J. Mietzner, R. Thobaben, and P. A. Hoeher, "Analysis of the expected error performance of cooperative wireless networks employing distributed space-time codes," in *Proc. IEEE GLOBECOM 2004*, Dallas, Texas, USA, Nov./Dec. 2004, pp. 2854–2858.

Analysis of the Expected Error Performance of Cooperative Wireless Networks Employing Distributed Space-Time Codes

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***Abstract*— In this paper, typical uplink scenarios in a cellular system are considered, where two cooperating mobile stations (serving, for example, as mobile relays) are transmitting the same information to a base station by using a distributed space-time coding scheme. Due to the distributed nature of the system, the transmitted signals are typically subject to different average path losses. For fixed distances between the mobile stations and the base station, the error performance of the distributed space-time coding scheme is determined analytically. Then, based on considerations concerning the spatial distribution of the mobile stations, analytical expressions for the distribution of the average path losses are derived and verified by means of simulations. These results are then used in order to compute the expected error performance of the system. It is shown that in most scenarios the average performance loss compared to a conventional multiple-antenna system with colocated antennas is less than 2 dB at a bit error rate of 10^{-3}. The most significant performance losses occur for a large path-loss exponent.**

***Index Terms*—Wireless communications, cooperative networks, distributed space-time codes.**

I. INTRODUCTION

THE PERFORMANCE of wireless systems is often limited by fading, due to multipath signal propagation. The system performance may, however, be significantly improved by exploiting some sort of diversity. In a *cooperative* wireless network (e.g. [1]-[4]), multiple single-antenna nodes share their antennas, e.g., by using a *distributed* space-time coding scheme. For example, an orthogonal space-time block code (OSTBC) [5]-[7] may be employed. Just as in a conventional multiple-antenna system, *spatial diversity* is exploited by this means, since the individual transmission links from the transmit (Tx) antennas to the receive (Rx) antenna(s) are likely to fade independently. The concept of cooperative wireless networks has recently gained considerable attention. On the one hand, cooperating nodes build the basis of any ad-hoc network. In addition, cooperation between different network nodes promises considerable benefits also for other types of networks, such as cellular networks or sensor networks.

Examples for cooperative wireless networks include simulcast networks and relay-assisted networks. Simulcast networks are normally used for broadcasting or for paging applications [8]. Conventionally, several nodes simultaneously transmit the same signal on the same carrier frequency. In a cellular system, simulcasting may be used in areas that are served by multiple base stations (BSs), in order to reduce the probability of shadowing. However, conventional simulcasting does not yield a diversity gain. In a relay-assisted network, the transmitted signal of a certain source node, e.g., a mobile station (MS), is received by several relay nodes, which then forward the signal to a certain destination node. Relaying may either be performed by fixed stations or by other MSs, as in [2]. In particular, a relay-assisted network may also be viewed as a type of simulcast network, if only a few transmission errors occur between the source node and the relay nodes, and if the individual relays simultaneously transmit on the same carrier frequency.

Within the scope of this paper, simulcasting in the *uplink* (UL) of a cellular system is considered, where several cooperating MSs – acting, for example, as mobile relays – transmit the same information to a BS, by using a distributed OSTBC. Typically, the distances between the individual MSs and the BS are different. Therefore, the transmitted signals are subject to different average path losses [9]. Since this effect is due to the distributed nature of the system under consideration, it is usually not addressed in the standard literature on space-time codes.

In this paper, two typical UL scenarios are considered, and analytical expressions for the expected error performance are derived. First, the error performance of the distributed OSTBC is determined analytically for fixed positions of the MSs, as a function of the path losses associated with the individual transmission links. Then, based on considerations concerning the spatial distribution of the MSs, analytical expressions for the distribution of the average path losses are derived and verified by means of simulations. These results are then used in order to compute the expected error performance of the system analytically. In particular, the influence of the path-loss exponent as well as the influence of geometrical parameters are investigated. It is shown that in most scenarios the average performance loss compared to a conventional multiple-antenna system with colocated antennas, where all transmission links are characterized by the same average path loss, is less than 2 dB at a bit error rate (BER) of 10^{-3}.

