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Performance of *N*th-best antenna selection diversity systems with co-channel interference and outdated channel information

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Abstract: In this study, the authors evaluate the performance of space diversity systems with the *N*th-best antenna selection scheme in the presence of interference and outdated channel information (OCI). The *N*th-best antenna selection scheme is efficient in situations where the second or even the *N*th best antenna is mistakenly selected by the destination instead of the first best antenna for data reception. In this study, they first derive the cumulative distribution function (CDF) of the end-to-end (e2e) signal-to-interference plus noise ratio at the selection scheme combiner output. This CDF is then used to derive exact closed-form expressions for the e2e outage probability and symbol error probability (SEP) of the system. In the analysis, the channels of the desired user and the interferers are assumed to follow Rayleigh distribution. Furthermore, to obtain more about system insights, the performance is studied at the high signal-to-noise ratio (SNR) regime where the diversity order and coding gain are derived. Monte Carlo simulations are provided to validate the derived analytical and asymptotic expressions. Main results illustrate that with an interference power that is not scaling with SNR, the system can still achieve diversity gain when more receive antennas are used. Also, findings show that the diversity order of the system is linearly decreasing with increasing the order of the antenna, and linearly increasing with decreasing it. Furthermore, results illustrate that as the higher the correlation coefficient between the SNRs of antennas at the selection and transmission time instances, the better the achieved performance.

1 Introduction

Space or antenna diversity is an efficient technique used to mitigate the multipath fading phenomenon of wireless channels [1, 2]. Among the linear diversity combining techniques are the maximal-ratio combining (MRC), equal-gain combining (EGC), selection combining (SC), and generalised SC (GSC). These schemes have been widely studied and analysed in literature which makes them as the basic diversity combining schemes. Also, the switch-based diversity combining schemes presented in [1] are among the important combining schemes. In the SC scheme, the combiner selects the branch with the largest instantaneous signal-to-noise ratio (SNR) value without the need to know the signal phases on each branch. However, the phase needs to be estimated when implementing MRC or EGC in coherent systems [1].

The performance of the aforementioned diversity combining schemes was widely studied in literature starting with the assumption of noise-limited environments [3–5]. Particularly, in [3], the error rate and outage probabilities of a dual-branch SC diversity system were derived assuming Rayleigh and Nakagami-*m* fading channels. Recently, Beaulieu *et al.* studied in [6] the error probability performance of space diversity systems with the MRC, SC and EGC linear diversity combining schemes assuming Nakagami-0.5 fading model. The Nakagami-0.5 fading model is an important special case of the Nakagami distribution as it represents the worst case fading scenario. Most recently, some new results for error probability in space diversity systems with MRC scheme and assuming Nakagami-*m* fading channels were presented in [7]. It was shown that the symbol error probability (SEP) of MRC diversity systems over Nakagami-*m* fading channels can be obtained by a simple modification of the diversity order and average SNR values of the Rayleigh fading case. Approximate closed-form expressions for secrecy capacity were derived in [8] for multi-antenna systems with MRC diversity scheme over Rayleigh fading channels. The performance of MRC diversity combining scheme was evaluated in [9] assuming $\eta-\mu$ fading channels. The $\eta-\mu$ fading model is suitable for non-line-of-sight (NLOS) mobile communication channels. Recently, approximate expression for the outage probability of MRC receivers over arbitrarily fading channels was derived in [10]. The authors employed a statistical analysis tool which only requires the knowledge of the moment generating functions of the SNR at the output of each diversity branch.

In [11], the authors derived the channel ergodic capacity for dual-branch MRC and EGC diversity combining schemes in correlated lognormal channels. This correlation could happen because of bulk geometrical and electromagnetic propagation characteristics experienced by the different propagation paths. The asymptotic performance of SC diversity combining scheme was evaluated in [12] assuming Nakagami-m fading channels. A novel generalised framework for the performance of SC scheme was recently proposed in [13]. It was shown that the performance of arbitrary systems with SC scheme can be expressed in terms of only the performance of the system on a single branch Rayleigh fading channel. In [14], the effective capacity of GSC cognitive systems was derived assuming imperfect channel knowledge. In the GSC receiver, the number of combined diversity branches is predetermined, that is, the L_c branches (among L available ones) with the highest SNR are selected and combined as per the rules of MRC. The impact of outdated channel information (OCI) between the secondary transmitter and the primary receiver on the performance of the secondary user was addressed in that study. It was shown that the performance gap because of imperfect channel information becomes smaller with the increase of the number of selected antennas at the secondary receiver. The capacity of spectrum-sharing systems with MRC diversity combining scheme was derived in [15] where the secondary source, secondary destination and primary user were assumed to possess multiple antennas. In [16], the capacity of cognitive radio systems with multi-antenna secondary receiver and MRC combining scheme was derived assuming Nakagami-m fading channels.

The effect of interference on the performance of diversity systems with linear diversity combining schemes was widely studied in literature. In [17], a multivariate statistical analysis approach was used to derive the outage and bit error probabilities of MRC space diversity systems assuming equal-power interference sources. A comparison between the outage performances of MRC, EGC and SC diversity combining techniques was conducted in [18] assuming interference-limited scenario and Rayleigh fading channels. The error rate and outage probabilities for diversity systems with MRC and SC combining techniques over Rayleigh and $\alpha-\mu$ fading channels and in the presence of interference were derived in [19, 20], respectively. The $\alpha-\mu$ fading model is a general fading distribution and it is useful in representing the small-scale variation of the fading signal in a NLOS fading condition. In [21], Radaydeh evaluated the performance of MRC diversity combining with asynchronous interference and Rayleigh fading channels. The outage and bit error probabilities of multi-antenna diversity systems with threshold-based MRC scheme with and without interference were derived in [22]. Most recently, the outage performance of various linear diversity combining schemes was evaluated in [23] in addition to proposing some combining algorithms that reduce the system outage probability. The minimum-selection (MS)-GSC scheme was proposed in [24] as a power-saving variant of conventional GSC scheme. In the MS-GSC scheme, a preselected threshold is placed on the instantaneous combined signal power to combine as few statistically ordered diversity branches as required to satisfy a target performance. In [25], the performance of diversity systems with SC scheme and interference was evaluated assuming correlated unbalanced Nakagami-m fading channels. Exact closed-form expressions for the outage probability of diversity systems with MRC scheme were derived in [26] assuming interference-limited scenario and $\eta-\mu/\eta-\mu$ and $\kappa-\mu/\eta-\mu$ fading channels. The $\kappa-\mu$ was proposed to model a general line-of-sight (LOS) propagation scenario.

