Directional Dependence of Large Scale Parameters in Wireless Channel Models

Niklas Jaldén, Per Zetterberg, Björn Ottersten
ACCESS Linnaeus Center
KTH EE Signal Processing Lab
Royal Institute of Technology, 100 44 Stockholm, Sweden
Email: {niklas.jalden,per.zetterberg,bjorn.ottersten}@ee.kth.se

Abstract—In this paper the autocorrelation properties of shadow fading and angle spread at both the base station (BS) and at the mobile station (MS) are analyzed using urban macro cellular measurement data. The shadow fading parameter is shown to have a longer decorrelation distance than the angle spread at both the BS and at the MS. Furthermore, we observe variations in the shadow fading that depend on the direction of the MS movement due to street canyons. The same dependence is not observed in the angle spreads. These results indicate that the origin of the angle spread is local to the transmitter and receiver, while the shadow fading depends on the intermediate environment.

I. INTRODUCTION

Future wireless communication systems will utilize the spatial properties of the wireless channel to improve the spectral efficiency and thus increase the system capacity. This is realized by deploying multiple antennas at both the transmitter and receiver. Utilizing the spatial properties of the channel demands channel models that properly reflect these characteristics.

Due to the unpredictable nature of the wireless channel, a common approach is to model its effects in a statistical fashion. Within the 3GPP, [1], or WINNER, [2], channel models intended for reference and standardization use have been developed. These models are partly based on bulk parameters which describe the characteristics of the channel over larger areas of several wavelengths. Such parameters include shadow fading, angle spread, and delay spread among others, and are often called large scale (LS) parameters. Considering the variations of these parameters, it is likely that they are correlated between closely located areas. Since channel models critically depend on these parameters, it is therefore of key interest to model their correlation properties properly instead of assuming independence for each link. Accurate modelling of LS parameter variations between closely located areas is of paramount importance when evaluating multiuser systems or systems with a moving MS.

The distributions of large scale parameters have been extensively studied in the past. In excess of this, [3] [4] [5] among some, have found shadow fading and angle spread to have an exponential autocorrelation function averaged over all possible moving directions. We verify these results and show in addition that the shadow fading variation is dependent on the moving direction of the MS relative the intermediate environment between MS and BS. A property that is not seen in the angle spread.

This paper is structured as follows. In Section II a background to the large scale parameters studied herein is given. Section III motivates this study, while Section IV describes the measurement campaigns conducted to collect the data used for analysis. In Section V and VI the estimation procedures and properties of the LS parameters are shown. Finally in section VII we show dependence of the MS movement on the autocorrelations and give physical explanations to these observations. This paper is concluded in Section VIII.

II. LARGE SCALE PARAMETERS

As mentioned above, large scale parameters describe the channel characteristics over larger areas of several wavelengths. Such parameters include shadow fading, angle spread, and delay spread etc. In this paper we only study shadow fading and angle spread at the BS and at the MS.

A. Shadow Fading

The received power for different locations in a urban macro cellular scenario, assuming that the fast fading effect is removed, is commonly modelled as linearly decreasing in dB with logarithmic distance, [6]. This model is approximate, so the power between two separate locations, at equal distance from the BS, may vary substantially. This variation is commonly termed shadow fading and is found to be well modelled by a normal distribution [7], [8]. Thus the difference, in dB, between the transmitted power $P_{Tx}$ and the received power $P_{Rx}$, at a distance $d$ from the BS, can be written as:

$$L_{dB}(d) = P_{Tx} - P_{Rx} = 10n \log_{10}(d) + X_{SF},$$  

(1)

where $n$ is the path loss slope [7], [9] for the given environment. The variable $X_{SF}$ is the shadow fading term to compensate for the mismatch of the linear path loss model.

