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Multi-cellular Alamouti Scheme Performance in Rayleigh and Shadow Fading

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Abstract In this paper we study the performance of two downlink multi-cellular systems: a Multiple Inputs Single Output (MISO) system using the Alamouti code and a Multiple Inputs Multiple Outputs (MIMO) system using the Alamouti code at the transmitter side and a Maximum Ratio Combining (MRC) as a receiver, in terms of outage probability. The channel model includes path-loss, shadowing and fast fading and the system is considered interference limited. Two cases are

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Part of the results presented in this paper have been published in [1].

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distinguished: constant shadowing and log-normally distributed shadowing. In the first case closed form expressions of the outage probability are proposed. For a log-normally distributed shadowing, we derive easily computable expressions of the outage probability. The proposed expressions allow for fast and simple performance evaluation for the two multi-cellular wireless systems: MISO Alamouti and MIMO Alamouti with MRC receiver. We use a fluid model approach to provide simpler outage probability expressions depending only on the distance between the considered user and its serving base station.

Keywords

Alamouti scheme, MISO, MIMO, MRC, multi-cellular, outage probability, shadowing, Rayleigh fading, fluid model.

1 Introduction

Multiple antenna systems have aroused many research considerations in recent years. In fact, the exploitation of the spatial dimension yielded through the use of multiple antennas at the transmitter and/or the receiver permits to increase capacity [2], [3] and to improve reliability [4]. In this context OSTBC (Orthogonal Space Time Block Codes) [5] have been proposed to provide a tradeoff between the capacity enhancement through the multiplexing gain and the reliability improvement through the diversity gain. Among the proposed codes, the Alamouti [6] scheme has attracted much attention thanks to its simple implementation and decoding. It is also an interesting scheme since it achieves the full transmission diversity for two transmit antennas. Unlike the receive diversity schemes such as the Equal Gain Combining (EGC), the Optimum Combining (OC) and the Maximum

Ratio Combining (MRC) that have been studied respectively in [7], [8] and [9], the Alamouti scheme removes the burden to the transmitter side. It was, hence, adopted for the downlink transmission of the WiMax standard (IEEE 802.16m).

In a point-to-point communication and for Rayleigh channel communication the Alamouti code was studied in terms of outage capacity probability in [10] and in terms of bit error rate (BER) with transmit antenna selection in [11]. In [12], different transmission strategies were compared. The Alamouti scheme was analyzed in single cell multiuser MISO (2×1) and MIMO (2×2) system scenarios for line-of-sight (LOS) and non-line-of-sight (NLOS) channels in terms of network outage probability. In [13], the Alamouti code performance was examined in the case of single cell multiuser uplink communication. The outage probability was derived for a MIMO system in Rayleigh fading channels. Always in a single cell context, several papers, e.g. [14], have studied the influence of an imperfect or low bit rate feedback channel for channel state information (CSI) on the system performance. In [15], the authors showed that, in a single cell multiuser system, the Alamouti STBC transmission approach combined with the MRC receiver provides high system throughputs when there is a big unbalance in users' channels gains. In [16], an analytical study of Almouti-MRC systems was derived in a single cell context. A closed form expression of the bit error rat (BER) was proposed.

Some papers have conducted MIMO Alamouti systems performance evaluations considering multicell interference. In [17], authors rely on Monte Carlo simulations, whereas we propose an analytical study. In [18] and [19], authors mainly focus their investigation on a scenario, where interferers are received with equal average powers. An approximation of the SINR distribution is given for only two interferers received with unequal average powers.

In the present work, we extend the results presented in [1]. We analyze the performance of the full transmit diversity Alamouti scheme in a multi-cellular system with an MRC receiver. We consider a channel model taking into account Rayleigh fading, shadowing and path-loss. We derive an expression of the SINR cumulative distribution function or equivalently the outage probability for a 2×1 multi-cellular Alamouti system and a $2 \times N$ multi-cellular Alamouti system with an MRC receiver.

The remainder of this paper is organized as follows. In the next section, we describe the system model. In Section 3, we derive outage probability expressions for 2×1 MISO Alamouti and $2 \times N$ MIMO Alamouti with MRC receiver systems considering constant shadowing. In Section 4, the same performance metrics are studied considering the joint impact of lognormal shadowing, path-loss and Rayleigh fading. A fluid model analysis allows us to remove the dependency to the distance between the considered user and interfering BSs and to obtain expressions of the outage probability that only depends on the distance to the serving Base Station (BS). Section 5 includes a comparison between simulated and analytical results and discussions. Finally, in Section 6 we conclude. In this paper, ^{T} and ^{H} denote the transpose and transpose conjugate operators respectively.

2 System Model

2.1 MISO (2×1) Alamouti Scheme

Consider a downlink, multi-cell single user communication. Each BS is equipped with two antennas and each user equipment (UE) with a single antenna as depicted in Fig 1. A user in a cell receives a useful signal from its serving BS and an interfering signal from the B neighboring BSs. Each BS uses the Alamouti scheme to code the information symbols. It consists in transmitting the symbols s_1 and s_2 from the two antennas in the first channel use period and $-s_2^*$, s_1^* in the second channel use period. It is a rate 1 code that achieves full transmission diversity for a two transmit antennas system even without channel knowledge at the transmitter. The Alamouti code matrix is given by [6]:

$$\mathbf{X} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}, \tag{1}$$

where $s_{(i=1,2)}$ are the transmitted symbols. At the receiver side, the signal can be represented in the following form:

$$\mathbf{y} = \sqrt{\frac{P_0}{2}} \underbrace{\begin{bmatrix} h_{1,0} & h_{2,0} \\ h_{2,0}^* & -h_{1,0}^* \end{bmatrix}}_{\mathbf{H}_0} \underbrace{\begin{bmatrix} s_{1,0} \\ s_{2,0} \end{bmatrix}}_{\mathbf{x}_0} + \sum_{j=1}^{B} \sqrt{\frac{P_j}{2}} \begin{bmatrix} h_{1,j} & h_{2,j} \\ h_{2,j}^* & -h_{1,j}^* \end{bmatrix} \underbrace{\begin{bmatrix} s_{1,j} \\ s_{2,j} \end{bmatrix}}_{\mathbf{x}_j} + \mathbf{n}, \tag{2}$$

