무선센서네트워크에서 순환부호를 사용한 사용자 협력에 관한 연구

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요 약

본 논문에서는 LEACH (Low-Energy Adaptive Hierarchy)를 사용한 무선센서네트워크에서 순환 부호를 사용하여 효율적인 사용자 협력 프로토콜을 제안한다. 제안한 시스템에서는 송수신단 간에 채널 상태 정보가 필요하지 않기 때문에 순환 부호를 부호화하는 것과 복호하는 것은 단순해지고 센서 노드의 처리 복잡도가 크게 줄어들 수 있다. 모의실험 결과를 통해서 순환 부호를 적용한 센서 네트워크는 단일 홉 전송의 비트오율 10^{-4}에서 네트워크 수명이 10dB까지 절약되는 것을 알 수 있었다.

키워드 : LEACH, 채널 상태 정보, 사용자 협력, 순환 부호, 무선센서네트워크

User-Cooperation and Cyclic Coding in Wireless Sensor Networks

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ABSTRACT

This paper presents an efficient user-cooperation protocol associated with cyclic coding for WSNs (Wireless Sensor Networks) using LEACH(Low-Energy Adaptive Clustering Hierarchy). Since the proposed user-cooperation requires no CSI(Channel State Information) at both transmitter and receiver, and encoding and decoding of cyclic codes are simple, the processing complexity of sensor nodes is significantly reduced. Simulation results reveal such a combination can save the network energy up to 10dB over single-hop transmission at BER of 10^{-4}.

Key Words : LEACH, CSI, User-cooperation, Cyclic Code, WSN

1. Introduction

High energy utilization efficiency is a stringent design criterion for WSNs since each sensor node (SN) must operate for several months on a single battery [1]. In addition, reliable communications over wireless channels which is a difficult problem due to fading is another requirement. The convolutional codes were proposed for forward error correction (FEC) in flat, slow Rayleigh fading channels [2]. However, they are inefficient because the average energy consumption per useful bit shows an exponential increase with the constraint length of the code and the complexity of Viterbi decoder is rather high. An alternative solution is to deploy user-cooperation (or cooperative communications) protocols [3-9] which enable nodes to use each other's antennas to obtain an efficient form of spatial diversity. This solution seems to be very appropriate in WSN scenario due to severe constraints on both node size and analog device power consumption.

There are three basic cooperative communications protocols: amplify-and-forward [3-5], decode-and-forward [3, 4, 7] and decode-and-reencode [4-5]. In general, they demand either CSI or complicated decoding algorithms and thus preventing from integrating to SNs. In this paper, we propose a simple cooperative protocol where no CSI is available at both transmitter and receiver. Moreover, the encoding and decoding of cyclic codes implemented by shift registers with very low cost and negligible hardware complexity [10] make these codes become a promising choice for FEC in WSNs. Therefore, it is easily realized that combining a new cooperative protocol with cyclic codes brings a considerable energy

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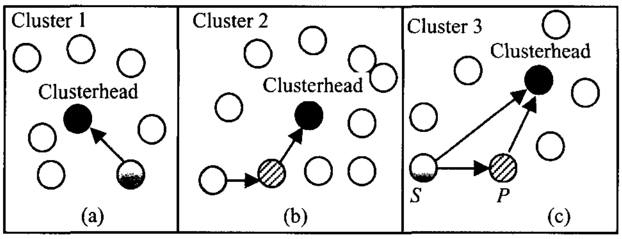
saving due to high BER performance.

The rest of this paper is organized as follows. In section 2, we present the proposed user-cooperation protocol associated with cyclic codes. The Monte-Carlo simulations are performed to verify its validity in section 3. Finally, the paper is concluded in section 4.

2. Cyclic coding and proposed user-cooperation

We investigate a typical communications protocol LEACH for WSNs [11]. This protocol divides a WSN into clusters with clusterheads each. The function of clusterheads is to assign the time on which the SNs can transmit data to them based on a TDMA (Time Division Multiple Access) approach and to aggregate data from the nodes in their cluster before sending these data to the base station. Therefore, the high energy dissipation in communicating with the base station is spread to all SNs in the WSN.



(a) Single-hop (b) Multi-hop (c) Cooperation
(Fig. 1) Clusters of wireless sensor network

Consider a certain cluster as shown in Fig. 1. The information sent from any SN can reach its clusterhead in the following ways:

1) *Single-hop communications*: SN sends its data directly to the clusterhead without the help of any intermediate node, namely partner.
2) *Multi-hop communications*: data transmission has to pass through several partners before reaching the destination. The partner's role is to simply decode the data it receives from the preceding node and again encode the message prior to retransmission to the next node. The destination detects the original data only based on the signal received from the last node (nearest to the destination). It is shown that this communications protocol can only extend range or save transmit power but achieves no diversity gain (diversity order of 1) [4].
3) *Cooperative communications*: this protocol is an extension of the multi-hop communications protocol where the receiver combines the data from the desired node and all its partners instead of only from the last partner as for the multi-hop communications protocol. A wide variety of cooperative communications protocols were proposed but a majority requires the channel estimation, leading to an additional increase in information processing energy. However, they can still bring many simultaneous advantages such as diversity gain, coverage extension, energy saving, etc. The maximum diversity order these protocols achieve equals the total number of cooperating nodes.

