논문 09-34-02-04 한국통신학회논문지 '09-02 Vol. 34 No. 2

An Energy Saving Cooperative Communications Protocol without Reducing Spectral Efficiency for Wireless Ad Hoc Networks

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ABSTRACT

Spectral efficiency of current two-phase cooperative communications protocols is low since in the second time the relay forwards the same siganl received from the source to the destination, the source keeps silent in this time. In this paper, we propose a novel cooperative communications protocol where the signal needed to transmit to the destination is sent in both phases, the source and the relay also transmit different signal to the destination thus no loss of spectral efficiency. This protocol performs signal selection based on log-likelihood ratio (LLR) at relay and maximum likelihood (ML) detection at destination. While existing protocols pay for a worse performance than direct transmission in the low SNR regime which is of special interest in ad hoc networks, ours is better over the whole range of SNR. In addition, the proposal takes advantages of bandwidth efficiency, long delay and interference among many terminals in ad hoc network. Simulation results show that the proposed protocol can significantly save total energy for wireless ad hoc networks.

Key Words : Cooperative communications, Selection relaying, LLR, ML, Rayleigh Fading

Ⅰ. Introduction

Spatial diversity due to the feasibility of deploying multiple antennas at both transmitter and receiver is very efficient in mitigating the fading in wireless communications[1]. However when wireless terminals may not be able to support multiple antennas due to size and power limitations or other constraints, this diversity technique is not exploited. To overcome such a restriction, cooperative communications was proposed to allow single-antenna terminals to gain some benefits of transmit diversity[2]. The philosophy is that a relay in wireless networks can assist information transmission of a source to a destination. Therefore, the destination will receive the transmitted information more reliably since from statistical viewpoint, the probability that all channels to the destination are deeply faded is significantly reduced. In addition, the cooperative communications can extend coverage range thank to path-loss reduction[3].

Some two-phase cooperative communications protocols were proposed in [2] where the source sends its data in the first phase and then the relay processes the received signals before forwarding to the destination in the second phase, leading to low spectral efficiency. In order to obtain the same spectral efficiency as direct transmission, the source must use higher-level modulation, causing a poor performance in the low signal-to-noise ratio (SNR) regime[2][4].

We propose a novel protocol which has a significant performance improvement over the whole range of SNR. This protocol allows the source to transmit the data consecutively in both phases, thus no loss of spectral efficiency. At the relay, it processes the received signals with the selection relaying protocol [2] and at the destination, the maximum likelihood detection technique is applied to recover the source data.

※ 이 논문은 2007년도 정부(과학기술부)의 재원으로 한국과학재단의 지원을 받아 수행된 연구임 (No. R01-2007-000-20400-0).

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논문번호 : KICS2008-09-394, 접수일자 : 2008년 9월 3일, 최종논문접수일자 : 2008년 12월 03일

Selection relaying (SR) means that the relay must make a decision on whether or not to detect and forward source data to the destination. Different performance criteria for making decision at the relay were mentioned. In [5] cyclic redundancy check (CRC) is used but causes a waste of transmission bandwidth due to redundant information insertion. A more commonly alternative criterion eliminating this waste is SNR or square amplitude of path gain[2][4]. In SNR-based SR, only received signals with quality exceeding a pre-determined threshold are detected and retransmitted to the destination.

Since SNR-based SR only relies on instantaneous fading level to decide retransmission without accounting for instantaneous noisy level at the relay, it reflects partially characteristics of received signals. Recently, we proposed log-likelihood ratio (LLR) in place of SNR and verified that LLR-based SR can outperform SNR-based SR with a gain of 2dB[6]. Therefore, we only consider LLR-based SR in this paper.

An ad hoc network is a self-organized and distributed entity, consisting of a number of mobile stations (MSs) without the coordination of any centralized access point[7]. Such a network can be used in situations where either there is no other wireless communication infrastructure present or where such infrastructure can not be used. MSs typically operate on battery, which means their consumed energy is extremely constrained. Hence how to minimize the average transmission energy is very important. In addition, reducing MSs' size is essential due to cost. It is obvious that the second problem can be solved with the cooperative communications (see the first paragraph). So can the first problem because once bit error rate (BER) performance is improved through spatial diversity, consumed energy to obtain a target BER can be naturally saved. In summary, the application of cooperative communications in ad hoc networks is very appropriate to fulfill the constraints of energy and size. Moreover, some problems in ad hoc networks such as interference among many terminals, long delay, bandwidth efficiency is solved with advantages of our proposal.

