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***Abstract*—In this paper we analyze the performance of a downlink single user multi-cellular multiple inputs single output (MISO) system using the Alamouti code. We derive, for the first time, an analytical expression of the cumulative distribution function of the output signal to interference plus noise ratio (SINR) or equivalently the outage probability in flat Rayleigh fading. The system is considered interference limited. Two assumptions are considered: equal received power and unequal received power from the interfering base stations. In the first case, a closed-form expression for the outage probability is derived. In the second case, from an approximation of the interference power distribution the outage probability expression is obtained.**

***Index Terms*—Multiple inputs single output (MISO), multi-cellular, Rayleigh fading, Alamouti, outage probability.**

I. Introduction

Multiple antennas systems have attracted many research attention due to their potential to increase capacity through the multiplexing gain [1], [2] and to enhance reliability owning to the diversity gain. However, the capacity gains promised by MIMO techniques degrade drastically in a multi-cellular system. Consequently many transmission and/or reception strategies have been proposed to mitigate this degradation. The performance of these strategies have been evaluated over multiple studies. In [3], the outage probability of the optimum combining (OC) receiver was studied for unequal co-channel interference plus noise power. In [4], [5] and [6], the performance of different reception strategies for MIMO systems in presence of co-channel interference have been compared based on an outage probability study. It was shown that the interference cancellation (IC) receiver yields better performance than the maximum ratio combining (MRC) in an interference limited system and for few number of dominant interferers (less than the number of receive antennas). It was also shown that the OC receiver achieves the best performance.

In [7], the performance of maximum ratio transmission (MRT) technique in a multi-cellular multi-user MIMO system was analyzed. A closed form expression of the outage probability was proposed for an arbitrary number of transmit and receive antennas. In [8], different transmission strategies were compared. The Alamouti [9] scheme was studied in a single cell multi-user MISO and MIMO system scenarios for line of sight (LOS) and non line of sight (NLOS) channels. In [10], the Alamouti code performance was examined in the case of multiuser uplink communication. The outage probability was derived for a MIMO system in Rayleigh fading channels.

In the present work, we will analyze the performance of the full transmit diversity Alamouti scheme in a multi-cellular system when considering Rayleigh fading. We derive, for the first time, an expression of the SINR cumulative distribution function or equivalently the outage probability for a 2×1 multi-cellular MISO system.

The remainder of this paper is organized as follows. In the next section, we describe the system model. In section III, we derive an expression for the outage probability in case of equal received interference power and unequal received power for 2×1 MISO Alamouti and SISO systems. Section IV includes a comparison between simulated and analytical results and discussions. Finally, in section V we conclude.

II. System Model

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 base station (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 diversity gain for a 2×1 MISO system is equivalent to the receive diversity when using a maximum ratio combining (MRC) receiver [11]. The Alamouti scheme presents the advantage of keeping the user equipments simple and unburdened. Owing to its implementation simplicity, the Alamouti scheme has been adopted for the W-CDMA, CDMA-2000 and WiMax standards.

The Alamouti code matrix is given by:

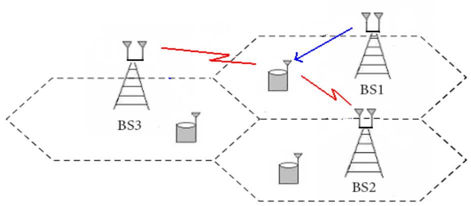

Fig. 1. Downlink multi-cell (3 BSs) single user communication.

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

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

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

where $s_{i,j}$ is the symbol transmitted from the antenna i of the BS j, $h_{i,j}$ is the flat fading Rayleigh channel gain between the antenna i of the BS j and the user it serves. 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 and is given by:

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

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:

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

The signal to interference plus noise ratio (SINR) per symbol is, thus, given by:

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

III. Outage Probability

The outage probability is an important metric for the evaluation of the performance of a wireless communication system. It measures the probability of failing to achieve an output SINR threshold value required for a desired service. It is given by the cumultaive distribution function (CDF) of the output SINR, i.e. :

$$P_{out} = P[\gamma < \gamma_{th}], \quad (5)$$

where γ_{th} is the threshold SINR value.