A main step in the operation of all previously mentioned linear diversity combining schemes is the need of receiver to estimate the channel amplitudes of all diversity branches in order to use them before the combining stage. In the SC scheme, the combiner simply chooses the branch with the best channel instantaneous SNR. The process of channel estimation is the responsibility of the receiver which sometimes falls in error in estimating the channel of the best branch among the available branches. This problem could happen because of channel estimation errors. In this case, the receiver may choose the second or even the Nth best branch instead of the first best one. This critical problem motivated us to propose an efficient diversity branch selection scheme which is the Nth-best antenna selection scheme. Also, the inherent existence of interference in wireless systems motivated us to consider its effect on the performance of this selection scheme. The problem of OCI is also an important issue in wireless systems. In such problem, the branch which was the best at the selection time instant t could not be the best at the transmission time instant $t+\tau$. This problem is also considered in our paper.

To the best of our knowledge, the performance of space diversity systems with Nth-best receive antenna selection scheme in the presence of co-channel interference (CCI) and OCI has not been presented yet. The contributions of our paper are as follows: (i) we propose the Nth-best selection scheme to select between the antennas at the receiver of space diversity systems. Also, we study the effect of the interference and OCI on the behaviour of such systems; (ii) we present exact analysis of the outage and error probability performances where the effect of interference, OCI and other system parameters on the system behaviour is provided; and (iii) furthermore, we study the outage performance at the high SNR regime where approximate expressions for the outage probability, SEP, diversity order and coding gain are derived and analysed. In this paper, we consider the generic non-identically distributed (i.n.d.) case of diversity branches and interferers channels. Also, the independent identically distributed (i.i.d.) case of diversity branches is considered in this paper.

This paper is organised as follows. Section 2 presents the system and channel models. The exact performance is analysed in Section 3. Section 4 provides the asymptotic performance analysis. Some simulation and numerical results are presented and discussed in Section 5. Finally, conclusions are given in Section 6.

2 System and channel models

The system under study consists of a source of single antenna and a destination of L antennas. We assume that the signal at the destination is corrupted by interfering signals from I_d co-channel interferers $\{x_i^I\}_{i=1}^{I_d}$. The signal at the jth antenna at the receiver side can be written as

$$y_j = h_j x_0 + \sum_{i=1}^{I_d} h_i^I x_i^I + n_d \tag{1}$$

where h_j is the channel coefficient between the source and the jth antenna, x_0 is the transmitted symbol with $\mathbb{E}\{|x_0|^2\} = P_0$, h_i^I is the channel coefficient between the ith interferer and the jth antenna, x_i^I is the transmitted symbol from the ith interferer with $\mathbb{E}\{|x_i^I|^2\} = P_i^I$, $n_d \sim \mathcal{CN}(0, N_0)$ is an additive white Gaussian noise (AWGN), and $\mathbb{E}\{\cdot\}$ denotes the expectation operation. All the channel gains are assumed to follow Rayleigh distribution. That is, the channel powers denoted by $\left\{|h_j|^2\right\}_{j=1}^{L}$ and $\left\{|h_i^I|^2\right\}_{i=1}^{I_d}$ are exponential distributed random variables (RVs) with average values σ_j^2 and $\sigma_{I,i}^2$, respectively. Using (1), with the Nth-best antenna selection scheme, the end-to-end (e2e) signal-to-interference plus noise ratio (SINR) at the destination output can be written as

$$\gamma_d \triangleq \frac{(P_0/N_0)\left|h_{N_b^{\text{th}}}\right|^2}{\sum_{i=1}^{I_d}\left(P_i^I/N_0\right)|h_i^I|^2+1} \tag{2}$$

where $h_{N_b^{\text{th}}}$ is the channel coefficient between the source and the Nth best antenna. Let $\bar{\gamma}_j=(P_0/N_0)\sigma_j^2$, $\bar{\gamma}_i^I=\left(P_i^I/N_0\right)\sigma_{I,i}^2$, $\lambda_j=1/\bar{\gamma}_j$, and $\lambda_i^I=1/\bar{\gamma}_i^I$ denote the average values and parameters of the jth branch and the ith interferer, respectively.

3 Exact performance analysis

In this section, we evaluate exact closed-form expressions for the outage probability and SEP of the studied system.

3.1 i.n.d. diversity branches

In this section, we evaluate the outage probability and SEP of the studied system when the cumulative distribution functions (CDFs) of branches are non-identical.

The outage probability is defined as the probability that the e2e SINR goes below a certain threshold γ_{out} and it is given by

$$P_{\text{out}} \triangleq P_{\text{r}}\left[\log_2(1+\gamma_d)<R\right]=P_{\text{r}}\left[\gamma_d<\gamma_{\text{out}}\right] \tag{3}$$

Lemma 1: The outage probability for diversity systems with Nth-best antenna selection and interference is given for the case of non-identical branches (λ_j, $j=1, \ldots, L$) and non-identical interferers $\left(\lambda_i^I,\, i=1,\,\ldots,I_d\right)$ by (see (4))

where $\sum_{\mathcal{P}}$, $\sum_{s_1<\cdots<s_q}$, Δ_1 and Δ_2 are as defined in Appendix 1.

Proof: Please see Appendix 1. □

The SEP can be written as

$$\begin{aligned}P_s&=\int_0^\infty aQ\left(\sqrt{2b\gamma}\right)f_{\gamma_D}(\gamma)\,\mathrm{d}\gamma\\&=\frac{a\sqrt{b}}{2\sqrt{\pi}}\int_0^\infty\frac{e^{-b\gamma}}{\gamma^{1/2}}F_{\gamma_D}(\gamma)\,\mathrm{d}\gamma\end{aligned} \tag{5}$$

where $Q(\cdot)$ is the Gaussian Q-function, a and b are the modulation-specific constants which, for example, given for BPSK modulation scheme as 0.5 and 1, respectively.

