Performance of Multiple-Input Multiple-Output Wireless Communications Systems Using Distributed Antennas

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***Abstract*— In this contribution we propose and investigate a multiple-input multiple-output (MIMO) wireless communications system, where multiple receive antennas are distributed in the area covered by a cellular cell and connected with the base-station (BS). We first analyze the total received power by the BS through the distributed antennas, when assuming that the mobile's signal is transmitted over lognormal shadowed Rayleigh fading channels. Then, the outage probability of the distributed antenna MIMO systems is investigated, when considering various antenna distribution patterns. Furthermore, space-time coding at the mobile transmitter is considered for enhancing the outage performance of the distributed antenna MIMO system. Our study and simulation results show that the outage performance of a distributed antenna MIMO system can be significantly improved, when either increasing the number of distributed receive antennas or increasing the number of mobile transmit antennas.**

I. INTRODUCTION

Among radio technologies, Multiple-Input-Multiple-Output (MIMO) systems have attracted wide research interests in recent years [1, 2]. It has been recognized as one of the most significant technical breakthroughs in modern communications. In MIMO systems multiple antennas are employed by both the transmitter and the receiver for improving the communication link quality, especially, for increasing the potential capacity and for supporting a high transmission rate [3–5].

In this contribution a MIMO system using distributed antennas is proposed and investigated, where multiple receive antennas are distributed in the area covered by a cellular cell. In the proposed distributed antenna MIMO system, space-time block coding [6,7] is employed by the mobile transmitter, since space-time coding is capable of offering spectral efficiency and diversity improvement simultaneously. In this contribution the uplink performance of the distributed antenna MIMO system is investigated by simulations, when various number of antennas and different location configurations are considered. Specifically, the performance in the context of the total received power by the BS from a mobile station and the outage probability of the distributed antenna MIMO system are investigated, when communication over lognormal shadowed Rayleigh fading channels. Our study and simulation results show that the performance of a conventional cellular system can be significantly improved, when a number of receive antennas are distributed in the area covered by the cellular cell, and/or when the mobile station employs multiple transmit antennas. Let us first give a brief overview for the MIMO space-time system.

II. OVERVIEW OF MIMO SYSTEMS

A MIMO system using multiple transmit antennas and multiple receive antennas can be well-described by the following input-output equation [1, 4]

$$\boldsymbol{y}(i) = \boldsymbol{H}(i)\boldsymbol{x}(i) + \boldsymbol{n}(i) \tag{1}$$

where the index i is related to the ith transmitted symbol. Let assume that the transmitter employs U number of transmit antennas and that the receiver employs V number of receive antennas. Then, we have

$$\boldsymbol{y}(i) = [y_1(i), y_2(i), \ldots, y_V(i)]^T \tag{2}$$
$$\boldsymbol{x}(i) = [x_1(i), x_2(i), \ldots, x_U(i)]^T \tag{3}$$
$$\boldsymbol{n}(i) = [n_1(i), n_2(i), \ldots, n_V(i)]^T \tag{4}$$

Furthermore, in (1) $\boldsymbol{H}(i)$ is the MIMO channel matrix, which connects each of the receive antennas with each of the transmit antennas. The MIMO channel matrix $\boldsymbol{H}(i)$ in general can be expressed as

$$\boldsymbol{H}(i) = \begin{bmatrix} h_{11}(i) & h_{12}(i) & \cdots & h_{1U}(i) \\ h_{21}(i) & h_{22}(i) & \cdots & h_{2U}(i) \\ \cdots & \cdots & \ddots & \cdots \\ h_{V1}(i) & h_{V2}(i) & \cdots & h_{VU}(i) \end{bmatrix} \tag{5}$$

where $h_{jk}(i)$ is the channel attenuation factor with respect to the ith transmitted symbol, the kth transmit antenna and the jth receive antenna.

When space-time block coding [7] is utilized by the transmitter, a symbol is usually first mapped to several space-time symbols and these space-time symbols are then transmitted using several symbol periods. In this case, correspondingly, the MIMO input-output equation of (5) can be modified for encompassing the space-time coding, which may be understood by referring to the following example.