where $\mathbf{y} = [y_1 \ y_2^*]^T$, y_k is the received signal at time instant k, $s_{i,j}$ is the symbol transmitted from the antenna i of the BS j, and $h_{i,j}$ is the flat fading Rayleigh channel gain between the antenna i of the BS j and the considered user. This latter parameter is modeled as a zero mean complex Gaussian random variable with unit variance. The flat fading is assumed quasi-static over the two channel use periods and $\mathbf{n}$ is the additive white Gaussian noise vector with covariance matrix $\sigma_n^2\mathbf{I}$. P_j is the received power from the j^{th} BS (P_0 is the power received from the serving BS) including path-loss and shadowing terms but without considering fast fading (i.e., averaged over a sufficient number of frames) and is given by:

$$P_j = P_T K d_j^{-\eta} 10^{\frac{\xi_j}{10}}, \tag{3}$$

where P_T is the transmit power, K is a constant, d_j is the distance between the considered user and BS j, η is the path-loss exponent and is characteristic of the propagation environment and ξ_j is a Normal random variable with zero mean and standard deviation σ. By pre-multiplying the received signal by the channel transpose conjugate of the channel $\mathbf{H}_0$, the signal at the receiver becomes:

$$\mathbf{H}_0^H\mathbf{y} = \sqrt{\frac{P_0}{2}}\begin{bmatrix} |h_{1,0}|^2 + |h_{2,0}|^2 & 0 \\ 0 & |h_{1,0}|^2 + |h_{2,0}|^2 \end{bmatrix}\mathbf{x}_0 + \sum_{j=1}^{B}\sqrt{\frac{P_j}{2}}\begin{bmatrix} h_{1,0} & h_{2,0} \\ h_{2,0}^* & -h_{1,0}^* \end{bmatrix}^H\begin{bmatrix} h_{1,j} & h_{2,j} \\ h_{2,j}^* & -h_{1,j}^* \end{bmatrix}\mathbf{x}_j + \begin{bmatrix} h_{1,0} & h_{2,0} \\ h_{2,0}^* & -h_{1,0}^* \end{bmatrix}^H\mathbf{n}.$$

The SINR per symbol is, thus, given by:

$$\gamma = \frac{\frac{P_0}{2}\left(|h_{1,0}|^2 + |h_{2,0}|^2\right)}{\sum_{j=1}^{B}\frac{P_j}{2}\left(\frac{|h_{1,0}^*h_{1,j}+h_{2,0}h_{2,j}^*|^2+|h_{1,0}^*h_{2,j}-h_{2,0}h_{1,j}^*|^2}{|h_{1,0}|^2+|h_{2,0}|^2}\right)+\sigma_n^2}. \quad (4)$$

2.2 MIMO $(2 \times N)$ Alamouti Scheme with MRC Receiver

In this case, we consider the same system as in the previous section, the receiver is however now equipped with N receive antennas. At the receiver side, the signal can be written as:

$$\mathbf{y} = \sqrt{\frac{P_0}{2}} \underbrace{\begin{bmatrix} h_{1,1,0} & h_{1,2,0} \\ h^*_{1,2,0} & -h^*_{1,1,0} \\ . & . \\ . & . \\ h_{N,1,0} & h_{N,2,0} \\ h^*_{N,2,0} & -h^*_{N,1,0} \end{bmatrix}}_{\mathbf{H}_0} \underbrace{\begin{bmatrix} s_{1,0} \\ s_{2,0} \end{bmatrix}}_{\mathbf{x}_0} + \sum_{j=1}^{B} \sqrt{\frac{P_j}{2}} \begin{bmatrix} h_{1,1,j} & h_{1,2,j} \\ h^*_{1,2,j} & -h^*_{1,1,j} \\ . & . \\ . & . \\ h_{N,1,j} & h_{N,2,j} \\ h^*_{N,2,j} & -h^*_{N,1,j} \end{bmatrix} \underbrace{\begin{bmatrix} s_{1,j} \\ s_{2,j} \end{bmatrix}}_{\mathbf{x}_j} + \mathbf{n}, \tag{5}$$

where $h_{i,j,k}$ is the Rayleigh flat fading channel between i^{th} antenna of the receiver and the antenna j of the BS k. The MRC receiver combines the received signals from the N antennas. The received signal is multiplied by the complex conjugate of the channel $\mathbf{H}_0$. The SINR per symbol is, hence, given by:

$$\gamma = \frac{\frac{P_0}{2} \sum_{n=1}^{N} \left(|h_{n,1,0}|^2 + |h_{n,2,0}|^2 \right)}{\sum_{j=1}^{B} \frac{P_j}{2} \left(\frac{|\sum_{n=1}^{N} h^*_{n,1,0} h_{n,1,j} + h_{n,2,0} h^*_{n,2,j}|^2 + |\sum_{n=1}^{N} h^*_{n,1,0} h_{n,2,j} - h_{n,2,0} h^*_{n,1,j}|^2}{\sum_{n=1}^{N} (|h_{n,1,0}|^2 + |h_{n,2,0}|^2)} \right) + \sigma_n^2}. \tag{6}$$

3 Outage Probability with Constant Shadowing

The outage probability is an important metric for the evaluation of the performance of a wireless communication system. In this paper, we define the outage probability as the probability that the SINR at the output of the Alamouti decoder is falling below a given threshold. This performance parameter is crucial for both coverage and capacity studies. In terms of coverage, mobile stations should be able to decode common control channels (like pilots or broadcast channels) and thus to attain a certain SINR threshold on these channels (for example around

-10 dB in LTE) with high probability. In this case, we are interested in the low SINR region of the SINR distribution in order to evaluate the cell coverage.

In terms of capacity and for systems implementing link adaptation on shared downlink channels (such as HSPA or LTE), the whole SINR distribution is needed for performance evaluation. The ergodic capacity at a certain distance from the base station is indeed evaluated as an expectation of the Shannon classical formula over the channel variations. The cell capacity is obtained by integration over the cell area. In this paper, we indifferently speak of outage probability (for coverage studies) or cumulative distribution function (for capacity studies) and it is defined as: $P_{out} = P[\gamma < \gamma_{th}]$, where γ_{th} is the SINR threshold value.

