A NOVEL COMBINING RECEIVER FOR A DUAL-DIVERSITY WIRELESS RELAY NETWORK

Tobias Renk
Universität Karlsruhe (TH)
Germany

Holger Jaekel
Universität Karlsruhe (TH)
Germany

Martin Braun
Universität Karlsruhe (TH)
Germany

Friedrich K. Jondral
Universität Karlsruhe (TH)
Germany

Abstract

We present a simple combining receiver for a dual-diversity wireless relay network. The main concern of the paper is to face the trade-off between performance and complexity. The receiver focuses on signal-to-noise ratio (SNR) monitoring and selects dynamically between selection combining (SC) and equal gain combining (EGC) depending on the SNR ratio of the two received branches. It is shown that SC suffers no SNR degradation compared to a single branch communications system if the two receive branches are unbalanced, wheres EGC suffers a loss of 3 dB. Error performance with respect to branch unbalance is considered as well and limiting values for a high degree of branch unbalance are derived.

I Introduction

The wireless communications channel is characterized by many scattered rays arriving at the receiver. Destructive and/or constructive superposition of these rays leads to multipath signal fading that causes a great fluctuation of the received signal strength. A powerful technique to mitigate these effects is the use of diversity combining at the receiver [1]. Traditionally, relays have only been used in form of analogue repeaters in order to face path loss degradation and enlarge the coverage area of a communications system. However, relays have recently been introduced into cooperative communications where several users share their resources and participate in transmitting information from a source to a destination. It is most likely that the different users transmit over independent branches and thus diversity gains are achieved at the destination which improves performance [2, 3, 4, 5, 6]. This kind of diversity is often referred to as user cooperation diversity [7]. Generally, the relays perform either amplify-and-forward, which means that they simply amplify the received signal and transmit it without further processing, or decode-and-forward, where they first refresh the received signal prior to retransmission.[1]

The three main techniques used for diversity combining are selection combining (SC), equal gain combining (EGC) and maximal ratio combining (MRC). The most valuable paper on those three combining techniques is "Linear Diversity Combining Techniques" by D. G. Brennan [9] as it gives a structured overview and quantitative analyses of the performance of each technique. SC refers to the fact that only the strongest branch is selected for further processing. In EGC all branches are co-phased, equally weighted and then summed, whereas in MRC the weighting is performed with respect to the individual channel gains. Thus, branches with higher signal strength have a larger weight. The principles of combining are widely discussed in literature [1, 10, 11].

[1]There is another relay strategy that is often called compress-and-forward. See [8] for more information.

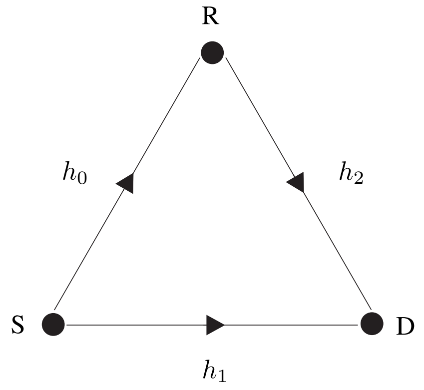

Figure 1: Schematic description of a symmetric relay network with source S, relay R and destination D. Channel coefficients are denoted as $h_i,\ i = 0, 1, 2$.

The remainder of the paper is organized as follows. In section II the system model is described. Section III deals with the comparison of different combining strategies with respect to SNR gain. In section IV the new receiver structure is described in detail and error analysis is performed. Section V faces practical implementation issues and finally section VI concludes the paper.