The outline of the paper is as follows: In Section II, the basic assumptions made throughout the paper are summarized, and some notations are introduced. The error performance of the distributed OSTBC as a function of the average path losses is calculated in Section III, where focus is on the case of two transmitting nodes. In Section IV, the two UL scenarios are introduced, and the analytical expressions for the distribution of the path losses are derived. Finally, the expected error performance of the system is obtained for the two UL scenarios. Conclusions are drawn in Section V.

II. BASIC ASSUMPTIONS AND NOTATION

OSTBCs yield full diversity in terms of the number n of transmitting nodes. A drawback of these schemes is, however,

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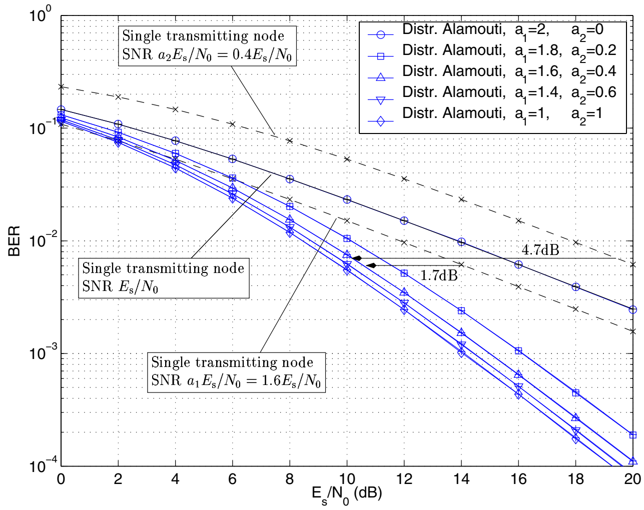

Fig. 1. BER performance of a distributed Alamouti scheme as a function of E_{s}/N_0 in dB, given different average path losses (simulative and analytical results; the analytical results are marked with '+').

that for $n > 2$ no OSTBC exists with a temporal rate of one [10]. For $n=2$, the well-known Alamouti scheme [5] provides a temporal rate of one; therefore focus will be on this OSTBC here. Even if there are more than two transmitting nodes available, it may still be useful to employ the Alamouti scheme – in conjunction with a selection diversity scheme [11] choosing those two nodes that are associated with the best transmission links toward the receiving node, e.g., in terms of signal-to-noise ratio (SNR).

Throughout the paper, the equivalent complex baseband representation is used. For simplicity, it is assumed that the transmitting nodes, i.e., the MSs, are perfectly synchronized in time and in frequency. Moreover, it is assumed that the MSs apply some sort of timing-advance protocol in order to counteract the different propagation delays[1]. Assuming a frequency-flat block-fading channel model and an overall impulse response of transmitter and receiver, which fulfills the first Nyquist criterion, the transmission link from the i-th mobile station MS_i $(i=1,...,n)$ to the BS is modeled by a single complex-valued channel coefficient h_i, which is constant over the duration of an entire data block. In this case, OSTBCs enable maximum-likelihood decoding at the receiver, based on linear processing [6],[7].

The channel coefficients h_i are assumed to be realizations of statistically independent complex Gaussian random variables with zero mean and variance $a_i := \mathrm{E}\{|h_i|^2\}$, where $1/a_i$ represents the average path loss for the i-th transmission link ($\mathrm{E}\{.\}$ denotes expectation). Normalization is done such that

$$\sum_{i=1}^{n} a_i = n. \tag{1}$$

The individual MSs are assumed to use the same average Tx power P/n. In order to provide a fair comparison with a (1x1)-system with only a single transmitting node, the overall Tx power P is fixed. For the individual MSs congenerous antennas are assumed and for the BS an omnidirectional antenna. The ratio a_j/a_i of the average path losses associated with the i-th and j-th transmission link may then be expressed as

$$\frac{a_j}{a_i} = \left(\frac{d_i}{d_j}\right)^{\rho}, \tag{2}$$

where d_i denotes the length of the i-th transmission link and ρ the path-loss exponent, which is typically between $\rho=2$ (free-space propagation) and $\rho=4$ (e.g. rural areas) [13, Ch. 1.2]. Note that due to the normalization (1), $1/a_i$ represents a *relative* average path loss, because it depends not only on the distance d_i, but also on the other distances d_j, $j \neq i$.