3.1 Outage Probability for the 2 × 1 MISO Alamouti System

The SINR expressed in (4) can be written as: $\gamma = \frac{X}{Y+\sigma_n^2}$, where

$$X = \frac{P_0}{2}(|h_{1,0}|^2 + |h_{2,0}|^2), \tag{7}$$

and

$$Y = \sum_{j=1}^{B} \frac{P_j}{2} \frac{|h_{1,0}^* h_{1,j} + h_{2,0} h_{2,j}^*|^2 + |h_{1,0}^* h_{2,j} - h_{2,0} h_{1,j}^*|^2}{|h_{1,0}|^2 + |h_{2,0}|^2}. \tag{8}$$

We consider an interference limited cellular system where the background noise is assumed to be negligible. The SINR can thus be approximated by: $SINR \approx \frac{X}{Y}$. In order to calculate the outage probability, we need first to calculate the probability density function (PDF) of X and then the PDF of Y. Since $|h_{i,j}|$ are zero mean unit variance Rayleigh distributed channel gains, it can be easily shown that X is Gamma distributed and that the PDF of X is given by:

$$f_X(x) = \frac{4x}{P_0^2} e^{-\frac{2x}{P_0}}. \tag{9}$$

The received powers from the different interfering BSs can be written as:

$$Y = \sum_{j=1}^{B} \frac{P_j}{2} Z_j, \quad (10)$$

where Z_j is given by:

$$Z_j = |c_j|^2 + |d_j|^2, \quad (11)$$

and $c_j = \frac{\mathbf{h}_0 \mathbf{h}_j^T}{||\mathbf{h}_0||}$, $d_j = \frac{\mathbf{h}_0 \mathbf{g}_j^T}{||\mathbf{h}_0||}$, where

$$\mathbf{h}_0 = [h_{1,0}^* \; h_{2,0}], \; \mathbf{h}_j = [h_{1,j} \; h_{2,j}^*] \quad \text{and} \quad \mathbf{g}_j = [h_{1,j} \; -h_{2,j}^*].$$

Since the channel are assumed Rayleigh distributed, the elements of $\mathbf{h}_0$, $\mathbf{h}_j^T$ and $\mathbf{g}_j^T$ are zero mean complex Gaussian. In this case, it was demonstrated in [9] (the demonstration is detailed in the Appendix A) that c_j and d_j are also complex Gaussian independent of $\mathbf{h}_0$. Z_j is, hence, the sum of two correlated exponentially distributed variables, so that the PDF of Z_j is given by [20]:

$$f_{Z_j}(z) = \frac{1}{\sqrt{\rho_z}} \exp\left(-\frac{z}{1-\rho_z}\right) \sinh\left(\frac{\sqrt{\rho_z}}{1-\rho_z} z\right), \quad \text{for} \quad z > 0, \quad (12)$$

where ρ_z is the correlation coefficient between the two correlated random variables $|c_j|^2$ and $|d_j|^2$. It is a constant obtained by simulation $\rho_z = 0.0167$.

From the expression (10) of the interference power, we can approximate the PDF $f_Y(y)$ using the central limit theorem for causal functions [21] by a Gamma distribution given by:

$$f_Y(y) = \frac{y^{\alpha-1} \exp(-\frac{y}{\beta})}{\Gamma(\alpha)\beta^{\alpha}}, \quad (13)$$

where $\alpha = \frac{\mathrm{E}[Y]^2}{\mathrm{var}(Y)}$ and $\beta = \frac{\mathrm{var}(Y)}{\mathrm{E}[Y]}$. Note that the application of the central limit theorem for causal functions requires that interference powers are independent but not necessarily identically distributed [21].

Let us derive the expression of α and β. As Z_j for $j = 1, ..., B$ are independent random variables, the mean of the interference power is given by:

$$\mathrm{E}[Y] = \sum_{j=1}^{B} \frac{P_j}{2} \mathrm{E}[Z_j] = \sum_{j=1}^{B} P_j. \tag{14}$$

The variance of Y can be expressed as:

$$\mathrm{var}(Y) = \sum_{j=1}^{B} \frac{P_j^2}{4} \mathrm{var}(Z_j). \tag{15}$$

$\mathrm{E}[Z_j]$ can be derived as:

$$\mathrm{E}[Z_j] = \mathrm{E}[|c_j|^2] + \mathrm{E}[|d_j|^2] = 2, \tag{16}$$

and $\mathrm{E}[Z_j^2]$ can be calculated using the PDF of Z_j as follows:

$$\begin{aligned} \mathrm{E}[Z_j^2] &= \int_0^{\infty} \frac{z^2}{\sqrt{\rho_z}} \exp\left(\frac{-z}{1-\rho_z}\right) \sinh\left(\frac{\sqrt{\rho_z}}{1-\rho_z} z\right) dz, \\ &= \frac{1}{\sqrt{\rho_z}} \frac{\Gamma(3)}{2} \left[\left(\frac{1-\sqrt{\rho_z}}{1-\rho_z}\right)^{-3} - \left(\frac{1+\sqrt{\rho_z}}{1-\rho_z}\right)^{-3} \right], \\ &= 2(3+\rho_z). \end{aligned} \tag{17}$$

The parameters α and β in (13) are, thus given by:

$$\alpha = \frac{2}{1+\rho_z} \frac{(\sum_{j=1}^{B} P_j)^2}{\sum_{j=1}^{B} P_j^2}, \quad \beta = \frac{1+\rho_z}{2} \frac{\sum_{j=1}^{B} P_j^2}{\sum_{j=1}^{B} P_j}. \tag{18}$$

As already stated, the random variables c_j and d_j are independent of $\mathbf{h}_0$ (see Appendix), and since Y is given by:

$$Y = \sum_{j=1}^{B} \frac{P_j}{2} \left(|c_j|^2 + |d_j|^2\right), \tag{19}$$

Y is also independent of $\mathbf{h}_0$, and since X can be written as:

$$X = \frac{P_0}{2} \|\mathbf{h}_0\|^2, \tag{20}$$

it can be asserted that Y is independent of X. The outage probability can thus be derived as follows:

$$P(\frac{X}{Y} < \gamma_{th}) = \int_0^\infty F_X(\gamma_{th} y) f_Y(y) dy \quad (21)$$

$$= \int_0^\infty (1 - e^{-\frac{2\gamma_{th}}{P_0} y}(1 + \frac{2\gamma_{th}}{P_0} y)) f_Y(y) dy. \quad (22)$$

Substituting $f_Y(y)$ by its expression, the outage probability can be written as:

$$P_{out}(\gamma_{th}) = 1 - \left(\frac{P_0}{2\gamma_{th}\beta + P_0}\right)^{\alpha} \left(1 + \frac{2\gamma_{th}\beta}{2\gamma_{th}\beta + P_0} \frac{\Gamma(\alpha+1)}{\Gamma(\alpha)}\right). \quad (23)$$

Note that in the previous derivation, the parameter ρ_z has been obtained by simulation, while considering 10000 samples of both involved random variables. As c_j and d_j only depend on Rayleigh channels gains, ρ_z does not depend on system parameters and can thus be considered as a constant, computed once for all. We have also noticed that the accuracy of the correlation coefficient estimate has very little impact on the results, and taking $\rho_z = 0$ is also a valid option.

