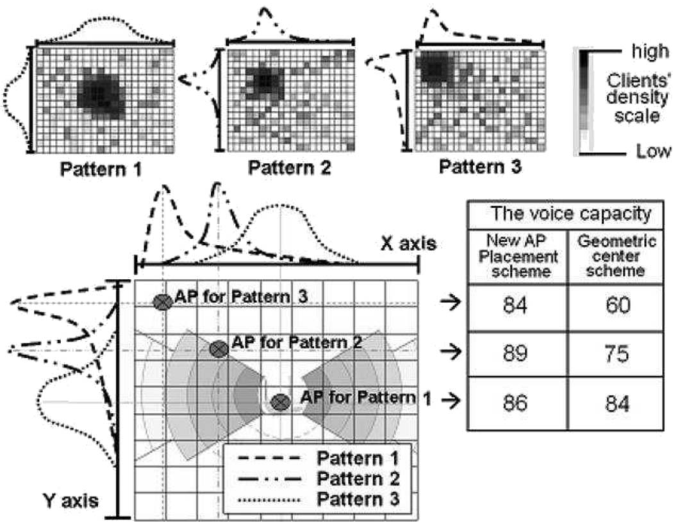

Fig. 6. AP placement under different CSDs.

in the WLAN coverage area. For example, for the first and second (asymmetric) patterns, the voice capacity improvements are 40% and 18%, respectively. On the other hand, for the third (symmetric) pattern, the enhancement is not so significant. The foregoing results indicate that the CSD should carefully be considered in the AP placement, particularly for WLANs that suffer from resource limitation and clients that are unsymmetrically distributed in the area under consideration.

VI. Conclusion

In this paper, we have developed a new model for R_{avg} estimation as well as a new scheme for WLAN AP placement with the consideration of CSD. We have shown through both simulation and analytical studies that the proposed model can provide a very efficient estimation for WLAN voice capacity and that this capacity can significantly be enhanced if we properly place the AP by using our new placement scheme, particularly when clients are unsymmetrically distributed in the WLAN area. It is expected that the work in this paper will contribute to the network planning and protocol design of future VoIP over WLANs.

Notice that the regular rate region pattern considered in this paper may be too simple to be realistic; therefore, one future work will be to examine the efficiency of our model for R_{avg} estimation based on a more realistic rate-region pattern that incorporates the effect of more factors like the channel fading and the shadowing effect. Another interesting future work will be to find a way to determine the required number of equal-sized squares for a given maximum-allowed estimation error of our model in voice-capacity estimation.

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Performance of Distributed Diversity Systems With a Single Amplify-and-Forward Relay

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***Abstract*—We study the error performance of the binary phase-shift keying (BPSK)-modulated distributed selection combining (SC) and distributed switched-and-stay combining (DSSC) schemes that utilize a single fixed-gain amplify-and-forward (AF) relay under Rayleigh fading conditions. The error performance of the distributed maximal ratio combining (MRC) is also investigated, which serves here as a benchmark. The numerical examples confirm that SC and DSSC offer a simpler substitute for MRC without much loss in performance. Moreover, we interestingly note that the performance of DSSC with a single fixed-gain AF relay is similar to that of DSSC with a single decode-and-forward relay, despite its relative simplicity.**

***Index Terms*—Amplify-and-forward (AF) relaying, error performance, selection combining (SC), switch-and-stay combining (SSC).**

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I. Introduction

Cooperative relaying has recently appeared as a suitable solution that meets the requirements of future wireless communication systems [1], [2]. It is well known that the deployment of relays in cellular networks could boost the coverage and capacity near to the cell edges or even beyond. The basic idea of relaying is that one or more nodes in the network overhear the information transmitted from a source and relay what is received to the intended destination. Since the same information is obtained at the destination from the geographically distributed relay nodes, a kind of spatial diversity, namely, cooperative diversity, is achieved [3]. Three main schemes of relaying have been proposed in the existing technical literature, i.e., amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF) [2], [4], [5]. Without performing any decoding, the AF relays retransmit a scaled replica of the received signal. Thus, AF leads to low-complexity relay transceivers as well as lower power consumption. However, one obvious undesirable characteristic of AF is that while the relays amplify the signals, they also amplify the noise at the relays [6].

Diversity is an effective technique to improve the performance of wireless systems [7], [8]. Among the different combining schemes presented in the literature, maximal ratio combining (MRC) gives the best possible performance (in the absence of any interference), and selection combining (SC) is considered as the least complicated [8]. A slight variation of SC is the well-known switch-and-stay combining (SSC) technique, where the receiver switches to and stays with a single branch for as long as the instantaneous SNR of that branch is above a predetermined threshold γ_T regardless of the fading conditions of the other branch. Many authors have analyzed the performance of the MRC, SC and SSC schemes in different fading scenarios. See, for example, [8]–[10] and the references therein. Alternatively, various relaying schemes can realize the spatial diversity in a distributed fashion.