Throughout this paper, random variables are denoted by upper-case letters and their realizations by the corresponding lower-case letters. The probability density function (pdf) of a random variable X is denoted by $p_X(x)$, and the corresponding cumulative distribution function (cdf) is denoted by $P(X \leq x)$.

III. Error Performance of a Distributed OSTBC

For the i-th transmission link, the effective SNR at the receiver is given by $a_i E_{\mathrm{s}}/nN_0$, where E_{s} denotes the average symbol energy and N_0 the single-sided noise power density. Given binary transmission, the BER performance of a distributed OSTBC can be calculated in closed form by using theoretical results for diversity reception [14, Ch. 14.5]. For a distributed Alamouti scheme ($n = 2$) and Rayleigh fading, one obtains[2]

$$P_{\mathrm{b}}(a_1) = \frac{1}{2}\left[\frac{a_1\,(1-\mu(a_1))}{a_1 - a_2} + \frac{a_2\,(1-\mu(a_2))}{a_2 - a_1}\right], \tag{3}$$

where

$$a_1 \in [0,2], \qquad a_2 = 2 - a_1,$$

and

$$\mu(a_i) := \frac{1}{\sqrt{1+\frac{2N_0}{a_i E_{\mathrm{s}}}}} \qquad (i=1,2). \tag{4}$$

Specifically, $P_{\mathrm{b}}(a_1) = P_{\mathrm{b}}(2-a_1)$ holds for all a_1. Fig. 1 illustrates the BER performance of the distributed Alamouti scheme as a function of E_{s}/N_0, for different values of a_1, a_2. The exact analytical results according to (3) are compared with simulation results obtained by means of Monte-Carlo simulations. It can be seen that the simulation results match the analytical curves (marked with '+') well.

As expected, the best performance results for $a_1 = a_2 = 1$. In this case, a diversity degree of two is observed, i.e., for large E_{s}/N_0 the BER decreases with $1/(E_{\mathrm{s}}/N_0)^2$. Both transmission links are associated with an SNR of $E_{\mathrm{s}}/2N_0$. On the other hand, for $a_1=2$, $a_2=0$ a diversity degree of one results, i.e., the same BER performance is observed as in the case of a (1x1)-system given an SNR of E_{s}/N_0. For all other values of a_1, a_2 the BER performance is between these two extremes. For the example $a_1=1.6$, $a_2=0.4$ it is shown that the distributed Alamouti scheme still significantly outperforms a single transmitting

[1] Concerning the influence of different propagation delays on the system performance (or, equivalently, the influence of non-perfect time synchronization of the transmitting nodes), the reader is referred to [9]. The influence of non-perfect synchronization of the carrier frequencies is investigated in [12].

[2] Although in this paper focus is on the case of $n=2$ transmitting nodes and on the case of Rayleigh fading, generalizations to $n>2$ transmitting nodes are possible as well as to other types of fading, such as Rician fading.

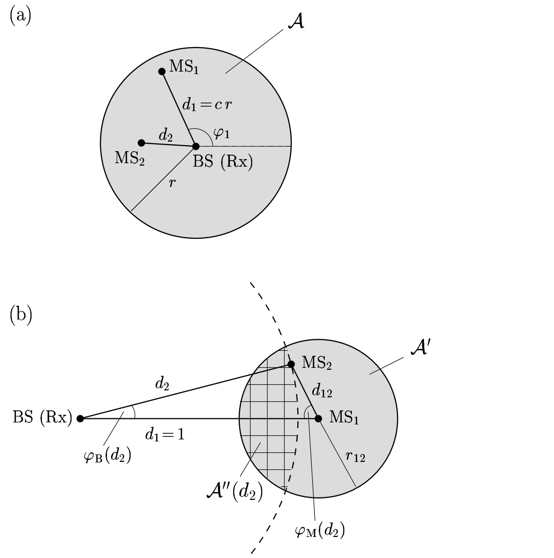

Fig. 2. Two typical UL scenarios; (a) General UL scenario, (b) UL scenario with an additional constraint on the distance d_{12} between the two MSs.

node (dashed curves). Compared to a single transmitting node, given a transmission link with an SNR of $a_1 E_\mathrm{s}/N_0$, a gain of 1.7 dB results at a BER of $6 \cdot 10^{-3}$. Compared to a single transmitting node, given an SNR of $a_2 E_\mathrm{s}/N_0$, the gain is even 4.7 dB at the same BER.