A. Outage probability for the 2×1 MISO Alamouti system

The SINR expressed in (4) can be written as:

$$\gamma = \frac{X}{Y + \sigma_n^2}, \quad (6)$$

where

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

and

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

We consider an interference limited cellular system where the background noise is assumed to be negligible. The SINR can, thus, be approximated by:

$$SINR \approx \frac{X}{Y}. \quad (9)$$

To calculate the outage probability we need to calculate first, the probability distribution function (PDF) of X and the PDF of Y. We will suppose that the shadowing remains constant during the period of our study.
Since $|h_{i,j}|$ are zero mean unit variance Rayleigh distributed channel gains, it can be easily shown [17] that X is Gamma distributed and that the PDF of X is given by:

$$f_X(x) = \frac{4x}{P_0^2\Gamma(2)} e^{-\frac{2x}{P_0}}. \quad (10)$$

1) Equal interference power assumption: In this section, we will assume that $P_j = P, \forall j = 1, ..., B$. This assumption allows us to derive a simple closed form expression of the outage probability. However this scenario is not completely unrealistic. It can correspond to the case where the considered user is close to its serving BS mainly interfered by the first surrounding layer of cells.
The interference power Y can be written as:

$$Y = \sum_{j=1}^{B} \frac{P}{2}(|c_j|^2 + |d_j|^2), \quad (11)$$

where

$$c_j = \frac{\mathbf{h}_0 \mathbf{h}_j^t}{|\mathbf{h}_0|} \quad \text{and} \quad d_j = \frac{\mathbf{h}_0 \mathbf{g}_j^t}{|\mathbf{h}_0|}.$$

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

As proven in [6], c_j and d_j are complex Gaussian random variables independent of $\mathbf{h}_0$. Hence, Y is the sum of two correlated Gamma distributed random variables. Using the analysis conducted in [12], we can prove that the probability distribution of Y is given by:

$$\begin{aligned} f_Y(y) &= \frac{2\sqrt{\pi}}{P(1-\rho)^B\Gamma(B)}\left(\frac{2y}{P^2\delta}\right)^{B-\frac{1}{2}} \\ &\times \exp(-\frac{2y}{P(1-\rho)})I_{B-\frac{1}{2}}(\delta y), \end{aligned} \quad (12)$$

where ρ is the correlation coefficient between the two correlated variables $Y_c = \sum_{j=1}^{B}|c_j|^2$ et $Y_d = \sum_{j=1}^{B}|d_j|^2$ and can be expressed as $\rho = \frac{Cov(Y_c,Y_d)}{\sqrt{\text{var}(Y_c)\text{var}(Y_d)}}$. $\delta = \frac{2\sqrt{\rho}}{P(1-\rho)}$ and $I_n(.)$ is the n^{th} order modified Bessel function of first kind.

Using the PDF expressions (10) and (12), the outage probability can be derived as follows:

$$\begin{aligned} P(\frac{X}{Y} < \gamma_{th}) &= \int_0^\infty F_X(\gamma_{th}y)f_Y(y)dy \quad (13) \\ &= \int_0^\infty (1-e^{-\frac{2\gamma_{th}}{P_0}y}(1+\frac{2\gamma_{th}}{P_0}y))f_Y(y)dy. \quad (14) \end{aligned}$$

Substituting $f_Y(y)$ by its expression and using the following formula [12]:

$$\begin{aligned} \int_0^\infty x^{\mu-1}e^{-\eta x}I_\nu(\beta x)dx &= \frac{\beta^\nu}{2^\nu\eta^{\mu+\nu}}\frac{\Gamma(\mu+\nu)}{\Gamma(\nu+1)} \times \\ & {}_2F_1\left(\frac{\mu+\nu}{2}, \frac{\mu+\nu+1}{2}; \nu+1; \frac{\beta^2}{\eta^2}\right), \end{aligned} \quad (15)$$

the outage probability is given by:

$$\begin{aligned} P_{out}(\gamma_{th}) = 1 &- \frac{C}{P^{2B-1}\varsigma^{2B}}\frac{\Gamma(2B)}{\Gamma(B+\frac{1}{2})} \\ &\times \Big({}_2F_1(B, B+\frac{1}{2}; B+\frac{1}{2}; \frac{\delta^2}{\varsigma^2}) \\ &+ \frac{4B}{\varsigma}\frac{\gamma_{th}}{P_0}{}_2F_1(B+\frac{1}{2}, B+1; B+\frac{1}{2}; \frac{\delta^2}{\varsigma^2})\Big), \end{aligned} \quad (16)$$

where ${}_2F_1(.,.;.;.)$ is the Gauss' hypergeometric function [14], $C = \frac{2\sqrt{\pi}}{P(1-\rho)^B\Gamma(B)}$ and $\varsigma = \frac{2\gamma_{th}}{P_0} + \frac{2}{P(1-\rho)}$.

