. Most beamforming algorithms are based either on the tapwise covariance matrix $\mathbf{R}_{xx}^{space}(l\tau_0)$ or on the total signal covariance matrix $\mathbf{R}_{xx}^{space} = \sum_{l=1}^{L} \mathbf{R}_{xx}^{space}(l\tau_0)$ [6].
In order to provide an impression about the spatial eigenvalues, the left plot in Figure 1 shows the eigenvalues of the spatial covariance matrix in dependence on the angular spread (root mean square RMS) . We assumed an 8-element uniform linear array with $\lambda/2$ spacing and a Laplacian distributed angular spread centered around 0^o.

Equivalently, we have correlations between consecutive results of the channel estimation, i.e. in the *observation time*. This is strongly related to the Doppler spectrum [8]. If we are interested in the correlations within sets of J consecutive impulse responses $\vec{h}_t(l\tau_0, m, jt_0) = [h(l\tau_o, m, jt_0), h(l\tau_o, m, (j{+}1)t_0), ..., h(l\tau_o, m, (j{+}J{-}1)t_0)]^T$ we can formulate a temporal covariance matrix

$$\mathbf{R}_{xx}^{time}(l\tau_0, m, jt_0) = \mathbf{E}\left\{\vec{h}_t(l\tau_0, m, jt_0) \cdot \vec{h}_t^H(l\tau_0, m, jt_0)\right\}. \quad (13)$$

Here, the WSSUS assumption leads to independence on m and j and the temporal covariance matrix reduces either to

[1] Most of the statements in this section are also valid for arbitrary antenna geometries. For the sake of correctness in terms of the WSSUS assumption we restrict to the uniform linear array.

the tapwise matrix $\mathbf{R}_{xx}^{time}(l\tau_0)$ or to the total temporal covariance matrix $\mathbf{R}_{xx}^{time} = \sum_{l=1}^{L} \mathbf{R}_{xx}^{time}(l\tau_0)$.
The right plot in Figure 1 shows the temporal eigenvalues versus the velocity, where we assumed a JAKES doppler spectrum, a temporal spacing of $t_0 = 21.5$ms and the covariance being set up for $J = 8$ consecutive sample.
This setting relates to the measurement setup and we will refer to these results later on.

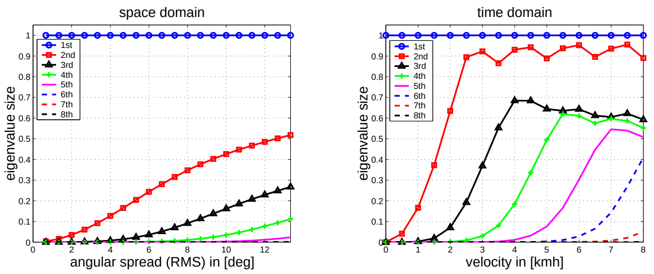

Fig. 1. Spatial and Temporal Eigenvalues (Theory)

D. QWSS Assumption and Second Order Statistics

For the reduction methods of the previous sections, we need knowledge about covariance matrices. First of all, it is not obvious how to determine those matrices.
In 1963, Bello formulated the *Quasi Wide Sense Stationarity* assumption [3], which states that second order statistics (such as covariance matrices) of the channel can be considered constant over certain time intervals. As a consequence we distinguish between (wide sense) stationary short-term effects, which arise from different interference situations of the different multipath components ("fast fading") and long-term effects due to changes in the environment like shadowing etc ("slow fading").
In [14], we demonstrated by means of measurements, that the time constants of the spatial long-term variations are significantly larger than those of the short-term variations which justifies the QWSS assumption in the spatial domain. Similar evaluations were done for the delay and time domain. Hence, we replace the expectation operations $\mathbf{E}\{\}$ by the temporal averaging over the short-term effects $\sum_{j=1}^{K}\{\}$, i.e. we assume the ensemble averages to be constant over the observation time Kt_0.
Since we can base the averaging on estimates of the impulse response only, we will have a noise component in the covariance estimates. In [15] it is shown that this component can be cancelled, so that we get almost perfect estimates of the second order statistics.

III. Measurement Setup

All measurements were performed with the MIMO capable wideband vector channel sounder RUSK-ATM, manufactured by MEDAV [17]. The sounder was specifically adapted to operate at a center frequency of 2GHz with an output power of 2 Watt distributed over a bandwidth of 120MHz.
At the mobile side a circular 15-element array of monopoles [18] was used whereas the base station was equipped with a linear eight element patch array provided by T-Nova, Germany.
A closer description on the equipment is given in [19].
With above arrangement, consecutive sets of 15×8 transfer functions, cross-multiplexed in time, were measured every 21.5ms.
However, for the investigations in this paper only the SIMO case is considered. In order to get more stable second order statistics, non-coherent averaging was applied over the transmit antennas.