Let us assume that the transmitter employs two transmit antennas and the receiver employs V number of receive antennas. Furthermore, we assume that the transmitted symbols are space-time coded using the Alamouti's scheme [6]. Specifically, the adjacent data symbols x_1 and x_2 are space-time block

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coded according to Alamouti's scheme [6]. The resultant space-time coded symbols are then transmitted during two consecutive symbol periods. In the first symbol period the symbol transmitted from antenna 1 is x_1 and the symbol transmitted from antenna 2 is x_2. By contrast, in the second symbol period the symbol transmitted from antenna 1 is $-x_2^*$ and the symbol transmitted from the antenna 2 is x_1^*, where the superscript * denotes the complex conjugate. Consequently, according to (1), we have

$$\boldsymbol{y}(1) = \underbrace{\begin{bmatrix} h_{11}(1) & h_{12}(1) \\ h_{21}(1) & h_{22}(1) \\ \cdots & \cdots \\ h_{V1}(1) & h_{V2}(1) \end{bmatrix}}_{\boldsymbol{H}(1)} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \boldsymbol{n}(1) \quad (6)$$

$$\boldsymbol{y}(2) = \begin{bmatrix} h_{11}(2) & h_{12}(2) \\ h_{21}(2) & h_{22}(2) \\ \cdots & \cdots \\ h_{V1}(2) & h_{V2}(2) \end{bmatrix} \begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + \boldsymbol{n}(2) \quad (7)$$

and upon conjugating $\boldsymbol{y}(2)$ and re-arranging the terms we have

$$\boldsymbol{y}^*(2) = \underbrace{\begin{bmatrix} h_{12}^*(2) & -h_{11}^*(2) \\ h_{22}^*(2) & -h_{21}^*(2) \\ \cdots & \cdots \\ h_{V2}^*(2) & -h_{V1}^*(2) \end{bmatrix}}_{\boldsymbol{H}(2)} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \boldsymbol{n}^*(2) \quad (8)$$

Let define

$$\begin{aligned} \boldsymbol{y} &= \begin{bmatrix} \boldsymbol{y}(1) \\ \boldsymbol{y}^*(2) \end{bmatrix}, \ \boldsymbol{H} = \begin{bmatrix} \boldsymbol{H}(1) \\ \boldsymbol{H}(2) \end{bmatrix}, \\ \boldsymbol{x} &= \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \ \boldsymbol{n} = \begin{bmatrix} \boldsymbol{n}(1) \\ \boldsymbol{n}^*(2) \end{bmatrix} \end{aligned} \quad (9)$$

Then, the MIMO input-output equation, which invokes the space-time coding, can be written as

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \quad (10)$$

which has the same form as (1).

It can be shown that, when independent fading channels are assumed, the MIMO channel matrix of $\boldsymbol{H}$ has a rank of two with a probability one. Hence, any, say x_1, of the two symbols in $\boldsymbol{x}$ can be detected, while suppressing the interference from the other symbol, say x_2. For example, assuming that the receiver has the knowledge of $\boldsymbol{H}$, then, for zero-forcing and minimum mean-square error (MMSE) interference suppression schemes [8], the estimate to $\boldsymbol{x}$ can be, respectively, expressed as

$$\begin{aligned} \hat{\boldsymbol{x}} &= \left(\boldsymbol{H}^H\boldsymbol{H}\right)^{-1}\boldsymbol{H}^H\boldsymbol{y}, \quad (11) \\ \hat{\boldsymbol{x}} &= \left(\boldsymbol{H}^H\boldsymbol{H} + \sigma^2\boldsymbol{I}\right)^{-1}\boldsymbol{H}^H\boldsymbol{y} \quad (12) \end{aligned}$$

where ^{H} represents complex transpose conjugate, while σ^2 is the variance of the background noise.

Having given a brief overview of the MIMO principles, let us now focus our attention on the proposed MIMO systems using distributed antennas.

III. MIMO Systems with Distributed Antennas

A. Antenna Distribution Patterns

In the context of our investigation, four types of antenna distribution patterns are considered, which are shown in Fig.1. Specifically, when the BS has only one antenna, certainly, this antenna is located at the BS. When the BS has 7 antennas, then, one of them is located at the BS, while the rest 6 are located at six corners of the hexagon, as indicated by the crosses ($\times$) in Fig.1. Similarly, when the BS employs 13 antennas, these 13 antennas are located at the positions indicated by the squares ($\square$) seen in Fig.1. Finally, when the BS employs 19 antennas, these 19 antennas are located at the positions indicated by the circles ($\bigcirc$) seen in Fig.1. We assume that the distributed antennas are connected with the BS at the cell center using optical fibber and the signals received by the distributed antennas are directly sent to the BS without any processing at the distributed antenna locations. All signals are only processed at at the BS. Note that, in Fig.1, R is the radius of the cell considered.