2) Unequal interference power assumption: Since the equal power assumption does not cover many possible scenarios, we will try to derive an expression for the outage probability in the case of unequal received power.

When the received powers from the different interfering BSs are unbalanced, it is more difficult to find a closed form expression for the interference power PDF. However it can be approximated using the central limit theorem for causal functions [13] by a Gamma distribution given by:

$$f_Y(y) = \frac{y^{\alpha-1}\exp(-\frac{y}{\beta})}{\Gamma(\alpha)\beta^\alpha}, \quad (17)$$

where $\alpha = \frac{\text{E}[Y]^2}{\text{var}(Y)}$ and $\beta = \frac{\text{var}(Y)}{\text{E}[Y]}$.

In order to compute $\text{E}[Y]$ and $\text{var}(Y)$, we will note $Y = \sum_{j=1}^{B}\frac{P_j}{2}Z_j$ where Z_j is given by:

$$Z_j = |c_j|^2 + |d_j|^2. \quad (18)$$

Z_j is the sum of two correlated exponentially distributed variables, thus, the PDF of Z_j is given by [12]:

$$f_{Z_j}(z) = \frac{1}{\sqrt{\rho_z}}\exp(-\frac{z}{1-\rho_z})\sinh(\frac{\sqrt{\rho_z}}{1-\rho_z}z), \quad for \quad z > 0. \quad (19)$$

where ρ_z is the correlation coefficient between the two correlated random variables $|c_j|^2$ and $|d_j|^2$. $\text{E}[Z_j]$ and $\text{E}[Z_j^2]$ can be derived as follows:

$$\text{E}[Z_j] = \text{E}[|c_j|^2] + \text{E}[|d_j|^2] = 2, \quad (20)$$

and

$$\begin{aligned} \text{E}[Z_j^2] &= \int_0^\infty \frac{z^2}{\sqrt{\rho_z}}\exp(-\frac{z}{1-\rho_z})\sinh(\frac{\sqrt{\rho_z}}{1-\rho_z}z)dz, \quad (21) \\ &= \frac{1}{\sqrt{\rho_z}}\frac{\Gamma(3)}{2}\left[\left(\frac{1-\sqrt{\rho_z}}{1-\rho_z}\right)^{-3} - \left(\frac{1+\sqrt{\rho_z}}{1-\rho_z}\right)^{-3}\right], \\ &= 2(3+\rho_z). \end{aligned}$$

As Z_j for $j = 1, ..., B$ are independent random variables, the mean of the interference power is given by:

$$\text{E}[Y] = \sum_{j=1}^{B}\frac{P_j}{2}\text{E}[Z_j] = \sum_{j=1}^{B}P_j. \quad (22)$$

The variance of Y can be expressed as:

$$\begin{aligned} \text{var}(Y) &= \sum_{j=1}^{B}\frac{P_j^2}{4}\text{var}(Z_j) \quad (23) \\ &= \sum_{j=1}^{B}\frac{P_j^2}{2}(1+\rho_z). \quad (24) \end{aligned}$$

The parameters α and β of Eq.17 are, thus given by:

$$\begin{aligned} \alpha &= \frac{2}{1+\rho_z}\frac{(\sum_{j=1}^{B}P_j)^2}{\sum_{j=1}^{B}P_j^2}, \quad (25) \\ \beta &= \frac{1+\rho_z}{2}\frac{\sum_{j=1}^{B}P_j^2}{\sum_{j=1}^{B}P_j}. \quad (26) \end{aligned}$$

The outage probability can be derived using (14) in section III-A1. Substituting the interference power PDF $f_Y(y)$ by its expression (17), the outage probability is given by:

$$P_{out}(\gamma_{th}) = 1 - \left(\frac{P_0}{2\gamma_{th}\beta + P_0}\right)^\alpha\left(1 + \frac{2\gamma_{th}\beta}{2\gamma_{th}\beta + P_0}\frac{\Gamma(\alpha+1)}{\Gamma(\alpha)}\right). \quad (27)$$