Upon substituting $\gamma_{\text{out}}=\gamma$ in (4) and then substituting it in (5), and with the help of [27, Eq. (3.381.4)] and [27, Eq. (3.383.10)], the SEP for the studied system with non-identical diversity branches (λ_j, $j=1, \ldots, L$) and non-identical interferers $\left(\lambda_i^I,\, i=1,\,\ldots,I_d\right)$ can be obtained in a closed-form expression as (see (6))

3.2 i.i.d. diversity branches

In this section, we evaluate the outage probability and SEP of the studied system when the CDFs of branches are identical.

Lemma 2: The outage probability for diversity systems with Nth-best antenna selection and interference is given for the case of identical branches $\lambda_j=\lambda_p$, $j=1, \ldots, L$) and non-identical interferers $\left(\lambda_i^I,\, i=1,\,\ldots,I_d\right)$ by (see (7))

Proof: In deriving (7), the e2e SINR is first written as Y_2/Z_1, where Z_1 is as defined in Appendix 1 and Y_2 is now having a

$$\begin{aligned}P_{\text{out}}=\prod_{i=1}^{I_d}\lambda_i^I\sum_{g=1}^{I_d}\frac{\exp\left(\lambda_g^I\right)}{\prod_{\substack{m=1\\m\neq g}}^{I_d}\left(\lambda_m^I-\lambda_g^I\right)}\sum_{l=1}^{L}\lambda_l\sum_{\mathcal{P}}\Bigg[&\frac{\left(\left(\exp\left(-\lambda_g^I\right)\right)/\lambda_g^I\right)-\exp\left(-\left(\Delta_1\gamma_{\text{out}}+\lambda_g^I\right)/\left(\Delta_1\gamma_{\text{out}}+\lambda_g^I\right)\right)}{\Delta_1}\\&+\sum_{q=1}^{L-N}(-1)^q\sum_{s_1<\cdots<s_q}\frac{\left(\left(\exp\left(-\lambda_g^I\right)\right)/\lambda_g^I\right)-\exp\left(-\left(\Delta_2\gamma_{\text{out}}+\lambda_g^I\right)/\left(\Delta_2\gamma_{\text{out}}+\lambda_g^I\right)\right)}{\Delta_2}\Bigg]\end{aligned} \tag{4}$$

$$\begin{aligned}P_s=\frac{a\sqrt{b}}{2}\prod_{i=1}^{I_d}\lambda_i^I\sum_{g=1}^{I_d}&\frac{1}{\prod_{\substack{m=1\\m\neq g}}^{I_d}\left(\lambda_m^I-\lambda_g^I\right)}\\\times\sum_{l=1}^{L}\lambda_l\sum_{\mathcal{P}}\Bigg[&\frac{\left(b^{-(1/2)}/\lambda_g^I\right)\left(\lambda_g^I\Delta_1\right)^{-(1/2)}\left(\Gamma\left((1/2),(\Delta_1+b)\lambda_g^I/\Delta_1\right)/\exp\left(-(\Delta_1+b)\lambda_g^I/\Delta_1\right)\right)}{\Delta_1}\\&+\sum_{q=1}^{L-N}(-1)^q\sum_{s_1<\cdots<s_q}\frac{\left(b^{-(1/2)}/\lambda_g^I\right)\left(\lambda_g^I\Delta_2\right)^{-(1/2)}\left(\Gamma\left((1/2),(\Delta_2+b)\lambda_g^I/\Delta_2\right)/\exp\left(-(\Delta_2+b)\lambda_g^I/\Delta_2\right)\right)}{\Delta_2}\Bigg]\end{aligned} \tag{6}$$

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probability density function (PDF) given by

$$f_{Y_2}(y) = \binom{L-1}{N-1} L f_{\gamma_p}(y) \left(F_{\gamma_p}(y)\right)^{L-N} \left(1 - F_{\gamma_p}(y)\right)^{N-1} \quad (8)$$

Upon substituting (8) and (27) in (26), and after some algebraic manipulations, the result in (7) can be obtained.

Upon substituting $\gamma_{out} = \gamma$ in (7) and then substituting it in (5), and with the help of [27, Eq. (3.381.4)] and [27, Eq. (3.383.10)], the SEP for the studied system with identical diversity branches ($\lambda_j = \lambda_p$, $j = 1, \ldots, L$) and non-identical interferers $\left(\lambda_i^I, i = 1, \ldots, I_d\right)$ can be obtained in a closed-form expression as (see (9))

3.3 Effect of OCI

In this section, we evaluate the outage probability and SEP of the studied system considering the effect of OCI when the CDFs of branches are identical and the interferers have unequal average powers.

With the effect of OCI being considered, the e2e SINR in (2) can be rewritten as

$$\gamma_d \triangleq \frac{\hat{\gamma}_B}{\sum_{i=1}^{I_d} \left(P_i^I/N_0\right) |h_i^I|^2 + 1} \quad (10)$$

where $\hat{\gamma}_B$ is the SNR of the branch which is selected to maximise $\max_{N_b^{\text{th}}} \left\{ \hat{\gamma}_j = (P_j/N_0) |\hat{h}_j|^2 \right\}$, where $\hat{\gamma}_j$ is the SNR of the jth branch available at the selection instant t, which can differ from the actual SNR γ_j during information retransmission at time $t + \tau$ because of channel variations. In other words, the Nth best branch selected according to the OCI at time t may not be the Nth best branch at the time of data transmission $t + \tau$. The relationship between the actual channel h_j and the outdated channel $\hat{h}_j$ is given by $h_j = \sqrt{\rho}\hat{h}_j + \sqrt{1-\rho}n$, where ρ is the correlation coefficient between h_j and $\hat{h}_j$ and n is a complex Gaussian RV [28]. Thus, the degree of discrepancy for the CSI of the jth branch is indicated by the coefficient ρ, where $0 \le \rho \le 1$.

