
Improving Energy Efficiency of Relay Systems Using Dual-Polarized Antenna

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Abstract

In this paper we study the bit error analyses of decode-and-forward (DF) relay system over Ricean fading channels, implementing polarization diversity at the relay node. Two correlated and non-identical Ricean fading channels are used to describe source to relay link, and maximal ratio combining (MRC) of the received signals is performed at the relay. Communication between the relay and destination is also assumed to be over Ricean fading channel. The performances of the considered system are compared to classic DF relay system with single antenna relay, in order to determine the level of BER (Bit Error Rate) improvement. A significant decrease of the average SNR per hop in order to achieve the same BER performance is realized using dual diversity at relay, despite certain levels of correlation and power unbalance between the diversity branches, which can further reduce the needed transmit power.

Keywords: Energy efficiency, decode-and-forward, relay, polarization diversity, bit error rate.

1 Introduction

In the past few decades wireless communications industry witnessed tremendous growth. Many new standards and network topologies have been developed in order to support more demanding applications. Along with

providing service to great number of subscribers with desirable throughput, service providers are also facing with significant energy consumption. The rising energy costs and carbon footprint of wireless networks continuously motivate research community, network operators and regulatory bodies to address energy-efficiency as an important issue in exploring new solutions for future wireless systems.

Recently, relay based communication systems have received a significant attention by both industry and academia due to their ability to improve wireless link performance and increase capacity of a wireless system. Furthermore, by using intermediate relays (R) to assist transmission from the source (S) to the destination (D), such systems can increase network coverage and enable more energy efficient service. They can also offer a virtual antenna array bringing spatial diversity benefits while still satisfying the size and power constraints of mobile devices [1–4]. In fact, one of the main advantages of such communication technique is that it distributes the use of power throughout the hops, reducing the need to use a large power at the transmitter. This can provide a longer battery life of mobile terminals and lower level of interference introduced to the rest of the network [3]. In order to enable further energy savings, different energy aware schemes can be used, such as different cooperative algorithms, power allocation, relay selection, sharing or distributing tasks among cooperating entities, etc.

Multiple antennas (diversity) are taken as another enabling technology to increase the wireless system performance. Recently, multi-antenna relaying systems have been proposed [5–8] implementing multiple antennas at S, R and/or D. However, the deployment of multiple antennas at wireless terminals may not be feasible in some scenarios, especially when future terminals are expected to be small and light. That is why multiple antennas are usually implemented at the relays (infrastructure based fixed relay) instead of terminals [5–7]. However, due to a limited space, it is still not always easy to accommodate multiple antennas. In this manner collocated antennas could be interesting for both relay and mobile terminals, but this makes diversity system worthless. However, using dual polarized antenna can be rather practical, because two orthogonally polarized antennas can be collocated. Different propagation characteristics in wireless communication systems for vertically and horizontally polarized waves enable implementation of single antenna structure employing two orthogonal polarizations. Multiple reflections of electromagnetic wave from source to destination depolarize and decorrelate signals, while different propagation characteristics for vertically (V) and horizontally (H) polarized waves make diversity possible.

This is why in this paper we assume that the source and the destination terminals are equipped with a single antenna, while relay terminal has dual-polarized receiving and single transmitting antenna. We use maximal ratio combining (MRC) of the received signals at the R, and regenerative decode-and-forward (DF) relay system which fully decodes the data packet at the relay prior to transmission over the second hop. Non-identical Ricean fading environment is assumed, since in many practical scenarios source-relay (S-R) link can experience different fading conditions than relay-destination (R-D) link. A lot of practical channel measurement results [9] have validated such asymmetric nature of the relay fading channels, termed as mixed type fading channels [10]. In contrast to the symmetric fading assumptions [11–13], there are few performance analysis results for mixed type fading channels [10, 14]. Despite the importance of the Ricean model, only a few works have analyzed the performance of relays under LoS (Line of Sight) fading conditions.

The paper is organized as follows. Following the introduction, a detailed description of the system model is given in Section 2, followed by the mathematical analysis in Section 3. The obtained results are presented in Section 4, and concluding remarks are given in Section 5.

2 System Model

In this paper we considered dual hop relay system where source communicate to destination via relay. R is assumed to be equipped with one transmit and dual-polarized receive antenna. Due to the half-duplex nature of operation of the relay, transmission protocol of the relaying paths divides each transmission period into two time intervals: in the first time slot S communicates with R. Relay then receives the signals from S through two orthogonally polarized links and performs MRC of the received signals, decodes and then forwards to D. Analyzed system is illustrated in Figure 1.