IV. Measurement Environments

The measurement data used for this paper was conducted during a measurement campaign in Vienna 2001. Main attention was drawn on measuring representative areas for mobile communication systems. For this paper the following three environments were chosen:

A. Urban

Measurements were performed in downtown Vienna near the University of Technology. The receiver was placed on top of one of the highest buildings in the surrounding at a height of about 30m. The transmitter was moved on the streets within the coverage area of the equipment at speeds of about 3kmh.

B. Rural/Suburban

These measurements were taken in a small village near Vienna with the receiver again at a height of about 20m mounted on a lift. The surrounding covers small one-family houses and open places.

C. Indoor

In addition to the outdoor measurements the office facilities of FTW were measured too. This is a modern ferroconcrete office building where the receiver was placed on the aisle and the transmitter was moved through several offices.

V. Results

From the recorded time- and space-variant impulse responses we determined the covariance matrices (or the PDP, respectively) as described in section II-C, where a 5MHz band with a raised-cosine shape around 2GHz was considered only[2]. The expectation was replaced by an averaging over time. The averaging interval was around 4 seconds in the outdoor scenarios and around 1 second for the indoor scenario. The slow fading effects are assumed to be constant over these intervals (cf. section II-D). At the end of each interval, a new covariance is initiated. In total, roughly 400 covariance

[2] This is a typical band for 3rd generation mobile communication [16]

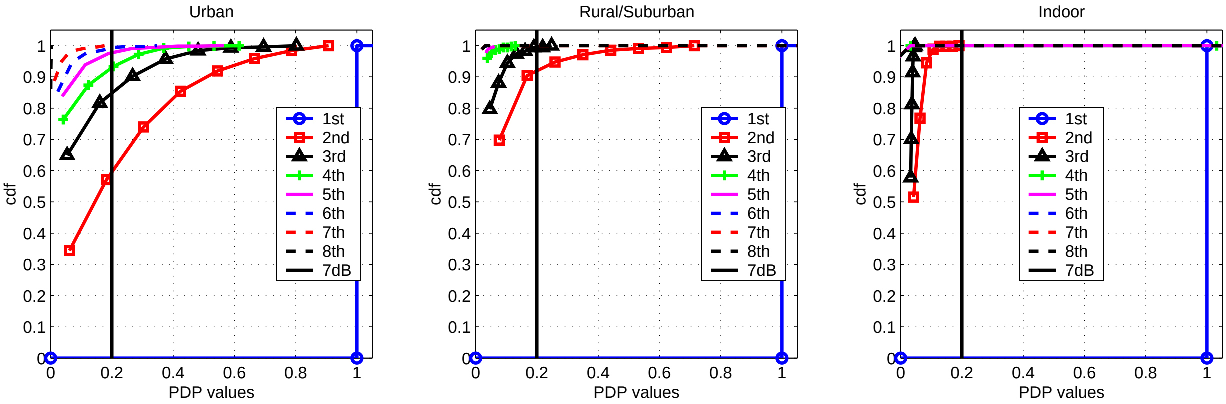

Fig. 2. Strongest PDP values in Delay Domain

matrices are evaluated for each environment.
From each covariance a separately measured noise component was subtracted. To get more stable results, we applied an incoherent averaging over the stationary domains in addition (cf. section II-C).
An eigenvalue decomposition was carried out and the resulting eigenvalues are sorted in descending order. The eigenvalues are scaled that the first (largest) eigenvalue is always equal to 1.
The following figures show cumulative distribution functions (CDFs) of the linear eigenvalues of all covariance matrices in the different environments . Due to the normalization, the CDF of the largest value is always exactly a step function at value 1.
Exemplarily, we added a threshold at the value 0.2 (-7dB). In the sequel, we will consider a dimension to be significant if the corresponding eigenvalue exceeds this threshold. We have chosen this relatively high value from two reasons. First, the SNR in the measurements was very low, so that it is hard to distinguish between signal and noise subspace for small eigenvalues. Second, in mobile communications we tend to have very low SNRs as well, which increases the value of an optimal threshold (cf. [9]).