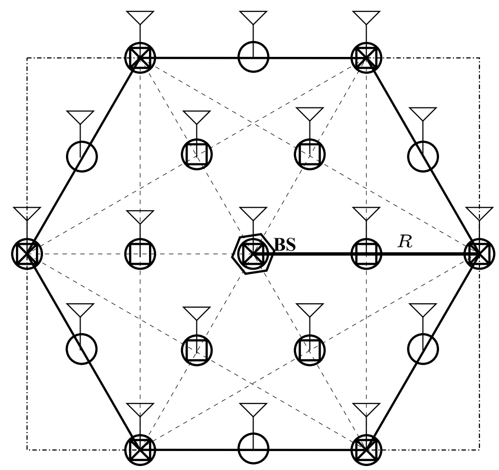

Fig. 1. A concept cell having one antenna at the base-station (BS), or 7, 13, 19 antennas distributed around the BS indicated by different shapes. Specifically, when the BS has 7 antennas, these antennas are distributed at the locations indicated by the cross ($\times$). When the BS has 13 antennas, these antennas are distributed at the locations indicated by the squares ($\square$). Finally, when the BS has 19 antennas, they are distributed at the locations indicated by the circles ($\bigcirc$).

B. Channel Model

In this section the channel model for evaluating the performance of the distributed antenna MIMO systems is described. Let $r_k(t)$ be the received signal from a MS by the kth distributed antenna. Upon neglecting the effect of thermal noise, the overall uplink received signal can be expressed as

$$r(t) = \sum_{k=1}^{N} r_k(t) \quad (13)$$

where N represents the number of distributed antennas. When taking both slow fading and fast fading into account, the received signal, $r_k(t)$, of the kth distributed antenna can be written as

$$r_k(t) = \alpha_k(t)\rho_k(t)\{\sqrt{P}s(t)\}, k = 1, ..., N \quad (14)$$

where $s(t)$ represents the signal transmitted by the MS, which is normalized such that $E[|s(t)|^2] = 1$, while P denotes the transmitted power. In (14) $\rho_k(t)$ represents the envelope encompassing the fast fading. By contrast, $\alpha_k(t)$ accounts for large-scale geographical variation [9]. Upon absorbing the average path loss into $\alpha_k(t)$, $\rho_k(t)$ can be viewed as having unit mean-square value, i.e., $E[|\rho_k(t)|^2] = 1$. Hence, the short-term power received by the kth antenna can be expressed as

$$\xi_k = |r_k(t)|^2 = P \cdot |\alpha_k(t)|^2 \cdot |\rho_k(t)|^2 = l_k P|\rho_k(t)|^2 \quad (15)$$

where $l_k = |\alpha_k(t)|^2$. Eq. (15) shows that the overall envelope of the power received by the kth distributed antenna has a lognormal distribution, which is governed by the variable of l_k. Furthermore, it can be shown that, for independent lognormal distributed variable l_k, $10\log_{10} l_k$ has a Gaussian distribution [10]. The practical measured data shows that the standard deviation σ_{ℓ_k} in this Gaussian distribution ranges from 6 dB to 12 dB [9] and its mean equals to

$$\mu_{\ell_k} = -\beta_k \cdot 10\log_{10} d_k \quad (16)$$

where $d_k = d/d_0$, d denotes the distance between the MS and the kth distributed antenna, while d_0 represents the close-in reference distance, which is determined from measurements close to the transmitter. Furthermore, in (16) β_k represents the associated path loss exponent, which takes a value of 2 in a free space, and a value of 4 in cellular mobile communications systems. Upon taking the above-mentioned issues into account, the PDF of l_k can be expressed as

$$f_{l_k}(x) = \frac{10}{\sqrt{2\pi}\sigma_{l_k} l_k \cdot \ln 10} \exp[-\frac{(10\log_{10} x - \mu_{\ell_k})^2}{2\sigma_{\ell_k}^2}] \quad (17)$$