3.2 Outage Probability for the $2 \times N$ MIMO Alamouti System with MRC Receiver

As in the previous section, in an interference limited system the SINR per stream of a MIMO Alamouti scheme with MRC receiver given by (6) can be approximated as: $SINR \approx \frac{X_{MRC}}{Y_{MRC}}$, where X_{MRC} and Y_{MRC} are given by the expressions:

$$X_{MRC} = \frac{P_0}{2} \sum_{n=1}^{N} (|h_{n,1,0}|^2 + |h_{n,2,0}|^2), \quad (24)$$

and

$$Y_{MRC} = \sum_{j=1}^{B} \frac{P_j}{2} \left(\frac{|\sum_{n=1}^N h^*_{n,1,0} h_{n,1,j} + h_{n,2,0} h^*_{n,2,j}|^2 + |\sum_{n=1}^N h^*_{n,1,0} h_{n,2,j} - h_{n,2,0} h^*_{n,1,j}|^2}{\sum_{n=1}^N (|h_{n,1,0}|^2 + |h_{n,2,0}|^2)} \right). \quad (25)$$

From the expression of X_{MRC} and since $|h_{i,j,b}|$ are zero mean unit variance Rayleigh distributed channel gains, it can be easily shown [22] that X_{MRC} is the sum of two Gamma distributed random variables $G(N, P_0/2)$ and that $X_{MRC} \sim G(2N, P_0/2)$. The PDF of X_{MRC} is hence given by:

$$f_{X_{MRC}}(x) = \frac{x^{2N-1}}{(\frac{P_0}{2})^{2N}(2N-1)!} e^{-\frac{2x}{P_0}}. \tag{26}$$

To derive the interference power PDF we use the same Gamma approximation as in Section 3:

$$f_{Y_{MRC}}(y) = \frac{y^{\nu-1}\exp(-\frac{y}{\lambda})}{\Gamma(\nu)\lambda^{\nu}}, \tag{27}$$

where $\nu = \frac{\mathrm{E}[Y_{MRC}]^2}{\mathrm{var}(Y_{MRC})}$ and $\lambda = \frac{\mathrm{var}(Y_{MRC})}{\mathrm{E}[Y_{MRC}]}$.

In order to compute $\mathrm{E}[Y_{MRC}]$ and $\mathrm{var}(Y_{MRC})$, we will use the notation $Y_{MRC} = \sum_{j=1}^{B} \frac{P_j}{2} V_j$, where V_j is given by:

$$V_j = |C_j|^2 + |D_j|^2, \tag{28}$$

and $C_j = \frac{\tilde{\mathbf{h}}_0 \tilde{\mathbf{h}}_j}{||\tilde{\mathbf{h}}_0||}$ and $D_j = \frac{\tilde{\mathbf{h}}_0 \tilde{\mathbf{g}}_j}{||\tilde{\mathbf{h}}_0||}$, $\tilde{\mathbf{h}}_0$, $\tilde{\mathbf{h}}_j$ and $\tilde{\mathbf{g}}_j$ being:

$$\tilde{\mathbf{h}}_0 = [h^*_{1,1,0} \;..\; h^*_{N,1,0} \; h_{1,2,0} \;..\; h_{N,2,0}],$$

$$\tilde{\mathbf{h}}_j = [h_{1,1,j} \;..\; h_{N,1,j} \; h^*_{1,2,j} \;..\; h^*_{N,2,j}]^T,$$

$$\tilde{\mathbf{g}}_j = [h_{1,2,j} \;..\; h_{N,2,j} \; -h^*_{1,1,j} \;..\; -h^*_{N,1,j}]^T.$$

As proven in Section 3, C_j and D_j are complex Gaussian random variables independent of $\tilde{\mathbf{h}}_0$ so that V_j is the sum of two correlated exponentially distributed variables. As a consequence, the PDF of V_j is given by [20]:

$$f_V(v) = \frac{1}{\sqrt{\rho_v}} \exp\left(-\frac{v}{1-\rho_v}\right) \sinh\left(\frac{\sqrt{\rho_v}}{1-\rho_v} v\right), \quad for \;\; v > 0. \tag{29}$$

where $\rho_v = 3.9267.10^{-4}$ (obtained by simulations) is the correlation coefficient between the two correlated random variables $|C_j|^2$ and $|D_j|^2$. $\mathrm{E}[V_j]$ and $\mathrm{E}[V_j^2]$ can be derived as in Section 3 and are given by: $\mathrm{E}[V_j] = 2$, and $\mathrm{E}[V_j^2] = 2(3+\rho_v)$. Since V_j for $j = 1, ..., B$ are independent random variables, the mean of the interference power is given by:

$$\mathrm{E}[Y_{MRC}] = \sum_{j=1}^{B} \frac{P_j}{2} \mathrm{E}[V_j] = \sum_{j=1}^{B} P_j. \tag{30}$$

The variance of Y_{MRC} can be expressed as:

$$\mathrm{var}(Y_{MRC}) = \sum_{j=1}^{B} \frac{P_j^2}{4} \mathrm{var}(V_j) = \sum_{j=1}^{B} \frac{P_j^2}{2}(1+\rho_v). \tag{31}$$

The parameters ν and λ in (27) are, thus given by:

$$\nu = \frac{2}{1+\rho_v} \frac{(\sum_{j=1}^{B} P_j)^2}{\sum_{j=1}^{B} P_j^2}, \quad \lambda = \frac{1+\rho_v}{2} \frac{\sum_{j=1}^{B} P_j^2}{\sum_{j=1}^{B} P_j}. \tag{32}$$

Since Y_{MRC} is independent of $\tilde{\mathbf{h}}_0$, it is consequently independent of $X_{MRC} = \tilde{\mathbf{h}}_0 \tilde{\mathbf{h}}_0^H$, the outage probability can be derived using the formula (21) and is given by:

$$P_{out}^{MRC}(\gamma_{th}) = 1 - \sum_{k=0}^{2N-1} \frac{(2\gamma_{th}\lambda)^k P_0^{\nu}}{k!(2\gamma_{th}\lambda + P_0)^{k+\nu}} \frac{\Gamma(k+\nu)}{\Gamma(\nu)}. \tag{33}$$

Again, the parameter ρ_v can be obtained off line once for all by simulations and is independent on the system parameters. Moreover, numerical experiments show that the accuracy of the estimate has little impact on the results and choosing $\rho_v = 0$ provides also very good results.

4 Outage Probability with Log-normal Shadowing

In this section, we will consider that the shadowing follows a log-normal distribution. The PDF of the received power can be expressed as:

$$f_{P_j}(x) = \frac{1}{ax\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln(x) - a\mu_j)^2}{2a^2\sigma^2}\right), \tag{34}$$

where $a = \frac{\ln 10}{10}$ and $\mu_j = \frac{1}{a} \ln\left(K P_T d_j^{-\eta}\right)$.