The performance of the different relay transmission schemes is often evaluated by the outage and the average bit error probability (ABEP). Assuming MRC at the destination, several works have analyzed the ABEP of the well-known time-divisioned multiple-access relaying scheme proposed by Laneman *et al.* [3] over Rayleigh, Nakagami-m, and log-normal fading channels [5]. Recent publications have also investigated the outage probability and the error performance of AF and DF relay-based distributed SC schemes [11]–[14]. In [11], the end-to-end performance of a dual-hop AF relay system equipped with an SC receiver at the destination over Nakagami-m fading has been studied. However, no closed-form expression for the overall ABEP was obtained. In [12], the performance of a distributed diversity system that utilizes multiple DF relays and SC at the destination under Rayleigh fading conditions has been investigated. In addition, in [14], the authors proposed a distributed version of SSC for relaying systems that employ a single DF relay. Their numerical results have shown that this system achieves the beneficial effects of diversity yet without employing any diversity combiner at the destination.

Motivated by this, in this paper, we analyze the performance of two distributed schemes that use a single fixed-gain AF relay, namely, distributed SC [11] and distributed SSC (DSSC) [14]. Assuming BPSK modulation, we derive a closed-form expression for the ABEP of the distributed SC scheme. Additionally, the performance of the DSSC scheme is evaluated, and an approximate expression for the ABEP is derived. The error performance of the distributed MRC is investigated as well, serving here as a benchmark. In addition, we verify the obtained closed-form results using numerical methods.

The rest of this paper is organized as follows. In Section II, we describe the distributed SC and DSSC schemes. In Section III, the ABEPs of the distributed SC, DSSC, and well-known MRC schemes are derived. The numerical results are presented in Section IV. Finally, we summarize the main findings of this paper in Section V and give our concluding remarks.

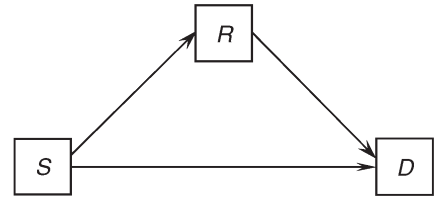

Fig. 1. System under consideration.

II. Distributed AF Relay Schemes

We briefly outline the system details of the distributed SC and DSSC schemes. As shown in Fig. 1, a source terminal S communicates with the destination terminal D with the aid of a single AF relaying terminal that is denoted by R. The destination can receive either directly from the source or indirectly through the virtual *S–R–D* link. In the sequel, these two paths are termed *direct and relayed branch* and denoted by $\mathcal{D}$ and $\mathcal{R}$, respectively; their end-to-end SNRs are represented by $\gamma_{\mathcal{D}}$ and $\gamma_{\mathcal{R}}$, respectively.

In case of receiving through $\mathcal{R}$, the time-divisioned AF scenario is assumed [3]. That is, each transmission period is divided in two subslots. In the first subslot, S transmits its data to the relay and the destination, whereas at the second subslot, the relay amplifies the received signal and retransmits to the destination. We model all the channels (*S–D*, *S–R*, *R–D*) as independent complex Gaussian random variables with variance of 0.5 per dimension, which leads to the flat Rayleigh fading scenario.

A. Distributed SC Scheme

In [11], the performance of a distributed SC scheme over integer m Nakagami fading channels has been studied. In this scheme, the destination combines the received signals from the *S–D* and *S–R–D* links using SC, i.e., the instantaneous SNR of the SC receiver is given by

$$\gamma_{\mathrm{sc}} = \max\{\gamma_{\mathcal{R}}, \gamma_{\mathcal{D}}\}. \tag{1}$$

The main difference between this distributed scheme and the traditional SC receiver is that, in the former, the composite *S–R–D* link is treated as a single virtual branch in the sense that the destination chooses whether to receive from the direct or the relayed branch according to their instantaneous end-to-end SNRs. It should be noted, however, that in AF relaying the destination needs to have the channel state information (CSI) knowledge of both the *S–R* and the *R–D* links since $\gamma_{\mathcal{R}}$ is a function of both of the parameters, as described in Section III.