B. Angle Spread

In wireless communications, the received signal is composed of several multipath propagation components, from here on termed rays, arriving from different directions. Assuming $N$ rays the angular spread is commonly defined as:

$$\sigma_{\phi} = \sqrt{\frac{\sum_{i=1}^{N} P_i(\phi_i - \bar{\phi})^2}{\sum_{k=1}^{N} P_k}},$$  

(2)
where $\phi_i$ is the $i$:th ray's angle of arrival (departure), $P_i$ its power, and the nominal direction, power weighted mean, $\bar{\phi}$ is defined as:

$$\bar{\phi} = \frac{\sum_{i=1}^{N} P_i \phi_i}{\sum_{k=1}^{N} P_k}.$$  (3)

Thus, the angle spread is a function of how the multipath components arrive (depart) relative the nominal angle of arrival (AoA) or angle of departure (AoD) respectively. With the above definition it is seen that the minimum angle spread, 0, is achieved when all the power is received from a single direction, while the maximum spread, $\sigma_{\phi} = \frac{360}{\sqrt{12}}$ is obtained when the power is uniformly received in $[-\pi, \pi]$. Thus, an elevated user usually experiences a smaller angle spread than a user surrounded by local scatterers.

III. LARGE SCALE VARIATIONS

Previous papers have studied the autocorrelation properties of the shadow fading parameter from measurement data, [3], [4] and found it to be well modelled by an exponential decay. In [5] similar results were found for the angle spread at the BS as well as the delay spread. These results have been derived by considering the Euclidian distance between each and every sample regardless of their relative orientation. Due to this, the average correlation over all possible (measured) MS moving directions is found. However, as argued in, [1], [2] the large scale parameters may depend on the scattering environments. Therefore, if the change of the local environment depends on the MS moving direction, this property may be reflected on the large scale parameters.

The shadow fading, for example, is usually considered to depend on the propagation path between the BS and the MS, [10], [11]. Thus, in theory, the variations of the shadow fading should be related to the rate of change of the intermediate environment. Moreover the rate of change of the environment between the BS and MS in an urban area, is not independent of the MS moving direction. To see this consider a mobile at two different locations. If the movement is transversal to the BS broadside, as in the case when the MS moves from T1 to T2 in Fig. 1, the change in the intermediate environment is often larger than it would be if the movement is radial, R1 to R2 in Fig. 1. A transversal movement in a urban area may result in completely new path (new buildings in the intermediate area), while radial movements result in two locations with a common part of the propagation path, with some additional path to the most distant location.

IV. MEASUREMENT CAMPAIGNS

To study large scale parameter distributions and variations two large narrowband measurement campaigns have been conducted in the Vasastan area of downtown Stockholm in 2004 and 2005. The environment can be characterized as typical European urban with mostly six to eight story high stone buildings with occasional higher buildings and church towers. The orientations of the streets in the measured area enables us to study the autocorrelations for different moving directions. Below the specifics of the two campaigns from 2004 and 2005 are described. In Fig. 2 the measurement route for the two campaigns are shown as well as the base station locations. The locations of the base stations are shown by the hexagonal marker, and the arrows indicate the pointing directions of the antennas. As can be seen from the figure the environments of the two measurement campaigns are very similar. For further description of the measurement equipment and of the environment see [12], [13].

A. 2004 Campaign

The 2004 measurements were conducted in uplink with a single mobile station, transmitting four separate continuous waves, with a frequency separation of 1 kHz and a nominal carrier frequency of 1766.6 MHz, on four separate antennas. The four antennas were mounted on separate sides of a wooden box, thus separated 90° from each other. This can be seen as an uniform circular array with 4 elements. Pictures and further explanation on this antenna can be seen found [13]. The frequency offset between the antennas enables easy separation of the channels and thus the calculations of the MIMO channel matrix elements. Three spatially separated base stations, with
4 element uniform linear arrays (ULA), were used as receivers. The two base stations used for the analysis in this paper, called 2004:A and 2004:B respectively, are seen in Fig. 2 and are separated some 900 meters. The mobile station was moved along the streets according to the routes shown in the figure at a velocity around 10m/s.

B. 2005 Campaign

The 2005 measurements were conducted in downlink, utilizing two base stations with 2 antenna elements each, and a receiving mobile station, with identical antennas as was used in 2004. The transmit signals was similarly to 2004 separated 1 kHz apart. The mobile was moved along the routes show in Fig. 2 at similar velocity as in the 2004 measurements. The two base stations were located on top of the same roof separated 50 meters. These base stations are called 2005:1 and 2005:2 respectively. Due to the close location of the two BSs, only one is shown in Fig. 2.

V. ESTIMATION PROCEDURE OF LARGE SCALE PARAMETERS

The large scale parameters were estimated by dividing the data into segments of length $30\lambda$, which is similar to the procedure in [5]. The LS parameters are assumed to be constant within this area. A segment of this size will in the following be termed a $30\lambda$-segment.

