Narrowband Fading Analysis of Indoor Distributed Antenna Systems

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***Abstract*—The effects of distributed antenna systems (DAS) on the Rice K factor by using practical measurements are presented, in order to investigate the degree of possible fading degradation caused by the incoherent signal combination of the conventional DAS architecture. The measured distributions are compared with the theoretical Rice distribution and it is seen that there is no strong indication to consider any other distributions. It is found that the DAS system slightly decreases the K factor, but not sufficiently to have a detrimental effect on availability. Therefore, it is inferred that the dominant effect of DAS is to provide macro-diversity gain.**

***Index Terms*—Antenna arrays, Rician channels.**

I. Introduction

DISTRIBUTED antenna systems (DAS) have been proposed as an alternative to single antenna cell architectures, as a means of providing in-building wireless access in time division multiple access (TDMA)- and code division multiple access (CDMA)-based systems. In DAS, simulcasting is deployed, whereby the same information is transmitted and received by all the antenna elements, which are distributed throughout the building. No intelligence is applied at the antenna elements (AEs), as all the signal-specific processing is performed at the central location. Distributed antennas provide many important characteristics such as macro-diversity, reduced transmit power levels, uniform coverage of the investigated area and also less interference to other systems [1], [2].

However, the use of many elements may cause increased fading depths due to artificial multipath interference between individual antennas in the DAS architecture. Therefore, it is important that analysis of the fading statistics of both single and DAS cells be performed to obtain the degree of fading degradation and to better understand and deploy distributed antennas indoors. Knowledge of the expected Rice K factor will allow the estimation of the fast fading margin required in a link budget calculation. Fading results were also presented in [3], [4] and it was seen that DAS slightly decrease the K factor. In the investigated scenario, two DAS configurations have been considered, using practical measurements. The first is a nonline-of-sight (NLOS) scenario and deploys six AEs, randomly distributed around the floor of the CCSR building at the University of Surrey, whereas the second deploys three AEs inside a meeting room [5], [6].

In order to analyze the performance of both single and distributed antenna systems, the Rice K factors are obtained for both systems and the resulting distributions are compared with the theoretical Rice distribution to obtain a confidence in the analysis.

II. Rice Distribution

In mobile radio channels when there is a dominant signal component present (e.g., LOS propagation path) the small-scale fading envelope distribution is Rice with probability density function (pdf) as given by [7]

$$P(r) = \frac{r}{\sigma^2} \cdot \exp\left[-\frac{r^2+s^2}{2\sigma^2}\right] \cdot I_0\left(\frac{r \cdot s}{\sigma^2}\right) \tag{1}$$

where σ^2 is the variance of either the real or imaginary components of the multipath part alone, s is the magnitude of the LOS component, and r is the received signal. It is noted that if s is set to zero the distribution becomes Rayleigh. The function I_0 is the modified Bessel function of the first kind and zeroth order. The Rice PDF is often expressed in terms of the K factor, which is defined as the ratio between the direct or strong component power of the signal and the variance of the multipath. In order to calculate K from a set of measurements, the method of moments is used, which takes advantage of the fact that the even order moments have closed form. Any arbitrary moment of the Rice pdf can be written as [5]

$$\begin{aligned} E[r^u] &= \int_0^\infty r^u \cdot P(r)dr \\ &= \int_0^\infty \frac{r^{u+1}}{\sigma^2} \cdot \exp\left[-\frac{r^2+s^2}{2\sigma^2}\right] \cdot I_0\left(\frac{rs}{\sigma^2}\right) dr. \end{aligned} \tag{2}$$

The second and fourth moments are calculated as

$$E[r^2] = 2\sigma^2 + s^2 \tag{3}$$

$$E[r^4] = 8\sigma^4 + 8\sigma^2 s^2 + s^4 \tag{4}$$

from which the closed solutions of s^2 and σ^2 are derived as

$$s^2 = \sqrt{2E^2[r^2] - E[r^4]} \tag{5}$$

$$\sigma^2 = \frac{\left(E[r^2] - s^2\right)}{2}. \tag{6}$$

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Finally, the K factor is calculated by

$$K = \frac{s^2}{2 \cdot \sigma^2}. \tag{7}$$

III. K Factor Results

For the investigation of the fading characteristics of the indoor environment, measurements taken in the Centre for Communication Systems Research (CCSR) building during a campaign for the Mobile Virtual Centre of Excellence (Mobile VCE) Core 1 Project were used, [5], [6]. The first scenario uses NLOS measurements on the same floor with different number of walls between the AEs and the transmitter, whereas the second scenario uses LOS measurements taken with 3 AEs in an unfurnished meeting room. The frequency of transmission was 2.4 GHz.

