Noncoherent Detection for Multi-hop Amplify-and-forward-based Multi-branch Cooperative Diversity Systems

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Abstract— Since the actual distribution of the received signals in multi-hop amplify-and-forward (AF) relaying transmission is no longer Gaussian, which is caused by the multiplication of fading gains and noise, a new fitted distribution named as logistic distribution is used to derive a novel noncoherent detector based on the maximum likelihood (ML) method. In order to get better performance of the receiver, one or more multi-hop AF links are added to form a multi-branch cooperative diversity system. Therefore, at the destination, combining method is applied to combine several signals together to obtain better diversity gains. Numerical results show that the new detector based on the logistic distribution outperforms the conventional energy detector. Also, it is shown that the performance of receiver is significantly improved when combining method is applied in the multi-branch cooperative diversity system especially when the number of branches increases.

1. INTRODUCTION

Since the demand of wireless applications, such as mobile phones, wireless sensing networks, smart home applications, is growing broadly, the research of mobile communications technology develops rapidly. In wireless communications, one of the main problems that impact signal performances is fading [1]. In order to overcome this problem, many different technologies have been developed. Cooperative diversity [2] with multi-hop relaying is a good candidate which stands out of them.

Space Diversity technology is a receiver technique that can improve the signal performance by adding wireless link at a low cost [1]. At the receiver, more than one transmission paths are received. If one path undergoes a deep fade, another path may have a robust signal. Therefore, selecting the robust paths or combining different paths with different weight factors can improve the signal to noise ratio (SNR) of the receiver, thus the signal quality is improved. In cooperative wireless communications, signals can be transmitted from a source to its destination through different cooperative links and combined in the receiver. In general, there are three combining methods which are selection combining (SC), equal-gain combining (EGC) and maximum-ratio combining (MRC). Only focusing on the performance point of view, MRC is the best, EGC is at the middle and SC is the worst. But SC is the easiest one for implement. In this work, MRC and SC are investigated for comparison.

Each cooperative link may consist of several relays in order to reduce the signal dispersion loss and the performance degradation [3]. There are two main relaying techniques that can be used in the multi-hop relaying transmission. One is the amplify-and-forward (AF) technique and the other is the decode-and-forward (DF) technique [4–6]. In this work, we consider using AF in each multi-hop relaying link due to its simplicity [7, 8]. Without any further processing, the AF relay amplifies its received signal and retransmits the amplified signal to the next relaying node until the signal arrives at the destination. Where fixed relaying is assumed due to its simplicity and no requirement of acknowledge in network layer [9]. Thus, each relay amplifies the noise at the same time when it amplifies the retransmitting signal.

In a multi-hop and multi-branch cooperative diversity system, estimating the fading gains which is required in coherent detection causes a huge amount of overhead. Thus, noncoherent detection is preferred for simplicity in the applications with limited system resources [10]. Energy detection is a widely used noncoherent detection technique [11, 12]. In energy detection, the energy of the received signal is calculated and compared with a threshold, which is based on the Gaussian assumption of the received sample [13]. However, in multi-hop AF relaying systems, due to the multiplication of fading gains and noise the overall noise in the received signal is no longer Gaussian after several relays, such that the received sample is not Gaussian either. Thus, new distribution should be proposed, and the performance of the conventional energy detector for noncoherent detection can be further improved by using the new distribution of the received signal.

In this work, the actual distribution of the received signal is first introduced based on the distribution fitting techniques. The derivation is based on the assumption of independent and identically distributed Rayleigh fading and Rician fading hops. Based on these distributions, the maximum likelihood (ML) method is used to generate the new noncoherent detector. Then the performance of the new detector is investigated and compared with the conventional energy detector. The performance of two combining methods with different number of branches are compared with the original performance in single hop Rayleigh channel. Numerical results show that the new detector based on the proposed distribution outperforms the energy detector and that the performance gain increases when the number of branches increases and the number of hops decreases.

2. SYSTEM MODEL

Cooperative diversity is composed of multi-hop diversity and multi-branch diversity. Multi-hop diversity allows a long distance signal transmission and multi-branch diversity combines multiple received signals together to get better received performance. A multi-branch multi-hop cooperative diversity system [2] is shown in Fig. 1. An information source S transmits signal x through M independent branches to its destination D. Each branch is a link that includes $N-1$ relays R_{ji} ($j = 1, 2, \ldots, M$; $i = 1, 2, \ldots, N$) with N hops over the fading channel. Where x is considered as an on-off keying (0-1) signal. For simplicity, the on-off keying signal is suitable for noncoherent energy detection. Each relay node incurs an additive white Gaussian noise n_{ji}. The fading coefficients for each hop of fading channel is h_{ji}. Thus, the received signal of the jth-branch is given by

