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Decorrelation Distance Characterization of Long Term Fading of CW MIMO Channels in Urban Multicell Environment

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Abstract- An analysis of long-term fading properties of 4×4 CW MIMO channels is presented in this paper. The main focus has been on the long-term variability of MIMO channels in urban cellular environments, with emphasis on the decorrelation distance over mid range distances along the mobile trajectory for different base station antenna heights. A model that characterizes the decorrelation distance at different probability levels of distribution of the decorrelation distance is proposed. The model predicts that at some probability level all measured decorrelation distances will be within $\frac{1}{2}\Delta x_0$ and $2\Delta x_0$, where Δx_0 is the decorrelation distance at the e^{-1} level of the autocorrelation function.

1 INTRODUCTION

Knowledge of the behavior of the radio channel is of vital importance to proper wireless communication system design. Multiple Input Multiple Output (MIMO) techniques use multiple elements antenna (MEA) at both link ends. These new degrees of freedom anticipate potential increase of both capacity and link reliability

In this paper we focus on the autocorrelation of the lognormally distributed long term fading, which is also known as shadowing. Shadowing has a direct impact on traditional cellular system planning, since it variability put constraints on as well cell coverage through coverage probability and signal quality (signal to noise ratio, SNR) variability as hand-off and scheduling algorithms, among many other aspects.

Our analysis is based on a measurement campaign presented in [1]. Here we propose a model that further extends the widely accepted exponential decaying correlation model in [2], to handle the fact that the autocorrelation is also a stochastic function itself. The main idea here is to study the decorrelation of the lognormal fading over a range corresponding to the “faster” component of the bi-exponential model [3].

2 MIMO MEASUREMENT CAMPAIGN

This MIMO measurement campaign uses the Wireless Development Laboratory (WIDELAB) test bed developed by the signal-processing group at the Royal Institute of Technology (KTH), Sweden. A detailed description of the hardware equipment can be found in [4]. The measurement campaign was conducted in the city center of Stockholm, Sweden. The operating frequency was 1766.6 MHz in the

uplink band in an urban area. The mobile station and the base stations were equipped with the antenna arrays. Three receiver (BS) arrays are used, with one at Kårhuset and two at Vanadis. The schematic scenario of the three-sector structure is drawn in Fig. 1, [1].

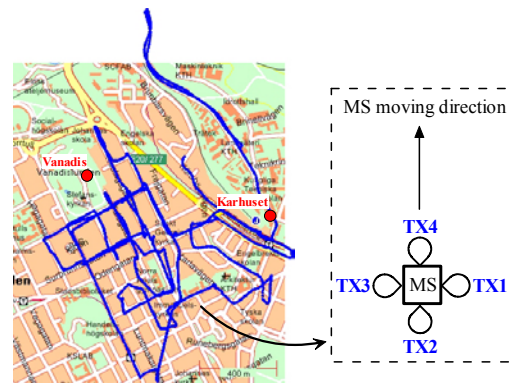


Figure 1 The map of the outdoor driving measurement. The two red dots denote the locations of the BS sites Kårhuset and Vanadis. The blue trajectory is the MS driving route during the measurement. The pointing directions of four TX antennas on the MS are also illustrated.

The pointing directions of the three receiver arrays are labeled with three letters, with ‘A’ for the one at Kårhuset, and ‘B’, ‘C’ for the two at Vanadis. ‘A’ points $5^\circ \sim 20^\circ$ counter-clock-wise off the direction of Vanadis. ‘B’ and ‘C’ point 60° clock-wise and counter-clock-wise off the direction of Kårhuset, respectively. The BS array ‘A’ is about 0 to 3 meters above rooftop, and the BS arrays ‘B’ and ‘C’ are about 10 meters above rooftop, by this means two different BS antenna heights are emulated. During the outdoor driving measurement, the mobile terminal was mounted on top

of a car at about 1.8 m above ground. The environment can be characterized as the heavily built up area with a uniform density of buildings, ranging from 4-6 floors. The driving speed varied approximately from 1 m/s to 12 m/s. The measurement was performed in the forenoon when the traffic was heavy. Fig. 1 also shows the mobile driving route during the measurement, together with the pointing directions of four TX antennas on the mobile. TX4 and TX2 point forward and backward to the mobile moving direction, respectively, while TX1 and TX3 point perpendicular to the moving direction.