IV. Two Typical Uplink Scenarios

In the sequel, two typical UL scenarios are considered for the case $n=2$. Based on considerations concerning the spatial distribution of the MSs, analytical expressions for the expected error performance are derived. In this context, the distances between the two MSs (MS_1 and MS_2) and the BS are considered as random variables, and the corresponding pdf $p_{A_1}(a_1)$ for a_1 is derived. Assuming a distributed Alamouti scheme, the expected BER may then be calculated as (cf. (3))

$$\bar{P}_\mathrm{b} \;=\; \int_0^2 p_{A_1}(a_1) P_\mathrm{b}(a_1)\,\mathrm{d}a_1\,. \qquad (5)$$

The two UL scenarios considered in the following sections are illustrated in Fig. 2 (a) and (b). In the first and more general scenario, the MSs may, for example, be mobile relays which forward the signal of a certain source node, e.g. another MS, to the BS. In this context, however, only the performance of the distributed Alamouti scheme will be considered here. It is therefore assumed that both forwarding MSs have the same (correct) data at their disposal, i.e., error propagation due to bit errors occurring between the source node and the relays are not taken into account. The coverage area $\mathcal{A}$ of the BS is assumed to be a disk of radius r (cf. Fig. 2 (a)). For the first MS, a fixed distance d_1 to the BS is assumed, where $d_1 := c\,r$, $c \le 1$. (Due to symmetry reasons, the angle φ_1 is not of interest in the sequel and may therefore be set to an arbitrary fixed value.) The second MS is located anywhere within the coverage area $\mathcal{A}$ of the BS, according to a uniform distribution.

In the second UL scenario, the distance d_1 between the first MS and the BS is normalized as $d_1 = 1$, and an additional constraint is introduced concerning the location of the second MS. The distance d_{12} between the two MSs is supposed to be significantly smaller than the distance d_1. It is therefore assumed that the second MS is located anywhere within a disk $\mathcal{A}'$ around the first MS, where the radius r_{12} of $\mathcal{A}'$ is significantly smaller than d_1 (cf. Fig. 2 (b)). This constraint is, for example, reasonable when the two MSs act as *mutual* relays. The MSs may determine whether the distance d_{12} is sufficiently small, so as to avoid error propagation. This may, e.g., be done based on measurements of the SNR offered by the link between the two MSs. If d_{12} is larger than a certain threshold r_{12}, the two MSs may decide not to cooperate.

A. General Uplink Scenario

In the sequel, the ratio $q := d_2/d_1$ is of interest. The corresponding random variable is given by $Q := D_2/d_1$. Since d_1 is fixed (cf. Fig. 2 (a)), the pdf of Q results as

$$\begin{aligned} p_Q(q) &= d_1 \cdot p_{D_2}(d_1 q) \;=\; c\,r \cdot \frac{\partial}{\partial d_2} P(D_2 \le d_2)\Big|_{d_2 = cr\,q} \\ &= \frac{c\,r}{|\mathcal{A}|}\frac{\partial}{\partial d_2}\,\pi d_2^2\Big|_{d_2=cr\,q} \;=\; \frac{2\pi\,c^2\,r^2\,q}{|\mathcal{A}|} \\ &= 2c^2\,q, \end{aligned} \qquad (6)$$

for $q \in [0, 1/c]$, and is zero otherwise ($|\mathcal{A}|$ denotes the area of $\mathcal{A}$). The pdf $p_Q(q)$ is depicted in Fig. 3 and verified by means of simulations, for the example $c = 0.5$.