Let $\gamma_k = \xi_k\gamma_c$ be the short-term signal-to-noise ratio (SNR) contributed by the kth receive antenna, where $\gamma_c = P/N_0$ represents the SNR in the corresponding AWGN channels. Then, when assuming that an optimum combiner is employed by the BS for combining the received signals from the N number of distributed antennas, the total SNR achieved is given by

$$\gamma = \gamma_c \times \sum_{k=1}^{N} \gamma_k \quad (18)$$

The above equation is suitable for the distributed antenna assisted wireless systems, where a mobile user employs only one transmit antenna. When the mobile user employs multiple, say U, transmit antennas, and when we assume that the space-time coding achieving a full transmit diversity is employed, (18) then can be written as

$$\gamma = \gamma_c \times \sum_{u=1}^{U}\sum_{k=1}^{N} \gamma_{uk} \quad (19)$$

where $\sum_{u=1}^{U} \gamma_{uk}\gamma_c$ represents the SNR contributed by the kth receive antenna after the space-time decoding. Let us now consider the outage probability of the MIMO wireless systems using distributed antennas.

C. Outage Probability

In a MIMO wireless system using distributed antennas, the SNR γ received by the BS from a given mobile should exceed a certain value, say γ_T, in order to achieve a satisfactory reception. Otherwise, an event of outage occurs. Hence, the outage probability can be expressed as

$$\begin{aligned} P_{out} &= P(\gamma < \gamma_T) \\ &= P\left(\gamma_c \times \sum_{u=1}^{U}\sum_{k=1}^{N} \gamma_{uk} < \gamma_T\right) \end{aligned} \quad (20)$$

Note that, in our simulation γ_T is set to be 4 dB.

IV. Simulation Results

In this section we provide a range of simulation results for the MIMO distributed antenna systems in the context of the average received power by the base station or of the outage probability. Note that, the total average received power illustrated in the figures in this section represents its normalized quantity, which is given by

$$\xi = \sum_{k=0}^{n} \ell_k \left|\rho_k(t)\right|^2 \quad (21)$$

Note furthermore that, in our simulation examples in the context of the received power, we assumed that the radius of the cell was $R = 6$ km, the path-loss exponent was $\beta_k = 6$dB. Four types of distributed antenna patterns were considered, which were shown in Fig.1 in correspondence with $N = 1, 7, 13$ and 19 number of distributed antennas. Furthermore, we assumed that a mobile moved randomly in the rectangular areas (dash-dot line) as shown in Fig.1.

Figs.2 to 5 show the total received power versus mobile's location performance of the conventional single antenna system and the wireless communications systems using various number of distributed antennas. Specifically, in these figures the total received power by the BS was simulated, when the mobile moved at different locations in the squared area bordered by the dash-dot lines. The antenna distribution patterns were shown in Fig.1, in the context of $N = 1, 7, 13$ and 19. From the results of Fig.2, it can be observed that the received power varies from about -25dB to 80dB, and the received power from the mobile in most case is low, when the mobile moves in the covered area by the cell. From the results of Fig.2 we can be implies that, unless the mobile is close to the BS at the center of the cell, it has to transmit a high power in order to achieve a relatively low outage probability.

By contrast, when the wireless system uses distributed antennas, there are a number of power peaks in the cell-covered area, as seen in Figs.3 to 5. When the mobile moves within the

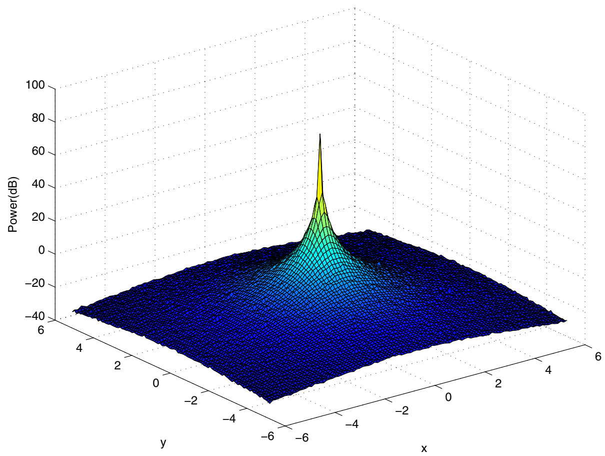

Fig. 2. The total received power by the base station in a conventional wireless system using single receive antenna located at the center of the cell, when a mobile at different locations.