3 CHANNEL MODEL

Ignoring the noise term, the relationship between the received signals, $\mathbf{y}(t)$ and transmitted signals, $\mathbf{s}(t)$ is modeled as,

$$\mathbf{y}(t) = \mathbf{H}(t)\mathbf{s}(t) \quad (1)$$

where the narrowband MIMO channel matrix is denoted as $\mathbf{H} \in C^{N_r \times N_t}$. We model the channel having N_r antennas at the base station (receiver) array and N_t antennas at the mobile station (transmitter) array. The overall channel variability between the n -th transmitter and m -th receiver antenna is further modeled according to the classical three-stage model – 1) the deterministic part of the local area mean, which stands for the distance path loss law, PL_{mn} , 2) the stochastic part of the local area mean, which is the shadow fading, S_{mn} and superimposed fast fading characterized by the normalized (instantaneous power normalized to the unit) complex channel impulse response H'_{mn} . Thus, the overall channel variability may be studied by representing the channel transfer function as follows,

$$H_{mn} = H'_{mn} \left(\frac{S_{mn}}{PL_{mn}} \right)^{1/2} \quad (2)$$

Our further focus will be on shadow fading, S_{mn} expressed in dB.

4 SHADOW FADING AUTOCORRELATION

The long-term fading is caused by obstacles in the propagation path between the mobile and the base station like buildings, mountains, other objects and humans. The long-term fading is also called slow fading or shadow fading. Shadow fading effect causes random variations in the local average received power. We denote the envelope in dB of the shadow fading component by S_{dB} , which has been found to follow a Gaussian distribution. S_{dB} is often considered a zero-mean Gaussian random variable with standard deviation σ_s (also in dB), which has also been assumed in the present paper.

To measure how fast the shadow fading component varies as the mobile moves along a certain route, we calculate the spatial autocorrelation as

$$\psi_{ss}(\Delta x) = \langle S_{dB}(x), S_{dB}(x + \Delta x) \rangle \quad (3)$$

where Δx is the spatial separation along the mobile route, and $S_{dB}(x)$ is the sampled shadow fading envelope (S_{mn}) in dB, with $\langle S_{dB}(x) \rangle = 0$. A widely accepted model for the autocorrelation function is the exponential model, [2],

$$\psi_0(\Delta x) = e^{-\Delta x / \Delta x_0} \quad (4)$$

where the decorrelation distance Δx_0 defined as the smallest distance traveled by the mobile such that the autocorrelation falls to e^{-1} ,

$$\psi_0(\Delta x_0) = e^{-1} = 0.3679 \quad (5)$$

A short decorrelation distance indicates that the shadow component varies quickly as the mobile moves, while a longer decorrelation distance corresponds to a more slowly shadowing. Further, since the channel reveals a stochastic behavior we have a number of realizations of the autocorrelation $\psi_{ss}(x)$ for each Δx , then we can obtain $\psi_p(x)$ defined as the autocorrelation at a certain pdf level p ,

$$\psi_p(\Delta x) = \{\psi \mid \Pr(\psi_{ss}(\Delta x) < \psi) = p\} \quad (6)$$

Based on the above we propose the autocorrelation model defined at the p pdf level to have the general form,

$$\psi_p(\Delta x) = \frac{e^{-\lambda \Delta x} + \text{sign}(p - 0.5)e^{-C_{0.5-p}^\lambda}}{1 + \text{sign}(p - 0.5)e^{-C_{0.5-p}^\lambda}} \quad (7)$$

where $\text{sign}(\cdot)$ is the signum function, $0 \leq p \leq 1$, $1/\lambda$ is the decorrelation distance at $\psi_{0.5}(1/\lambda) = e^{-1}$ and $C_{p-0.5}^\lambda \neq 0$ is a constant in Δx but is an even function of $p-0.5$.