Following the same reasoning as for the equation (23), we will derive an expression for the outage probability for the 2 × 1 MISO Alamouti system and the MIMO Alamouti with MRC receiver system.

4.1 Outage Probability for the 2 × 1 MISO Alamouti System

Considering the PDF of the received power given by (34), the outage probability conditioned on the useful received power can be written as:

$$P_{out}(\gamma_{th}|P_0 = x) = 1 - \left(\frac{x}{2\gamma_{th}\beta_s + x}\right)^{\alpha_s} \left(1 + \frac{2\gamma_{th}\beta_s}{2\gamma_{th}\beta_s + x} \frac{\Gamma(\alpha_s + 1)}{\Gamma(\alpha_s)}\right), \quad (35)$$

where $\alpha_s = \frac{\mathrm{E}[Y]^2}{\mathrm{var}(Y)}$ and $\beta_s = \frac{\mathrm{var}(Y)}{\mathrm{E}[Y]}$, the subscript $_s$ refers to the shadowing. To calculate α_s and β_s we will consider the log-normal distribution of the received powers P_j. The mean of Y is, hence, given by:

$$\mathrm{E}[Y] = \sum_{j=1}^{B} \mathrm{E}[\frac{P_j}{2}]\mathrm{E}[Z_j]. \quad (36)$$

Using (34), the mean of P_j is given by:

$$\mathrm{E}[P_j] = e^{a\mu_j + \frac{a^2\sigma^2}{2}}. \quad (37)$$

Since $\mu_j = \frac{1}{a}\ln\left(KP_T d_j^{-\eta}\right)$, $E[P_j]$ can be written as:

$$\mathrm{E}[P_j] = e^{\frac{a^2\sigma^2}{2}} KP_T d_j^{-\eta}. \quad (38)$$

The mean of Y can, thus, be written as:

$$\mathrm{E}[Y] = e^{\frac{a^2\sigma^2}{2}} \sum_{j=1}^{B} KP_T d_j^{-\eta}. \quad (39)$$

The variance of the interference power can be derived as:

$$\mathrm{var}(Y) = \sum_{j=1}^{B} \mathrm{E}[\frac{P_j^2}{4}]\mathrm{E}[Z_j^2] - \frac{1}{4}\mathrm{E}[P_j]^2\mathrm{E}[Z_j]^2, \quad (40)$$

where $\mathrm{E}[P_j^2]$ is given by:

$$\mathrm{E}[P_j^2] = e^{2a^2\sigma^2}\left(KP_T d_j^{-\eta}\right)^2. \tag{41}$$

Hence, the variance of Y can be expressed as:

$$\begin{aligned}\mathrm{var}(Y) &= \sum_{j=1}^{B} e^{2a(\mu_j + a\sigma^2)}\frac{1}{2}(3+\rho_z) - e^{2a(\mu_j + \frac{a\sigma^2}{2})}, \qquad (42)\\ &= (\frac{1}{2}(3+\rho_z)e^{2a^2\sigma^2} - e^{a^2\sigma^2})\sum_{j=1}^{B}\left(KP_T d_j^{-\eta}\right)^2.\end{aligned}$$

The parameters α_s and β_s are, thus given by:

$$\alpha_s = \frac{1}{\frac{1}{2}(3+\rho_z)e^{a^2\sigma^2} - 1}\frac{(\sum_{j=1}^{B} d_j^{-\eta})^2}{\sum_{j=1}^{B} d_j^{-2\eta}}, \tag{43}$$

$$\beta_s = \left(\frac{1}{2}(3+\rho_z)e^{a^2\sigma^2} - 1\right)e^{\frac{a^2\sigma^2}{2}}KP_T\frac{\sum_{j=1}^{B} d_j^{-2\eta}}{\sum_{j=1}^{B} d_j^{-\eta}}. \tag{44}$$

The outage probability can be derived by integrating the conditional outage probability over the PDF of the received power given by (34) as follows:

$$\begin{aligned}P_{out}(\gamma_{th}) = 1 - \int_0^\infty &\left(\frac{x}{2\gamma_{th}\beta_s + x}\right)^{\alpha_s}\left(1 + \frac{2\gamma_{th}\beta_s}{2\gamma_{th}\beta_s + x}\frac{\Gamma(\alpha_s+1)}{\Gamma(\alpha_s)}\right)\\ &\times\frac{1}{ax\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln(x) - a\mu_0)^2}{2a^2\sigma^2}\right)dx, \qquad (45)\end{aligned}$$

where $\mu_0 = \frac{1}{a}\ln\left(KP_T d_0^{-\eta}\right)$, d_0 is the distance between the considered user and its serving BS.

4.2 Outage Probability for the $2 \times N$ MIMO Alamouti System with MRC Receiver

We now consider the case where the receiver is equipped with N antennas and performs MRC. The Gamma approximation of the interference power PDF is always valid, we have however to calculate the new parameters ν_s and λ_s of the Gamma distribution.

Following the same approach as in Section 4.1, and considering the log-normal random variation of the received power, the mean and the variance of Y_{MRC} are given by:

$$\mathrm{E}[Y_{MRC}] = e^{\frac{a^2\sigma^2}{2}} \sum_{j=1}^{B} KP_T d_j^{-\eta}, \tag{46}$$

and

$$\mathrm{var}(Y_{MRC}) = e^{a^2\sigma^2} \left(\frac{3+\rho_v}{2} e^{a^2\sigma^2} - 1 \right). \tag{47}$$

Hence, ν_s and λ_s can be expressed as:

$$\nu_s = \frac{1}{\frac{3+\rho_v}{2} e^{a^2\sigma^2} - 1} \frac{(\sum_{j=1}^{B} d_j^{-\eta})^2}{\sum_{j=1}^{B} d_j^{-2\eta}}, \tag{48}$$

$$\lambda_s = e^{\frac{a^2\sigma^2}{2}} \left(\frac{3+\rho_v}{2} e^{a^2\sigma^2} - 1 \right) KP_T \frac{\sum_{j=1}^{B} d_j^{-2\eta}}{\sum_{j=1}^{B} d_j^{-\eta}}. \tag{49}$$

Conditioned on the useful received power, the outage probability of a MIMO Alamouti system with an MRC receiver is given by:

$$P_{out}^{MRC}(\gamma_{th}|P_0 = x) = 1 - \sum_{k=0}^{2N-1} \frac{(2\gamma_{th}\lambda_s)^k P_0^{\nu_s}}{k!(2\gamma_{th}\lambda_s + P_0)^{k+\nu_s}} \frac{\Gamma(k+\nu_s)}{\Gamma(\nu_s)}. \tag{50}$$