2.1 Polarization Diversity

It is well known that the usage of multiple antennas on one or both ends of a wireless link enables necessary improvements of the system performance. The most commonly used diversity technique is space diversity. However, for reaching a full diversity gain, the received antennas must be adequately separated. At the same time, a space for mounting two or more antennas can be limited. A promising alternative for overcoming such a problem is polarization diversity [15]. Since it utilizes only one dual polarized antenna,

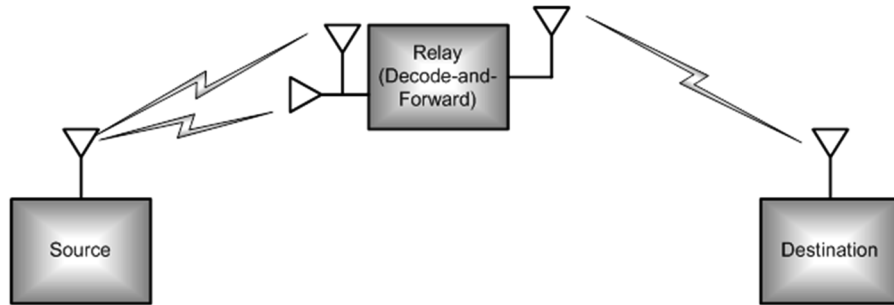


Figure 1 System model.

this type of diversity is space and cost effective solution despite the fact that the collocation of antennas necessary leads to signal correlation.

Polarization diversity is based on the fact that propagation characteristics in wireless communication system are different for vertically and horizontally polarized waves. Multiple reflections between the transmitter and the receiver lead to the depolarization of radio waves, coupling some energy into the orthogonal polarization. Due to that characteristic of multipath radio channel, vertically/horizontally polarized transmitted waves have also horizontally/vertically component.

There are two main parameters describing polarization diversity: cross-polar discrimination (XPD), that indicates power difference between the average powers of copolarized and crosspolarized signals, and correlation coefficient between the received signal envelopes. Many measurements conducted in different environments show that typical values of XPD vary from 1-10 dB in urban and suburban environment, and 10-18 dB in rural environment [16]. Correlation coefficient is usually very small (generally even less than 0.3), and does not significantly affect system performances.

2.2 Channel Model

In this paper we consider Ricean fading channel, which is often used to model propagation paths consisting of one strong direct line-of-sight signal and many randomly reflected and usually weaker signals. It is a very useful and widely used channel model as it spans in range from Rayleigh fading to no fading cases [17].

In many practical scenarios S-R and R-D links can be characterized with asymmetric fading conditions, for example, one link may have a strong line-of-sight component (typical Ricean fading), while the other link may have

greater severity of fading (closer to Rayleigh) [10]. We assume that there is no direct communication between source and destination, and R is equipped with a dual polarized antenna, with MRC of the received signals.

In order to analytically describe such system, taking into account the existing signal correlation between two diversity branches available at R, first in [18] we propose an analytical method for transforming the correlated signals into uncorrelated ones. In that manner, effects of the branch correlation are expressed through modification of the following system parameters: the average received signal-to-noise ratio (SNR) per diversity branch and Ricean K factor. According to the procedure completely described in [18], the transformed average SNRs and K factors are given by

$$\bar{\gamma}_{iT} = a_i^2 \bar{\gamma}_1 + (1 - a_i^2) \bar{\gamma}_2 + 2a_i \sqrt{\frac{(1 - a_i^2) \bar{\gamma}_1 \bar{\gamma}_2}{(1 + K_1)(1 + K_2)}} (\rho + \sqrt{K_1 K_2}) \quad (1)$$

and

$$K_{iT} = \frac{\frac{a_i^2 X K_1}{1 + K_1} + \frac{(1 - a_i^2) K_2}{1 + K_2} + 2a_i \sqrt{\frac{(1 - a_i^2) X K_1 K_2}{(1 + K_1)(1 + K_2)}}}{\frac{a_i^2 X}{1 + K_1} + \frac{1 - a_i^2}{1 + K_2} + 2\rho a_i \sqrt{\frac{(1 - a_i^2) X}{(1 + K_1)(1 + K_2)}}} \quad (2)$$

with a_i [18]:

$$a_i = \sqrt{\frac{1}{2} - \frac{(-1)^i}{2} \sqrt{\frac{\left(\frac{X}{1 + K_1} - \frac{1}{1 + K_2}\right)^2}{\left(\frac{X}{1 + K_1} - \frac{1}{1 + K_2}\right)^2 + \frac{4\rho^2 X}{(1 + K_1)(1 + K_2)}}}} \quad (3)$$

K_i and $\bar{\gamma}_i$ ($i = 1, 2$) are the original channel parameters: Ricean factors and average SNR per diversity branch, ρ is correlation coefficient between the signals, and X denotes XPD, that is the level of power imbalance, i.e. $X = \bar{\gamma}_1 / \bar{\gamma}_2$.