II System Model

Fig. 1 shows a symmetric relay network consisting of one source S, one relay R and one destination D. Each branch represents a slowly varying flat Rayleigh fading channel with channel coefficients $h_i,\ i = 0, 1, 2$. The channel coefficients are circular-symmetric complex-valued Gaussian random variables. Consequently, $|h_i|$ follows a Rayleigh distribution with the probability density function (pdf)

$$f_{|H_i|}(|h_i|) = \frac{2\,|h_i|}{\Omega_i} e^{-|h_i|^2/\Omega_i}, \quad i = 0, 1, 2, \tag{1}$$

where $\Omega_i = \mathcal{E}(|h_i|^2)$ represents the average power on branch i. The values $|h_i|^2$ are generally chi-square distributed with two degrees of freedom (corresponding to an exponential distribution). Each signal is further disturbed by additive white Gaussian noise (AWGN) with one-sided power spectral density N_0. Assume noise to be statistically independent from branch to branch and independent of the channel coefficients. Let source and relay transmit with equal power and let E_s denote the energy of a transmitted signal, then the average signal-to-noise ratio (SNR) of a single branch is $\overline{\gamma_i} = \Omega_i \cdot E_s/N_0$.

Each terminal is equipped with a single antenna and cannot receive and transmit simultaneously. To cope this restriction, transmission is divided into two phases. During the first phase the source transmits its information to the relay and the destination. During the second phase the relay transmits a refreshed version of its received signal to the destination and the source remains quiet. Since we are interested in proper combining at the destination, we assume that the relay is able to perform some kind of error detection and correction so that an error-free refreshed signal is transmitted from the relay to the destination. All distances are equal and without loss of generality have been normalized to one, so that no path loss considerations are necessary.

III Relative Comparison

In this section we compare the commonly used combining strategies SC, EGC and MRC with respect to SNR gains and branch unbalance for a dual-diversity communications system. We first denote the cumulative distribution function (cdf) and pdf of SC and EGC. We will show later that the asymptotic gain of MRC and SC are the same for a high degree of branch unbalance. That's why we omit the cdf and pdf of MRC here.

III.A CDF and PDF of Combiner Output SNR

For EGC the incoming signals are co-phased, equally weighted and then summed. Thus, for a dual-diversity relay network the output SNR of EGC is given by [1, 12]

$$\gamma_{\text{egc}} = \frac{(|h_1| + |h_2|)^2}{2} \frac{E_s}{N_0} \tag{2}$$

The cdf of $|h_1| + |h_2|$ has been derived by Halpern in [13]. It is shown in [12] that the cdf of γ_{egc} after a transformation of random variables then becomes

$$\begin{aligned} F_{\gamma_{\text{egc}}}(\gamma) &= 1 - \frac{\overline{\gamma}_1 e^{-(2\gamma/\overline{\gamma}_1)} + \overline{\gamma}_2 e^{-(2\gamma/\overline{\gamma}_2)}}{\overline{\gamma}_1 + \overline{\gamma}_2} \\ &\quad - \frac{2\sqrt{2\overline{\gamma}_1\overline{\gamma}_2\pi\gamma}}{(\overline{\gamma}_1 + \overline{\gamma}_2)^{3/2}} e^{-2\gamma/(\overline{\gamma}_1+\overline{\gamma}_2)} \\ &\quad \times \left[1 - Q\left(2\sqrt{\frac{\overline{\gamma}_1\gamma}{\overline{\gamma}_2}(\overline{\gamma}_1 + \overline{\gamma}_2)}\right) \right. \\ &\quad \left. - Q\left(2\sqrt{\frac{\overline{\gamma}_2\gamma}{\overline{\gamma}_1}(\overline{\gamma}_1 + \overline{\gamma}_2)}\right)\right], \end{aligned} \tag{3}$$

where $\overline{\gamma}_i,\ i = 1, 2$, denotes the average SNR per symbol on branch i and $Q(\cdot)$ is the Gaussian Q-function defined as [11]

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^\infty e^{-t^2/2} \mathrm{d}t. \tag{4}$$

