무선 중계 네트워크의 협력 통신 방법에 대한 LLR 적용 연구

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요 약

● 복호 후 전달 협력 통신 프로토콜(DFP: Decode-and-Forward Cooperative Communication Protocol)은 하나의 안테나를 쓰는 사용자에게 물리적인 안테나의 증가 없이 다중 안테나 시스템의 강력한 장점을 얻을 수 있는 통신 방법이다. 지금까지는 신호 대 잡음 비율(SNR: Signal to Noise Ratio)이나 경로이득 크기의 루트를 취한 값들을 이용하여 중계 노드에서 복호한 데이터를 전달할지 안 할지를 결정하여 중계 노드에서 부정확한 결과가 되지 않도록 방지하였다. 본 논문에서는 기존의 DFP에서 사용되던 SNR을 대체할 수 있는 LLR(Log-Likelihood Ratio)를 이용하는 방법을 제안하였다. 여러 가지 많은 모의 실험을 통해 레일리 페이딩 환경과 AWGN환경에서 기준값이나 중계 노드의 위치에 상관없이 LLR기반의 DFP가 SNR기반의 DFP보다 아주 우수한 성능을 보이는 것을 확인하였다.

키워드 : 복호 후 전달 협력 통신 프로토콜, 로그 비율, 레일리 페이딩, AWGN

Application of LLR on Cooperative Communications for Wireless Relay Networks

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ABSTRACT

Decode-and-forward cooperative communications protocol (*DFP*) allows single-antenna users in wireless medium to obtain the powerful benefits of multi-antenna systems without physical antenna arrays. For this protocol, so far the relays have used *SNR* to evaluate the reliability of the received signal before deciding whether to forward the decoded data so as to prevent their unsuccessful detection. However, *SNR* only characterizes the long-term statistic of Gaussian noise and thus leading to inaccurate assessment. Therefore, we propose using log-likelihood ratio (*LLR*) which accounts for the instantaneous noise in the received signal as an alternative to *SNR*. A variety of simulation results reveal the significant superiority of the LLR-based *DFP* to the SNR-based *DFP* regardless of threshold level and relay position under the flat Rayleigh fading channel plus AWGN (Additive White Gaussian Noise).

Key Words : DFP, LLR, Rayleigh Fading, AWGN

1. Introduction

Signal fading due to multi-path propagation is a serious problem in wireless communications. Using a diversified signal in which information related to the same data appears in multiple time instances, frequencies, or antennas that are independently faded can reduce considerably this effect of the channel[1]. Among well-known diversity techniques, the spatial diversity has received a great deal of attention in recent years because of the feasibility of deploying multiple antennas at both transmitter and receiver[2]. However, when wireless mobiles may not be able to support multiple antennas due to size or other constraints[3], the spatial diversity is unobtainable. To overcome this restriction, a new technique, called cooperative communications, was born which allows single-antenna mobiles to gain some benefits of transmit diversity. The main idea is that in a

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※ This work was supported by the BK 21 Research Fund of Korea.
This research was supported by the MIC(Ministry of Information and Communication), Korea, under the ITRC(Information Technology Research Center) support program supervised by the IITA(Institute of Information Technology Assessment).

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논문접수 : 2005년 9월 22일, 심사완료 : 2006년 7월 31일

multi-user network, two or more users share their information and transmit jointly as a virtual antenna array. This enables them to obtain higher diversity than they could have individually. The way the users share information is by tuning into each other's transmitted signals and by processing information that they overhear. Since the inter-user channel is noisy and faded, this overheard information is not perfect. Hence, one has to carefully study the possible cooperative protocols that can exploit the benefits of cooperative communications at most. Among three basic cooperative protocols[3], *decode-and-forward* protocol demonstrates the most reasonable trade-off between implementation complexity and BER performance. So, it is extensively discussed in the literature[4-10].