B. DSSC Scheme

In [14], the performance of a DSSC scheme that uses a DF relay over Rayleigh fading channels has been analyzed. In each transmission slot, the destination compares the received SNRs (which equals $\gamma_{\mathcal{D}}$ or $\gamma_{\mathcal{R}}$, depending on which branch was the active branch on the previous time slot) with a preselected fixed switching threshold γ_T. If the received SNR is lower than γ_T, then a branch switching occurs; that is, the destination stops receiving from the active and switches to the (until the moment of switching) idle branch regardless of its SNR. An important point to stress on the DSSC system is that, contrary to distributed SC, only one of the two end-to-end channels needs to be estimated in each combining period. That is, only one of the two possible input branches is active each time.

III. Error Performance

In this section, assuming that the source employs BPSK, we evaluate the ABEPs of the SC, SSC, and the well-known MRC schemes. When a single fixed-gain AF relay is employed, $\gamma_{\mathcal{R}}$ is given by [6]

$$\gamma_{\mathcal{R}} = \frac{\gamma_1 \gamma_2}{C + \gamma_2} \tag{2}$$

where γ_1 and γ_2 are the instantaneous SNRs for the *S–R* and *R–D* links with the average values denoted by $\bar{\gamma}_1$ and $\bar{\gamma}_2$, respectively, and C is a constant that is determined by the fixed relay gain. In the sequel, we adopt the semi-blind choice for the relay gain, where the fixed value of the relay gain employed is determined by the average *S–R* channel conditions, which leads to an expression for C that has the form of [6, eq. (16)]

$$C = \frac{\bar{\gamma}_1}{e^{1/\bar{\gamma}_1} E_1\left(\frac{1}{\bar{\gamma}_1}\right)} \tag{3}$$

where $E_1(x) = \int_1^\infty (e^{-tx}/t)dt$ is the exponential integral function. The probability density function (pdf) $p_{\gamma_{\mathcal{R}}}(\gamma)$ and the cumulative distribution function (cdf) $F_{\gamma_{\mathcal{R}}}(\gamma)$ of $\gamma_{\mathcal{R}}$ [6, eqs. 9 and 10] are given by

$$p_{\gamma_{\mathcal{R}}}(\gamma) = \frac{2}{\bar{\gamma}_1} e^{-\gamma/\bar{\gamma}_1} \left[\sqrt{\frac{C\gamma}{\bar{\gamma}_1\bar{\gamma}_2}} K_1\left(2\sqrt{\frac{C\gamma}{\bar{\gamma}_1\bar{\gamma}_2}}\right) + \frac{C}{\bar{\gamma}_2} K_0\left(2\sqrt{\frac{C\gamma}{\bar{\gamma}_1\bar{\gamma}_2}}\right)\right] \tag{4}$$

$$F_{\gamma_{\mathcal{R}}}(\gamma) = 1 - 2\sqrt{\frac{C\gamma}{\bar{\gamma}_1\bar{\gamma}_2}} e^{-\gamma/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C\gamma}{\bar{\gamma}_1\bar{\gamma}_2}}\right) \tag{5}$$

where $K_\nu(x)$ is the νth-order modified Bessel function of the second kind. Since we model the direct path between S and D as a Rayleigh-faded link, the pdf and cdf of $\gamma_{\mathcal{D}}$ are given, respectively, by

$$p_{\gamma_{\mathcal{D}}}(\gamma) = (1/\bar{\gamma}_0) e^{-\gamma/\bar{\gamma}_0} \tag{6}$$

$$F_{\gamma_{\mathcal{D}}}(\gamma) = 1 - e^{-\gamma/\bar{\gamma}_0}. \tag{7}$$

In the foregoing pdf and cdf expressions, $\bar{\gamma}_0$ denotes the average SNR of the *S–D* link.

The ABEP is a useful measure of evaluating the performance of the wireless communication applications and can be computed using

$$P_b(e) = \int_0^\infty P_b(e|\gamma) p_\gamma(\gamma)\, d\gamma \tag{8}$$

where $P_b(e|\gamma)$ is the conditional ABEP in an additive white Gaussian noise (AWGN), and $p_\gamma(\gamma)$ is the pdf of the SNR at the output of the destination receiver. For BPSK, $P_b(e|\gamma) = Q(\sqrt{2\gamma})$, where the Gaussian Q-function is defined as $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-t^2/2} dt$. It is also trivial to extend the following error performance derivations to other well-known modulation schemes such as QPSK and square/rectangular M-quadratic-amplitude modulation (M-QAM). For QPSK $P_b(e|\gamma) = Q(\sqrt{\gamma})$ and in the case of square/rectangular M-QAM, $P_b(e|\gamma)$ can be written as a finite weighted sum of $Q(\sqrt{\beta\gamma})$ terms, where β is a constant [15].