B. Outage Probability for a SISO system

In a multi-cellular single input single output (SISO) communication system and assuming a flat fading Rayleigh channel, the SINR is given by:

$$\gamma_{SISO} = \frac{P_0|h_0|^2}{\sum_{j=1}^{B} P_j|h_j|^2 + \sigma_n^2}. \quad (28)$$

We consider an interference limited system, the SINR can be written as:

$$\gamma_{SISO} = \frac{X_{SISO}}{Y_{SISO}}, \quad (29)$$

where:

$$X_{SISO} = P_0|h_0|^2, \qquad Y_{SISO} = \sum_{j=1}^{B} P_j|h_j|^2. \quad (30)$$

The PDF of the useful power is given by [17]:

$$f_{X_{SISO}}(x) = \frac{1}{P_0} e^{-\frac{x}{P_0}}. \quad (31)$$

As in section III, we consider two assumptions: equal received interference powers and unequal received interference power.

1) Equal interference power: Consider $P_j = P, \forall j = 1, ..., B$, in this case, it can be easily proven that the interference power is Gamma distributed [17] and that the PDF of the interference power is given by:

$$f_{Y_{SISO}}(y) = \frac{y^{B-1}}{\Gamma(B)P^B} e^{-\frac{y}{P}}. \quad (32)$$

Using the useful power PDF (31) and the interference power PDF (32), the outage probability for a SISO system can be derived as explained in section III-A1 using the expression (14) and can be written as:

$$P_{out}^{siso}(\gamma_{th}) = 1 - \frac{1}{(\frac{P}{P_0}\gamma_{th} + 1)^B}. \quad (33)$$

2) Unequal interference power: In this section we consider the case of unequal power and considering path-loss and log-normal shadowing in our analysis. As in section III-A2, the interference power PDF can be approximated by a Gamma distribution given by:

$$f_{Y_{SISO}}(y) = \frac{y^{\nu-1}}{\Gamma(\nu)\lambda^{\nu}} e^{-\frac{y}{\lambda}}, \quad (34)$$

where the parameters $\nu = \frac{\mathrm{E}[Y_{SISO}]^2}{\mathrm{var}(Y_{SISO})}$ and $\lambda = \frac{\mathrm{var}(Y_{SISO})}{\mathrm{E}[Y_{SISO}]}$ are given by:

$$\nu = \frac{1}{2}\frac{(\sum_{j=1}^{B} P_j)^2}{\sum_{j=1}^{B} P_j^2}, \quad (35)$$

$$\lambda = 2\frac{\sum_{j=1}^{B} P_j^2}{\sum_{j=1}^{B} P_j}. \quad (36)$$

The outage probability can be obtained using the expression (14) and is given by:

$$P_{out}^{siso}(\gamma_{th}) = 1 - \frac{1}{(\frac{\lambda}{P_0}\gamma_{th} + 1)^{\nu}}. \quad (37)$$

IV. Simulation Results

In Fig. 2, we plot simulated and analytical outage probability in the case of equal received interference power for the Alamouti scheme and for a SISO system. We consider 6 interfering BSs. The cell radius is $R_c = 1$ Km, the mobile station is at a distance $d = 0.2$ Km from the BS and the interfering BSs are at distance $d_{int} = 2R_c$. The path-loss exponent is taken $\eta = 3.41$ and the standard deviation of the log-normal shadowing is taken $\sigma = 6$ dB, the shadowing is considered constant over the period of study. Simulated curves are obtained using the Jakes' model [18] to generate zero mean unit variance Rayleigh fading. The correlation factor ρ is estimated by simulation.

We can see that the Alamouti scheme achieves better performance. In fact, as can be seen in Fig. 2 (b), the outage probability of the Alamouti scheme decreases faster owning to a higher slope corresponding to the diversity gain of the scheme $G_D = 2$. Thus, the Alamouti scheme allows a better coverage. It can also be remarked from Fig. 2 (a) that the variance of the SINR output when using the Alamouti scheme is less than the variance of the SISO output SINR. The simulated curves fit very well the analytical ones.