Hence, for $p=0.5$, (7) agrees with model (4)

$$\psi_{0.5}(\Delta x) = e^{-\lambda \Delta x} \quad (8)$$

with $1/\lambda = \Delta x_0$, that is at the 50 % pdf level of the $\psi_{ss}(\Delta x)$ distribution. The decorrelation distance of our model and model in [2] agree.

If $p \neq 0$, then

$$\psi_p(\Delta x) = \frac{e^{-\lambda \Delta x} \pm e^{-C_{p-0.5}^\lambda}}{1 \pm e^{-C_{p-0.5}^\lambda}} \quad (9)$$

It is easy to see that equation (9) above works for almost all values of λ , except in the limit case when λ tends to infinity. In that case $C_{p-0.5}^\lambda$ must also tend to infinity in order to give a satisfactory result. Namely,

that for zero decorrelation distance any consecutive values will remain uncorrelated.

Now, let assume that $C_{p=0.5}^\lambda = 1$. Thus equation (9) becomes

$$\psi_p(\Delta x) = \frac{e^{1-\lambda\Delta x} \pm 1}{e \pm 1} \quad (10)$$

Hence, the decorrelation distances, Δx_+ ($p>0$) and Δx_- ($p<0$) defined at e^{-1} ,

$$\begin{aligned} \Delta x_+ &= 2/\lambda = 2\Delta x_0 & p > 0 \\ \Delta x_- &\approx 1/2\lambda = \Delta x_0/2 & p < 0 \end{aligned} \quad (11)$$

Clearly, for p such as $C_{p=0.5}^\lambda = 1$ the decorrelation distance will be within the interval $[\frac{1}{2}\Delta x_0, 2\Delta x_0]$ at the e^{-1} level of the autocorrelation function, where Δx_0 is the decorrelation distance for $p=0.5$ at the same level.

5 MEASUREMENT RESULTS

The shadow fading properties of all 16 channels in the 4×4 MIMO channel matrix are analyzed. The distance traveled by the MS during a measurement round varies from 80 m to 250 m. Furthermore, we resample the extracted shadow fading components at a spatial distance of 5λ (about 0.85m) to get equally spaced data along the mobile route. The fast fading was filtered using a window of 6 m in average. Within each one-minute measurement run, the spatial autocorrelation sequence $\psi_{ss}(\Delta x)$ is calculated using equation (3), and the corresponding decorrelation distance Δx_0 is estimated according to equation (5). Combining results from all measurement rounds, we select the autocorrelation curves at three pdf levels, $\psi_{1\%}(\Delta x)$, $\psi_{50\%}(\Delta x)$ and $\psi_{99\%}(\Delta x)$, as defined by equation (6). We also estimate the decorrelation distance from the $\psi_{50\%}(\Delta x)$ curve, which we will refer to as the median decorrelation distance $\bar{\Delta x}_0$. It is worthwhile to notice that the usual approach is to extract data over larger distances along the mobile trajectory and the normalization is done relative the overall path loss trend. Obviously, in that case no variability of the decorrelation distance would be observed.

Fig. 2 and Fig. 3 show the empirical $\psi_{1\%}(\Delta x)$, $\psi_{50\%}(\Delta x)$, and $\psi_{99\%}(\Delta x)$ of 16 channels, for base station A and B respectively. For comparison, we also plot $\psi_0(\Delta x)$ according to equation (4). The estimated $\bar{\Delta x}_0$ (in meters) of 16 channels for base station A are listed in Table I and base station B in Table II.