A. Distributed SC Scheme

A method for evaluating the ABEP in the distributed SC scheme has been reported in [11]. However, no closed-form expression was obtained. To derive the ABEP, we begin with the cdf of the SC output, which is given by

$$F_{\gamma_{\text{sc}}}(\gamma) = F_{\gamma_{\mathcal{D}}}(\gamma) F_{\gamma_{\mathcal{R}}}(\gamma). \tag{9}$$

The ABEP of the SC scheme using (8) is given by $P_b(e) = \int_0^\infty Q(\sqrt{2\gamma}) p_{\gamma_{\text{sc}}}(\gamma) d\gamma$, where $p_{\gamma_{\text{sc}}}(\gamma)$ is the pdf of the SC output. Using integration by parts, $P_b(e)$ can be reexpressed as

$$P_b(e) = \frac{1}{\sqrt{2\pi}} \int_0^\infty F_{\gamma_{\text{sc}}}\left(\frac{t^2}{2}\right) e^{-\frac{t^2}{2}} dt. \tag{10}$$

Substituting (9) into (10) and after some manipulations, we obtain the ABEP of the SC receiver as

$$P_b(e) = \frac{1}{2}\left(1 - \frac{\psi(\lambda_1)}{\sqrt{1 + (1/\bar{\gamma}_1)}} - \frac{1}{\sqrt{1 + (1/\bar{\gamma}_0)}} + \frac{\psi(\lambda_2)}{\sqrt{1 + (1/\bar{\gamma}_0) + (1/\bar{\gamma}_1)}}\right) \tag{11}$$

where $\lambda_1 = (C/2(1+\bar{\gamma}_1)\bar{\gamma}_2)$, $\lambda_2 = (C/2(1+(\bar{\gamma}_1/\bar{\gamma}_0)+\bar{\gamma}_1)\bar{\gamma}_2)$, and the auxiliary function $\psi(\cdot)$ is defined as $\psi(z) = ze^z[K_1(z) - K_0(z)]$.

B. DSSC Scheme

The pdf of the SSC instantaneous output SNR is given in (12), shown at the bottom of the page [8, eq. (9.272)]. After substituting (12) in (8) for a BPSK receiver, we get

$$P_b(e|\gamma_T) = \frac{F_{\gamma_{\mathcal{D}}}(\gamma_T) F_{\gamma_{\mathcal{R}}}(\gamma_T) (\mathcal{J}_1 + \mathcal{J}_2)}{F_{\gamma_{\mathcal{D}}}(\gamma_T) + F_{\gamma_{\mathcal{R}}}(\gamma_T)} + \frac{F_{\gamma_{\mathcal{R}}}(\gamma_T)\mathcal{J}_3 + F_{\gamma_{\mathcal{D}}}(\gamma_T)\mathcal{J}_4}{F_{\gamma_{\mathcal{D}}}(\gamma_T) + F_{\gamma_{\mathcal{R}}}(\gamma_T)}. \tag{13}$$

To derive the ABEP of the DSSC scheme, four integrals ($\mathcal{J}_i$ for $i = 1, 2, 3, 4$) must be evaluated. The integral $\mathcal{J}_1$ in (13) is the ABEP

$$p_\gamma(\gamma) = \begin{cases} \frac{F_{\gamma_{\mathcal{D}}}(\gamma_T) F_{\gamma_{\mathcal{R}}}(\gamma_T)}{F_{\gamma_{\mathcal{D}}}(\gamma_T) + F_{\gamma_{\mathcal{R}}}(\gamma_T)} \left[p_{\gamma_{\mathcal{D}}}(\gamma) + p_{\gamma_{\mathcal{R}}}(\gamma)\right], & \gamma \le \gamma_T \\ \frac{F_{\gamma_{\mathcal{D}}}(\gamma_T) F_{\gamma_{\mathcal{R}}}(\gamma_T)}{F_{\gamma_{\mathcal{D}}}(\gamma_T) + F_{\gamma_{\mathcal{R}}}(\gamma_T)} \left[p_{\gamma_{\mathcal{D}}}(\gamma) + p_{\gamma_{\mathcal{R}}}(\gamma)\right] + \frac{p_{\gamma_{\mathcal{D}}}(\gamma) F_{\gamma_{\mathcal{R}}}(\gamma_T) + F_{\gamma_{\mathcal{D}}}(\gamma_T) p_{\gamma_{\mathcal{R}}}(\gamma)}{F_{\gamma_{\mathcal{D}}}(\gamma_T) + F_{\gamma_{\mathcal{R}}}(\gamma_T)} & \gamma > \gamma_T \end{cases} \tag{12}$$

of the BPSK in Rayleigh fading, for which a closed-form expression is known [8, eq. (5.6)]. Therefore, $\mathcal{J}_1$ can be written as

$$\mathcal{J}_1 = \int_0^\infty Q(\sqrt{2\gamma}) p_{\gamma_\mathcal{D}}(\gamma) d\gamma = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\gamma}_0}{1+\bar{\gamma}_0}}\right). \tag{14}$$