Ⅱ. System model

2.1 System Model

Consider cooperative communications in a dual-hop wireless ad hoc network where information is transmitted from a source S to a destination D with the assistance of a relay R as shown in Fig. 1. All MSs equipped with single antenna transceivers and sharing the same frequency band are under investigation. In addition, each MS does not transmit and receive signal at the same time to mitigate implementation complexity since considerable attenuation over wireless channels and insufficient electrical isolation between transmit and receive circuitry make a MS's transmitted signal dominate the signals of other MSs at its receiver input.

Assuming that channels between MSs experience independent slow and frequency-flat Rayleigh fading, i.e., they are constant during an N-symbol frame but change independently to the next. Without loss of generality, we only illustrate the analysis for the first data symbol of each frame. Because of slow fading, accurate channel estimation is possible at receivers[8]. Thus, we will assume perfect channel-state information (CSI) at all the respective receivers but not at the transmitters.

To capture the effect of path-loss on BER performance, we use the model [9] where the variance of h_{ij_p} is given by $\lambda_{ij} = K/d_{ij}^{\eta}$. Here h_{ij_p} and d_{ij} denote the path gain and distance between transmitter i and receiver j, respectively, p the frame index, η the path-loss exponent and K a constant that depends on the environment; $i \subset (S,R)$ and $j \subset (R,D)$ hereafter.

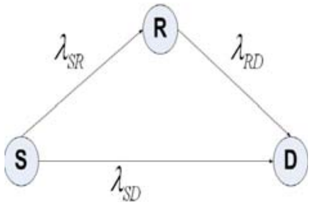

Fig. 1. Cooperative system model

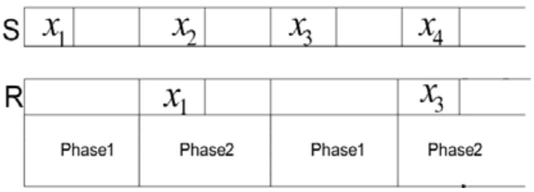

Fig. 2. Data sequence of S and R

For convenience of presentation, we utilize discrete-time complex equivalent base-band models to express all signals. In addition, we only consider binary phase shift keying (BPSK) modulation (i.e., modulated symbols take on values +1 and -1).

The cooperative communications is repeated every two symbols (or frames) as shown in Fig. 2. In the first symbol duration, S broadcasts a symbol x_1, so the signals received at R and D are given by

$$y_{D_1} = h_{SD_1}\sqrt{E_S}x_1 + n_{D_1} \tag{1}$$

$$y_{R_1} = h_{SR_1}\sqrt{E_S}x_1 + n_{R_1} \tag{2}$$

where y_{j_p} denotes a signal received at the terminal j, n_{j_p} a zero mean complex Gaussian noise sample with variance ζ_i at terminal j, E_i average symbol energy (ASE) of terminal i.

Now R processes the received signal according to the selection relaying protocol[2]. That means it checks whether received instantaneous BER is below a threshold BER γ_T. If this is the case, R detects and forwards the restored symbol x_1 to D in the next symbol duration. Otherwise, it keeps silent. The original symbol x_1 is recovered by maximum likelihood (ML) decoding as

$$x'_1 = sign(Re(h^*_{SR_1}y_{D_1})) \tag{3}$$

where γ_i is the received instantaneous BER at R and Λ is the LLR of x_1 which is given by $\Lambda = 4real(h^*_{SR_i}y_{R_1})\sqrt{E_S}/\zeta_R$. Both γ_i and Λ are found in [6].