$$y_{jN} = h_{j1}h_{j2}\ldots h_{jN}x + h_{j2}h_{j3}\ldots h_{jN}n_{j1} + h_{j3}h_{j4}\ldots h_{jN}n_{j2} + \ldots + h_{jN}n_{jN-1} + n_{jN}, \quad (1)$$

when $x = 1$, the received signal of the j-th branch at the destination is

$$y^1_{jN} = P_{sj} + P_{nj}, \quad (2)$$

where the signal part $P_{sj} = \prod_{i=1}^{N} h_{ji}$, and the noise part $P_{nj} = \sum_{i=1}^{N} (\prod_{k=i+1}^{N} h_{jk})n_{ji}$. When $x = 0$, the received signal of the j-th branch at the destination becomes

$$y^0_{jN} = P_{nj}. \quad (3)$$

In conventional researches, the noise part P_{nj} is assumed to follow Gaussian distribution [14]. But for the noncoherent detection in this work, since h_{ji} is unknown, P_{nj} is not Gaussian anymore. In particular, the number of terms in P_{nj} increases when the number of hops increases and P_{nj} becomes less Gaussian. Finding the exact distribution for the noise part is an entry point of this work.

Due to the variable number of hops, it is difficult to derive the theoretical distribution of y^0_{jN} and y^1_{jN}, if not impossible. Therefore, the distribution fitting is performed. Tests show that the logistic distribution has the smallest fitting errors when SNR is large enough for the AF relaying

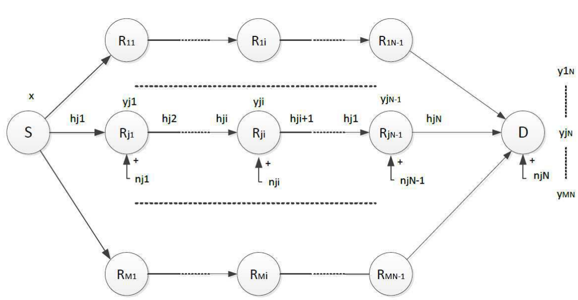

Figure 1: System model.

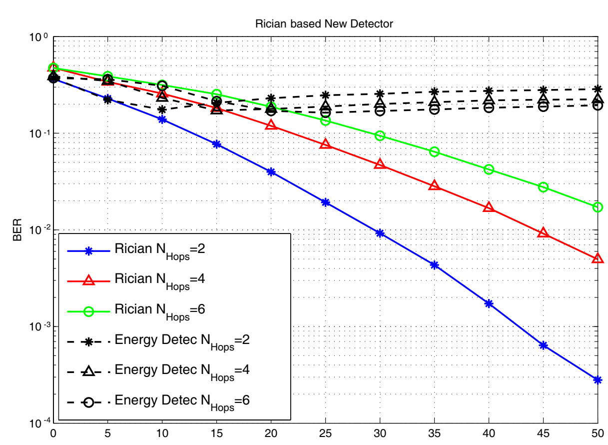

Figure 2: Performance comparison with Rician factor $K = 1$.

multi-hop transmission. The probability density function (PDF) of the logistic distribution is given by

$$f(x) = \frac{e^{-\frac{x-\mu}{\sigma}}}{\sigma\left(1+e^{-\frac{x-\mu}{\sigma}}\right)^2}, \tag{4}$$

where μ is the mean and σ is the standard deviation. These two parameters can be calculated in the fitting. Based on the numerical calculation results for each branch, the relationships between these distribution parameters and the values of SNR and N_{Hops} can be derived. Since the mean μ can be approximated as 0. Using curve fitting, one has

$$\sigma_{0j} = 0.02497 - 0.01882 \cdot \sin\left(0.6969 \cdot \pi \cdot N_{\text{Hops}} \cdot \text{SNR}_j\right) + 0.428 \cdot e^{-(0.1103 \cdot \text{SNR}_j)^2}, \tag{5}$$

where $j = 1, 2, \ldots, M$,

$$\sigma_{1j} = 0.001402 \cdot N_{\text{Hops}}^2 - 0.04206 \cdot N_{\text{Hops}} + 0.4462. \tag{6}$$

Then the PDFs of the received signal can be approximated as: when $x = 0$,

$$f\left(y_{jN}|x=0\right) = \frac{e^{-\frac{y_{jN}}{\sigma_{0j}}}}{\sigma_{0j}\left(1+e^{-\frac{y_{jN}}{\sigma_{0j}}}\right)^2}, \tag{7}$$

when $x = 1$,

$$f\left(y_{jN}|x=1\right) = \frac{e^{-\frac{y_{jN}}{\sigma_{1j}}}}{\sigma_{1j}\left(1+e^{-\frac{y_{jN}}{\sigma_{1j}}}\right)^2}. \tag{8}$$