Averaging over the distribution of P_0, the outage probability when considering the log-normal shadowing is given by:

$$\begin{aligned} P_{out}^{MRC}(\gamma_{th}) = 1 - &\sum_{k=0}^{2N-1} \frac{(2\gamma_{th}\lambda_s)^k}{k! a\sigma\sqrt{2\pi}} \frac{\Gamma(k+\nu_s)}{\Gamma(\nu_s)} \\ &\times \int_0^\infty \frac{x^{\nu_s - 1}}{(2\gamma_{th}\lambda_s + x)^{k+\nu_s}} \exp\left(-\frac{(\ln(x) - a\mu_0)^2}{2a^2\sigma^2} \right) dx. \end{aligned} \tag{51}$$

4.3 Fluid Model Approach

We have seen in the previous section that several parameters depends on the distances d_j between the user and each of the interfering base-stations. For dimensioning purposes (e.g. for the computation of the coverage probability at cell edge or of the achievable throughput at a given distance), it is very interesting to obtain formulas that depend only on the distance to the serving station. In this section, we thus use the fluid model that was presented for the first time in [23] to derive an outage probability expression depending only on the distance between the considered user and the serving BS. The fluid model concept consists in replacing a fixed number of BSs by an equivalent continuum characterized by a given density. Denoting:

$$g(\eta) = \sum_{j=1}^{B} d_j^{-\eta}, \tag{52}$$

for a homogeneous network and a BS density ρ_{BS} and admitting an infinite network radius, the fluid model allows us to write $g(\eta)$ as (the approach is explained in details in [24]):

$$g(\eta) = (1 + A(\eta))\frac{2\pi\rho_{BS}}{\eta - 2}(2R_c - d_0)^{2-\eta}, \tag{53}$$

where R_c is the considered cell radius. Parameter $A(\eta) := 0.15 - 0.32\eta$ has been introduced in [25] as a corrective factor for hexagonal networks.

In terms of $g(\eta)$, the parameters of the outage probability of the 2×1 Alamouti system α_s (43) and β_s (44) can be written as:

$$\alpha_s = \frac{1}{\frac{3+\rho}{2}e^{a^2\sigma^2} - 1}\frac{g(\eta)^2}{g(2\eta)}, \tag{54}$$

$$\beta_s = e^{\frac{a^2\sigma^2}{2}}\Big(\frac{3+\rho}{2}e^{a^2\sigma^2} - 1\Big)KP_T\frac{g(2\eta)}{g(\eta)}. \tag{55}$$

Similarly, the parameters of the MIMO $(2 \times N)$ system with MRC receiver ν_s (49) and λ_s (49) are given by:

$$\nu_s = \frac{1}{\frac{3+\rho_v}{2}e^{a^2\sigma^2} - 1}\frac{g(\eta)^2}{g(2\eta)}, \tag{56}$$

$$\lambda_s = e^{\frac{a^2\sigma^2}{2}}\Big(\frac{3+\rho_v}{2}e^{a^2\sigma^2} - 1\Big)KP_T\frac{g(2\eta)}{g(\eta)}. \tag{57}$$

5 Simulation Results

As several approximations have been made in the previous sections, we compare in this section our formulas with results obtained using Monte Carlo simulations. We also draw conclusions on the use of Alamouti and MRC schemes in multi-cellular environments.

In Fig. 2, we plot simulated and analytical outage probabilities for the MISO Alamouti scheme compared to a 2×2 and a 2×4 MIMO Alamouti schemes with MRC receiver. We consider a user at a distance $d = 0.5$ Km from its serving BS and 18 dominant interfering BSs (two rings of BS in a hexagonal network). The standard deviation of the log-normal shadowing is set to $\sigma = 6$ dB and the path-loss exponent to $\eta = 3.41$. The shadowing is considered constant over the period of study.

It can be seen that the MIMO Alamouti coded system with MRC receiver achieves better performance. The higher slope obtained with several receive antennas is explained by the additional receiver diversity gain achieved by the MRC receiver. The transmit diversity order achieved by the Alamouti code is indeed $G_T = 2$, while MRC brings a receive diversity order of $G_R = 2$ for the 2×2 MIMO system and $G_R = 4$ for the 2×4 MIMO system. Thus, the Alamouti scheme associated with the MRC receiver allows a better coverage. The simulated curves fit well the analytical ones. Fig. 3 shows that the central limit approximation used to derive the outage probability is valid even when considering only six interfering BSs.

Fig. 4 presents a comparison between the performance of the 2×1 MISO Alamouti scheme in a single cell and in a multi-cellular system with the performance of the 2×2 MIMO Alamouti coded system with MRC receiver for the same scenarios. As expected, the performance gain of the two systems degrades considerably in the multi-cellular scenario compared to the single cell one, we can also see that the Alamouti scheme in association with an MRC receiver always achieves better performance.

Assuming constant shadowing, we have studied the impact of the user location by varying its distance to the serving BS from 50 m to 0.99 Km. Some examples are provided in Fig. 5. In all cases, simulation and analysis curves are very close.

Fig. 6 presents the influence of the shadowing on the performance of the two systems 2×1 Alamouti and 2×4 Alamouti with MRC receiver. Simulated and analytical curves are displayed for a user at a distance $d = 0.5$ Km from its serving BS, a cell radius $R_c = 1$ Km, a shadowing standard deviation $\sigma = 6$ dB and 18 dominant interfering BSs. It can be noticed that the log-normal random variation of the shadowing degrades the performance of the two systems. It can be remarked that for an outage probability of 1%, the loss in terms of SINR is about 10 dB for the Alamouti with MRC receiver scheme and 7 dB for the Alamouti scheme. From the same figure we can also see that there is a good match between theoretical results and simulations.

Assuming variable shadowing, we have studied the impact of the standard deviation of the masks at a distance of $d = 0.5$ Km from the base station. As shown on Fig. 7, our formulas are valid for $\sigma \leq 6$ dB.

In Fig. 8, we present a comparison between simulated and theoretical outage probability results for the same two systems when using the fluid model approach. We consider the same system parameters as for Fig. 6 except for the shadowing standard deviation set to 4 dB. At this distance from the BS and for this standard deviation, we can still observe a good agreement between analytical results and simulations. Figure 9, obtained at a distance $d = 0.5$ Km from the serving BS show that we have good results up to $\sigma = 7$ dB, although inaccuracy increases at high SINR and as the number of receive antennas increases. Figure 10, obtained for $\sigma = 4$ dB, shows that we obtain good results from $d = 0.25$ Km to $d = 0.9$ Km for low SIR values. Again, inaccuracy is increasing with increasing SINR and number of receive antennas. The loss of accuracy and the narrowed limits of validity of the formulas are the price for the much simpler expressions of the outage probability provided by the fluid model.