In the second symbol duration, both S and R transmit data simultaneously to D. Assuming that their transmission is perfectly synchronized at D, the signal received at D is given by

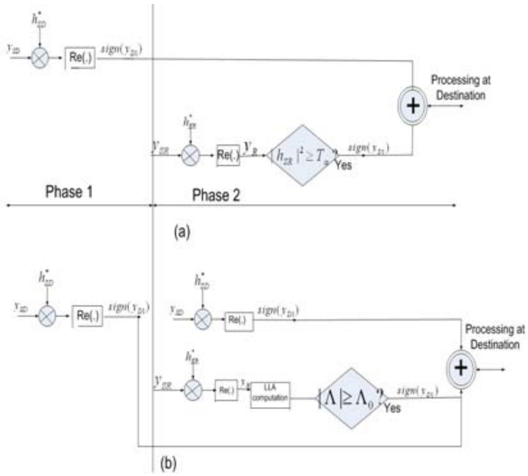

Fig. 3. Data sequence of select relaying. (a) Select relaying protocol in [2] (b) our proposed protocol

$$y_{D_2} = h_{RD_2}\sqrt{\widetilde{E}_R}x'_1 + h_{SD_2}\sqrt{E_S}x_2 + n_{D_2} \tag{4}$$

where $\widetilde{E}_R = E_R$ if (4) holds, otherwise $\widetilde{E}_R = 0$; x_2 is data symbol transmitted by S.

We assume that the presence of x'_1 or not in (5) is exactly known at D . Since S transmits data consecutively, the proposed protocol suffers no loss of spectral efficiency. This is a salient advantage of our proposal compared to the existing two-phase ones (e.g. [2] in which S is idle in the second symbol duration) considerably reducing the spectral efficiency. It also decreases long delay in network for waiting signal from the relay in each symbol.

Now if we expect that once (4) holds, R can recover the source symbol correctly (i.e., x'_1 in (5) is substituted by x_1), D can rearrange its received signals in both symbol durations in the vector form as

$$\begin{bmatrix} y_{D_1} \\ y_{D_2} \end{bmatrix} = \begin{bmatrix} \sqrt{E_S}h_{SD_1} & 0 \\ \sqrt{\widetilde{E}_R}h_{RD_2} & \sqrt{E_S}h_{SD_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{D_1} \\ n_{D_2} \end{bmatrix} \tag{5}$$

Maximum likelihood detection can be applied to (6) to jointly recover x_1 and x_2 as

$$\begin{bmatrix} \widetilde{x}_1 \\ \widetilde{x}_2 \end{bmatrix} = \arg\min \| Y - H\widetilde{X} \|^2 \tag{6}$$

where

$$\widetilde{X} = \left\{ \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} -1 \\ -1 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix} \right\} \tag{7}$$

2.2 Spectral Efficiency and Bandwidth Consumption

From [12], the spectral efficiency is calculated by the ratio of the number of symbol sending from the source and the number of needed time slots.

So in the direct transmission, each symbol is transmitted in different time slot so the spectral efficiency equals 1. In cooperative communication such as using AF at the destination, each symbol is transmitted in two time slots. So the spectral efficiency equal 1/2. Our proposal needs 2 time slots for transmitting 2 symbols. So spectral efficiency also equals 1.

Ⅲ. Numerical results and discussion

A network geometry is examined where R is located on a straight 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. Additionally, we only consider $\eta = 4$ and K=1.

Monte-Carlo simulations are performed to compare the BER performance of the proposed cooperative communications protocol with direct transmission. 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. Therefore, complying with this energy constraint requires:

$$2E_S + E_R = 2E_{DT} \tag{8}$$

Where E_{DT} is ASE of S in case of the direct transmission. Optimum selection of E_S and E_R is related to optimum energy allocation problem which is outside the scope of this paper. Therefore for simplicity, we examine the case that the ASEs of R and S received at D are equal, i.e.

$$E\left\{|h_{SD_2}\sqrt{E_S}\,x_2|^2\right\} = E\left\{|h_{RD_2}\sqrt{\widetilde{E_R}}\,x_2|^2 \,|\, \widetilde{E_R} = E_R\right\} \tag{9}$$

or

$$\lambda_{SD}E_S = \lambda_{RD}E_R \tag{10}$$

From (9) and (10), we can allocate the energy for S and R as

$$E_S = \frac{2D_{DT}}{2+\lambda_{SD}/\lambda_{RD}}, \quad E_R = \frac{\lambda_{RD}E_S}{\lambda_{RD}} \tag{11}$$

Note that the energy allocation according to (11) only depends on the long-term statistics of fading (i.e., variance of fading process), thus it can be done before the system comes to operation without increasing the implementation complexity. Assume that noise variances at R and D are equal $\zeta_R = \zeta_D = N_0$.