A. Delay Domain

It was already mentioned, that with the WSSUS assumption the covariance matrix in the delay domain $\mathbf{R}_{xx}^{delay}$ is close to a diagonal. Therefore, most RAKE implementations concentrate on the power delay profile (PDP) which is the main diagonal of $\mathbf{R}_{xx}^{delay}$. Hence, we will not look at the eigenvalue spectrum, but at the PDP.
The sampling frequency was chosen to be twice the 3dB bandwidth of the raised cosine spectrum. This oversampling increases the delay resolution, but forces signal and noise correlations between adjacent taps.
To overcome this effect, we determine the largest tap powers as follows. We look for the strongest tap in the PDP. For the next search, we will not consider this value as well as its left and right neighbors. The largest value of the remaining PDP is assumed to be the second strongest tap and so forth.
The resulting tap powers are a good approximation for the eigenvalues. The CDFs in Figure 2 consider the 8 largest tap powers.
Surprisingly, in the urban environment the second strongest tap power is very low in most of the cases. The 7dB threshold is exceeded in 40% of the cases only. In other words, even for the urban environment we have an approximately frequency-flat channel in 60% of the cases. The probability for having more than 3 significant taps is almost negligible and close to usual values of outage.
As expected, the probability for a flat channel is very high in the rural/suburban environment (>90% with the 7dB threshold). In most cases, we have a LOS, over-roof-top diffraction or scatterers very close to the mobile which do not cause significant delay spread. The case of more than 2 significant taps can be excluded.
In the indoor environment, all occurring delays are that low, that no delay spread can arise due to the small distance between base station and mobile station. That is, the channel is frequency-flat almost in general.

B. Space Domain

In contrast to the delay domain, we will have strong correlations in the antenna and time domain. Hence, we do carry out the eigenvalue decompositions as described in section II-B.
The results for the antenna domain are given in Figure 3. Similar to the delay domain, the second dimension is weaker than expected in the urban environment. With the 7dB threshold, we have in 50% of the cases one significant dimension only and still in 85% less than three significant dimensions. This means for the azimuth domain, that the angular spread is fairly small. This is in conjunction with other results not presented here, where direction-finding techniques have been applied. The reason is, that due to the high base station position, most waves take the direct azimuth direction and are diffracted over the roof tops.
We find higher correlations in the rural/suburban environment. The angular spread is very small due to the same as-

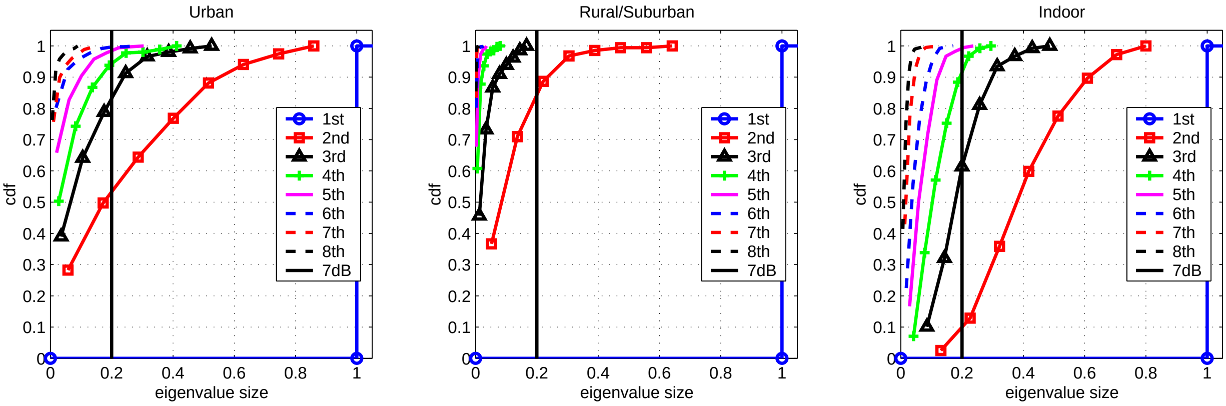

Fig. 3. Eigenvalues in Space Domain

pects as mentioned for the delay spread. The probability for having more than a single spatial dimension is only 15%.
In the indoor environment, the situation looks very different. Provided base and mobile station in different rooms, the waves can take any paths, so there is no preferred direction as in the latter cases. However, even here we are far away from full rank covariance matrices. We have at least two dimensions in 90%, but less than four dimensions also in 90% of the cases.
If we compare the medians (at CDF-value 0.5) of the eigenvalues with the theoretical plots in Figure 1, we observe a rough match for angular spread values of around $5^o, 3^o, 9^o$, where a Laplacian distribution was assumed. These values are in conjunction with other campaigns, e.g. [20].