It is at last interesting to see on Fig. 11 that the well known 3 dB difference between Alamouti 2×1 and MRC 1×2 [6] can also be observed in a multi-cellular environment. Curves have been here obtained using the fluid model, $R_c = 1$ Km and $d = 0.5$ Km.

6 Conclusion

In this paper, the performance of two multi-cellular network interference limited systems are analyzed: a 2×1 MISO Alamouti coded system and a $2 \times N$ MIMO Alamouti coded system with an MRC receiver. Outage probability expressions for the case of constant shadowing and the case of log-normal shadowing are derived. In the two cases, a comparison between the performance of the two multi-cellular systems is illustrated. The fluid model approach permits to derive expressions of outage probability depending only on the distance between the considered user and its serving BS. This analysis is an important starting point to address issues related to network dimensioning.

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A Independence Result

In this appendix, we recall an independence result presented in [9]. Consider zero mean complex Gaussian vectors $\mathbf{h}_0 = [h_{1,0}, h_{2,0}, ..., h_{N,0}]^H$ and $\mathbf{h}_j = [h_{1,j}, h_{2,j}, ..., h_{N,j}]^H$ and let g_j be a random variable given by:

$$g_j = \frac{\mathbf{h}_0^H \mathbf{h}_j}{\|\mathbf{h}_0\|}. \tag{58}$$

Since the elements of $\mathbf{h}_j$ are i.i.d zero mean complex Gaussian, g_j conditioned on $\mathbf{h}_0$ is also zero-mean complex Gaussian. The mean and the variance of g_j can be calculated as follows:

$$\mathrm{E}[g_j|\mathbf{h}_0] = \frac{\mathbf{h}_0^H}{\|\mathbf{h}_0\|}\mathrm{E}[\mathbf{h}_j] = 0, \tag{59}$$

$$\mathrm{E}[|g_j|^2|\mathbf{h}_0] = \frac{\mathbf{h}_0^H \mathrm{E}[\mathbf{h}_j \mathbf{h}_j^H]\mathbf{h}_0}{\|\mathbf{h}_0\|^2}, \tag{60}$$

$$= \frac{\mathbf{h}_0^H \mathbf{I}_N \mathbf{h}_0}{\|\mathbf{h}_0\|^2}, \tag{61}$$

$$= 1, \tag{62}$$

$\mathbf{I}_N$ being the identity matrix of dimension N.

The pdf of g_j conditioned on $\mathbf{h}_0$ can thus be written as:

$$f_{g_j}(g_j/\mathbf{h}_0) = \frac{1}{\pi}\exp(-|g_j|^2). \tag{63}$$

From the expression of the pdf, it can be clearly stated that g_j is independent of $\mathbf{h}_0$.

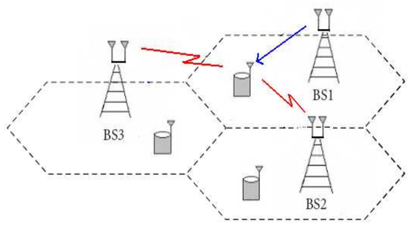


Fig. 1 Downlink multi-cellular system.

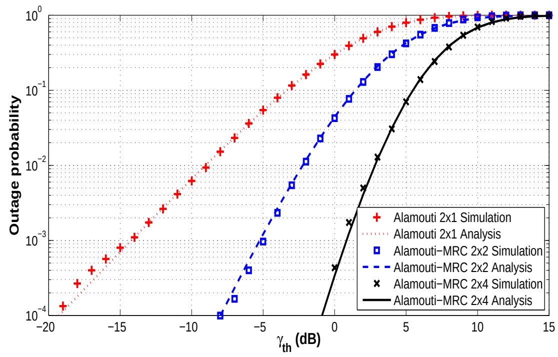


Fig. 2 Outage probability versus SINR threshold for 2×1 MISO Alamouti, 2×2 and 2×4 MIMO Alamouti with MRC (18 interfering BSs).

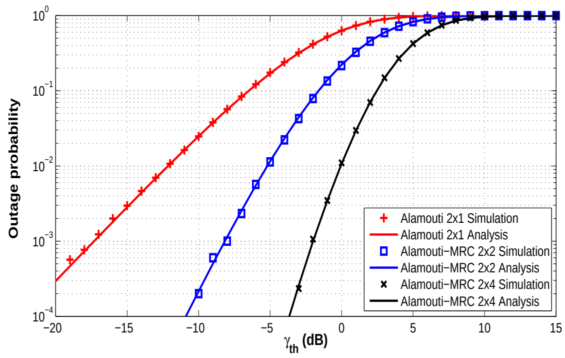
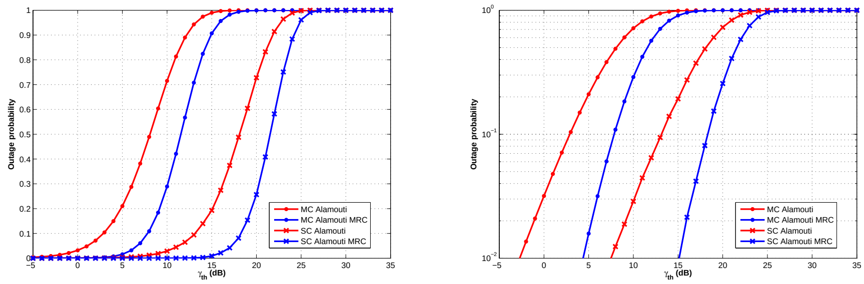


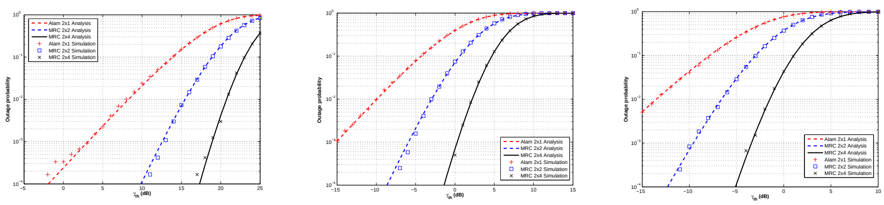
Fig. 3 Outage probability versus SINR threshold for 2×1 MISO Alamouti, 2×2 and 2×4 MIMO Alamouti with MRC (6 interfering BSs).