Since $a_1/a_2 = (d_2/d_1)^\rho = q^\rho$ (cf. (2)) and $a_2 = 2 - a_1$, one may write

$$a_1 \;=\; \frac{2\,q^\rho}{1 + q^\rho}\,. \qquad (7)$$

The pdf of A_1 is therefore given by [14, Ch. 2.1]

$$p_{A_1}(a_1) \;=\; \frac{(1+\xi(a_1))^2}{2\rho\;\xi(a_1)^{(\rho-1)/\rho}} \cdot p_Q(\xi(a_1)^{1/\rho})\,, \qquad (8)$$

for $a_1 \in [0, a_{1\max}(\rho)]$ with $a_{1\max}(\rho) := 2/(1+c^\rho)$, and is zero otherwise, where

$$\xi(a_1) \;:=\; \frac{a_1}{2 - a_1}\,. \qquad (9)$$

Altogether, one obtains

$$p_{A_1}(a_1) \;=\; \begin{cases} \dfrac{c^2\,(1+\xi(a_1))^2}{\rho\;\xi(a_1)^{(\rho-2)/\rho}} & \text{for} \quad a_1 \in [0, a_{1\max}(\rho)] \\ 0 & \text{else} \end{cases}.$$

For $a_1 \to 0$ one finds that

$$\begin{aligned} \lim_{a_1\to 0}\; p_{A_1}(a_1) &= \lim_{a_1 \to 0} \frac{4c^2}{\rho}\left(\frac{1}{2-a_1}\right)^{(\rho+2)/\rho}\left(\frac{1}{a_1}\right)^{(\rho-2)/\rho} \\ &= \begin{cases} c^2/2 & \text{for} \quad \rho = 2 \\ +\infty & \text{for} \quad \rho > 2 \end{cases}, \end{aligned} \qquad (10)$$

and for $a_1 = a_{1\max}(\rho)$ one finds

$$p_{A_1}(a_{1\max}(\rho)) \;=\; \frac{1}{\rho}\left(2 + c^\rho + \frac{1}{c^\rho}\right). \qquad (11)$$

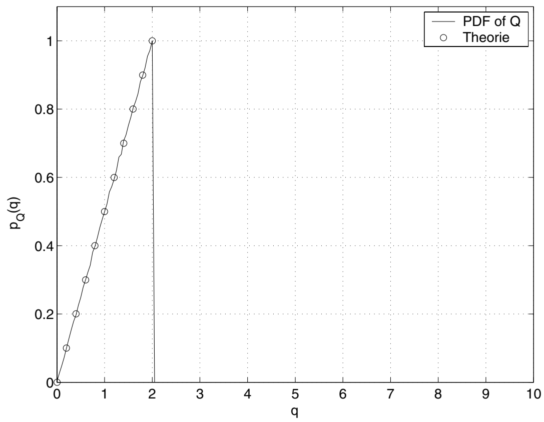

Fig. 3. General UL scenario: Analytical result for the pdf $p_Q(q)$ and verification by means of simulations, for the example $c = 0.5$.

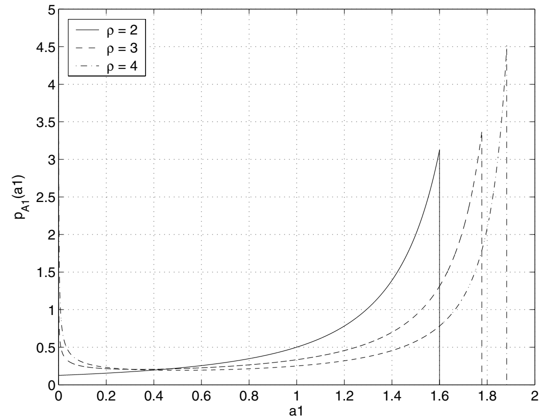

Fig. 4. General UL scenario: Analytical results for the pdf $p_{A_1}(a_1)$, for the example $c = 0.5$ and path-loss exponents of $\rho = 2$, $\rho = 3$, and $\rho = 4$.

The pdf $p_{A_1}(a_1)$ is depicted in Fig. 4, for $c=0.5$ and path-loss exponents of $\rho = 2$, $\rho = 3$, and $\rho = 4$. The resulting expected BER performance is shown in Fig. 5. It has been obtained by numerical integration of (5), using (3) and the analytical result (8) for $p_{A_1}(a_1)$. It can be seen that the difference between the expected BER and the one obtained in the case $a_1 = a_2 = 1$ grows with growing path-loss exponent ρ, because the probability that a_1 has a value close to one decreases (cf. Fig. 4). For $\rho=4$, the performance loss is about 2 dB, at a BER of 10^{-3}.