A. Shadow fading

To estimate the shadow fading the received power is calculated as the average over all antennas at both the BS and the MS over the entire $30\lambda$-segment. The path loss slope is then estimated by making a linear least squares fit to the power in dB, from the set of all $30\lambda$-segments, against log-distance. The shadow fading is the resulting term of the average received power when the distance dependence is removed. The same procedure is used in [13], where more details are provided.

B. Angle spread

The base stations from 2005 are only equipped with two antennas. Due to this advanced angle spread estimation techniques, like the maximum likelihood approach presented in [14], cannot be applied here. In this paper different estimation methods are used for calculating the spread at the BS and MS, as explained below. More thorough explanation and evaluation of the estimators is given in [13].

1) Angle spread at the BS: The angle spread at the base station is estimated using a correlation based table lookup method. A table is created by assuming a macro cellular setup, with scatterers close to the mobile only. Then, for a given mean angle of arrival and angle spread the correlation coefficient between two antenna elements (with same spacing as was used in the measurements) is calculated and stored. This is done for all possible AoA in $[-\pi, \pi]$, and spreads in the range $[0, 100^\circ]$. To estimate the angle spread from the measurement data the correlation coefficient between the signal of two antenna elements is calculated for the $30\lambda$-segment, as well as the direction to the MS, where the latter is obtained from the GPS data supplied by the measurements. This angle spread estimation procedure is similar to the one presented in [15].

2) Angle spread at the MS: The conventional angle spread is defined as shown in (2). Note that the angle spread is a measure of the azimuth signal spread relative a mean angle of arrival, and thus should be invariant of the mobile antenna orientation, i.e linear shift in the received AoA of all rays should not affect the estimated spread. The estimated spread given by replacing $\phi_s$, see (2), by $\phi_i + \alpha$ is $\sigma_{AS}(\alpha)$ and should thus be a constant independent of $\alpha$. However due to the ambiguity of the modulo $2\pi$ operation, this is not always the case. Therefore the angle spread at the MS should be the minimum angle spread for each linear shift $\alpha \in [0, 2\pi]$. With these assumptions the angle spread at the mobile station, $\sigma^2_{AS, MS}$, is defined as

$$\sigma^2_{AS, MS} = \min_\alpha \left\{ \frac{1}{N} \sum_{n=1}^{N} \sum_{i=1}^{4} p_n (\mod(\alpha_n - \bar{\alpha}))^2 \right\}, \quad (4)$$

where $p_n$ is the power of the $n$th ray and mod is short for modulo and defined as:

$$\mod(\alpha) = \{ \begin{array}{l l} \alpha + 180, \text{ when } \alpha < -180 \\ \alpha, \text{ when } |\alpha| < 180 \\ \alpha - 180, \text{ when } \alpha > 180 \end{array} \right.. \quad (5)$$

The definition of the MS angle spread is equivalent to the circular spread definition in Annex A of [1].

At the mobile-station side, all that is available for estimating the angle spread is the power level of the four MS antennas, since the MS is not using an ULA and the phase information is unknown. The method to estimate the AS at the MS is to assume a four ray model where the AOs of the four rays are identical to the bore-sights of the four MS antennas i.e $\alpha_n = 90^\circ(n - 2.5)$. The power of the four rays $p_1, \ldots, p_4$, are obtained from the power of the four antennas i.e. the Euclidean norm of the rows of the channel matrices $H$. These estimates are averaged over the fast-fading over the $30\lambda$ segment. From these powers the angle spread is calculated using the circular model defined above. Since the angle spread at the MS is generally very large due to the surrounding scattering environment reasonable estimates of the shadow fading can be obtained, as shown in [13].