Assuming i.i.d. branches ($\lambda_j = \lambda_p$, $j = 1, \ldots, L$) and non-identical interferers $\left(\lambda_i^I, i = 1, \ldots, I_d\right)$, the e2e SINR in (10) can be written as $\hat{\gamma}_B/Z_1$, where Z_1 is as defined in Appendix 1 and $\hat{\gamma}_B$ is as defined in (8) in Lemma 2 but now for an outdated SNR and with a PDF given by

$$f_{\hat{\gamma}_B}(\gamma) = \binom{L-1}{N-1} L f_{\hat{\gamma}_p}(y) \left(F_{\hat{\gamma}_p}(y)\right)^{L-N} \left(1 - F_{\hat{\gamma}_p}(y)\right)^{N-1} \quad (11)$$

with the help of the binomial rule, (11) can be simplified as

$$f_{\hat{\gamma}_B}(\gamma) = L\lambda_p \binom{L-1}{N-1} \sum_{k=0}^{L-N} \binom{L-N}{k} (-1)^k \times \exp\left(-(k+N)\lambda_p \gamma\right) \quad (12)$$

where we have assumed in (12) that the channels are slowly varying and hence, the average fading power remains constant over the time delay τ [1]. In other words, we have assumed that $\bar{\gamma}_p$ and $\bar{\hat{\gamma}}_p$ or equivalently, λ_p and $\hat{\lambda}_p$ are equal.

The PDF of actual γ_B at the data transmission instant can be obtained from

$$f_{\gamma_B}(\gamma) = \int_0^\infty f_{\gamma_B|\hat{\gamma}_B}(\gamma|x) f_{\hat{\gamma}_B}(x)\,\mathrm{d}x \quad (13)$$

The conditional PDF $f_{\gamma_B|\hat{\gamma}_B}(\gamma|x)$ can be expressed as [29]

$$f_{\gamma_B|\hat{\gamma}_B}(\gamma|x) = \frac{\exp\left(-\left((\rho x + \gamma)/(1-\rho)\bar{\gamma}_p\right)\right)}{(1-\rho)\bar{\gamma}_p} I_0\left(\frac{2\sqrt{\rho x \gamma}}{(1-\rho)\bar{\gamma}_p}\right) \quad (14)$$

where $I_0(.)$ denotes the modified Bessel function of the first kind and order zero.

Now, upon substituting (12) and (14) in (13), and with the help of [27, Eq. (6.614.3)] and [27, Eq. (9.215.1)], and after

$$P_{out} = \prod_{i=1}^{I_d} \lambda_i^I \sum_{g=1}^{I_d} \frac{\exp\left(\lambda_g^I\right) L \binom{L-1}{N-1}}{\prod_{\substack{m=1\\ m\neq g}}^{I_d} \left(\lambda_m^I - \lambda_g^I\right)} \times \sum_{k=0}^{L-N} \frac{\binom{L-N}{k}(-1)^k}{(k+N)} \left[\frac{\exp\left(-\lambda_g^I\right)}{\lambda_g^I} - \frac{\exp\left(-\left((k+N)\lambda_p \gamma_{out} + \lambda_g^I\right)\right)}{(k+N)\lambda_p \gamma_{out} + \lambda_g^I} \right] \quad (7)$$

$$P_s = \frac{a\sqrt{b}}{2} \prod_{i=1}^{I_d} \lambda_i^I \sum_{g=1}^{I_d} \frac{L \binom{L-1}{N-1}}{\prod_{\substack{m=1\\ m\neq g}}^{I_d} \left(\lambda_m^I - \lambda_g^I\right)} \sum_{k=0}^{L-N} \frac{\binom{L-N}{k}(-1)^k}{k+N} \left[\frac{b^{-(1/2)}}{\lambda_g^I} - \left((k+N)\lambda_p \lambda_g^I\right)^{-(1/2)} \times \exp\left(\left(1 + \frac{b}{(k+N)\lambda_p}\right)\lambda_g^I\right) \Gamma\left(\frac{1}{2}, \left(1 + \frac{b}{(k+N)\lambda_p}\right)\lambda_g^I\right) \right] \quad (9)$$

some algebraic manipulations we obtain

$$f_{\gamma_B}(\gamma) = \frac{L\binom{L-1}{N-1}}{\bar{\gamma}_p(1-\rho)} \sum_{k=0}^{L-N} \frac{\binom{L-N}{k}(-1)^k}{\left(k+N+(\rho/(1-\rho))\right)} \exp\left(-\Delta_3 \gamma\right) \tag{15}$$

where

$$\Delta_3 = \left(\frac{1}{(1-\rho)\,\bar{\gamma}_p} - \frac{\rho\bar{\gamma}_p\left[(1-\rho)\bar{\gamma}_p\right]^{-2}}{(k+N+(\rho/(1-\rho)))} \right)$$

Upon substituting (15) and (27) in (26), and after some algebraic manipulations we obtain (see (16))

Upon substituting $\gamma_{\text{out}} = \gamma$ in (16) and then substituting it in (5), and with the help of [27, Eq. (3.381.4)] and [27, Eq. (3.383.10)], the SEP for the studied system with identical diversity branches ($\lambda_j = \lambda_p$, $j = 1, \ldots, L$) and non-identical interferers $\left(\lambda_i^I, i = 1, \ldots, I_d\right)$ can be obtained in a closed-form expression as (see (17))

4 Asymptotic outage performance

Owing to complexity of the achieved expressions, it is hard to obtain more details on the system performance. To simplify these expressions and to obtain more insights about the system performance, we see it is important to study the system performance at the high SNR regime where the outage probability can be expressed as $P_{\text{out}} \simeq (G_c \text{SNR})^{-G_d}$, where G_c denotes the coding gain of the system and G_d is the diversity order of the system [1]. Obviously, G_c represents the horizontal shift in the outage probability performance relative to the benchmark curve $(\text{SNR})^{-G_d}$ and G_d refers to the increase in the slope of the outage probability against SNR curve. The parameters on which the diversity order depends will affect the slope of the outage probability curves and the parameters on which the coding gain depends will affect the position of the curves. In the upcoming analysis, the diversity branches are assumed to be identical and the interferers are also assumed to be identical. Furthermore, the number of interferers I_d and the interferers power $\bar{\gamma}^I$ are assumed to be constant.