After the proposed transformation, standard mathematical model for performance analysis of uncorrelated signals can be applied.

2.3 DF Relay System

Implementation of relays in wireless network extends coverage of a base station (BS). Considering well-known properties of the wireless channel, including large path losses, shadowing and multipath fading, covering very distant users via direct transmission becomes very demanding in terms of

required power for establish a reliable connection. High power transmission requirement further claims high power consumption and also introduces high level of interference. Dividing a direct path between S and D into several shorter links (hops) using relays reduces signal attenuation, and thus reduces the transmitting power necessary to achieve a same signal-to-noise ratio (SNR) level. This is the key point which makes relay systems a good candidate for green communications.

In this paper a decode-and-forward (DF) technique is employed in dual-hop relay communication systems. DF has several advantages over another well-known relay technique: the amplify-and-forward (AF). One of these advantages is the fact that R first decodes the received signal, re-encodes it and then transmits to D. In this manner, the total noise at D is decreased compared to AF which amplifies the noise along with the signal. Another advantage of such system is that it is possible to implement different modulation schemes at S-R and R-D links, depending on the link conditions. However, DF signal processing at R can have certain drawbacks, especially in the case of channels with severe fading. When BER is concerned, if the decoding error occurs at R, those erroneous symbols will be further transmitted to D. There is no doubt that the characteristics of the R-D link contribute to an overall BER performance degradation of DF relay system. In addition, errors might be also introduced in the signal at terminal D.

In order to reduce those negative implications of the error propagation and to improve BER performance, several techniques can be applied. Different encoding schemes for error detection and correction can be applied in the process of signal regeneration at DF relay stations [19]. Knowing that diversity systems are a standard solution for BER performance improvement, we propose to implement diversity combining at R.

3 Performance Analysis

In DF relay systems a signal is transmitted over two cascade links and its decoding is done twice. If the transmission implies a binary signal with two possible symbol states (DPSK or BPSK), an error will appear at the final destination terminal only if an error in the signal detection is performed once (either on the first or on the second link):

$$P = P_{SR}(1 - P_{RD}) + (1 - P_{SR})P_{RD}, \quad (4)$$

where P_{SR} and P_{RD} are the bit error rates at the S-R and R-D links, respectively. In order to determine PSR and PRD, we use the MGF (Moment Generating Function) approach [17].

If the MRC of the received diversity signals at R is applied, the MGF of total received SNR at R can be obtained as a product of individual MGFs, in the case that the received signals are independent. If we apply the above described transformation of correlated signals into uncorrelated ones, proposed in [18], the MGF for S-R link in the case of Ricean fading channels becomes

$$\begin{aligned} \text{MGF}_{SR}(s) &= \frac{1 + K_{1T}}{1 + K_{1T} - s\bar{\gamma}_{1T}} \frac{1 + K_{2T}}{1 + K_{2T} - s\bar{\gamma}_{2T}} \\ &\times \exp\left(\frac{K_{1T}s\bar{\gamma}_{1T}}{1 + K_{1T} - s\bar{\gamma}_{1T}} + \frac{K_{2T}s\bar{\gamma}_{2T}}{1 + K_{2T} - s\bar{\gamma}_{2T}}\right), \end{aligned} \quad (5)$$

while the MGF for the S-R link, also in the case of Ricean fading is given as [17]

$$\text{MGF}_{RD}(s) = \frac{1 + K_{RD}}{1 + K_{RD} - s\bar{\gamma}_{RD}} \exp\left(\frac{K_{RD}s\bar{\gamma}_{RD}}{1 + K_{RD} - s\bar{\gamma}_{RD}}\right) \quad (6)$$

Knowing the MGF, the probability of error in the case of BPSK mapping can be determined as [17]

$$P_{BPSK} = \frac{1}{\pi} \int_0^{\pi/2} \text{MGF}\left(-\frac{1}{\sin^2 t}\right) dt \quad (7)$$

Putting (5) and (6) into (7) P_{SR} and P_{RD} are determined. Finally, the overall BER is determined using (4).