To evaluate the integral $\mathcal{J}_2 = \int_0^\infty Q(\sqrt{2\gamma}) p_{\gamma_\mathcal{R}}(\gamma) d\gamma$ in (13), the integration by parts method is similarly employed in (10), and using [16, eq. (2.16.8.4)], $\mathcal{J}_2$ can be written as

$$\mathcal{J}_2 = \frac{1}{2}\left(1 - \frac{\psi(\lambda_1)}{\sqrt{1+(1/\bar{\gamma}1)}}\right). \tag{15}$$

The integral $\mathcal{J}_3 = \int_{\gamma_T}^\infty Q(\sqrt{2\gamma}) p_{\gamma_0}(\gamma) d\gamma$ in (13) can be evaluated by using [14, eq. (8)] to yield

$$\mathcal{J}_3 = e^{-\gamma_T/\bar{\gamma}_0} Q(\sqrt{2\gamma_T}) - \sqrt{\frac{\bar{\gamma}_0}{1+\bar{\gamma}_0}} Q\left(\sqrt{2\gamma_T + \frac{2\gamma_T}{\bar{\gamma}_0}}\right). \tag{16}$$

To the best of our knowledge, there is no closed-form solution for the final integral of (13) defined as

$$\mathcal{J}_4 = \int_{\gamma_T}^\infty Q(\sqrt{2\gamma}) p_{\gamma_\mathcal{R}}(\gamma) d\gamma. \tag{17}$$

Hence, to get an approximate solution of the integral $\mathcal{J}_4$, we use the following approximation for the end-to-end SNR of the relayed branch:

$$\gamma_\mathcal{R} \approx \min(\gamma_1, \gamma_2) \tag{18}$$

which is based upon the fact that the relayed branch is dominated by the weakest of the *S–R* and *R–D* links. This approximation has been used in several works dealing with the performance analysis of relaying systems, such as [17] and [18]. Consequently, we derive the cdf and pdf of $\gamma_\mathcal{R}$ as

$$F_{\gamma_\mathcal{R}}(\gamma) \approx 1 - \Pr\{\gamma_1 > \gamma \cap \gamma_2 > \gamma\} = 1 - e^{-(\gamma/\bar{\gamma}_1)} e^{-(\gamma/\bar{\gamma}_2)} \tag{19}$$

$$p_{\gamma_\mathcal{R}}(\gamma) \approx \frac{\bar{\gamma}_1 + \bar{\gamma}_2}{\bar{\gamma}_1 \bar{\gamma}_2} e^{-\left(\frac{\bar{\gamma}_1+\bar{\gamma}_2}{\bar{\gamma}_1\bar{\gamma}_2}\right)\gamma}. \tag{20}$$

Under this assumption, the integral $\mathcal{J}_4$ can easily yield a closed-form solution using the same procedure as that in $\mathcal{J}_3$ to yield

$$\mathcal{J}_4 \approx e^{-\left(\frac{\bar{\gamma}_1+\bar{\gamma}_2}{\bar{\gamma}_1\bar{\gamma}_2}\right)\gamma_T} Q(\sqrt{2\gamma_T}) - \frac{1}{\sqrt{1+\frac{\bar{\gamma}_1+\bar{\gamma}_2}{\bar{\gamma}_1\bar{\gamma}_2}}} Q\left(\sqrt{2\gamma_T + \frac{2(\bar{\gamma}_1+\bar{\gamma}_2)\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}}\right). \tag{21}$$

Substituting (14)–(16) and (21) into (13) yields an approximate ABEP for the DSSC scheme, which is given by (22), shown at the bottom of the page.

The approximation is due to the simplified pdf made to evaluate $\mathcal{J}_4$, and note that $\mathcal{J}_1, \mathcal{J}_2$, and $\mathcal{J}_3$ are exact. However, as we show in Section IV, the approximate ABEP results match very well with the results derived via the numerical integration.