(a) Linear scale.

(b) Logarithmic scale.

Fig. 4 Outage probability versus SINR threshold for 2×1 MISO Alamouti and 2×2 Alamouti with MRC for a single-cell (SC) and for a multi-cellular (MC) communications.



(a) $d = 0.25$ Km.

(b) $d = 0.75$ Km.

(c) $d = 0.9$ Km.

Fig. 5 Outage probability versus SINR threshold for 2×1 MISO Alamouti, 2×2 and 2×4 MIMO Alamouti with MRC (18 interfering BSs) at various distances from the BS.

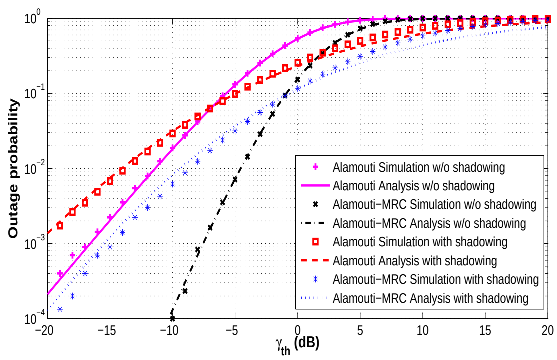
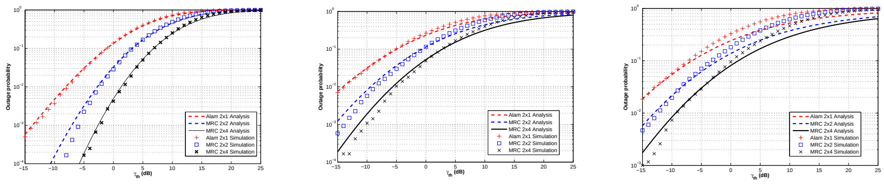


Fig. 6 Influence of the shadowing: outage probability versus SINR threshold for 2×1 MISO Alamouti and the 2×4 MIMO Alamouti with MRC receiver systems.



(a) $\sigma = 4$ dB. (b) $\sigma = 6$ dB. (c) $\sigma = 7$ dB.

Fig. 7 Influence of the shadowing: outage probability versus SINR threshold for 2×1 MISO Alamouti and the 2×4 MIMO Alamouti with MRC receiver systems with various standard deviations of the shadowing.

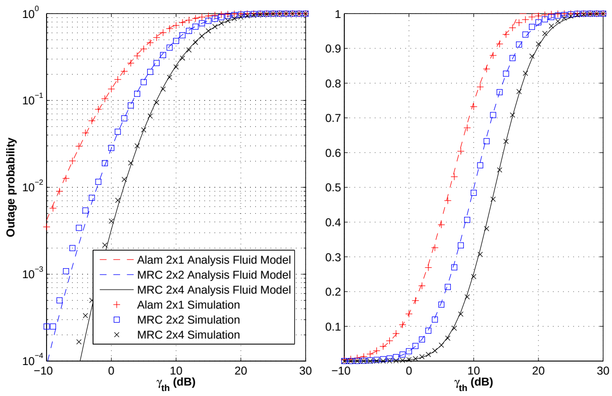
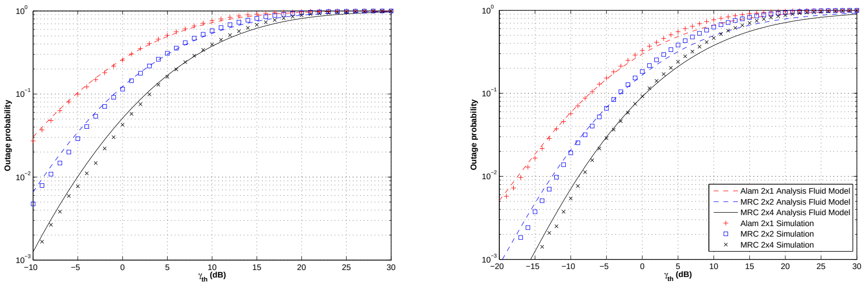


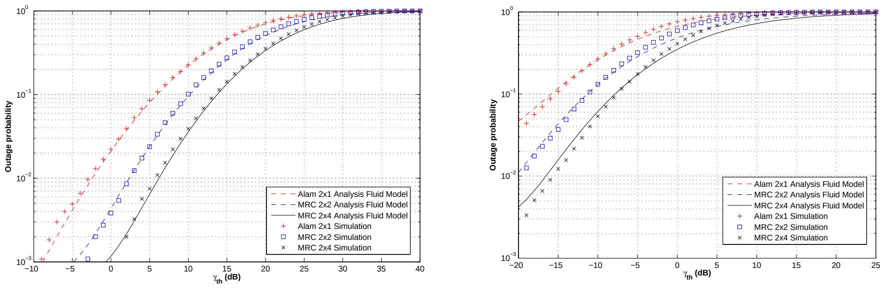
Fig. 8 Fluid model approximation: Outage probability versus SINR threshold for 2×1 MISO Alamouti, 2×2 and 2×4 MIMO Alamouti with MRC receiver systems using the fluid model ($d = 0.5$ Km, $\sigma = 4$ dB).



(a) $\sigma = 6$ dB

(b) $\sigma = 7$ dB

Fig. 9 Fluid model approximation: Outage probability versus SINR threshold for 2×1 MISO Alamouti, 2×2 and 2×4 MIMO Alamouti with MRC receiver systems using the fluid model for two values of the shadowing standard deviation.



(a) $d = 0.25$ Km

(b) $d = 0.9$ Km

Fig. 10 Fluid model approximation: Outage probability versus SINR threshold for 2×1 MISO Alamouti, 2×2 and 2×4 MIMO Alamouti with MRC receiver systems using the fluid model at two different distances from the base station.

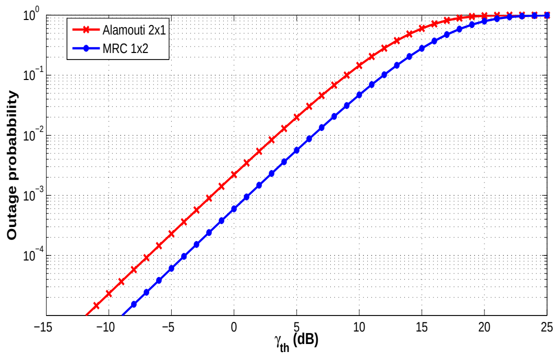


Fig. 11 Outage probability versus SINR threshold for Alamouti 2×1 and with MRC 1×2 systems using fluid model.