In the case of DPSK mappings, BER can be determined as:

$$P = 0.5\text{MGF}(1). \quad (8)$$

Using (5), (6) and (4), BER can be determined as

$$P_{DPSK} = 0.5[\text{MGF}_{SR}(1) - (1 - 0.5\text{MGF}_{RD}(1)) + (1 - 0.5\text{MGF}_{SR}(1_{\text{MGF}_{RD}}(1))]. \quad (9)$$

Or, equivalently:

$$P_{DPSK} = 0.5[\text{MGF}_{SR}(1) + \text{MGF}_{RD}(1) - \text{MGF}_{SR}(1)\text{MGF}_{RD}(1)]. \quad (10)$$

4 Results

When system with polarization diversity is analyzed, it has been shown that it is necessary to take into account the influence of the two main parameters characterizing this type of diversity: correlation coefficient between the

received signals and XPD. These two parameters are strongly dependent on the environment, thus greatly affect system performance. However, various experimental results have shown that typical values for correlation coefficient vary from 0.2–0.4 [16], while studies have shown that systems based on multiple antennas can achieve a significant performance improvement as long as the correlation coefficient is less than 0.7 [20]. The other very important parameter in assessing the effectiveness of the polarization diversity system is XPD. This parameter is strongly dependent on environment, and has larger influence on overall system performance than correlation coefficient. High XPD increases BER, and if too large can make the whole diversity system worthless. As it is already noted, typical values of this parameter vary from 1 to 10 dB in urban and suburban environments, and from 10 to 18 dB in rural environments [16].

Still, it has been shown that despite a certain level of the correlation between the signals from different diversity branches and power imbalance between them, polarization diversity system provides significant performance improvements of wireless systems. It can be considered as an alternative to commonly used space diversity, especially in urban environments with the lack of space to mount two or more spatially separated antennas. Fortunately, in urban environments the effect of depolarization is stronger, leading to lower XPD, thus better performances. Since it utilizes only one dual polarized antenna, this type of diversity presents an attractive space and cost effective solution [18]. That motivated us to analyze achievable level of performance improvement using polarization diversity at R.

Some of the BER results obtained using the analytical model described in the previous section, are illustrated in Figure 2 for BPSK and in Figure 3 for DPSK mapping. In order to determine the level of BER improvement obtained by implementing dual polarized receive antenna at R, BER curve for the relay system with no diversity at R is also presented. It is assumed that the average total received SNR at the output of the MRC combiner has the same value as in the case with no diversity. Equal average SNRs per hop is assumed. In order to verify the proposed analytical model for BER determination of the analyzed wireless relay system with polarization diversity implemented at R, the above presented mathematical results are compared with the results obtained with the adequate simulation model of the analyzed system.

It has been showed that implementing dual-polarized antenna at the R leads to significant BER improvements. As it could have been expected, the level of the achieved performance enhancements depends on power differ-

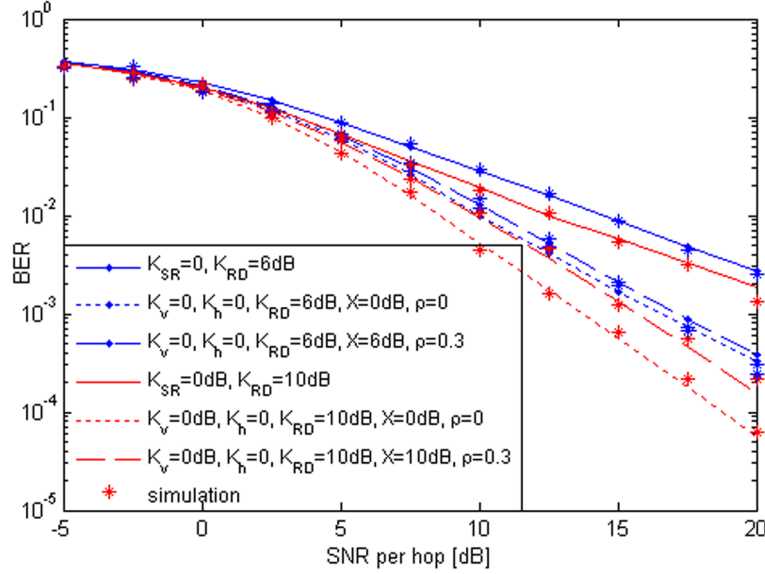


Figure 2 BER performances of DF relay system, BPSK.

ence between diversity branches and correlation coefficient. However, still, for some typical XPD and ρ values, the improvement cannot be neglected.