To make use of cooperative communications protocols most efficiently without sacrificing the information processing energy, a low-complexity protocol is needed which is our goal in this paper.

We assume that each SN is equipped with the encoder and decoder of cyclic codes, a BPSK modem, a single-antenna for both reception and transmission, and a perfect carrier-frequency and carrier-phase synchronizer (see (Fig. 2)).

2.1 Channel model

Assuming that the channels between SNs are independent. This is possible since the SNs' antennas are relatively far apart from each other. Moreover, all channels experience fast and frequency-flat Rayleigh fading[1)], i.e., the amplitude of path gain α_{ij} between transmitter i and receiver j is Rayleigh distributed (equivalently, α_{ij}^2 is exponential random variable with mean λ_{ij}^2) and the phase ϕ_{ij} has uniform distribution in the interval $[0, 2\pi]$, and they are constant during one code-chip period but change independently to the next.

2.2 Cyclic coding and proposed user-cooperation

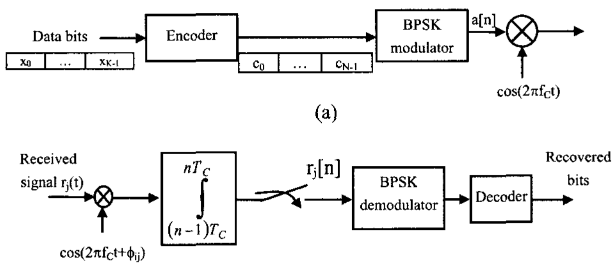
For simplicity of exposition, we only consider a pair of SNs communicating each other with the assistance of single partner. We also denote the transmitting SN as *S*, its partner as *P* and clusterhead as *D*. The proposed user-cooperation protocol consists of two phases.

In the first phase, S encodes a K-bit data block $(x_{K-1} \ldots x_0)$ with an (N, K) cyclic code to generate a N code-chip codeword $(c_{N-1} \ldots c_0)$. This codeword is BPSK-modulated and up-converted to the carrier frequency before sent over the channel in its own time slot (see (Fig. 2) (a)). Specifically, if the output signal of the modulator is $a[n]$ which takes on values +1 and -1 with equal probability where n denotes n^{th} code-chip interval, the transmitted signal corresponding to $a[n]$ is

1) For slow or block fading, a channel interleaver is required after the encoder and so symbols in the same codeword experience approximately independent fading. Thus, the assumption that the channels between terminals are independently fast is reasonable in general and easy for exposition without mentioning the interleaving mechanism.

$$s_S(t) = \sqrt{2P_S}\, a[n] \cos(2\pi f_C t) . p(t - nT_C) \quad (1)$$

where f_C is carrier frequency, $p(t)$ a unit-amplitude rectangular pulse with T_C-width, T_C the chip duration, P_S the average power of S.



(Fig. 2) Block diagram of sensor node (a) transmitter (b) receiver

At the same time, both P and D also receive the faded noisy versions of $s_S(t)$ as

$$r_j(t) = \sqrt{2P_S}\, \alpha_{Sj}[n] a[n] \cos(2\pi f_C t + \phi_{Sj}(t)) p(t - nT_C) + \eta_j(t) \quad (2)$$

where $\alpha_{ij}[n]$ is the fading amplitude caused by the channel between the transmitter i and receiver j; $\phi_{ij}(t)$ captures the fading phase and propagation delay; $\eta_j(t)$ represents additive white Gaussian noise (AWGN) with variance ρ_j at the receiver j; j=P or D.

Now, the signal processing at P and D works as follows. First, the received signal $r_j(t)$ is down-converted and integrated over a code-chip duration. The integrator output is then sampled every T_C, resulting in the following signal at the time instant nT_C

$$r_j[n] = \sqrt{2P_S}\, \alpha_{Sj}[n] a[n] + \eta_j[n] \quad (3)$$

where $\eta_j[n]$ is also Gaussian random variable with zero-mean and the same variance as $\eta_j(t)$. Exact phase and frequency synchronization has also been assumed in determining (3).