VI. PROPERTIES OF THE LARGE SCALE PARAMETERS

The large scale parameters were estimated according to the procedure explained in Section V. The estimated mean values, $\bar{\mu}$ and standard deviations, $\bar{\sigma}$, were estimated for all parameters and is shown in Table I. The shadow fading was, in accordance to previously reported results found to be normally distributed in dB. The logarithm of the angle spread at the base station in degrees was also found be well modelled by a normal distribution, while the angle spread in degrees at the mobile was found to be better modelled by a scaled beta function as:

$$f(x, \alpha, \beta) = \frac{1}{B(\alpha, \beta)} \frac{x^{\alpha-1}}{\eta^{\alpha}} (1 - \frac{x}{\eta})^{\beta-1}, \quad (6)$$
where the best fit $\alpha$ and $\beta$ are shown in Table II. These parameters are found by brute force search using two decimals precision. The parameter $B(\alpha, \beta)$ is a constant dependent on $\alpha$ and $\beta$ such that $\int_{0}^{\eta} f(x, \alpha, \beta) = 1$. This is further explained in [13].

A. Autocorrelation Properties of the Large Scale Parameters

The average autocorrelation functions for all possible MS moving directions were calculated by sorting the data based on their Euclidian distance to each other. The correlation coefficient as a function of distance separation was then calculated as:

$$\rho_{a,b} = \frac{E[ab] - m_a m_b}{\sqrt{(E[a^2] - m_a^2)(E[b^2] - m_b^2)}}. \quad (7)$$

This gives autocorrelation functions as can be seen in Fig. 3, 4, and 5, for the shadow fading and angle spread at the BS and at the MS respectively. For these autocorrelation functions the decorrelation distances are calculated as the distance to which the correlation coefficient drops below $e^{-1}$, a commonly used value in the literature, [16], and shown in Table. III. These distances are slightly larger than those reported earlier for urban scenarios, but smaller than those of suburban.

As can be seen in the figures (Fig. 3, 4, and 5) the exponential decay seem to give a reasonable fit to the autocorrelation functions of all three parameters. Furthermore it can be noted that the shadow fading has the longest decorrelation distance while the angle spread at the MS has the shortest.

VII. DIRECTIONAL DEPENDENCE

Observing the city map in Fig. 2 it can be seen that the building blocks are square shaped and the two main directions of the streets are orthogonal to each other. The direction of the streets measured in 2005 appear to be tilted $\sim 45^\circ$, as seen from the BS, compared to the streets in 2004. If we would segment the data for the 2004 measurements into two sets, such that each set only contains streets parallel to each other, it is seen that one of the main directions (of the streets) is transversal to the BS broadside while the other is parallel, see Fig. 6 and compare to Fig. 1. Further, it can be noted that the streets that are transversal to 2004:A are radial to 2004:B and vice versa. Similar segmentation for the 2005 measurements results in data sets containing streets that are either $+45^\circ$ or $-45^\circ$ compared to the BS broadside, for both base stations,
considering MS movement directions. Studying Fig. 8(b), which contains data segmented for the considered base stations.

The autocorrelation functions for the two separate directional segmentations have been calculated in a similar fashion as the average autocorrelation functions described in Section VI-A. However, in this case each road has been treated separately, in order not to get the effect of radial movement on the transversal analysis and vice versa. The autocorrelation functions of the large scale parameters from the two different measurement campaigns, and directional segmentations, are shown in Fig. 8.

By observing Fig. 8(a) we see that transversal movement indeed increases the variation of the shadow fading, and thus decreases the decorrelation distance. Similarly, radial movement increases the decorrelation distance compared to the average, which is calculated over all possible moving directions. Studying Fig. 8(b), which contains data segmented considering MS movement directions ±45° relative the BS broadside, we see similar autocorrelation functions, for both directions. Thus the shadow fading does not depend on the actual direction of movement, but rather the rate of change of the intermediate environment for this case.

More notably it can be seen by observing Fig. 8c-f that these segmentations, as presented in Fig 6 and 7, has no affect on the variations of the angle spread at either the BS or the MS. This may be an indication that the properties giving rise to the angle spread are local to BS and MS, and thus changes in the same rate, independently of the MS moving direction.

VIII. CONCLUSIONS

This paper has analyzed the autocorrelation functions for shadow fading and angle spread at both the BS and at the MS, using urban measurement data. The exponential decay has been verified to give a good fit to the autocorrelation. Furthermore, a directional dependence of the MS movement is shown in the shadow fading parameter. However such a dependence has not been seen in the angle spreads at either the BS or at the MS. These results indicate that the properties giving rise to the angle spread are local to the transmitter and receiver while the shadow fading depends on the intermediate environment.

REFERENCES

Fig. 8. Autocorrelation functions for directionally segmented data.