Derivation of (3) with respect to γ leads to the expression of the pdf [12]:

$$\begin{aligned} f_{\gamma_{\text{egc}}}(\gamma) &= \frac{2\left(\overline{\gamma}_1 e^{-(2\gamma/\overline{\gamma}_1)} + \overline{\gamma}_2 e^{-(2\gamma/\overline{\gamma}_2)}\right)}{(\overline{\gamma}_1 + \overline{\gamma}_2)^2} \\ &\quad + \sqrt{\frac{2\pi\overline{\gamma}_1\overline{\gamma}_2}{\gamma}} \frac{e^{-2\gamma/(\overline{\gamma}_1+\overline{\gamma}_2)}}{(\overline{\gamma}_1 + \overline{\gamma}_2)^{3/2}} \left(\frac{4\gamma}{\overline{\gamma}_1 + \overline{\gamma}_2} - 1\right) \\ &\quad \times \left[1 - Q\left(2\sqrt{\frac{\overline{\gamma}_1\gamma}{\overline{\gamma}_2}(\overline{\gamma}_1 + \overline{\gamma}_2)}\right) \right. \\ &\quad \left. - Q\left(2\sqrt{\frac{\overline{\gamma}_2\gamma}{\overline{\gamma}_1}(\overline{\gamma}_1 + \overline{\gamma}_2)}\right)\right] \end{aligned} \tag{5}$$

In contrast to EGC, SC uses only the branch with higher SNR for further processing. This has the advantage that no co-phasing is necessary. However, SNR monitoring is indispensable. The output SNR of SC can be obtained as

$$\gamma_{\text{sc}} = \max\left\{|h_1|^2, |h_2|^2\right\} \frac{E_s}{N_0}. \tag{6}$$

The cdf of γ_{sc} for independent but not necessarily identically distributed branches is well-known and can be looked up in, e.g., [1, 11]. It is given by

$$F_{\gamma_{\text{sc}}}(\gamma) = \left(1 - e^{-\gamma/\overline{\gamma}_1}\right)\left(1 - e^{-\gamma/\overline{\gamma}_2}\right). \tag{7}$$

Differentiating (7) relative to γ finally yields the pdf of γ_{sc}:

$$f_{\gamma_{\text{sc}}}(\gamma) = \frac{1}{\overline{\gamma}_1} e^{-\gamma/\overline{\gamma}_1} + \frac{1}{\overline{\gamma}_2} e^{-\gamma/\overline{\gamma}_2} - \left(\frac{1}{\overline{\gamma}_1} + \frac{1}{\overline{\gamma}_2}\right) e^{-\gamma\left(\frac{1}{\overline{\gamma}_1} + \frac{1}{\overline{\gamma}_2}\right)} \tag{8}$$

III.B SNR Gain

Generally, there are two types of performance gains in diversity systems, namely diversity gain and SNR gain[2]. We concentrate on the SNR gain in this section and define it as

$$\Delta_\gamma \triangleq \frac{\overline{\gamma}_\xi}{\max\{\overline{\gamma}_1, \overline{\gamma}_2\}}, \tag{9}$$

where $\overline{\gamma}_\xi$ represents the average SNR of the combining schemes and $\xi \in \{\text{mrc}, \text{egc}, \text{sc}\}$.

It is well-known that the average SNR of MRC is the sum of the individual mean SNRs [1, 10, 11]. Hence,

$$\overline{\gamma}_{\text{mrc}} = \overline{\gamma}_1 + \overline{\gamma}_2. \tag{10}$$

The average SNR of EGC can be calculated by averaging γ over the pdf $f_{\gamma_{\text{egc}}}(\gamma)$. We have

$$\overline{\gamma}_{\text{egc}} = \int_0^\infty \gamma\, f_{\gamma_{\text{egc}}}(\gamma)\, \mathrm{d}\gamma \tag{11}$$

and get after some algebraic manipulation

$$\overline{\gamma}_{\text{egc}} = \frac{1}{2}\overline{\gamma}_1 + \frac{1}{2}\overline{\gamma}_2 + \frac{\pi}{4}\sqrt{\overline{\gamma}_1\overline{\gamma}_2}. \tag{12}$$

[2] In [1], p. 192, SNR gain is referred to as array gain.