C. Time Domain

We will now proceed with the temporal correlations. The plots in Figure 4 give insights into the correlations between 8 consecutive impulse responses, where the temporal spacing was 21.5ms and the velocity was in the range of 1.5-6kmh. Assuming non-moving scatterers, reflectors and diffractors, the time axis scales linearly with the velocity. For instance, for a temporal spacing of 0.66ms (slot spacing in UMTS FDD [16]), the results would be approximately valid with the velocity being scaled by factor $\approx$ 30, e.g. 100kmh in the case of 3kmh.
In the urban environment we moved roughly with 3kmh. We observe in 90% of the cases less than 4 dimensions, i.e. we can cut 5 of 8 dimensions which could yield an SNR gain in the channel estimation of more than 4dB, provided white Gaussian noise.
In the rural/suburban environment, the matrices seem to have a higher rank, namely 5 significant dimensions in more than 20% of the cases. The reason is, that we moved faster (ca.6kmh), than in the urban scenarios due to less pedestrians on the pavement etc.
In the indoor environment, we slightly reduced the velocity to approximately 1.5kmh in order to get more snapshots for more stable second order statistics. The correlations are very high, we can reduce to a single dimension in almost 95% of the cases.
The high sensitivity of the eigenvalues against the velocity between 1.5kmh and 6kmh is also reflected by the theoretical curves in Figure 1. Again comparing the medians of the eigenvalue distributions with the theoretical values in Figure 1, we are not able to find a reasonable match at any velocity. The JAKES spectrum assumes, that the waves at the mobile are uniformly distributed in the complete azimuth domain, i.e. between -180^o and 180^o. This generates the lowest possible correlation given a velocity, i.e. the most balanced eigenvalue distribution. However, reality seems to have much more correlations. This suggests, that the Doppler spectrum exhibits clear energy concentrations instead of the continuous JAKES spectrum.

VI. Conclusion

Measurement results for the correlations and energy concentrations in delay, space and time have been demonstrated. We have reviewed the general concept of reducing correlated and/or concentrated estimates. The application to the estimation of the time-variant impulse responses on the antenna elements has been derived and we have recalled the idea and the consequences of the WSSUS assumption.
We have described the measurement setup which was a MIMO capable sounder with 120MHz bandwidth featuring an 8-element uniform linear array with $\lambda/2$ spacing at the base station side and a temporal impulse response spacing of 21.5ms. Details for the three considered environments urban, rural/suburban and indoor have been given.
Especially in the urban case, the correlation and concentrations have been much higher than expected. On one hand, this leads to less diversity provided by the channel, but on the other hand this allows for simpler receiver structures and more reliable channel estimation.
Except in the time domain, the correlations and concentrations are very high in the rural/suburban environment. The low temporal correlations are due to a higher velocity.
The indoor environment shows very high correlations in delay and time domain. But also in space domain we are far away from full rank matrices.

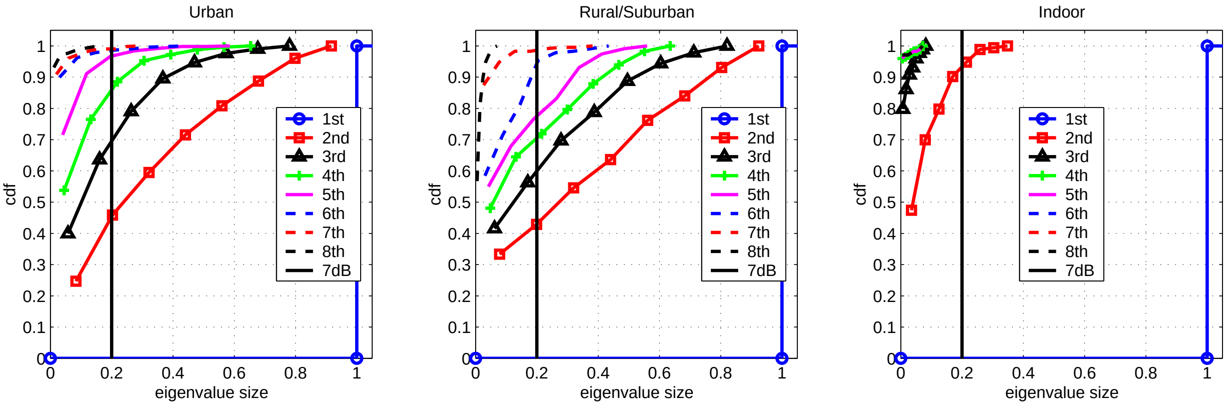

Fig. 4. Eigenvalues in Time Domain

A comparison with theoretical eigenvalues in space has lead to a rough match for Laplacian distributed angular spreads of $5^o, 3^o, 9^o$ for urban, rural/suburban or indoor, respectively. In time domain, no reasonable match with the JAKES model has been found.

In general all correlations have been higher than expected. As a consequence, very simple channel models do match parts of the reality indeed. Furthermore, the need of reduced rank processing is emphasized by these measurements.

An interesting thing would be to combine the results of the three domains in order to get knowledge about the total rank of the mobile channel. This is for further study.

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