Second, for D it simply stores N values of $r_D[n]$, n=$0,\dots,N-1$, in the buffer. However, P has to perform much more signal processing. It continues BPSK-demodulating $r_P[n]$ to generate the estimated code-chip of c_n as (see (Fig. 2) (b))

$$\bar{c}_n = \begin{cases} 1 & , r_P[n] \ge 0 \\ 0 & , r_P[n] < 0 \end{cases} \quad (4)$$

Then, a block of N *recovered code-chips* $\bar{c}_n$, n=$0,1,\dots,N-1$, are fed to the cyclic decoding circuit. Its K output bits $\bar{x}_k$, k=$0,\dots,K-1$ is considered as input data of the partner which will be transmitted in its own time slot.

In the second phase, the partner sends the estimated data of S, $\bar{x}_k$, to the destination. Generating the transmitted signal at P is completely similar to that at S. That means $\bar{x}_k$ is passed through the blocks in (Fig. 2) (a). Therefore, P forwards the signal in (5) to the clusterhead as its turn is reached.

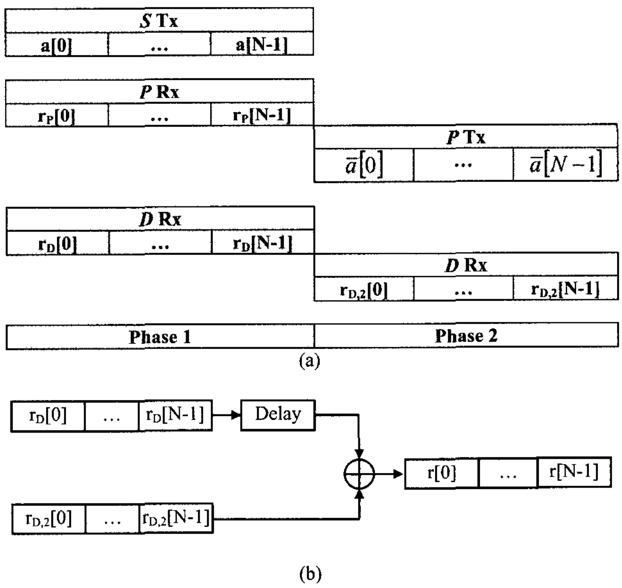
$$s_P(t) = \sqrt{2P_P}\, \bar{a}[n] \cos(2\pi f_C t) . p(t - nT_C) \quad (5)$$

where $\bar{a}[n]$ is n^{th} BPSK-modulated code-chip of the codeword generated by $(\bar{x}_{K-1} \dots \bar{x}_0)$; P_P represents the average power of P.

The above signal is also affected by the channel fading and AWGN at D. Similarly as in the first phase, we obtain the signal at the output of the sampler of D as

$$r_{D,2}[n] = \sqrt{2P_P}\, \alpha_{PD}[n] \bar{a}[n] + \eta_P[n] \quad (6)$$

where $\alpha_{PD}[n]$ is the amplitude of P-D path gain.



(Fig. 3) (a) Time diagram of receiving and transmitting at nodes in WSN (b) Combining technique at D. Tx: transmitting and Rx: receiving

Now, the clusterhead combines the signal received from S given in (3) which is available in its buffer, with that from its partner in (6) to detect each original chip-code c_n. In [7], the authors suggested the optimal and sub-optimal detectors but both require the knowledge of path gains α_{SP}, α_{SD}, α_{PD} which is hard to achieve precisely from the channel estimator. Moreover, adding such an estimator increases the complexity as well as the size of SNs and thus eventually, reducing the energy efficiency.

In order to overcome this problem, we propose a simple combiner without the channel state information at both transmitter and receiver (see (Fig. 3) (b)). This combiner simply takes a sum of those in (3) and (6); that is, its output is given by

$$r[n] = r_D[n] + r_{D,2}[n] \tag{7}$$

Such combining yields spatial diversity gain since under good S-P channel conditions the partner can decode correctly and resend versions of the original data over an uncorrelated channel to the clusterhead. In addition, we benefit from path-loss reduction: a partner located between S and D will receive the information transmitted by S much more reliably than the clusterhead, and in turn it needs to use a dramatically smaller transmit power to reach the clusterhead.

The samples $r[n]$, $n=0,\dots,N-1$ are passed through the demodulator (see (Fig. 2) (b)). The resultant signals are the estimated copies of the original c_n transmitted from S as

$$\hat{c}_n = \begin{cases} 1 & , r[n] \geq 0 \\ 0 & , r[n] < 0 \end{cases} \tag{8}$$

Then, the N code-chips of $(\hat{c}_{N-1} \dots \hat{c}_0)$ are packed into a block and fed to the decoder to restore the transmitted data $(x_{K-1} \dots x_0)$.