Basically, *DFP* has two ways to process the received signal at the relay in a wireless relay network. First, the relay always decodes and forwards the decoded data to the destination[4-5]. This way, which is referred to as *M1* in the sequel, is simple but causing the adverse effect on the eventual detection of the symbols at the destination if the relay fails in detecting the signal from the source. To overcome such a situation,[4-5] proposed *DFP* with thresholding based on the signal-to-noise *(SNR)* or the square amplitude of path gain. We refer it to as *M2-SNR* where only the received signal lying above the preset threshold is decoded and retransmitted to the destination. It is shown that *M2-SNR* outperforms *M1*[3]. Nevertheless since *M2-SNR* only relies on fading level to decide the retransmission without accounting for the noisy level, it reflects partially the characteristic of the received signal. In this paper, *LLR* instead of *SNR* is used to assess the quality of the received signal more reliably in that both noise and fading are taken into account. This proposed method is named *M2-LLR*. In fact, *LLR* is mentioned much in literature, especially in [11-12] where it is employed for the optimum receive antenna selection and its advantage over *SNR* is proved mathematically. Therefore, our work here is considered as the application extension of *LLR* in a different scenario: cooperative communications.

The rest of this paper is organized as follows. Section 2 summarizes the conventional versions of *DFP* to point out their disadvantages which are solved by the new LLR-based *DFP*. Then section 3 presents simulation results to verify the validity of the proposed protocol and finally, the paper concludes in section 4.

2. Proposed LLR-based DFP

Consider a wireless relay network consisting of single-antenna terminals: a source (*S*), a relay (*R*) and a destination (*D*) as shown in (Fig. 1). Assuming that the channels between terminals experience slow frequency-flat Rayleigh fading; that is, they are constant during one-symbol period but change independently to the next. To capture the effect of path loss on BER performance, we use the same model as discussed in [5] where the variance of α_{ij} is given by $\lambda_{ij}^2=(d_{SD}/d_{ij})$ with d_{ij} and a_{ij} being the distance and the channel coefficient between transmitter i and receiver j, respectively and η being the path loss exponent.

For convenience of presentation, we utilize discrete-time complex equivalent base-band models to express all the signals. In addition, we assume perfect channel-state information at all the respective receivers but not at the transmitters. The general *DFP* consists of two phases.

2.1 First phase

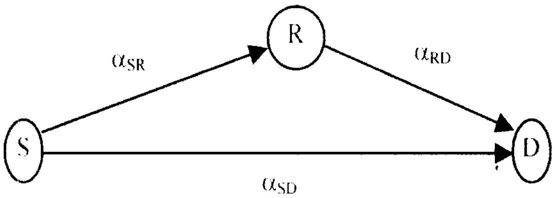
In the first phase, *S* broadcasts a BPSK-modulated symbol a and so, the signals received at *R* and *D* are given by

$$y_{SR}=\alpha_{SR}\sqrt{E_S}\,a+n_{SR} \tag{1}$$

$$y_{SD}=\alpha_{SD}\sqrt{E_S}\,a+n_{SD} \tag{2}$$

where y_{ij} denotes a signal received at the terminal j from the terminal i, n_{ij} a zero-mean unit-variance complex additive noise sample at the terminal j, E_i the average symbol energy (*ASE*) of the terminal i.

There are two conventional ways to process the received signal at R according to DFP:



(Fig. 1) Relay network model

Method 1

For *M1*, *R* always recovers the original data by maximum likelihood (ML) decoding as

$$\hat{a} = sign(y_R) \tag{3}$$

where *sign(.)* is a signum function and

$$y_R = \mathrm{Re}(\alpha_{SR}^* y_{SR}) = |\alpha_{SR}|^2 \sqrt{E_S}\, a + n_R \tag{4}$$

with $n_R = \mathrm{Re}(\alpha_{SR}^* n_{SR})$ is a Gaussian r.v. with zero-mean and variance $|\alpha_{SR}|^2/2$, given channel realization; Re(.) is a real part.

Although *M1* is simple, if the detection at *R* is unsuccessful, the cooperation can be detrimental to the eventual detection of the symbols at *D*.

Method 2

This method forces *R* to evaluate the quality of the received signal and check whether it satisfies the preset requirement. If this is the case, the relay detects and forwards the restored data to *D*. Otherwise, it keeps silent in the second phase. Therefore, the problem of error propagation in *M1* is avoided. So far, only the signal to noise ratio (*SNR*) or the square amplitude of the channel coefficient $|\alpha_{SR}|^2$ is for use in assessing the reliability of a signal in *DFP*.

The instantaneous BER at *R* for BPSK transmission is computed from (4) as

$$P_{e-SR} = Q\left(\sqrt{2E_S |\alpha_{SR}|^2}\right) \tag{5}$$

where *Q(.)* is a Q-function.

Since P_{e-SR} can also be calculated in term of *LLR* in [11], the preset requirement is adopted according to the error probability P_{e-T}.