B. Uplink Scenario with Additional Constraint

Given the additional constraint on the distance d_{12} between the two MSs (cf. Fig. 2 (b)), the derivation of the pdf $p_Q(q)$ of $Q = D_2/d_1 = D_2$ is as follows:

$$p_Q(q) \;=\; p_{D_2}(q) = \frac{\partial}{\partial d_2} P(D_2 \le d_2)\Big|_{d_2=q}, \tag{12}$$

where

$$P(D_2 \le d_2) \;=\; \frac{|\mathcal{A}''(d_2)|}{|\mathcal{A}'|} \;=\; \frac{|\mathcal{A}''(d_2)|}{\pi r_{12}^2} \tag{13}$$

(cf. Fig. 2 (b)). The area $|\mathcal{A}''(d_2)|$ is given by

$$\begin{aligned} |\mathcal{A}''(d_2)| \;&=\; d_2^2 \cdot \left(\varphi_{\mathrm{B}}(d_2) - \frac{1}{2}\sin\left(2\varphi_{\mathrm{B}}(d_2)\right)\right) \\ &+\; r_{12}^2 \cdot \left(\varphi_{\mathrm{M}}(d_2) - \frac{1}{2}\sin\left(2\varphi_{\mathrm{M}}(d_2)\right)\right), \end{aligned} \tag{14}$$

$1 - r_{12} \le d_2 \le 1 + r_{12}$, where

$$\varphi_{\mathrm{B}}(d_2) \;=\; \arccos\left(\psi(d_2)\right), \quad \psi(d_2) \;=\; \frac{1 + d_2^2 - r_{12}^2}{2\, d_2} \tag{15}$$

and

$$\varphi_{\mathrm{M}}(d_2) \;=\; \arccos\left(\zeta(d_2)\right), \quad \zeta(d_2) \;=\; \frac{1 - d_2^2 + r_{12}^2}{2\, r_{12}}. \tag{16}$$

Specifically, $\varphi_{\mathrm{B}}(1 - r_{12}) = 0$, $\varphi_{\mathrm{M}}(1 - r_{12}) = 0$, i.e.

$$|\mathcal{A}''(1 - r_{12})| = 0$$

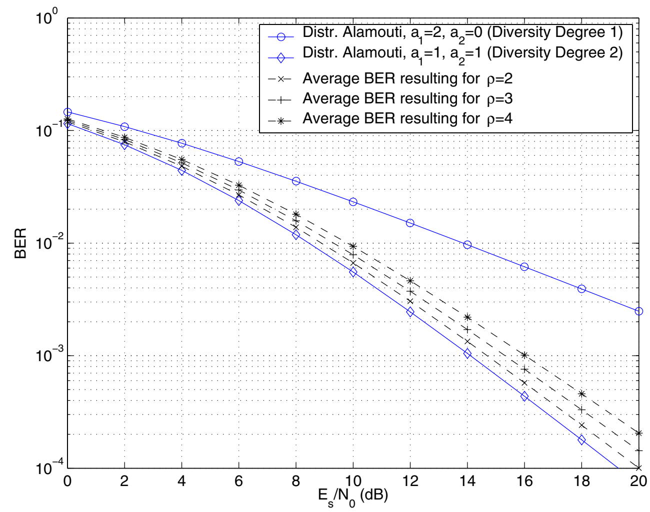

Fig. 5. General UL scenario: Expected BER performance according to (5) resulting for $c = 0.5$ and path-loss exponents of $\rho = 2$, $\rho = 3$, and $\rho = 4$.

and $\varphi_{\mathrm{B}}(1 + r_{12}) = 0$, $\varphi_{\mathrm{M}}(1 + r_{12}) = \pi$, i.e.