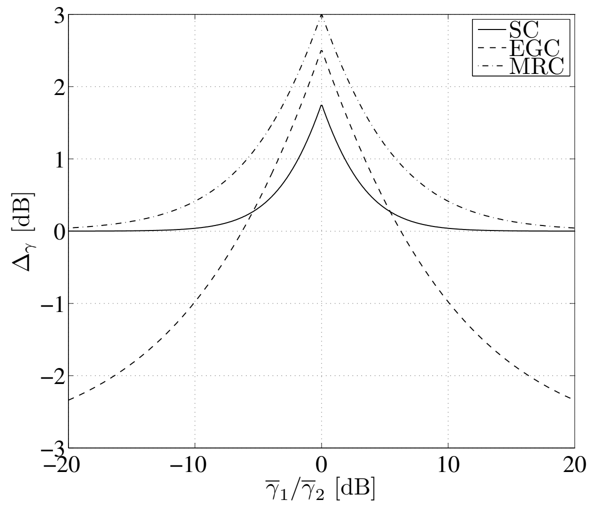

Figure 2: Comparison of the SNR gain Δ_γ of selection combining (SC), equal gain combining (EGC) and maximal ratio combining (MRC) with respect to branch unbalance $\overline{\gamma}_1/\overline{\gamma}_2$ [dB].

The term $\pi/4$ in (12) is typical for Rayleigh fading, where $(\mathcal{E}(|h_i|))^2 = \pi/4 \cdot \mathcal{E}(|h_i|^2) = \pi/4 \cdot \Omega_i$.

The average SNR of SC is calculated the same way as the average SNR of EGC. Accordingly,

$$\overline{\gamma}_{\text{sc}} = \overline{\gamma}_1 + \overline{\gamma}_2 - \frac{\overline{\gamma}_1\overline{\gamma}_2}{\overline{\gamma}_1 + \overline{\gamma}_2}. \tag{13}$$

Fig. 2 illustrates the SNR gain Δ_γ [dB] for SC, EGC and MRC over the branch unbalance $\overline{\gamma}_1/\overline{\gamma}_2$ [dB]. For branch balance, i.e., $\overline{\gamma}_1/\overline{\gamma}_2 = 0\,\text{dB}$, we see the well-known results for dual-diversity and independent and identically distributed (i.i.d.) branches. SNR gain for SC then is 1.8 dB, for EGC it is 2.5 dB and for MRC SNR gain becomes 3 dB. The maximal SNR gain of a dual-diversity communications system without fading is 3 dB. Hence, it can be seen that MRC performs optimal if the system suffers no branch unbalance. However, MRC requires the knowledge of channel state information which is a challenging task, especially for time-variant channels. Furthermore, MRC outperforms all other combining strategies, whereas EGC only performs better than SC for low SNR unbalances. This issue is further discussed in the following subsection which is concerned with the asymptotic behavior of the different SNR gains.

The interception point between the SNR gain of SC and EGC can be calculated by simply equating (12) and (13). This leads to a fourth-order equation with respect to branch unbalance $\overline{\gamma}_1/\overline{\gamma}_2$ and can be solved by applying Ferrari's method which is implemented in most mathematical tools. There, the biquadratic equation is divided into two quadratic equations, where the first one possesses two complex-conjugate solutions (they can be skipped since our solution has to be real) and the second one has two real solutions. In our case, we get

$$\begin{aligned} \overline{\gamma}_1/\overline{\gamma}_2 &= 3.488 \quad \rightarrow \quad 5.42\,\text{dB} \\ \overline{\gamma}_1/\overline{\gamma}_2 &= 0.287 \quad \rightarrow \quad -5.42\,\text{dB} \end{aligned}$$

which corresponds to the results illustrated in Fig. 2.