In deriving the asymptotic outage probability for this case, the e2e SINR is first written as Y_2/Z_2, where Y_2 has a PDF as defined in (8) and Z_2 is now consisting of i.i.d. exponential RVs $Z_2 = \sum_{i=1}^{I_d} (P^I/N_0)|h_i^I|^2 + 1 = X_2 + 1$ with a PDF of X_2 given by

$$f_{X_2}(x) = \frac{(\lambda^I)^{I_d}}{\left(I_d - 1\right)!} x^{I_d - 1} \exp\left(-\lambda^I x\right) \tag{18}$$

Using the transformation of RVs and then the binomial rule, the PDF of Z_2 can be obtained as

$$\begin{aligned} f_{Z_2}(z) = &-\frac{(\lambda^I)^{I_d}}{\left(I_d-1\right)!} \exp(\lambda^I)(-1)^{I_d} \sum_{g=0}^{I_d-1} \binom{I_d-1}{g} \\ &\times (-1)^g z^g \exp\left(-\lambda^I z\right) \end{aligned} \tag{19}$$

At high SNR values, the exponential CDF and PDF can be, respectively, approximated by $F_\gamma(\gamma) \simeq (\gamma/\bar{\gamma})$ and $f_\gamma(\gamma) \simeq (1/\bar{\gamma})$. Upon using these statistics, the PDF of Y_2 in (8) simplifies to

$$\begin{aligned} f_{Y_2}(y) \simeq\, & L\binom{L-1}{N-1}(\lambda_p)^{L-N+1} \sum_{k=0}^{N-1} \binom{N-1}{k} \\ &\times (-1)^k (\lambda_p)^k (y)^{k+L-N} \end{aligned} \tag{20}$$

Upon substituting (20) and (19) in (26), and after some algebraic manipulations, the outage probability of the studied system can be obtained at high SNR as

$$\begin{aligned} P_{\text{out}} \simeq & -\frac{(\lambda^I)^{I_d} L\binom{L-1}{N-1}(\lambda_p)^{L-N+1}}{\left(I_d-1\right)! \exp(-\lambda^I)(-1)^{-I_d}} \\ &\times \sum_{g=0}^{I_d-1} \binom{I_d-1}{g} (-1)^g \sum_{k=0}^{N-1} \frac{\binom{N-1}{k}(-1)^k(\lambda_p)^k}{L+k-N+1} \\ &\times \frac{\Gamma\left(L+g+k-N+2, \lambda^I\right)}{(\lambda^I)^{L+g+k-N+2}} (\gamma_{\text{out}})^{L+k-N+1} \end{aligned} \tag{21}$$

$$\begin{aligned} P_{\text{out}} = &\prod_{i=1}^{I_d} \lambda_i^I \sum_{g=1}^{I_d} \frac{\exp\left(\lambda_g^I\right) L\binom{L-1}{N-1}(1-\rho)^{-1}}{\prod_{\substack{m=1\\ m\neq g}}^{I_d} \left(\lambda_m^I - \lambda_g^I\right)\bar{\gamma}_p} \\ &\times \sum_{k=0}^{L-N} (-1)^k \binom{L-N}{k} \frac{\left[\left(\exp\left(-\lambda_g^I\right)/\lambda_g^I\right) - \left(\exp\left(-\left(\Delta_3\gamma_{\text{out}} + \lambda_g^I\right)\right)/\Delta_3\gamma_{\text{out}} + \lambda_g^I\right)\right]}{\Delta_3\left(k+N+(\rho/(1-\rho))\right)} \end{aligned} \tag{16}$$

$$\begin{aligned} P_s = &\frac{a\sqrt{b}}{2} \prod_{i=1}^{I_d} \lambda_i^I \sum_{g=1}^{I_d} \frac{L\binom{L-1}{N-1}}{\prod_{\substack{m=1\\ m\neq g}}^{I_d}\left(\lambda_m^I - \lambda_g^I\right)} \sum_{k=0}^{L-N} \frac{\binom{L-N}{k}(-1)^k}{\Delta_3\left(k+N+(\rho/(1-\rho))\right)} \\ &\times \left[\frac{b^{-(1/2)}}{\lambda_g^I} - (\Delta_3\lambda_g^I)^{-(1/2)} \exp\left(\left(1+\frac{b}{\Delta_3}\right)\lambda_g^I\right) \Gamma\left(\frac{1}{2}, \left(1+\frac{b}{\Delta_3}\right)\lambda_g^I\right) \right] \end{aligned} \tag{17}$$

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After applying the result in (21) in Maple, we noticed that it is still dominant for the first term of the second summation $k = 0$ and hence, it simplifies to

$$P_{\text{out}} \simeq -\frac{(\lambda^I)^{I_d} L \binom{L-1}{N-1} (\lambda_p)^{L-N+1} (-1)^{I_d}}{(L-N+1)(I_d-1)!\exp(-\lambda^I)} \times \sum_{g=0}^{I_d-1} \binom{I_d-1}{g} (-1)^g \frac{\Gamma(L+g-N+2, \lambda^I)}{(\lambda^I)^{L+g-N+2}} (\gamma_{\text{out}})^{L-N+1} \quad (22)$$

With noticing that $\text{SNR} = 1/\lambda_p$, the outage probability in (22) can be written in a more compact form as (see (23))

where

$$\mu = \frac{(\lambda^I)^{I_d} L \binom{L-1}{N-1} \exp(\lambda^I)(-1)^{I_d}}{(L-N+1)(I_d-1)!}$$

Upon substituting $\gamma_{\text{out}} = \gamma$ in (22) and then substituting it in (5), and with the help of [27, Eq. (3.351.3)], the SEP for the studied system can be obtained at high SNR as (see (24))

With noticing that $\text{SNR} = 1/\lambda_p$, the SEP in (24) can be written in a more compact form as (see (25))

where

$$\beta = \frac{a\sqrt{b}(\lambda^I)^{I_d} L \binom{L-1}{N-1} \exp(\lambda^I)(-1)^{I_d}(L-N+(1/2))!}{2\sqrt{\pi}(L-N+1)(I_d-1)! b^{L-N+(3/2)}}$$

As can be seen from (23) and (25), the coding gain of the system is affected by several parameters such as λ^I, I_d and γ_{out}; while the diversity order is fixed and equal to $L - N + 1$. Note that having more antennas provides extra diversity order. Also, one can see that the diversity order of the system is linearly proportional with the order of the selected antenna where increasing the order of the selected antenna decreases the diversity order and decreasing the order of the selected antenna increases the diversity order of the system.