A. NLOS Measurements

To determine the fast fading statistics of the received signal envelope, the effects of the path loss and shadowing (or slow fading) have to be removed first. In order to extract the fading envelope, the received signal is normalized to its local root mean square (rms) value. So, for the received sample $r(x_i)$, the local rms is given by [9]:

$$\text{RMS} = \left[\frac{1}{W} \cdot \sum_{i-W/2}^{i+W/2} \left[r\left(x_i\right)\right]^2\right]^{1/2} \tag{8}$$

where W represents the window length for the computation. This local rms estimate is computed for each individual sample in a sliding window and the normalized samples $r(x_i)/\text{rms}$ are subjected to distribution fitting algorithms. It has been suggested by [8] that a window size of 40 wavelengths λ be used for macrocells. However, as proposed in [9] and [10], for small-cell analysis, a window-size of about 4λ–10λ is more appropriate since the local rms received signal level undergoes significant fluctuations in such wide windows. A window size of 10λ was used for this analysis, which corresponds to an averaging window distance of approximately 1.25 m. For the sampling rate used for these measurements, this distance translates to approximately 200 samples per window (or bin).

Table I presents the Rice K factors (as a linear power ratio) of the individual elements and also of the combined component for a representative number of bin indexes (1–10 of a total of 33 bins), as calculated using (5)–(7). The mean and standard deviation (SD) of the K factors of this sample and also of all available bins are also shown at the bottom of the table. It is seen that they represent a moderately severe fading channel since in most cases K is within the interval 0–3.

The K factor of the combined (DAS) component is maintained at approximately the same levels as that of the individual components, although in most cases a slight degradation is observed due to the fact that incoherent combination of signals is taking place. The K values for the DAS component are usually seen to be around 1, resulting in a more severe fading channel if not a Rayleigh distribution (i.e., $K < 1$). It is also observed that there are cases where the K factor degradation of the DAS architecture is more apparent when the K value of one of the individual antennas is greater than 3 (approximately 5 dB), as happens for, e.g., element 3 at bin index 3 or for element 2 at bin index 8. The SD of the combined component is smaller than that of the individual AEs, indicating that the variability of the channel is less with DAS and, therefore, an overall more severe fading channel is present. Similar findings regarding K factor degradation due to DAS were also reported in [4]. However, the mean signal strength of the combined component is much higher compared to that of the individual AEs and, therefore, it is expected that macrodiversity will be the dominant effect of DAS when deployed in NLOS environments where the main target is to overcome path loss and shadowing losses and meet high coverage and capacity requirements as shown in, e.g [11].

TABLE I
K Factor Values of the Individual Elements and of the Combined Component for the NLOS Scenario

Bin Index	Elem. 1	Elem. 2	Elem. 3	Elem. 4	Elem. 5	Elem. 6	DAS
1	1.97	0.92	1.75	0.00	0.00	2.18	0.30
2	1.42	1.33	0.84	0.98	2.43	1.23	0.57
3	0.00	2.18	4.90	0.67	3.60	1.08	1.49
4	2.44	3.10	2.19	0.00	2.78	0.86	2.48
5	1.55	3.13	0.92	1.18	2.28	0.37	1.08
6	0.67	1.08	2.62	1.93	0.00	0.00	1.08
7	2.24	0.91	1.93	2.60	3.35	1.80	1.25
8	0.40	4.52	1.24	0.97	2.97	3.87	0.35
9	1.03	0.49	1.55	0.00	2.07	0.00	0.42
10	0.00	0.78	0.64	2.16	2.19	0.68	1.06
(μ,σ)	**Mean and SD of the K values for Bins Indexes 1 to 10**						
	(1.2,0.9)	(1.8,1.3)	(2.0,1.2)	(1.1,0.9)	(2.2,1.2)	(1.2,1.2)	(1.0,0.7)
	Mean and SD of the K values for all Bin Indexes						
	(3.0,3.1)	(2.1,1.9)	(1.4,1.3)	(1.2,0.9)	(1.3,1.2)	(1.2,1.0)	(0.9,0.7