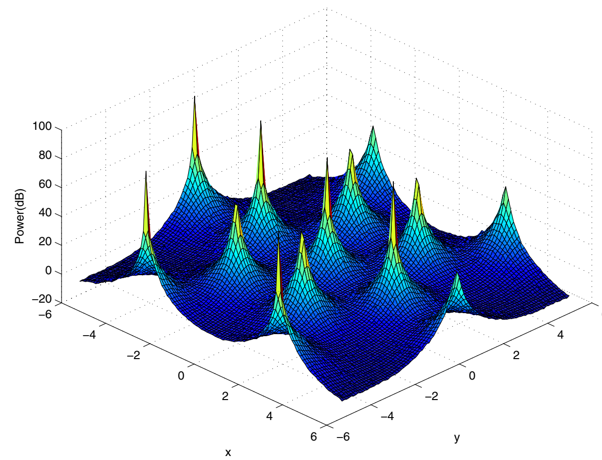

Fig. 4. The total received power by the base station in a wireless system using 13 distributed antennas at locations shown by the squares (□) in Fig.1, when a mobile at different locations.

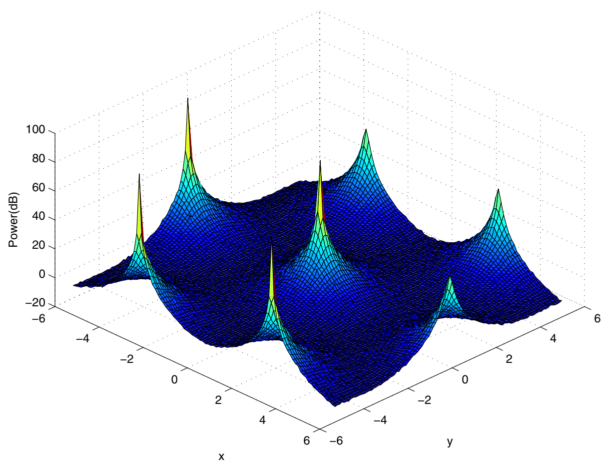

Fig. 3. The total received power by the base station in a wireless system using 7 distributed antennas at locations shown by the crosses (×) in Fig.1, when a mobile at different locations.

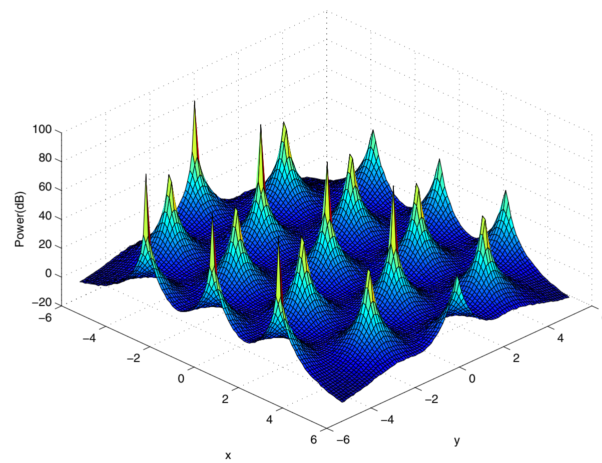

Fig. 5. The total received power by the base station in a wireless system using 19 distributed antennas at locations shown by the circles (◯) in Fig.1, when a mobile at different locations.

areas showing the power peaks, the BS is capable of receiving a relatively high power. Specifically, Fig.3 shows 7 power peaks in correspondence with the wireless system using 7 distributed antennas. Fig.4 has 13 power peaks, since the cell uses 13 distributed antennas. Finally, in Fig.5 there are 19 power peaks for the wireless system using 19 distributed antennas. From the results of Figs.2 to 5 it can be shown that the BS has a higher and higher chance to receive a relatively high power, when increasing the number distributed antennas in a cell. This high chance of receiving higher power implies that a lower outage probability can be obtained, when a wireless communications system uses more distributed antennas, which can be shown below in Fig.6 and Fig.7.