$$|\mathcal{A}''(1 + r_{12})| = |\mathcal{A}'|.$$

Altogether, one obtains

$$\begin{aligned} p_Q(q) \;&=\; \frac{2q}{\pi r_{12}^2}\left(\varphi_{\mathrm{B}}(q) - \frac{1}{2}\sin\left(2\varphi_{\mathrm{B}}(q)\right)\right) \\ &+\; \frac{1 - q^2 - r_{12}^2}{2\pi r_{12}^2\sqrt{1 - \psi^2(q)}}\left(1 - \cos\left(2\varphi_{\mathrm{B}}(q)\right)\right) \\ &+\; \frac{q}{\pi r_{12}\sqrt{1 - \zeta^2(q)}}\left(1 - \cos\left(2\varphi_{\mathrm{M}}(q)\right)\right) \end{aligned} \tag{17}$$

for $q \in [1 - r_{12}, 1 + r_{12}]$, and $p_Q(q) = 0$ otherwise. The pdf $p_Q(q)$ is depicted in Fig. 6 and verified by means of simulations, for the example $r_{12} = 0.3$ and $r_{12} = 0.9$.

Using the above expression (17) for $p_Q(q)$, the pdf $p_{A_1}(a_1)$ may be calculated according to (8). The pdf $p_{A_1}(a_1)$ is depicted in Fig. 7, for path-loss exponents of $\rho = 2$, $\rho = 3$, and $\rho = 4$. The pdf is non-zero for

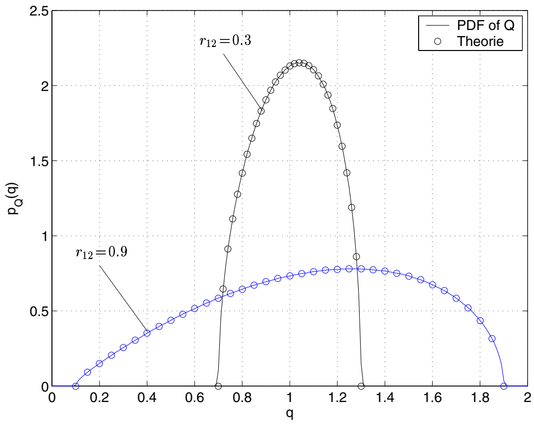

Fig. 6. UL scenario with an additional constraint on the distance d_{12} between the two MSs: Analytical results for the pdf $p_Q(q)$ and verification by means of simulations, for $r_{12}=0.3$ and $r_{12}=0.9$.

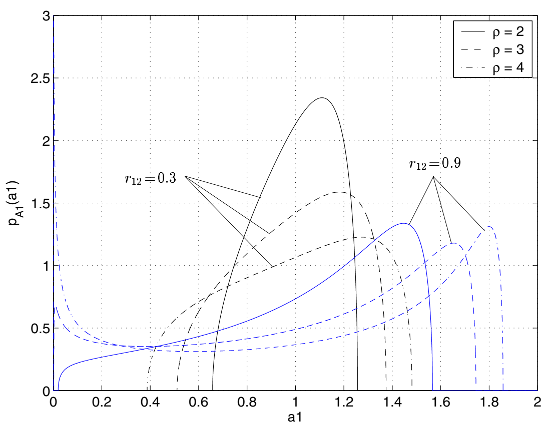

Fig. 7. UL scenario with an additional constraint on the distance d_{12} between the two MSs: Analytical results for the pdf $p_{A_1}(a_1)$, for $r_{12}=0.3$, $r_{12}=0.9$ and path-loss exponents of $\rho=2$, $\rho=3$, and $\rho=4$.

$$\frac{2(1-r_{12})^{\rho}}{1+(1-r_{12})^{\rho}} < a_1 < \frac{2(1+r_{12})^{\rho}}{1+(1+r_{12})^{\rho}}$$

and zero otherwise. As expected, the probability that a_1 has a value close to one is comparably large for the small radius $r_{12}=0.3$, even for large values of the path-loss exponent ρ. Consequently, as shown is Fig. 8, the resulting expected BER performance is very close to the one obtained in the case $a_1 = a_2 = 1$. As opposed to this, for the large radius $r_{12}=0.9$ a performance loss is observed, which is about 1.9 dB at a BER of 10^{-3}, given a path-loss exponent of $\rho=4$.