III.C Asymptotic Behavior

A short glance at Fig. 2 reveals that the SNR gain possesses an asymptotic behavior for high branch unbalances. The asymptotic values can easily be derived by letting $\overline{\gamma}_1/\overline{\gamma}_2 \rightarrow \infty$. Since all transmitted signals are power constrained, this is achieved by letting $\overline{\gamma}_2 \rightarrow 0$ and holding $\overline{\gamma}_1$ fixed. Afterwards, the division by $\max\{\overline{\gamma}_1, \overline{\gamma}_2\}$ makes the asymptotes independent of single average SNR values.

SC and MRC tend to 0 dB which means that the SNR gain of these combining strategies can never get worse than if only one branch has been taken into consideration. For SC this is due to the fact that only the branch with higher SNR is selected for further processing. For MRC the reason is that each branch is weighted with its individual channel gain, therefore, bad channels are 'filtered out.' However, EGC shows a different behavior since both branches are weighted equally. This means that if one branch is very good and the other one is very bad, the latter merely increases the noise level with respect to the first branch. Worst case is doubling the noise power, which leads to an asymptotic value of -3 dB. In this case the SNR at the output of the combiner is the same as if only one branch with half the SNR has been considered.

IV Receiver Structure

In this section we describe a new combining receiver that selects dynamically between EGC and SC on the basis of an SNR criterion. We present closed-form expressions on error probability in section IV.B.

IV.A Description

In practice, EGC is often preferred to MRC due to reduced complexity as no estimation of the channel state information is required. Moreover, EGC is typically used for modulation schemes with constant envelopes [12]. However, as we can see in Fig. 2, EGC suffers a great SNR gain degradation for a high degree of branch unbalance. That is why we propose a receiver structure that combines EGC and SC. The basis is that the receiver selects dynamically between EGC and SC. For low branch unbalances, EGC is the preferred combining strategy, whereas SC is preferable for high branch unbalances. The great advantage of that scheme is that the receiver will always perform better than if only one branch could have been received.

Fig. 3 shows the structure of the combining receiver. The destination receives two signals in orthogonal time frames as discussed in section II. The first signal comes directly from the source, the second one comes from the relay and is a refreshed version of the original source signal. After SNR monitoring the receiver calculates the ratio $\theta = \gamma_1/\gamma_2$. Thereafter, the absolute value of this linear ratio is expressed in dB by

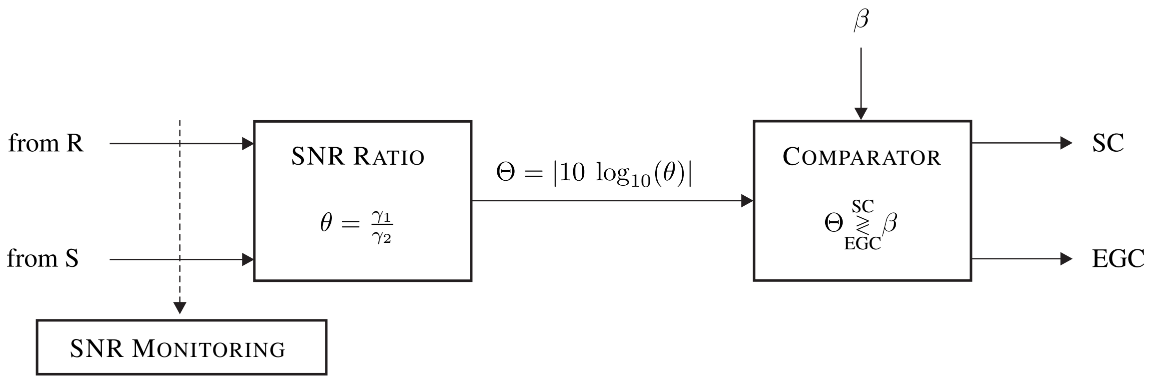

Figure 3: Structure of a dual-diversity combining receiver that selects between selection combining (SC) and equal gain combining (EGC) on the basis of an SNR criterion.