Several observations may be done from the presented plots. As can be seen from Fig. 2 and Fig. 3 the model fits the measured data very well for $p=0.5$. However, due to lack of data we do not validate the presented model for $p=0.01$ and $p=0.99$. However, there is a trend that shows that this model could

provide good agreement with observed data. Further, we see that in average (median) the decorrelation distance does not depend that strongly on the BS antenna height as shown in Table 1 and 2. On the other hand, the variance is larger for the BS with higher height. This may be explained by the fact that at lower BS antenna height the propagation environments is more ‘‘homogeneous’’, basically, the Non Line Of Sight (NLOS) scenario prevails between the MS and the BS, hence the lower variance. For the same reason at higher BS antennas the sight conditions between the MS and BS is more ‘‘heterogeneous’’ since the LOS probability is higher in this case.

Table 1 Median of shadow decorrelation distance Δx_0 in meters (estimated from the $\psi_{50\%}(\Delta x)$ curve), and standard deviation in meters, of 16 channels for base station A.

A	Tx1		Tx2		Tx3		Tx4	
	μ	σ	μ	σ	μ	σ	μ	σ
Rx1	8.5	5.0	3.4	3.0	6.8	3.9	3.4	2.8
Rx2	7.6	5.0	3.4	3.7	6.8	3.7	4.2	3.9
Rx3	7.6	5.0	4.2	3.8	6.8	5.1	4.2	4.3
Rx4	8.5	4.6	3.4	2.9	5.9	3.7	3.4	3.5

Table 2 Ibid. Table 1, Base station B.

B	Tx1		Tx2		Tx3		Tx4	
	μ	σ	μ	σ	μ	σ	μ	σ
Rx1	6.8	6.8	3.4	4.0	7.6	6.5	3.4	4.9
Rx2	7.6	6.3	3.4	3.9	5.1	6.7	3.4	4.2
Rx3	8.5	6.4	4.2	3.9	5.9	6.7	3.4	3.6
Rx4	6.8	6.4	3.4	4.0	6.8	6.6	4.2	4.4

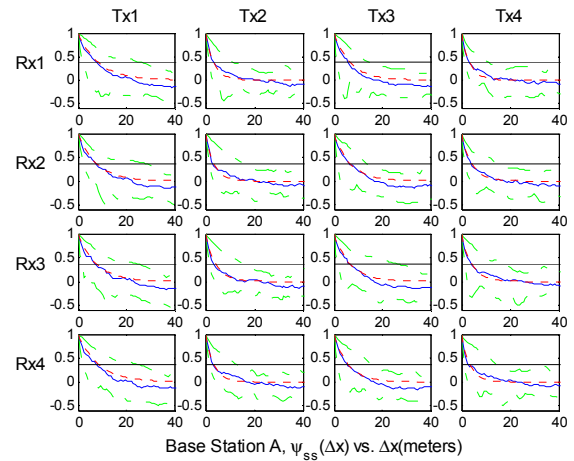


Figure 2 Shadow fading spatial autocorrelations of 16 channels. The lower and the upper dashed lines are $\psi_{1\%}(\Delta x)$ and $\psi_{99\%}(\Delta x)$, respectively. The solid and the dotted lines are $\psi_{50\%}(\Delta x)$ and $\psi_0(\Delta x)$, respectively. Base station A.

From Table 1 and 2 it follows that, the antenna pair pointing parallel to the MS path direction (TX2 and TX4) experience a faster-varying shadow fading, while the antenna pair pointing perpendicular to the MS movement direction (TX1 and TX3) experience a more stable shadowing environment. A plausible explanation could be found in the orientation of the MS relative the BS. Since, the BS antenna has a relatively

constant gain over the propagation area, the MS antenna pattern orientation (directive antennas are used) may have a great impact not only on the fast fading but also on the long term fading. It is also well known that the main propagation mechanism in urban environments is diffraction over the roof tops. Now, for parallel orientation of antennas (TX2, TX4) in LOS conditions the decorrelation distance should be larger than in the NLOS case, since in LOS there are no larger shadowing objects in the propagation path. But as we said, it is most probable that the signals reach the mobile over the roof top and therefore propagation path will be shadowed by buildings besides the streets lowering the decorrelation distance. Similarly, for the orthogonally oriented antennas the main propagation mechanism is still the same and the received signal will vary the most at street crossings or when turning around the corner. However, in this case the probability that the MS antennas are actually oriented towards the direction from which the main contribution to the received signal comes from is obviously higher. Hence, the received signals fade slower along the mobile path compared to the case of parallel oriented antennas.