Fig. 1 displays the theoretical Rice and measured distribution for two single antennas and for the DAS case. By performing a simple Kolmogorov–Smirnov goodness-of-fit test [9] for a number of different bins, it is seen that a given distribution (measured) is not significantly different from the theoretical, as the significance levels [or confidence measures (CM)] indicate reasonable degree of confidence in the fit. For example, for element 1 and for the first bin index, where $K = 1.97$ the maximum difference (D_{MAX}) between the measured and theoretical distributions is 0.06, corresponding to CM of approximately 0.4 (i.e., $D_{\text{MAX}} \times \text{SAMPLES}^{1/2} = 0.06 \times 200^{1/2} \approx 0.85$, which translates to CM of approximately 0.4, [9]). Since the CM is much greater than the suggested threshold of 10^{-3}, the hypothesis pdf should not be rejected.

B. LOS Measurements

Additional measurements using three AEs, were performed in an unfurnished room of the CCSR building with approximate dimensions $7 \times 13 \times 3$ m. The first two antenna elements were located at the two opposite corners on the same, 13 m side of the room, whereas the third antenna was located in the middle

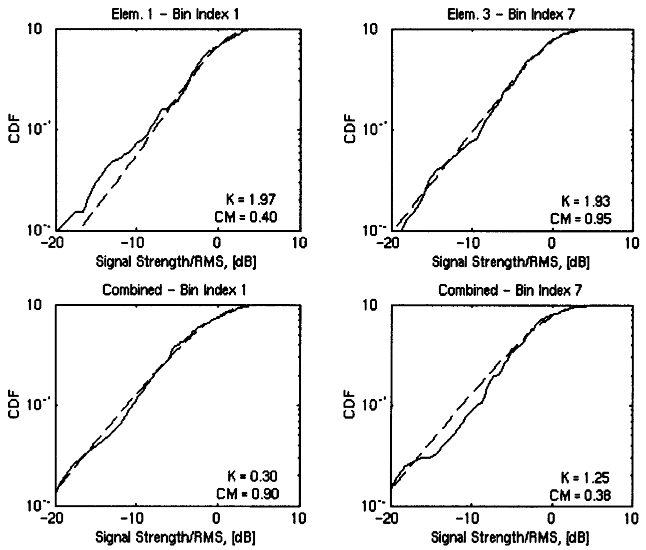

Fig. 1. A sample of comparisons between the ricean CDFs with K determined by the method of moments (dashed lines), and measured CDFs (solid lines), together with their confidence measures (CM) for the NLOS scenario.

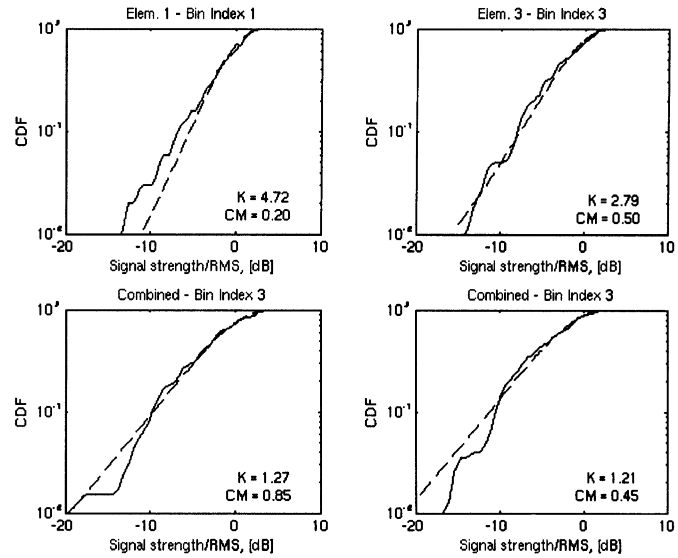

Fig. 2. A sample of comparisons between the ricean CDFs with K determined by the method of moments (dashed lines) and measured CDFs (solid lines), together with their confidence measures (CM) for the LOS scenario.