5 Simulation and numerical results

In this section, we illustrate the validity of the achieved analytical results via a comparison with Monte Carlo simulations [In generating the simulation curves, 60 000 samples/each SNR value have been used.]. Also, we give some numerical examples to show the effect of interference, OCI and other parameters such as number of diversity branches on the system performance.

Fig. 1 studies the effect of order of antenna on the outage performance. It is clear from this figure that the analytical and asymptotic results perfectly fit with Monte Carlo simulations. Also, we can noted from this figure that as the order of antenna N increases, the diversity order decreases and the system performance is more degraded. On the other hand, as N decreases, the diversity order increases and hence, better the achieved performance. Another important result of this figure

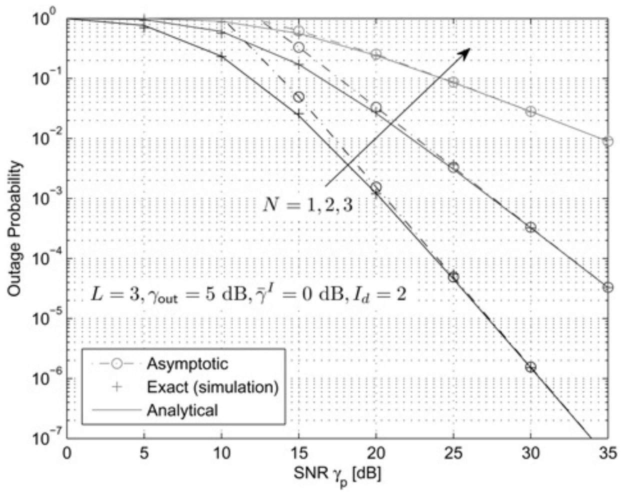

Fig. 1 *Outage probability against SNR for diversity systems with Nth-best antenna selection and CCI for different values of N*

$$P_{\text{out}} \simeq \left(\left\{ -\mu \sum_{g=0}^{I_d-1} \binom{I_d-1}{g} (-1)^g \frac{\Gamma(L+g-N+2, \lambda^I)}{(\lambda^I)^{L+g-N+2} (\gamma_{\text{out}})^{-(L-N+1)}} \right\}^{(-1/(L-N+1))} \text{SNR} \right)^{-(L-N+1)} \quad (23)$$

$$P_s \simeq -\frac{a\sqrt{b}(\lambda^I)^{I_d} L \binom{L-1}{N-1} (\lambda_p)^{L-N+1} (-1)^{I_d}}{2\sqrt{\pi}(L-N+1)(I_d-1)!\exp(-\lambda^I)} \sum_{g=0}^{I_d-1} \binom{I_d-1}{g} (-1)^g \frac{\Gamma(L+g-N+2, \lambda^I)}{(\lambda^I)^{L+g-N+2}}$$

$$P_s \simeq \left(\left\{ -\beta \sum_{g=0}^{I_d-1} \binom{I_d-1}{g} (-1)^g \frac{\Gamma(L+g-N+2, \lambda^I)}{(\lambda^I)^{L+g-N+2} (\gamma_{\text{out}})^{-(L-N+1)}} \right\}^{(-1/(L-N+1))} \text{SNR} \right)^{-(L-N+1)} \quad (24)$$

$$\times \left(L - N + \frac{1}{2}\right)! b^{-(L-N+(3/2))}$$

$$P_s \simeq \left(\left\{ -\beta \sum_{g=0}^{I_d-1} \binom{I_d-1}{g} (-1)^g \frac{\Gamma(L+g-N+2, \lambda^I)}{(\lambda^I)^{L+g-N+2} (\gamma_{\text{out}})^{-(L-N+1)}} \right\}^{(-1/(L-N+1))} \text{SNR} \right)^{-(L-N+1)} \quad (25)$$

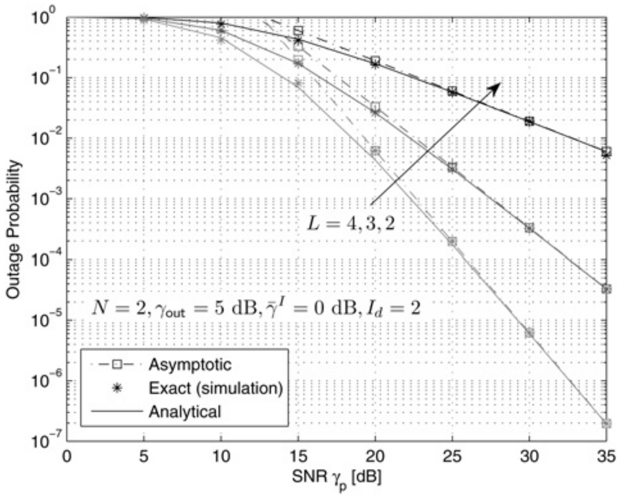

Fig. 2 *Outage probability against SNR for diversity systems with Nth-best antenna selection and CCI for different values of L with interference power not scaling with SNR*

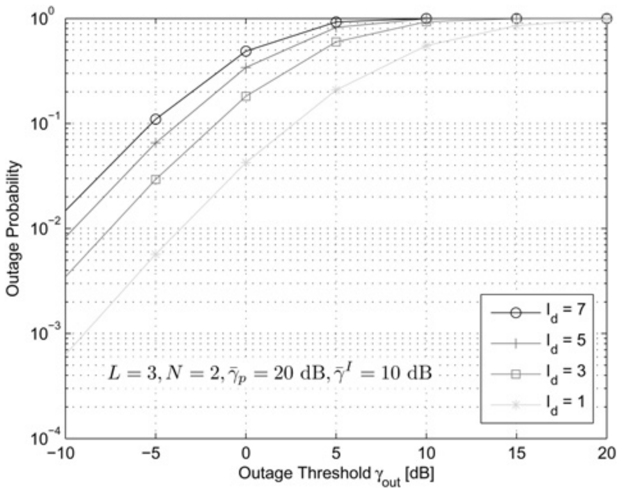

Fig. 3 *Outage probability against γ_{out} for diversity systems with Nth-best antenna selection and CCI for different values of I_d*

is that with the interference power $\bar{\gamma}^I$ being fixed and not scaling with SNR, the system can still achieve performance gain when better antenna is selected. This is clear also from the diversity order of the system which is $L - N + 1$.