V. Conclusions

In this paper, two typical UL scenarios in a cellular system were considered, where two cooperating MSs are transmitting the same information to a BS, using a distributed Alamouti scheme. First, for fixed distances between the MSs and the BS, theoretical results for the error performance of diversity reception were utilized in order to determine the error performance of the distributed Alamouti scheme. Then, the expected error performance was calculated for both scenarios, based on considerations concerning the spatial distribution of the MSs. It

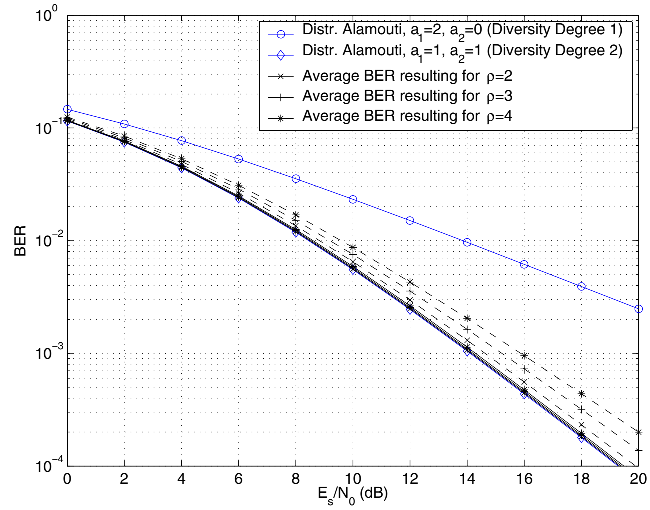

Fig. 8. UL scenario with an additional constraint on the distance d_{12} between the two MSs: Expected BER performance according to (5) resulting for $r_{12} = 0.3$ (solid lines), $r_{12}=0.9$ (dashed lines) and path-loss exponents of $\rho=2$, $\rho=3$, and $\rho=4$.

was shown that in most scenarios the performance loss compared to a conventional multiple-antenna system with colocated antennas is less than 2 dB at a BER of 10^{-3}, where the most significant loss occurs for large path-loss exponents (e.g. $\rho=4$).

References

[1] M. Janani, A. Hedayat, T. E. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: Space-time transmission and iterative decoding," *IEEE Trans. Signal Processing*, vol. 52, no. 2, pp. 362-371, Feb. 2004.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity – Part 1: System description; Part 2: Implementation aspects and performance analysis," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927-1948, Nov. 2003.

[3] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2415-2425, Oct. 2003.

[4] P. A. Anghel, G. Leus, and M. Kaveh, "Distributed space-time coding in cooperative networks," in *Proc. V IEEE Nordic Signal Processing Symposium (NORSIG–2002)*, 2002, paper no. SunAmOR2–2.

[5] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451-1458, Oct. 1998.

[6] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block coding for wireless communications: Performance results," *IEEE J. Select. Areas Commun.*, vol. 17, no. 3, pp. 451-460, Mar. 1999.

[7] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inform. Theory*, vol. 45, no. 5, pp. 1456-1467, June 1999.

[8] A. Wittneben, "Basestation modulation diversity for digital SIMULCAST," in *Proc. IEEE Veh. Technol. Conf. (VTC'91)*, 1991, pp. 848-853.

[9] J. Mietzner and P. A. Hoeher, "Distributed space-time codes for cooperative wireless networks in the presence of different propagation delays and path losses," in *Proc. 3rd IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2004)*, 2004, paper no. S5-5.

[10] X.-B. Liang and X.-G. Xia, "On the nonexistence of rate-one generalized complex orthogonal designs," *IEEE Trans. Inform. Theory*, vol. 49, no. 11, pp. 2984-2989, Nov. 2003.

[11] Z. Chen, J. Yuan, B. Vucetic, and Z. Zhou, "Performance of Alamouti scheme with transmit antenna selection," *IEEE Electron. Lett.*, vol. 39, no. 23, pp. 1666-1668, Nov. 2003.

[12] J. Mietzner, J. Eick, and P. A. Hoeher, "On distributed space-time coding techniques for cooperative wireless networks and their sensitivity to frequency offsets," in *Proc. ITG Workshop on Smart Antennas (WSA)*, 2004, paper no. 15.

[13] R. Steele (Ed.), *Mobile Radio Communications.* New York: IEEE Press, 1994.

[14] J. G. Proakis, *Digital Communications.* 4th ed., New York: McGraw-Hill, 2001.