C. Distributed MRC

Finally, we derive the ABEP of the well-known distributed implementation of the MRC scheme [4], [18], where the destination MRC combines the buffered signal received in the first time slot with the new version received from the AF relay. To the best of the authors' knowledge, although expressions for the ABEP of several distributed MRC variations have been provided, an ABEP analysis of the specific case of fixed-gain AF relaying has not been conducted in the literature. Hence, it is evaluated in this section.

The instantaneous SNR γ at the output of the MRC is

$$\gamma = \gamma_\mathcal{D} + \gamma_\mathcal{R}. \tag{23}$$

As far as the authors are concerned, the pdf of γ cannot be expressed in closed form. Instead, the moment-generating functions of $\gamma_\mathcal{D}$, $\mathbb{E}(e^{-s\gamma_\mathcal{D}})$ (where $\mathbb{E}(\cdot)$ is the statistical expectation operator), and $\gamma_\mathcal{R}$, $\mathbb{E}(e^{-s\gamma_\mathcal{R}})$, are given, respectively, by $\mathcal{M}_{\gamma_\mathcal{D}}(s) = (1+\bar{\gamma}_0 s)^{-1}$ and [6, eq. (12)]

$$\mathcal{M}_{\gamma_\mathcal{R}}(s) = \frac{1}{1+\bar{\gamma}_1 s} + \frac{C\bar{\gamma}_1 e^{\frac{C}{(1+\bar{\gamma}_1 s)\bar{\gamma}_2}} s}{(1+\bar{\gamma}_1 s)^2 \bar{\gamma}_2} E_1\left(\frac{C}{(1+\bar{\gamma}_1 s)\bar{\gamma}_2}\right). \tag{24}$$

Therefore, using the well-known Moment Generating Function-based performance evaluation method presented in [8], the ABEP for the distributed MRC scheme can be evaluated as

$$P_b(e) = \frac{1}{\pi} \int_0^{\pi/2} \mathcal{M}_{\gamma_\mathcal{D}}\left(\frac{1}{\sin^2\theta}\right) \mathcal{M}_{\gamma_\mathcal{R}}\left(\frac{1}{\sin^2\theta}\right) d\theta. \tag{25}$$

$$\begin{aligned} P_b(e|\gamma_T) \approx\ & \frac{\left(1-e^{\gamma_T/\bar{\gamma}_0}\right)\left(1-2\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}} e^{-\gamma_T/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}}\right)\right)\left[1-\frac{1}{2}\left(\sqrt{\frac{\bar{\gamma}_0}{1+\bar{\gamma}_0}} + \frac{\psi(\lambda_1)}{\sqrt{1+(1/\bar{\gamma}_1)}}\right)\right]}{\left(2\left[1-\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}} e^{-\gamma_T/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}}\right)\right] - e^{-\gamma_T/\bar{\gamma}_0}\right)} \\ & + \frac{\left(1-2\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}} e^{-\gamma_T/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}}\right)\right)\left(e^{-\gamma_T/\bar{\gamma}_0} Q(\sqrt{2\gamma_T}) - \sqrt{\frac{\bar{\gamma}_0}{1+\bar{\gamma}_0}} Q\left(\sqrt{2\gamma_T + \frac{2\gamma_T}{\bar{\gamma}_0}}\right)\right)}{\left(2\left[1-\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}} e^{-\gamma_T/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}}\right)\right] - e^{-\gamma_T/\bar{\gamma}_0}\right)} \\ & + \frac{\left(1-e^{-\gamma_T/\bar{\gamma}_0}\right)\left(e^{-\left(\frac{\bar{\gamma}_1+\bar{\gamma}_2}{\bar{\gamma}_1\bar{\gamma}_2}\right)\gamma_T} Q(\sqrt{2\gamma_T}) - \frac{1}{\sqrt{1+\frac{\bar{\gamma}_1+\bar{\gamma}_2}{\bar{\gamma}_1\bar{\gamma}_2}}} Q\left(\sqrt{2\gamma_T + \frac{2(\bar{\gamma}_1+\bar{\gamma}_2)\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}}\right)\right)}{\left(2\left[1-\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}} e^{-\gamma_T/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C\gamma_T}{\bar{\gamma}_1\bar{\gamma}_2}}\right)\right] - e^{-\gamma_T/\bar{\gamma}_0}\right)} \end{aligned} \tag{22}$$