Fig. 2 studies the effect of number of antennas on the outage performance. Again, it is clear from this figure that the analytical and asymptotic results perfectly fit with Monte Carlo simulations. Also, we can noted from this figure that as the number of antennas L increases, the diversity order increases and the system performance is more enhanced. On the other hand, as L decreases, the diversity order decreases and hence, worse the achieved performance, as expected. Another important result of this figure is that with the interference power $\bar{\gamma}^I$ being fixed and not scaling with SNR, the system can still achieve performance gain when more antennas are used. This is clear from the diversity order of the system which is $L - N + 1$.

The outage probability is plotted against the outage threshold γ_{out} in Fig. 3 for different number of interferers I_d. It is clear from this figure that as γ_{out} increases, the system performance is more degraded. Also, we can see from this figure that as I_d increases, the system performance is more degraded with the worst performance being achieved at the highest value of I_d. Finally, one can noted from this figure that increasing I_d degrades the system performance through affecting its coding gain without affecting the diversity order.

Fig. 4 studies the effect of the correlation coefficient ρ on the system performance. It is clear from this figure that as ρ increases or equivalently, as γ_B and $\hat{\gamma}_B$ are more correlated, better the achieved performance, as expected. On the other hand, the outage performance is severely degraded when ρ deviates from 1. Also, we can see from this figure that the effect of OCI on the system performance obtains larger as the order of the selected antenna decreases or equivalently, as the quality of the selected antenna enhances. In other words, increasing ρ is more beneficial for system performance as the quality of the selected antenna is made better. Finally, as the interference power is assumed to be scaling with SNR in this figure, a noise floor appears and a zero diversity gain is achieved by the

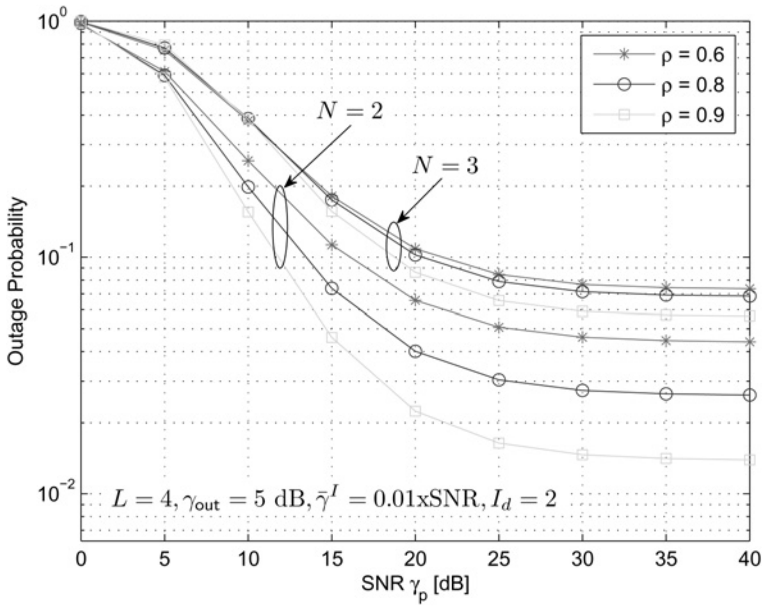

Fig. 4 *Outage probability against SNR for diversity systems with Nth-best antenna selection and CCI for different values of N, ρ*

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system because of the effect of interference on the system behaviour.

The outage performance is portrayed against number of antennas L in Fig. 5 for different values of interference power $\bar{\gamma}^I$ and outage threshold γ_{out}. It is clear from this figure that when the interference power is not scaling with SNR, the system can still achieve performance gain as more antennas are used. Also, we can noted from this figure that the best performance is achieved at the smallest value of $\bar{\gamma}^I$, as expected.

Fig. 6 portrays the SEP of the system against the order of antenna N. As expected, as N increases, the system performance is more degraded. Another important notice of this figure is that the gain achieved in system performance because of having more receiving antennas becomes larger as SNR increases. This is clear from the slope of the curves which increases as SNR increases.

The error performance is studied in Fig. 7 for different values of interference power $\bar{\gamma}^I$. It can be seen from this figure that as $\bar{\gamma}^I$ increases, worse the achieved performance, as expected. Also, it is obvious from this figure that the interference power is degrading the system performance via reducing the coding gain.

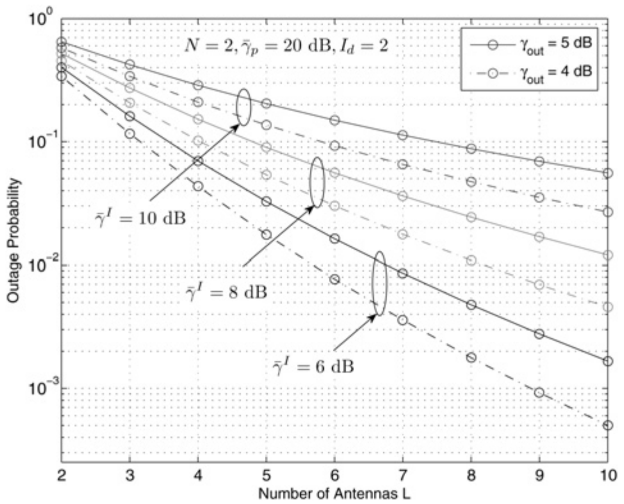

Fig. 5 *Outage probability against L for diversity systems with Nth-best antenna selection and CCI for different values of $\bar{\gamma}^I$, γ_{out}*

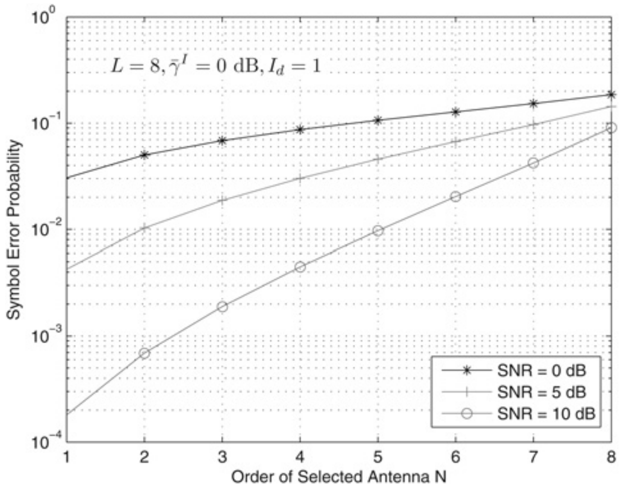

Fig. 6 *SEP against N for diversity systems with Nth-best antenna selection and CCI for different values of SNR*