3. Simulation results

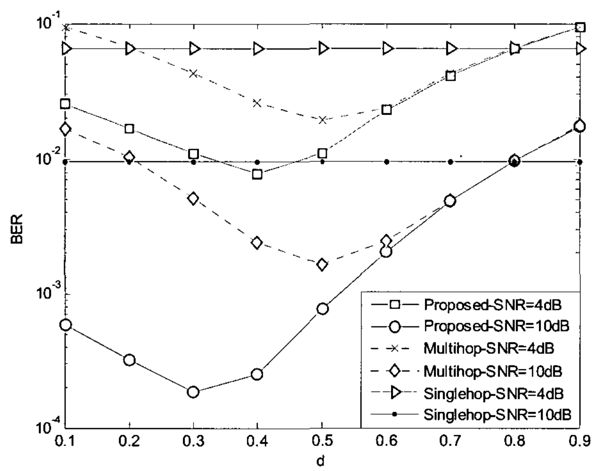
In this section, we investigate the performances of three communications protocols in a cluster as mentioned in section 2 through Monte Carlo simulations, and we limit the number of partners to *1*. In addition, all protocols are associated with the (23,12) cyclic Golay code of the generator polynomial [10, p. 434]: $g(p) = p^{11} + p^9 + p^7 + p^6 + p^5 + p + 1$. This code can correct up to 3 errors.

For a fair comparison, it is essential that the total consumed energy of the cooperative system does not exceed that of corresponding single-hop communications system. This is a strict and conservative constraint. Applying this energy constraint requires $P_S = P_P = P_T/2$ where P_T is total power of the system which is also the transmit power of SN in case of single-hop communications.

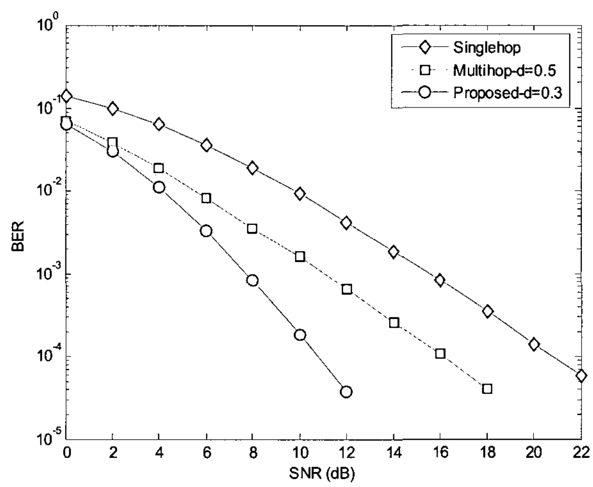
We set the noise variances at all nodes in the network to 1 and represents the axis of all presented Figs as the total signal-to-noise ratio $SNR = P_T/\rho$ *where* $\rho = \rho_R = \rho_D$.

To capture the effect of path loss on overall performance, we reuse the model as discussed in [9] where $\lambda_{ij}^2 = (d_{SD}/d_{ij})^\beta$ with d_{ij} being the distance between transmitter i and receiver j and β being the path loss exponent. For suburban environment, we have $\beta=3$ *[4]* and only this case is considered in the simulation. In addition, we assume the partner is located on a line between S and D; and the direct path length S-D is normalized to *1*. We also denote d as the distance between S and P.

(Fig. 4) studies the influence of the partner location on the performance of cooperative communications for two different values of SNR of 4dB and 10dB. The multi-hop communications is really better than the single-hop one only when the partner is placed in the interval [0.2, 0.8] while the proposed cooperative communications always outperforms the single-hop communications unless the



(Fig. 4) BER performance versus d



(Fig. 5) BER performance of communications protocols distance between P and S is greater than 0.8. (Fig. 4) also illustrates the optimal partner position for the multi-hop transmission is at the center of S-D line since it presents a good trade-off between good receive conditions for the partner and transmit power saving. Moreover, the cooperative protocol exposes its considerable superiority to comparable ones when it is closer to S and attains the best performance at roughly d=0.3.

(Fig. 5) compares the optimal performances of communications protocols via SNR. At the target BER of 10^{-4}, the user-cooperation can save the system energy up to 5.5dB and 10dB in comparison to the multi-hop and single-hop cases, respectively. In addition, energy saving keeps increasing proportional to the higher performance requirement, which is represented by the steeper slope of BER curve in the cooperative case than those in the other cases. This is because the cooperation benefits from diversity gain as well as from path-loss reduction.

4. Conclusion

A combination of simple cooperative protocol and cyclic coding increases a significant energy efficiency with negligibly increased implementation complexity for SNs. This was confirmed by simulations under the fast and flat Rayleigh fading. For block fading, the similar results can be obtained by simply supplementing an interleaver after the encoder. Energy saving the cooperation achieves is equivalent to prolonging sensor network lifetime and better satisfying the critical design condition of WSNs.

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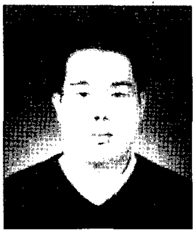

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