3. RECEIVER FOR SINGLE BRANCH

Using the derived PDFs in the previous section, new noncoherent detectors can be proposed. Based on the ML principle [13], assume that the probabilities for the source transmitting "0" and "1" are the same, or $P(x=0) = P(x=1)$, the detector can be derived as

$$\mathcal{D}(y_N) = \prod_{j=1}^{M} \frac{f(y_{jN}|x=1)}{f(y_{jN}|x=0)} \underset{0}{\overset{1}{\gtrless}} \frac{P(x=0)}{P(x=1)} = 1. \tag{9}$$

Substitute (7) and (8) into (9), one has

$$\mathcal{D}(y_N) = \prod_{j=1}^{M} \frac{\sigma_{0j}}{\sigma_{1j}} e^{\frac{\sigma_{1j}-\sigma_{0j}}{\sigma_{0j}\sigma_{1j}} y_{jN}} \left(\frac{1+e^{-\frac{y_{jN}}{\sigma_{0j}}}}{1+e^{-\frac{y_{jN}}{\sigma_{1j}}}}\right)^2 \underset{0}{\overset{1}{\gtrless}} 1. \tag{10}$$

4. COMBINING METHODS

In this paper, MRC and SC combining methods are considered. For SC, as shown in the system model Fig. 1, the destination D receives M copies of the transmitted source signal. The signal of the branch with the highest instantaneous SNR is chosen by the combiner and used for demodulation. The choice of the instantaneous SNR γ_c can be obtained by

$$\gamma_{c,\text{SC}} = \max(\gamma_1, \gamma_2, \ldots, \gamma_M), \tag{11}$$

where $\gamma_1, \gamma_2, \ldots, \gamma_M$ represent the instantaneous SNRs of the received signals at the first, the second, ..., and the M-th branches. Since each branch is independent, assume that there is a SNR threshold γ below which the received signal of the corresponding branch should be eliminated.

Since a SNR which is always guaranteed to be above the threshold is selected in SC, the diversity improves signal performance and reduces outage probability without additional transmit power. But it is not the best diversity technique due to its not using all of the branches.

For MRC, the combiner weights all the received signals according to their own qualities. Thus the instantaneous SNR at the output of the combiner is

$$\gamma_{c,\mathrm{MRC}} = \sum_{i=1}^{M} \gamma_i, \quad i = 1, 2, \ldots, M. \tag{12}$$

Intuitively, MRC can be applied to any diversity application and provide a great performance improvement at the expense of high implementation complexity and high cost of time and money.

5. NUMERICAL RESULTS

This section presents numerical results to evaluate the BER of the new detector for single branch and multi branches with combining methods when different hop numbers are implemented. A number of 10^5 data symbols are used in the simulation. Fig. 2 shows the BER vs. SNR for different numbers of hops using the new detector based on the logistic distribution compared with the conventional energy detector in Rician fading channel, where the parameter K of Rician fading channel is assumed to be 1. One find that the energy detector based on the three hops numbers all have BER floors. Notably, the BER of energy detector decreases when the hops number increases if the SNR is larger than 20 dB. The reason may be that the Gaussian distribution parameters estimated by the distribution fitting tool is not so accurate when the fading channel is Rician. The new detector makes significant performance improvement. Obviously, when the number of hops increases the BER increases.

To check the effect when assumption does not match reality, Fig. 3 shows the effect when Rayleigh fading channel is used to do distribution fitting but the actual channel is Rician and the received signals are Rician signals. One sees that the BER curves of the non-matched new detector based on Rayleigh channel parameters but using Ricain samples are higher than the matched new detector. The non-matched BER performance will degradate even worse when the number of hops and SNR increase. One should also note that, compared with Fig. 2, the novel detector still have better performance than energy detector even when the channel condition is non-matched.

Figure 4 shows the comparison of the BER using different combining methods with different number of hops and the original BER of single branch and single hop. One sees that, to achieve the same performance of the original BER more than two branches with two hops should be combined when SC combining method is implemented, while more than one branch is needed when MRC is implemented. Based on the same transmission condition, the MRC method outperforms the SC method. And the more the number of branches is combined, the better the BER performance will be. This indicates the advantage of the implementation of diversity combining methods in the multi-hop multi-branch cooperative systems.

Figure 5 compares the conventional energy detection on single branch with the new detector based on logistic distribution using MRC methods with different branches when the source signal is transmitted by 5 AF relaying hops. One sees that, all the MRC combining curves based on the new detector outperforms the conventional energy detector. And the BER of the new detector can further decrease when the branche number increases and the MRC method is applied.