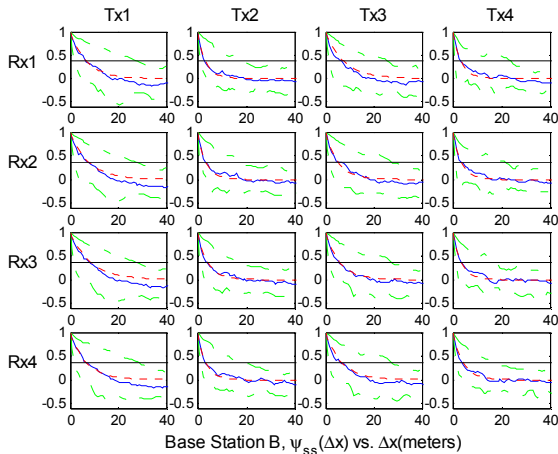


Figure 3 Ibid. Fig. 2, Base station B.

6 DECORRELATION DISTANCE AND STANDARD DEVIATION

The decorrelation distance Δx_0 describes how fast the shadow fading component varies, and the standard deviation σ_s measures the severity of shadow fading. Here we look at the possible correlation between Δx_0 and σ_s .

Fig. 4 and Fig.5 plot Δx_0 (in meters) together with σ_s (in dB) observed at each TX, for base stations A and B, respectively. As is clear, σ_s vary from 1 dB to 7 dB and Δx_0 vary from 2 m to 28 m. In some measurement rounds, σ_s and Δx_0 seem to have a positive correlation, i.e., they increase and decrease at the same time. Namely, for values of σ_s remarkably deviating from average the decorrelation distance also tends to increase but not vice versa. The value of Δx_0 depends on local topology. Large σ_s values usually occur when the mobile is turning around street corners, where the

shadowing envelope would most probably experience some deep fades. Besides corner places, large σ_s may also occur as long as the shadowing environment has a sharp change.

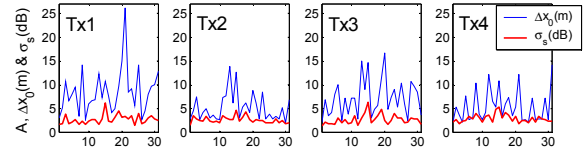


Figure 4 Δx_0 in meters (the blue curve) and σ_s in dB (the red curve), observed at TX1, TX2, TX3, and TX4, respectively for Base station A. The x-axis labels the measurement round indices. Base Station A.

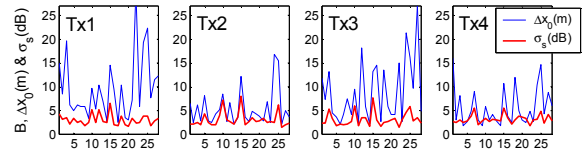


Figure 5 Ibid. Fig. 4, Base station B.

7 DISCUSSION

A new model for the autocorrelation function of the long-term fading component has been provided. The model describes the decorrelation distance as a stochastic variable for which a probability level of interest may be defined according to the modeling needs. For the 50 % pdf level the model agrees with the exponentially shaped autocorrelation function.

It is also shown that the base station antenna height has a larger impact on the variance of the decorrelation distance rather than on its average. Namely, the higher the BS the larger is the variance. Further, it was also observed that the orientation of the antenna plays a substantial role in the variability of the shadow fading. It is slower for antennas oriented perpendicularly to the MS path. Finally, it was observed a weak correlation between the standard deviation of the shadow fading and the decorrelation distance, which was higher for the higher BS.

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