For *M2-SNR*, the condition for *R* to transmit $\hat{a}$ in (3) in the second phase is

$$P_{e-SR} \le P_{e-T} \quad \text{or} \quad |\alpha_{SR}|^2 \ge T_a \tag{6}$$

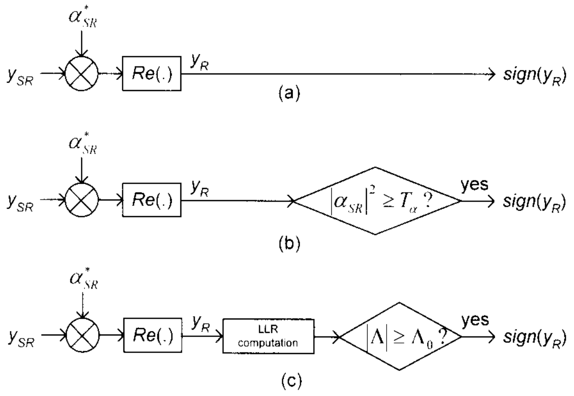
where $T_a = (erfinv(1-2P_{e-T}))^2 / E_S$ because[1]

$$P_{e-T} = Q\left(\sqrt{2E_S T_a}\right) = \frac{1}{2}\left(1 - erf\left(\sqrt{E_S T_a}\right)\right)$$

(6) shows that the retransmission of *R* only depends on instantaneous fading level regardless of instantaneous noisy level in (4). Therefore, it reflects partially the characteristic of the received signal and thus in several cases the condition in (6) does not guarantee for *R* to detect the signal reliably at a priorly desired degree. For example if *a=+1* is transmitted, then the large negative values of n_R can still cause the sum in (4) to be negative (equivalently, wrong decision is made) even though $|\alpha_{SR}|^2$ is extremely larger than T_a. As a consequence, we propose using *LLR* as [11] to account for the noise term in (4).

(4) yields the conditional probability density

$$p\left(y_R \middle| a, |\alpha_{SR}|^2\sqrt{E_S}\right) = \frac{\exp\left(-\dfrac{\left(y_R - |\alpha_{SR}|^2\sqrt{E_S}\,a\right)^2}{2|\alpha_{SR}|^2/2}\right)}{\sqrt{2\pi|\alpha_{SR}|^2/2}}$$



(Fig. 2) Signal processing at the relay for (a) *M1*, (b) *M2-SNR*, (c) *M2-LLR*

Assuming that *a* = *-1* or *+1* is equally likely, its a-posteriori LLR is given by

$$\begin{aligned}\Lambda &= \ln\frac{p\left(a=1 \middle| y_R, |\alpha_{SR}|^2\sqrt{E_S}\right)}{p\left(a=-1 \middle| y_R, |\alpha_{SR}|^2\sqrt{E_S}\right)} \\ &= \ln\frac{p\left(y_R \middle| a=1, |\alpha_{SR}|^2\sqrt{E_S}\right)}{p\left(y_R \middle| a=-1, |\alpha_{SR}|^2\sqrt{E_S}\right)} \\ &= \ln\frac{\dfrac{1}{\sqrt{2\pi|\alpha_{SR}|^2/2}}\exp\left(-\dfrac{\left(y_R - |\alpha_{SR}|^2\sqrt{E_S}(1)\right)^2}{2|\alpha_{SR}|^2/2}\right)}{\dfrac{1}{\sqrt{2\pi|\alpha_{SR}|^2/2}}\exp\left(-\dfrac{\left(y_R - |\alpha_{SR}|^2\sqrt{E_S}(-1)\right)^2}{2|\alpha_{SR}|^2/2}\right)} \\ &= 4y_R\sqrt{E_S}\end{aligned} \tag{7}$$

It is well-known that the sign of Λ is the hard decision value, and its magnitude is a good measure of the reliability of symbols. Moreover, BER in term of Λ is also derived as [11]

$$P_{e-SR} = \frac{1}{1+e^{|\Lambda|}} \tag{8}$$

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[1] erfinv(.) is the inverse error function easily calculated by Matlab software; erf(.) denotes the error function.