$\Theta = |10\ \log_{10}(\theta)|$, which represents the input to a comparator. Here, Θ is compared to a threshold value β and the better combining strategy, i.e., SC or EGC, is selected. The crucial point of this structure is the determination of the threshold value β. This issue is further discussed in the following section.

IV.B Error Performance

Error performance of EGC and SC for several fading characteristics has been widely investigated in literature. We state results that are necessary for our further analysis of the receiver structure. The interested reader is referred to the publications [12, 14, 15, 16, 17] and the references therein.

Bit error probability (BER) of EGC for BPSK/QPSK and two independent but not identically distributed branches is given by [15, 17]

$$P_{\text{egc}} = \frac{1}{2}\left(1 - \frac{\sqrt{\overline{\gamma}_1(\overline{\gamma}_1+2)} + \sqrt{\overline{\gamma}_2(\overline{\gamma}_2+2)}}{\overline{\gamma}_1+\overline{\gamma}_2+2}\right). \quad (14)$$

For SC probability of decoding error for BPSK/QPSK can be expressed as [14]

$$P_{\text{sc}} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}_1}{\overline{\gamma}_1+1}} - \sqrt{\frac{\overline{\gamma}_2}{\overline{\gamma}_2+1}} + \sqrt{\frac{\overline{\gamma}_1\overline{\gamma}_2}{\overline{\gamma}_1\overline{\gamma}_2+\overline{\gamma}_1+\overline{\gamma}_2}}\right). \quad (15)$$

Error probabilities versus branch unbalance are illustrated in Fig. 4 for $\overline{\gamma}_1 = 10$ dB and Fig. 5 for $\overline{\gamma}_1 = 5$ dB. As expected, BER increases as branch unbalance increases. This corresponds to the decrease in SNR gain, that can be seen in Fig. 2. The intersection point between EGC and SC denotes the threshold value β.

We further see that both BER curves tend to an asymptotic value for a high degree of branch unbalance. For SC this asymptote corresponds to a single-branch system with an average SNR of $\overline{\gamma} = \overline{\gamma}_1$. This can be made intuitively clear with a look at the SNR gain that tends to zero for SC. The asymptote for EGC is determined by a single-branch system with an average SNR of $\overline{\gamma} = \overline{\gamma}_1/2$. Again, this becomes clear if we consider the SNR gain. SNR gain for EGC tends to -3 dB for high branch unbalances. This is exactly the factor $1/2$ that constitutes in the average SNR expression. BER then equals that of a non-diversity receiver, which is

$$P = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}}{\overline{\gamma}+1}}\right) \quad (16)$$

with the values for $\overline{\gamma}$ given above. The two values for P can also be derived from (14) and (15) by letting $\overline{\gamma}_2 \to 0$.

V PRACTICAL IMPLEMENTATION ISSUES

In our proposal MRC has been skipped due to complexity issues. The advantage of EGC and SC over MRC is that no estimation of channel state information is necessary. Though EGC does not require SNR monitoring as both received signals are simply summed, so does SC. In practice, measuring true SNR of a branch, $|h_i| \cdot E_s/N_0$, is a complex task. It is therefore better to measure the total power of the received signal, $|h_i| \cdot E_s + N_0$ [1, 11], which is also equivalent if the noise power on each channel can be considered as equal. Another issue is the derivation of the threshold value β as a function of $\overline{\gamma}_1$ and $\overline{\gamma}_2$. We can see in Fig. 4 and Fig. 5 that β is strongly varying depending on the branch unbalance. That makes the declaration of a simple and probably fixed threshold value involved. Indeed, the value for β can be found by equating (14) and (15), but there exists no closed-form solution to this problem. A suitable way would be to find proper approximations of error probabilities that simplify the calculation of the intersection point. Research concerning this issue is still ongoing.