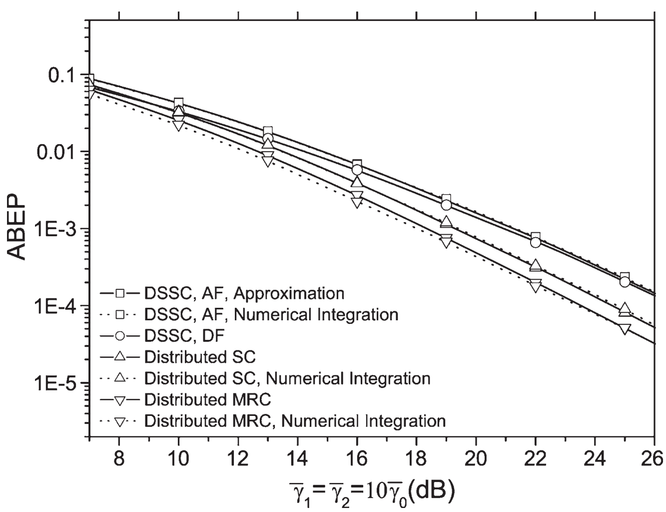

Fig. 2. ABEP of DSSC, distributed SC, and MRC versus the average channel conditions assuming BPSK modulation and $\bar{\gamma}_1 = \bar{\gamma}_2 = 10\,\bar{\gamma}_0$.

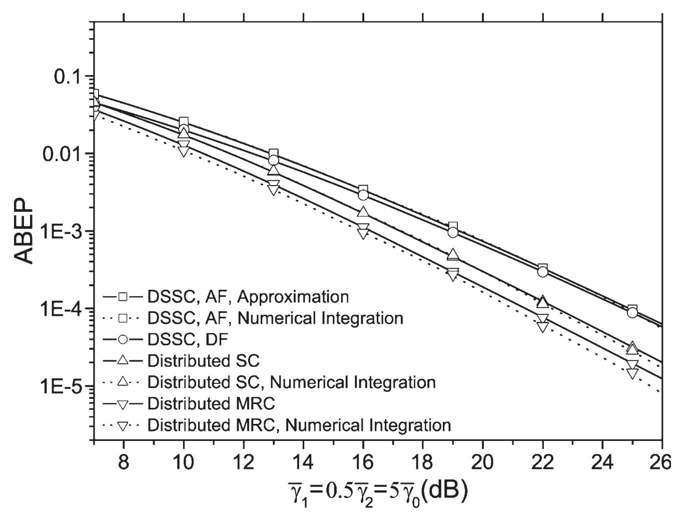

Fig. 3. ABEP of DSSC, distributed SC, and MRC versus the average channel conditions assuming BPSK modulation and $\bar{\gamma}_1 = 0.5\bar{\gamma}_2 = 5\bar{\gamma}_0$.

The BPSK-modulated ABEP can also accurately be approximated by using the following approach. First, we express the ABEP as

$$P_b(e) = \int_0^\infty \int_0^\infty Q(\sqrt{2\gamma}) p_{\gamma_\mathcal{D}}(\gamma_\mathcal{D}) p_{\gamma_\mathcal{R}}(\gamma_\mathcal{R})\, d\gamma_\mathcal{D}\, d\gamma_\mathcal{R}. \qquad (26)$$

Using [19, eq. (14)], $Q(\sqrt{2\gamma})$ is approximately written as

$$Q(\sqrt{2\gamma}) \approx \frac{1}{12} e^{-(\gamma_\mathcal{D}+\gamma_\mathcal{R})} + \frac{1}{4} e^{-\frac{4}{3}(\gamma_\mathcal{D}+\gamma_\mathcal{R})}. \qquad (27)$$

Using [16, eq. (2.16.8.5)] and after some manipulations, we get

$$P_b(e) \approx \frac{\lambda_1 e^{2\lambda_1}}{6(1+\bar{\gamma}_0)} \left(\frac{\Gamma(-1, 2\lambda_1)}{1+\bar{\gamma}_1} - \mathrm{Ei}(-2\lambda_1) \right) + \frac{\lambda_3 e^{\lambda_3}}{4(1+\frac{4}{3}\bar{\gamma}_0)} \left(\frac{\Gamma(-1, \lambda_3)}{1+\frac{4}{3}\bar{\gamma}_1} - \mathrm{Ei}(-\lambda_3) \right) \qquad (28)$$

where $\lambda_3 = (3C/(3+4\bar{\gamma}_1)\bar{\gamma}_2)$, $\mathrm{Ei}(x) = -\int_{-x}^{\infty}(e^{-t}/t)dx$ is the integral exponential function, and $\Gamma(a,x) = \int_x^\infty t^{a-1}e^{-t}dt$ is the incomplete gamma function [20]. We note that the accuracy of (28) is verified in the ensuing section, where the approximated results are compared with the numerical integration-based results, which leads to a very good match.