For *M2-LLR*, *R* sends $\hat{a}$ in (3) in the second phase when

$$P_{e-SR} = \frac{1}{1+e^{|\Lambda|}} \leq P_{e-T} \quad \text{or} \quad |\Lambda| \geq \ln\left(\frac{1}{P_{e-T}} - 1\right) = \Lambda_0 \qquad (9)$$

From (7)-(9), we realize that the proposed method is different from *M2-SNR* in that it accounts for both fading and noise terms in (4) and Λ provides the reliability information of the maximum a-posteriori probability decision which minimizes the error probability. Therefore, it is expected that it will result in a better performance than *M2-SNR*.

2.2 Second phase

In the second phase, that the relay to send $\hat{a}$ in (3) to *D* or not depends on the signal processing way in the first phase[2]. Assuming that *R* assists *S* in data transmission, the signal arriving at *D* is of the form

$$y_{RD} = \alpha_{RD}\sqrt{E_R}\,\hat{a} + n_{RD} \qquad (10)$$

For a fair comparison, it is essential that the total consumed energy of the cooperative system does not exceed that of corresponding direct transmission system. This is a strict and conservative constraint; allowing the relays to add additional power can then only increase the attractiveness of the cooperation. Therefore, complying this energy constraint requires $E_S=E_R=E_T/2$ where E_T is total *ASE* of the system which is also the *ASE* of the source in case of direct transmission.

Now *D* combines the received signals from both phases based on MRC (Maximum Ratio Combining) to detect the transmitted signal *a*

$$\bar{a} = sign\left(\mathrm{Re}\left(\alpha_{SD}^{*} y_{SD} + \alpha_{RD}^{*} y_{RD}\right)\right) \qquad (11)$$

Using (2), (10) and the fact that $E_S=E_R$ to rewrite (11) as

$$\begin{aligned} \bar{a} &= sign\left(\sqrt{E_S}\left(|\alpha_{SD}|^2 a + |\alpha_{RD}|^2 \hat{a}\right) + n\right) \\ &= sign\left(\sqrt{E_S}\left(|\alpha_{SD}|^2 + \varepsilon|\alpha_{RD}|^2\right)a + n\right) \qquad (12) \end{aligned}$$

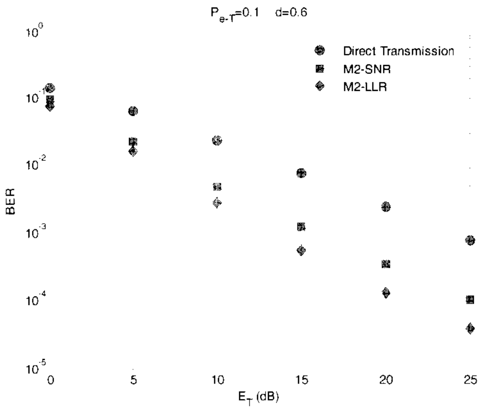
Here $n = \mathrm{Re}\left(\alpha_{SD}^{*} n_{SD} + \alpha_{RD}^{*} n_{RD}\right)$ is a Gaussian r.v. with zero-mean and variance $(|\alpha_{SD}|^2+|\alpha_{RD}|^2)/2$, given channel realizations; $\varepsilon = -1$ means that the relay made the wrong decision on the symbol a and otherwise, $\varepsilon=1$.

3. Simulation results and discussions

An asymmetric network geometry is examined where the relay is located on a line between *S* and *D*. The direct path length *S-D* is normalized to be *1*. We also denote *d* as the distance between *S* and *R*. In all presented results, the path loss exponent η = 3 is under investigation.

Monte-Carlo simulations are performed to verify the effectiveness of the proposed protocol. (Fig. 3) depicts the BER performance of different transmission modes for P_{e-T} = 0.1 and d = 0.6. It is observed that no matter which version of *DFP* is used, the cooperation significantly improves the BER performance in comparison with the direct transmission with E_T gain of about 8dB and 11dB at the target BER of 10^{-3} for *M2-SNR* and *M2-LLR*, respectively. These results are obvious because the cooperation benefits from diversity gain as well as from path-loss reduction.