We also considered the case when average SNR at S-R link is not necessary equal to the average SNR at R-D link. Three scenarios are presented: the average SNR of S-R link is greater, equal or less than the average SNR of R-D link. In all the considered scenarios, performance improvement is evident, as shown in Figure 4.

From the results presented it can be concluded that in all considered cases, implementing diversity at R can significantly contribute to energy savings. For example, in order to achieve BER of the order of 10^{-3} up to 5 dB lower SNR is required, implying a lower transmit power.

5 Conclusions

Motivated by the importance of relaying systems, we analyzed in this paper the possibility for BER performance improvement of DF relay system through implementation of diversity reception on relay. Polarization diversity provides the possibility to implement two collocated antennas with sufficiently low correlation coefficient. However, due to the existing correlation,

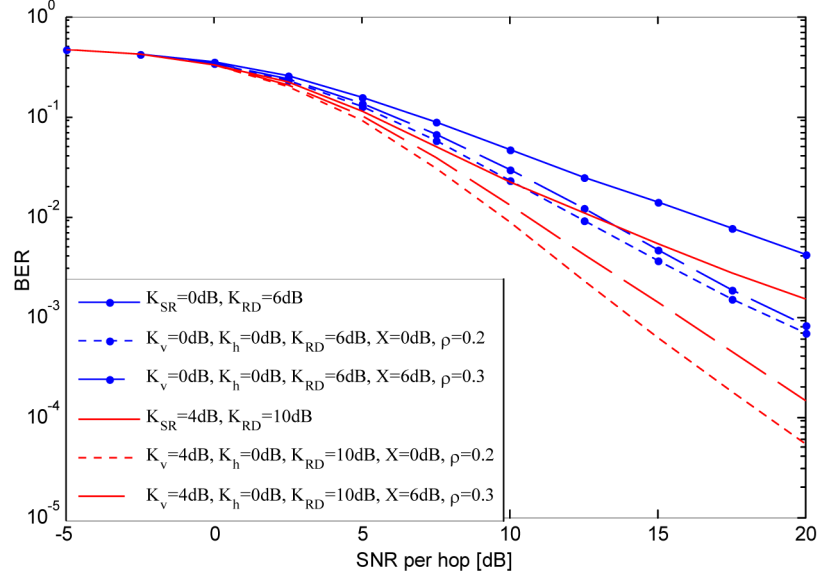


Figure 3 BER performances of DF relay system, DPSK.

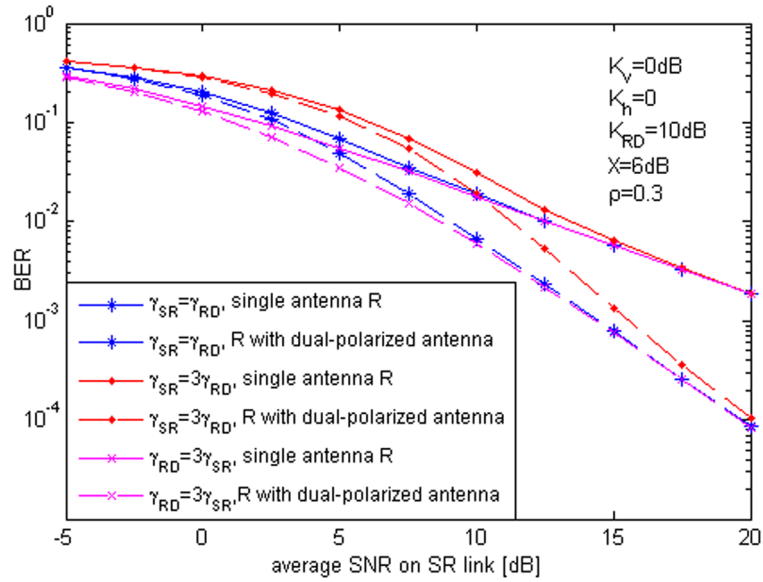


Figure 4 BER performances of DF relay system (γ_{SR} constant), BPSK.

and SNR unbalance per diversity branch, the analytical model describing such system is very complex. This is why we used a previously defined linear transformation of correlated signals into uncorrelated ones, and applied a standard MGF approach for conditional BER.

The obtained results show significant performance improvements for various XPD and ρ . In addition, such a system further improves energy efficiency of classical relay systems. Namely, splitting the communication link into several shorter hops, instead of direct communication between the S and D, the transmitted power is effectively distributed throughout the system. Further enhancement means that lower transmitted power is needed for equal system performance, with only slight modification at the relay. This implies a more energy efficient system that will provide longer battery lives for mobile terminals, which is considered as a first step towards green communications.

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