Finally, in Fig.6 and Fig.7, we evaluated the outage versus SNR performance for the MIMO wireless communications systems using distributed antennas. Specifically, in our simulations we assumed that, for both Fig.6 and Fig.7, the radius of the cell considered was $R = 10$ km, and the cell employed $N = 1, 7, 13$ or 19 receive antennas distributed according to Fig.1. Additionally, associated with Fig.6 we assumed that the mobile used only one transmit antenna, while with Fig.7 the mobile employed two transmit antennas and the transmitted data was space-time coded. In both Fig.6 and Fig.7 we assumed that the transmitted signal experienced lognormal shadowed Rayleigh fading having a parameter of $\sigma_{l_k} = 6$dB and the pathloss factor of $\beta_k = 4$dB. Furthermore, in both Fig.6 and Fig.7 a SNR threshold of $\gamma_T = 4$dB was set for guaranteeing a satisfactory performance. From the results we can observe that the performance of the distributed antenna system improves upon increasing the number of distributed antennas. Specifically, the distributed antenna system using 19 antennas achieves

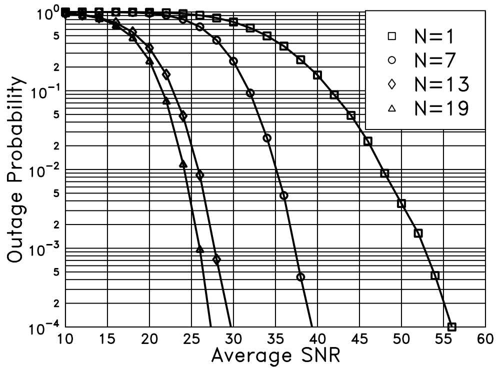

Fig. 6. Outage probability of the distributed antenna wireless communications system using $N = 1, 7, 13$ or 19 number of distributed antennas, when the radius of the cell is $R = 10$ km, the threshold is $\gamma_T = 4$dB, and when communicating over a lognormal shadowed Rayleigh fading channel having the parameter of $\sigma_{l_k} = 6$dB and a pathloss factor of $\beta_k = 4$dB.

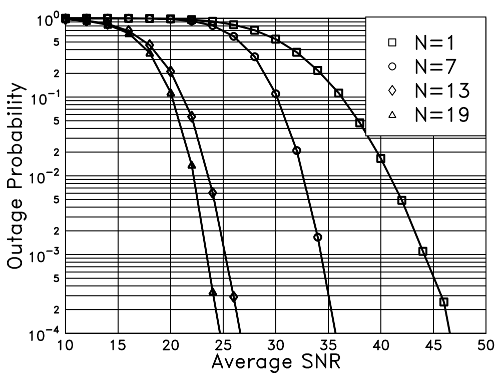

Fig. 7. Outage probability of the space-time coding assisted distributed antenna wireless communications system using $N = 1, 7, 13$ or 19 number of distributed antennas, when the radius of the cell is $R = 10$ km, the threshold is $\gamma_T = 4$dB, and when communicating over a lognormal shadowed Rayleigh fading channel having the parameter of $\sigma_{l_k} = 6$dB and a pathloss factor of $\beta_k = 4$dB.

the best outage performance among all the cases, while the conventional wireless system using no distributed antenna has the worst outage performance. As shown in Fig.6, at an outage probability of 10^{-4}, the required SNR is about 27dB for the system using 19 number of distributed antennas, 29.5dB for the system using 13 number of distributed antennas, 39dB for the system using 7 distributed antennas, and, finally, 57dB for the system using one antenna. These results show that, when an existing wireless system employs 19 distributed antennas instead of only one at the BS, 30dB SNR gain might be achieved. We can also have the above observations from the results of Fig.7, where two transmit antennas were employed by the MS. Furthermore, upon comparing the results of Fig.7 with that of Fig.6, it can be shown that, for a given number of distributed antennas, further SNR gains can be obtained owing to the multiple transmit antennas and space-time coding employed by the MS.

V. Conclusion

In this contribution we have proposed and investigated a distributed antenna MIMO wireless system, where multiple BS antennas are distributed in the area covered by a cell. Specifically, we have investigated the performance of the distributed antenna MIMO wireless system in the context of the total received power by the BS from a mobile station as well as of the outage probability, when the distributed antenna MIMO system without and with using space-time coding. Our simulation results in a lognormal shadowed Rayleigh fading environment show that, in a distributed antenna wireless system, both the number of antennas and the locations of antennas affect the system performance significantly. The performance of a wireless system can be significantly improved, by increasing the number of distributed antennas and/or increasing the number of mobile transmit antennas associated with using space-time coding. From our study in the context of the distributed antenna MIMO systems, we can expect that MIMO techniques will play an important role in the future generations of mobile communications systems and standards, while MIMO techniques have already been incorporated into wireless LAN standards such as IEEE 802.11 and HiperLAN/2.

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