When *R* is near *S*, the quantity $|\alpha_{SR}|^2$ is usually large due to small path-loss, leading to the first term in (4) to dominate the remaining term. Therefore in such case, *M2-SNR* and *M2-LLR* obtain the same performance. This is illustrated in (Fig. 4) for *d*=0.3. Moreover as *d* increases, the above property is no longer correct and now, the noise term n_R dramatically affects the sign of the expression (4). As a result, *M2-SNR* performs worse for *d*=0.5 and 0.7. The performance degradation occurs similarly for *M2-LLR*. However, since *M2-LLR* evaluates the reliability of the received signal based on y_R, not on $|\alpha_{SR}|^2$ and n_R individually, its performance is superior to *M2-SNR*. Specifically, *M2-LLR* achieves a total energy gain of



(Fig. 3) BER comparison among direct transmission, *M2-SNR*, *M2-LLR*

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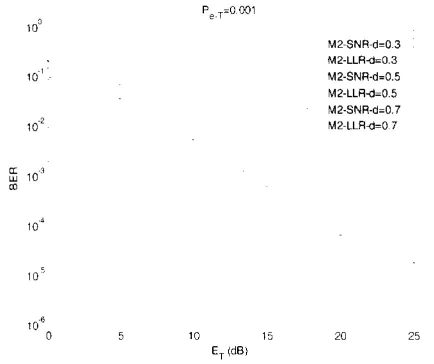
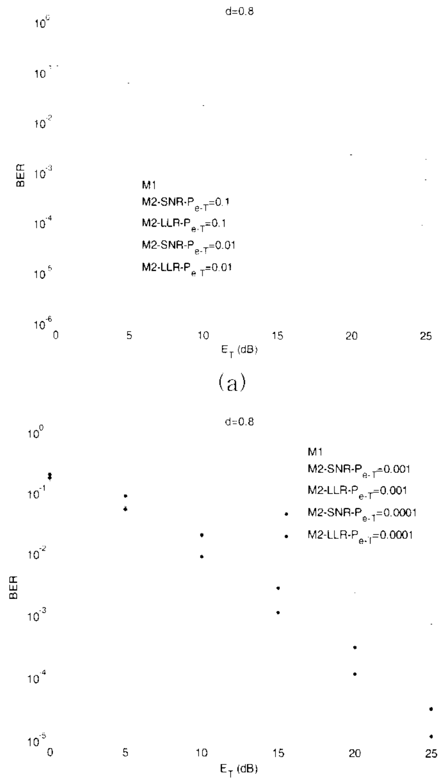
[2] If (6) or (9) is satisfied, the signal restoration at *D* is based on (11). Otherwise, the term y_{RD} in (11) is considered as zero. *D* can detect the presence of the signal from *R* by measuring the signal strength in the second phase.



(Fig. 4) BER comparison between *M2-SNR* and *M2-LLR* via *d*

2dB over *M2-SNR* for d=0.5 and 0.7 over the whole range of E_T.

The influence of the threshold on BER performance of *M2-SNR* and *M2-LLR* is shown in (Fig. 5) for d=0.8. It is well-known that if the threshold (T_a or Λ_0) is so large, then the diversity order is reduced since the probability that the relay retransmits the source data is small. Also, the small threshold (T_a or Λ_0) increases the percentage of incorrect detection at the relay and thus decaying the performance of the receiver. This remark is once again shown in (Fig. 5) for both *M2-SNR* and *M2-LLR*. Moreover, we expect the optimal threshold values but unfortunately, so difficult to find out unless through exhaustive experiments.



(a)

(b)

(Fig. 5) BER performance via thresholds

(Fig. 5) also demonstrates that *M2-LLR* performs considerably better than *M1* for any value of E_T and the investigated threshold. Nevertheless, *M2-SNR* is really superior to *M1* when E_T is high. This is consistent with the remark in section 2 about the performance of evaluating the reliability of the received signal through *SNR* and *LLR*. For large values of E_T, *M2-SNR* really performs well because of the dominance of the first term in (4) over the second one. Otherwise, the noise term n_R plays an important role and the wrong decision can be made if ignoring it. Therefore, *M2-LLR* which considers both terms shows its advantage under any condition of threshold as well as E_T. Moreover, it is realized that *M2-LLR* attains better performance than *M2-SNR* with the energy savings of 2dB at any target BER.

4. Conclusion

LLR is an efficient measure for evaluating the reliability of a signal. Its application in *DFP* illustrates that the LLR-based *DFP* dramatically outperforms SNR-based *DFP* and threshold-free *DFP* (*M1*) under any scenario of BER threshold, relay position and transmit power. Therefore, *M2-LLR* which is very simple with high BER performance should be considered as a promising technical solution for cooperative communications in the future wireless relay networks to improve the quality of information transmission and extend the coverage area as well.

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