VI CONCLUSION

In this paper we presented a new and simple combining receiver for a dual-diversity wireless relay network. The receiver at the destination dynamically selects between equal gain combining (EGC) and selection combining (SC) based on a signal-to-noise ratio (SNR) criterion. The main purpose was to meet the trade-off between performance and complexity of the receiver structure. Therefore, maximal ratio combining (MRC), where an estimation of channel state information becomes necessary, has not been taken into consideration. We demonstrated that the SNR gain of SC suffers no degradation with respect to branch unbalance in contrast to the SNR gain of EGC where a degradation of -3 dB can be recognized as worst case. This is

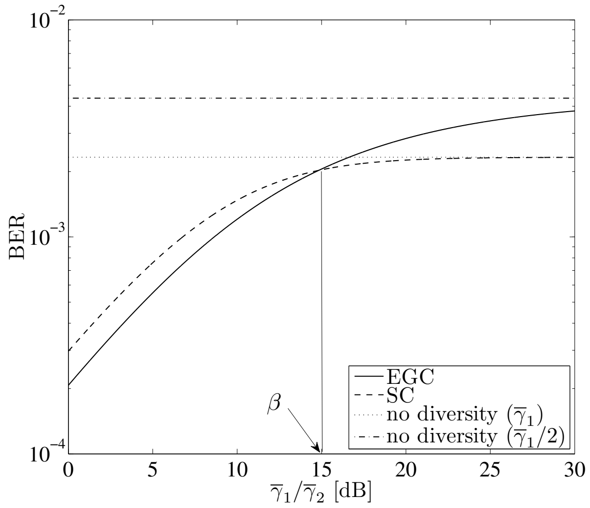

Figure 4: Bit error rate (BER) of selection combining (SC) and equal gain combining (EGC) for BPSK/QPSK with respect to branch unbalance $\overline{\gamma}_1/\overline{\gamma}_2$ [dB]. Parameter $\overline{\gamma}_1$ has been set to 10 dB.

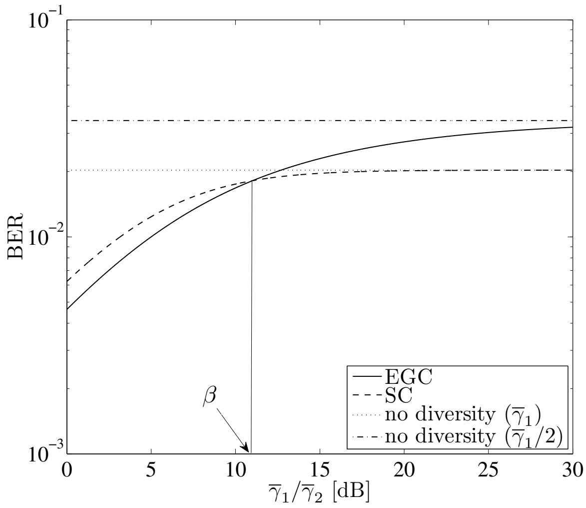

Figure 5: Bit error rate (BER) of selection combining (SC) and equal gain combining (EGC) for BPSK/QPSK with respect to branch unbalance $\overline{\gamma}_1/\overline{\gamma}_2$ [dB]. Parameter $\overline{\gamma}_1$ has been set to 5 dB.

due to the fact that SC only takes the best of the two branches into consideration. For EGC both branches are summed and for a high degree of branch unbalance, one branch merely consists of noise and thus noise power is doubled. The bit error rate (BER) of each combining scheme has been presented as well. Evidentially, BER increases as branch unbalance increases. Both curves for SC and EGC intersect. This intersection point β serves as decision threshold in the receiver. It has been shown that SC tends to a single-branch system with an average SNR of $\overline{\gamma} = \overline{\gamma}_1$ for a high branch unbalance, and that EGC tends to a single-branch system with an average SNR of $\overline{\gamma} = \overline{\gamma}_1/2$.

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