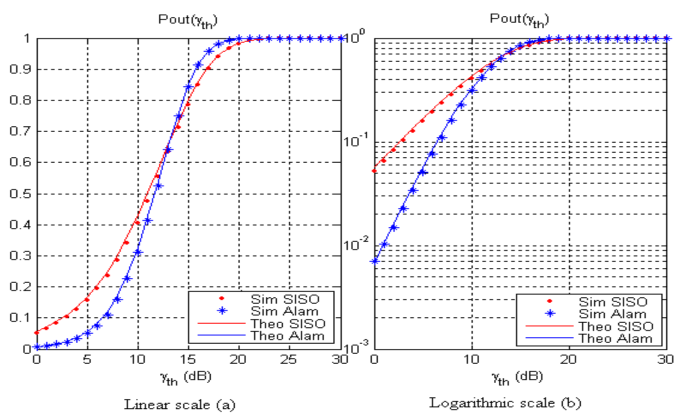

Fig. 2. Equal received interference power: P_{out} versus SINR threshold 2×1 MISO Alamouti scheme and SISO systems.

Fig. 3 shows a comparison between the performance of the Alamouti scheme of a 2×1 MISO system and a SISO system in terms of outage probability in the case of unbalanced received interference powers. Simulated and analytical curves are presented. The considered user is at a distance $d = 0.5$ Km from its serving BS, the standard deviation of the shadowing is $\sigma = 4$ dB and we consider 18 dominant interfering BSs (two rings of BS in a hexagonal network).

It can be seen that there is a good match between the simulated results and the analytical approximation of the outage probability.

As in the case of equal received interference power (Fig. 2 (b)), the diversity gain of the Alamouti scheme allows for better performance.

Fig. 4 presents a comparison between the simulated per-

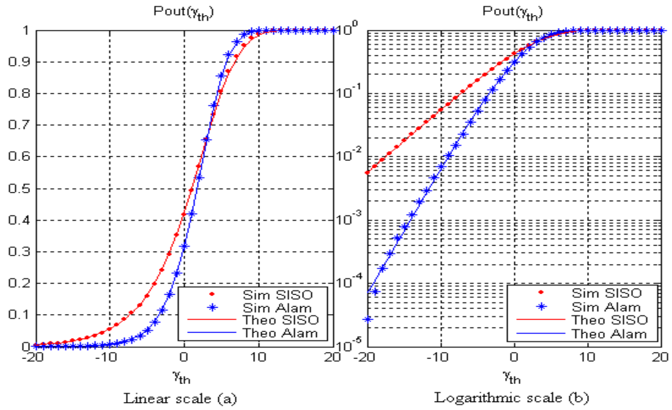

Fig. 3. Unequal received interference power: P_{out} versus SINR threshold 2×1 MISO Alamouti scheme and SISO systems.

formance of the Alamouti scheme in a 'point-to-point' communication and in a multi-cellular system with the simulated performance of a SISO system for the same scenarios. As expected, the performance gain of the Alamouti scheme degrades considerably in a multi-cellular system compared to a single cell system. This degradation can be explained by the fact that, as for the useful signal, the Alamouti scheme induces a diversity gain on the interference channel.

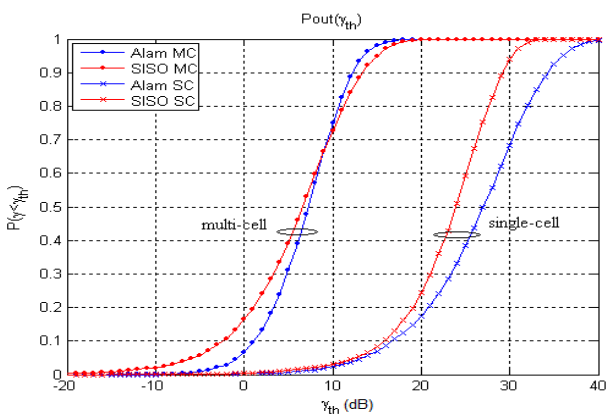

Fig. 4. Multi cell versus single cell outage probability for the 2×1 MISO Alamouti scheme and SISO systems.

V. Conclusion

In this paper, the performance of multi-cellular network interference limited system using the Alamouti scheme is analyzed. Outage probability expressions for the case of equal received interference power and unequal interference power are derived. In the two cases, a comparison between the performance of the 2 MISO Alamouti scheme and SISO system is illustrated.

As a future work, we can use the fluid model [15] approach to express the outage probability as function of the distance between the considered user and its serving BS. This analysis will allow us to address issues related to network dimensioning.

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