IV. Performance Comparison

The BPSK-modulated ABEP performance of the systems under consideration is shown in Figs. 2 and 3, along with that of DSSC with a single DF relay. The reader may notice the tightness of the approximate closed-form expressions derived in the previous section since they very well match with the exact curves derived through numerical integrations. All the channels in both figures are assumed to experience independent Rayleigh fading. In Fig. 2, the average SNRs $\bar{\gamma}_1$ and $\bar{\gamma}_2$ of the *S–R* and *R–D* channels are supposed to be identical with one another as well as ten times higher than the average SNR $\bar{\gamma}_0$ of the direct *S–D* link. In Fig. 3, the *R–D* channel is assumed to be slightly stronger than the *S–R* channel in an average sense, whereas the *S–D* average SNR is five times lower than that of the *S–R* link. The switching threshold γ_T that was used for all the DSSC curves was the optimal threshold, i.e., the value that minimizes the corresponding ABEP expressions via numerical calculations.

As expected, the distributed MRC scheme outperforms the distributed SC and DSSC since it represents the most complex combining option that weights each branch according to the instantaneous end-to-end channel conditions. Moreover, the DSSC performance is inferior to both distributed SC and MRC owing to the simplicity that it offers by only estimating a single end-to-end branch instead of two in each combining period. However, we notice that for any of the cases considered, the ABEP penalty of DSSC compared to distributed SC is not larger than 3 dB, implying that DSSC offers a much simpler yet not much inferior substitute of SC and rendering it appropriate for applications with low-complexity tolerance. Furthermore, one may notice that the performance of DSSC that uses a single fixed-gain AF relay closely resembles that of DSSC with a single DF relay despite its relative simplicity. Finally, we should point out that all the ABEP results were also verified via Monte Carlo simulations; however, these simulation results are omitted so as not to reduce the figures' clarity.

V. Conclusion

In this paper, we have investigated the error performances of two different schemes, namely, distributed SC and DSSC for systems that utilize a single fixed-gain AF relay, as compared with that of distributed MRC, which serves here as a benchmark. Being a distributed version of the well-known SSC technique, DSSC offers a simpler substitute for SC since it requires the estimation of only a single end-to-end branch in each combining period. The use of a fixed-gain AF relaying instead of DF offers more simplicity to the system without much loss in performance, as demonstrated in the presented figures. As a result, DSSC with fixed-gain AF relaying appears to be an appropriate solution for low-complexity relaying applications.

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Opportunistic Beamforming Communication With Throughput Analysis Using Asymptotic Approach

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***Abstract*—The opportunistic beamforming system (OBS) is currently receiving much attention in the field of downlink beamforming due to its simple random beamforming, low feedback complexity, and same throughput scaling obtained with perfect channel-state information using dirty paper coding at the transmitter. In this paper, we focus on its closed-form throughput evaluation over Rayleigh fading channels, based on the asymptotic theory of extreme order statistics. First, the throughput of a single-beam OBS is investigated, and an analytical solution tighter than the previously reported one is derived. Then, the asymptotic throughput bounds on a multibeam OBS are presented, and also, our analytical expression is shown to be very tight with the simulation results even with fewer users. After that, we argue that the reported conclusion that the single-beam OBS is much preferable to the multibeam OBS in the high-signal-to-noise-ratio (SNR) regime is inaccurate, but that, instead, it is satisfied only when the number of users is very small, due to its limited multiuser diversity gain. Finally, we show that four transmit beams is the most preferable in the multibeam OBS with a large number of users and moderate SNR, which arrives at the tradeoff between increasing spatial multiplexing gain and disappearing multiuser diversity gain.**

***Index Terms*—Multiple-input single-output (MISO), multiuser diversity, opportunistic beamforming system (OBS), spatial multiplexing, throughput.**

I. Introduction

Multiple-input multiple-output (MIMO) is a promising technique for the next generation wireless communications due to its potential for high spectral efficiency, increased diversity gains, and improved interference mitigation capabilities. The multiuser diversity is introduced as a new dimension of degrees of freedom to further increase the capacity of MIMO systems in a multiuser environment, but channel-state information (CSI) is needed at the transmitter [1], [2]. The feedback overhead increases with the number of transmit antennas and the number of users [3], and additional power/bandwidth has to be allocated to the feedback channel, which inevitably occupies valuable system resources and may reduce the spectral efficiency. Therefore, designing a system with less feedback is of great interest [4]. The opportunistic beamforming system (OBS) presents an excellent way to meet this requirement by feeding back only the signal-to-noise ratio (SNR) or signal-to-interference-plus-noise ratio (SINR) of the overall channel from each user [5], [6], and furthermore, it achieves the same

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