TABLE II
K FACTOR VALUES OF THE INDIVIDUAL ELEMENTS AND OF THE COMBINED COMPONENT FOR THE LOS SCENARIO

Bin Index	Elem. 1	Elem. 2	Elem. 3	DAS
1	4.72	2.99	2.28	1.27
2	2.37	2.89	4.88	1.90
3	2.98	4.21	2.79	1.21
4	4.07	1.37	5.73	1.54
5	4.32	0.56	2.37	0.98
6	2.78	1.17	0.74	2.49
7	3.20	2.18	1.43	1.56
8	4.59	0.60	2.72	0.82
9	5.99	4.40	2.39	0.77
10	8.52	1.68	4.99	0.73
(μ,σ)	**Mean and SD of the K values for bin indexes 1-10**			
	(4.4,1.8)	(2.2,1.4)	(3.0,1.6)	(1.3,0.6)
	Mean and SD of the K values for all bin indexes			
	(3.2,2.1)	(1.9,1.6)	(3.2,2.0)	(1.2,0.7)

of the opposite side. The transmitter moved inside the room following a predefined regular pattern, whereas the total number of bins collected for this scenario was 26. Table II presents the K factor values of the individual elements and of the combined component for the first ten bin indexes together with their mean values for the bins shown and also for the total number of bins. Low K values for LOS situations are present (i.e., less than five, in most cases) due to the fact that the indoor environment is rich in scattering. The effect of the DAS architecture on the fast fading degradation now becomes more apparent compared to the NLOS scenario, since K reduces in between zero and two translating in a decrease of the order of 2 to 5 dB depending on which element is used as a reference. This degradation of the fading characteristics is more apparent in the cases where the K value of the individual element is high (>4, or 6 dB), as can be observed from, e.g., bin indexes 8–10. This happens because the received signal strength is approximately the same for all the elements due to the small distances between the moving transmitter and the individual elements and none dominates. This results in more frequent events of destructive interference during the incoherent summation of the signals. As in the NLOS case, the theoretical and measured distributions present a reasonable degree of confidence in the fit, Fig. 2.

Therefore, care should be taken so that the effects of the distributed antennas on the fast fading are minimal if an intelligent combination technique is to be avoided. This should be achieved by placing the antennas in a way to ensure that one element is always closer to the user location increasing the LOS situations throughout the cell coverage area and also averaging out the shadowing effects. In order to overcome both the shadowing effects and the increased fading of the channel using DAS, a form of intelligent combining should be performed (e.g., selection combining, MRC or RAKE) at the expense of complexity.

IV. CONCLUSION

Fast fading analysis of narrowband measured data, taken in NLOS and LOS environments, was performed and it was found that in most cases the DAS architecture reduces the Rice K factor. The decrease in K was more apparent in LOS scenarios where, depending on which AE is used as a reference, a degradation of approximately 2–5 dB occurs due to the similar signal strengths of the AEs and incoherent signal summation. The K degradation is observed to be even higher when strong LOS component exists with K higher than 3 (i.e., 5 dB). In NLOS scenarios, the K factors of the combined component were similar to those of the individual AEs, although a small degradation was again obtained, in the order of approximately 1–3 dB.

These results indicate that the DAS architecture slightly degrades the fading of the channel and this is more apparent when strong LOS components exist. Therefore, one has to ensure that the shadowing averaging effects provided by DAS significantly overcome the fading degradation due to the artificial multipath interference between the individual AEs. However, since DAS are usually deployed to lessen the effect of shadowing, their overall performance is expected to be much better than that of single antennas, especially in NLOS indoor environments (e.g., multifloor buildings, airports, etc.), where the main aims are to provide ubiquitous services for future wireless communication systems. In cases where strong LOS exist a form of more intelligent combining of the AE's signals should be pursued.

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More detailed technical reports on this research are available to the Industrial Members of Mobile VCE.

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