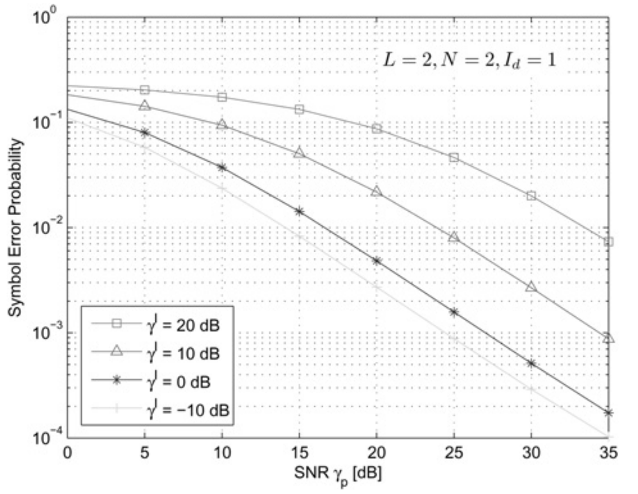

Fig. 7 *SEP against SNR for diversity systems with Nth-best antenna selection and CCI for different values of $\bar{\gamma}^I$*

6 Conclusion

In this paper, exact and asymptotic outage and SEPs were derived for space diversity systems with the *N*th-best antenna selection in the presence of interference and OCI. Monte Carlo simulations proved the accuracy of the achieved analytical and asymptotic results. Findings illustrated that for fixed interference power, the system can still achieve diversity gain when more antennas are used. Also, results showed that the diversity order of the system is linearly increasing with decreasing the order of the antenna, and linearly decreasing with increasing it. Furthermore, findings illustrated that the diversity order is linearly increasing with increasing the number of antennas, and linearly decreasing with decreasing it. Also, results showed that when the interference power scales with SNR, a noise floor appears in the results and a zero diversity gain is achieved by the system because of the effect of interference on the system performance. Finally, findings illustrated that the effect of OCI on the system performance obtains larger as the order of the selected antenna decreases or equivalently, as the quality of the selected antenna enhances.

7 Acknowledgment

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9 Appendix

9.1 Appendix 1 Proof of Lemma 1

In this appendix, we derive the outage probability of the studied system for the case of non-identical branches (λ_j, $j = 1, \ldots, L$) and non-identical interferers $\left(\lambda_i^I, i = 1, \ldots, I_d\right)$. The e2e SINR given in (2) can be written as a ratio of two RVs $\gamma_d = Y_1/Z_1$. The CDF of γ_d is given by Salhab *et al.* [30]

$$P_r[\gamma_d < \gamma_{\text{out}}] = \int_1^{\infty} f_Z(z) \int_0^{\gamma_{\text{out}} z} f_Y(y)\,\mathrm{d}y\,\mathrm{d}z \tag{26}$$

First, we evaluate the PDF of

$$Z_1 = \sum_{i=1}^{I_d} \frac{P_i^I}{N_0} |h_i^I|^2 + 1 = X_1 + 1$$

The PDF of X_1 is given by

$$f_{X_1}(x) = \prod\nolimits_{i=1}^{I_d} \lambda_i^I \sum_{g=1}^{I_d} \frac{\exp\left(-\lambda_g^I x\right)}{\prod_{\substack{m=1\\ m\neq g}}^{I_d} \left(\lambda_m^I - \lambda_g^I\right)}$$

Using the transformation of RVs, we obtain

$$f_{Z_1}(z) = \prod_{i=1}^{I_d} \lambda_i^I \exp\left(\lambda_i^I\right) \sum_{g=1}^{I_d} \frac{\exp\left(-\lambda_g^I z\right)}{\prod_{\substack{m=1\\ m\neq g}}^{I_d} \left(\lambda_m^I - \lambda_g^I\right)} \tag{27}$$

Now, we evaluate the PDF of $Y_1 = (P_0/N_0)\left|h_{N_b^{\text{th}}}\right|^2$ which is given by Vaughan and Venables [31]

$$f_{Y_1}(y) = \sum_{l=1}^{L} f_{\gamma_l}(y) \sum_{\mathcal{P}} \prod_{j=1}^{L-N} F_{\gamma_{i_j}}(y) \prod_{w=L-N+1}^{L-1} \left(1 - F_{\gamma_{i_w}}(y)\right) \tag{28}$$

where $\sum_{\mathcal{P}}$ denotes the summation over all $N!$ permutations $(i_1, i_2, \ldots, i_L)$ of $(1, 2, \ldots, L)$.

For Rayleigh fading, the PDF $f_{\gamma_l}(y)$ and the CDF $F_{\gamma_{i_j}}(y)$ are, respectively, given by $\lambda_l \exp(-\lambda_l y)$ and $1 - \exp\left(-\lambda_{i_j} y\right)$. Upon substituting these statistics in (28) and after some algebraic manipulations, the final result can be obtained as (see (29))

where

$$f_{Y_1}(y) = \sum_{l=1}^{L} \lambda_{l,d} \sum_{P} \left[\exp\left(-\Delta_1 y\right) + \sum_{q=1}^{L-N} (-1)^q \sum_{s_1 < \cdots < s_q} \exp\left(-\Delta_2 y\right) \right] \tag{29}$$

$$\sum_{s_1<\cdots<s_q} = \sum_{s_1=1}^{L-N-q+1} \sum_{s_2=s_1+1}^{L-N-q+2} \sum_{s_q=s_{q-1}+1}^{L-N}, \quad \Delta_1 = \sum_{w=L-N+1}^{L-1} \lambda_{i_w} \cdots$$

and $\Delta_2 = \Delta_1 + \sum_{n=1}^{q} \lambda_{s_n} + \lambda_l$

Upon substituting (29) and (27) in (26), and after some algebraic manipulations, the result in (4) can be obtained.