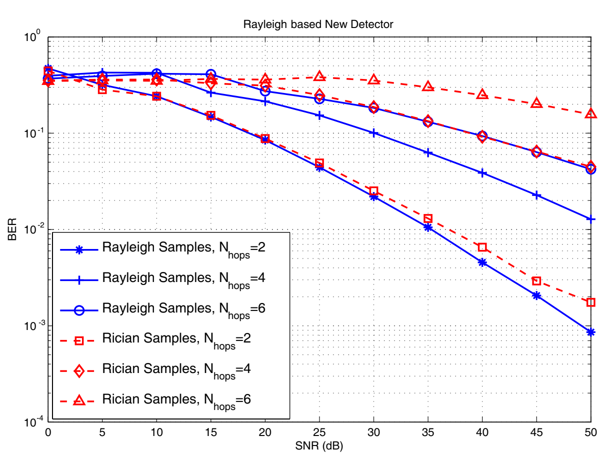

Figure 3: Assumption not matching reality.

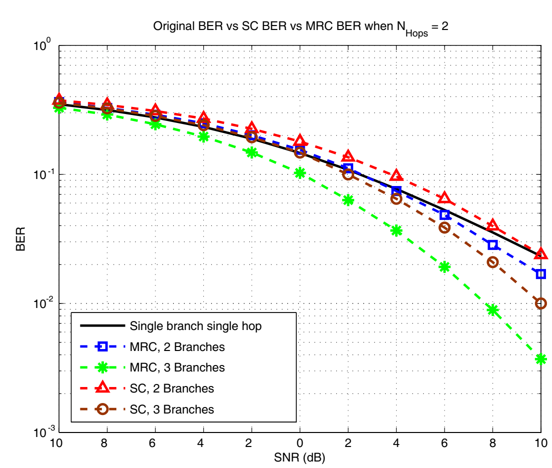

Figure 4: Different combining methods.

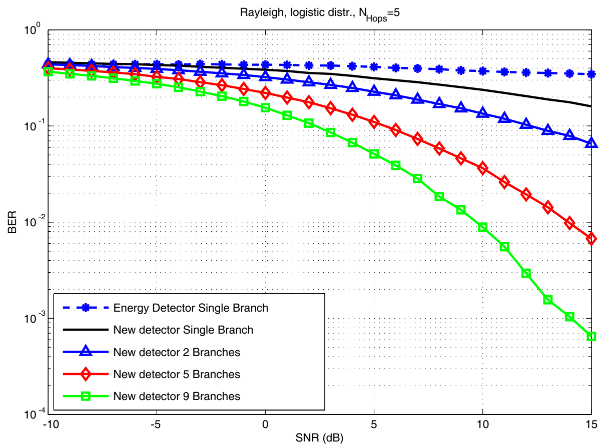

Figure 5: Different branch numbers with 5 hops.

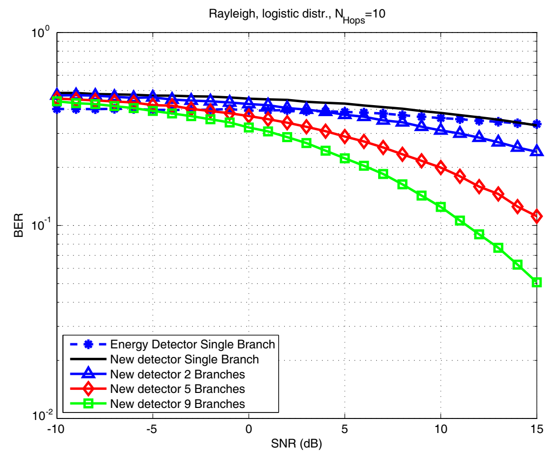

Figure 6: Different branch numbers with 10 hops.

Figure 6 shows the different results from Fig. 5 when the number of hops is changed into 10. Comparing with Fig. 5 one sees that, the performance of new detector combining different numbers of branches all degradates when the number of hops increases, while the performance of energy detection almost does not change. Notably, as the number of hops increases the new detector with single branch does not outperform the energy detector. This indicates the importance of the diversity combining in multi-branch systems. One observes that more branches can provide higher performance. However, the increasing number of branches is at the expense of the increasing complexity and cost. Thus, there is a trade off between performance and the cost of complexity and money.

6. CONCLUSIONS

In multi-hop AF relaying channel, the actual distribution of the received signals is not Gaussian any more, while the Gaussian distribution is always assumed to be the distribution in conventional researches. In this paper, novel detector using ML principle for the multi-hop AF multi-branch cooperative diversity system has been proposed based on the new fitted logistic distribution of received signals. Numerical results have shown that the new detector outperforms the conventional energy detector when the number of hops is low especially when use combining methods to combine multi branches. To investigate the case when the channel assumption does not match reality, the effect when Rayleigh fading channel is used to do distribution fitting but the actual channel is Rician and the received signals are Rician signals has been shown to indicate that the new detector can even outperform the conventional energy detector. The performance gain increases when the SNR increases or when the branch number increases and the hop number decreases.

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