Fig. 4 displays BER via E_{DT}/N_0 for $\gamma_T = 10^{-1}$. We consider representative attenuation levels that correspond to those in which R is located either close to S, close to D, or equidistant from both; the corresponding d are 0.1, 0.9, and 0.5, respectively of all cases. It is observed that the proposed protocol outperforms the direct transmission for any relay position over the whole range of E_{DT}/N_0. It is also better than the system uses fix decode and forward or our proposal uses SNR based SR to decide forwarding signal to the destination. Specifically at the target BER of 10^{-3}, our protocol can save the total energy of around 2dB and 3dB in comparison to the direct

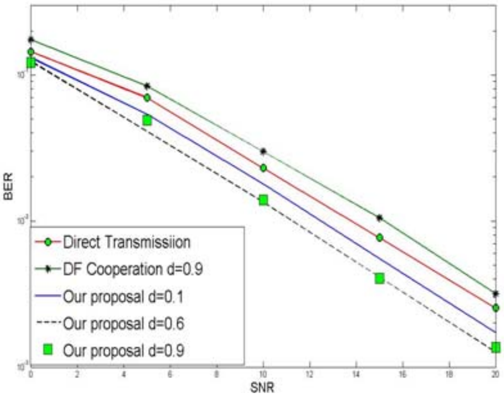

Fig. 4. BER performance of using cooperation and without cooperation

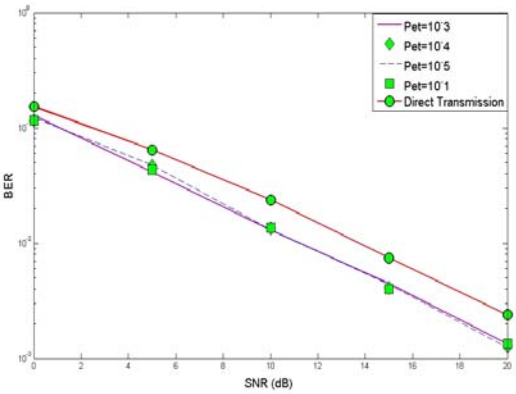

Fig. 5. BER performance of proposed protocol via threshold

transmission for $d=0.1$ and 0.5 (or 0.9), respectively. This is a remarkable advantage of our proposal besides its advantage of no loss of spectral efficiency compared to the existing protocols (e.g. [2][4]) which perform worse in the low E_{DT}/N_0regime and suffer the low spectral efficiency. Additionally, that the performance of the proposed protocol slightly changes with d makes a relay selection for cooperation relaxed. In other words, S can cooperate with any R to improve its performance.

The impact of the threshold on the performance of the proposed protocols is illustrated in Fig. 5 with $\gamma \subset (10^{-3}, 10^{-4}, 10^{-5})$ and $d=0.6$. For small considered thresholds, the proposed protocol performs almost in differently and always improves the performance of the direct transmission about 3 dB for any E_{DT}/N_0. As such, it is robust to the threshold selection.

Ⅳ. Conclusion

In this paper, we proposed a novel cooperative communications protocol together with the signal processing technique at the relay and the detection technique at the destination. Simulation results showed that the proposal significantly outperforms the direct transmission over the whole range of SNR without any loss of spectral efficiency. Although the operation of the proposed protocol is same as normal cooperative communication, it can obtain high bandwidth efficiency because it can transmit two useful signals instead of one signal at two time slots as cooperation. Therefore, it should be considered as a promising technical solution for cooperative communications in wireless ad hoc networks to save the transmission energy and extend the coverage area as well.

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