Code Combining Cooperative Diversity in Long-haul Transmission of Cluster based Wireless Sensor Networks

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Abstract

A simple modification of well known Low Energy Adaptive Clustering Hierarchy (LEACH) protocol is proposed to exploit cooperative diversity. Instead of selecting a single cluster-head, we propose M cluster-heads in each cluster to obtain a diversity of order M. The cluster-heads gather data from all the sensor nodes within the cluster using same technique as LEACH. Cluster-heads transmit gathered data cooperatively towards the destination or higher order cluster-head. We propose a code combining based cooperative diversity protocol which is similar to coded cooperation that maximizes the performance of the proposed cooperative LEACH protocol. The implementation of the proposed cooperative strategy is analyzed. We develop the upper bounds on bit error rate (BER) and frame error rate (FER) for our proposal. Space time block codes (STBC) are also a suitable candidate for our proposal. In this paper, we argue that the STBC performs worse than the code combining cooperation.

Keywords: Wireless sensor network, cooperative diversity protocol, LEACH, code combining, fading channel.

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1. Introduction

Transmit diversity techniques are getting popular to overcome the adverse effect of fading and to provide a reliable communication in wireless environment. The spatial diversity has received a great deal of attention in recent years as an efficient solution by deploying multiple antennas at both transmitter and receiver. However, it is impossible to apply this technique in wireless sensor networks, because sensor nodes may not be able to support multiple antennas due to power, size, cost etc [1]. To provide transmit diversity when users cannot support multiple antennas a new method of transmit diversity for mobile users termed as cooperative diversity focused on the cooperation of active users. When two users transmit their information cooperatively, a diversity order of two can achieve [2]. Various cooperative transmission protocols, their performance analysis and implementation issues have been studied in literature for example [2][3][4][5].

Unlike any other wireless networks, wireless sensor networks (WSNs) are structure less and highly energy limited. The total average power consumption in wireless sensor networks can be divided into two main components: transmission energy and processing-circuit energy. Therefore the conventional cooperative communication protocol may not applicable in WSNs for their extreme energy efficiency. It has been shown in [6] that virtual MIMO (Multi-Input Multi-Output) systems are more energy efficient than SISO (Single-Input Single-Output) systems in Rayleigh fading channels when both transmission energy and circuit energy consumption are considered. Various cooperative MIMO protocols for cluster based WSNs have also been proposed in literature [6][7][8][9]. They analyzed the energy and delay efficiency, synchronization among the nodes, propagation delay, modulation and coding aspects etc.

All these protocols proposed a cooperation in long haul i.e., cluster-head to sink node level communication. In [6] and [7], they proposed a virtual MIMO based cooperation where cooperative nodes (also termed as, cooperative-cluster-head or secondary nodes) form a cluster to exchange their information (termed as local communication) and they encode their information using STBC code for a long haul transmission. A STBC encoded cooperative transmission for LEACH based protocol has proposed in [7] and [8]. They proposed a conventional cooperative communication in cluster-head (CH) to data sink level where CHs collect information from all the nodes within the cluster and transmit them towards a group of cooperative nodes (or secondary cluster-head). These cooperative nodes then transmit using STBC structure to data sink.

In this work, we propose a cooperative LEACH protocol for wireless sensor network to exploit the spatial diversity in physical layer. Instead of using only one CH, we propose M CHs within a single cluster. Due to the broadcast nature of wireless transmission, it is possible for all CHs within a cluster to receive the same transmission. Then, M CHs cooperatively transmit towards the sink or higher layer CHs to obtain a diversity of order M. In the proposed cooperative LEACH protocol, we exploit the multi-hop transmission scenario which is different from the actual system model proposed for cooperative communication in [2][3][4][5]. We consider all the CHs of a cluster receive from the sensor nodes and generate a portion of codeword for cooperative transmission. The effect of adding an extra CCH on the network lifetime has been presented in [10]. The destination performs a code combining operation [18] to combine the signals from CHs. We avoid channel coding for local communication (sensor node to CH) to reduce the processing complexity of the system. The main focus of [10] is the diversity analysis and the system life time. In [10], we show that the proposed scheme can achieve full diversity which significantly improves the system life time compare to the conventional LEACH protocol. This work, on the other hand, focuses on the details of the implementation of the proposed code combining based scheme (section 3) and the derivation of closed form end-to-end BER and FER expressions (section 4).

The proposed cooperative LEACH protocol is also suitable for STBC based cooperative transmission as proposed in [6][7][8][9]. For same data rate and transmit power constraint both STBC encoded cooperative transmission and coded cooperation can achieve full diversity when local communication is perfect. In this paper, we also argue that STBC encoded cooperative transmission is highly sensitive with local communication error. If any one of the cooperative nodes fails to receive the source information correctly then it forces a wrong STBC decoding at destination. In code combining based cooperative transmission, there is a possibility to detect the information correctly, even though any one of the cooperative nodes fails to receive the source information. Therefore, our proposal performs better than STBC when local communication is vulnerable to error. The main Contributions of this paper are summarized as follows.

- The main contribution of this paper is to exploit cooperative diversity in the long-haul transmission of cluster based wireless sensor network. To do this, we propose multiple CHs in each cluster of the well known LEACH protocol. We also propose a code-combining based cooperative transmission scheme for the proposed cooperative LEACH protocol. A cooperative CH selection algorithm for the proposal is presented.
- We propose a practical implementation of the code-combining technique in wireless sensor network with convolutional codes. Proposed cooperative strategy requires only packet level synchronization [18] whereas, the conventional STBC based schemes [7][8][9] requires symbol level synchronization. Moreover, our results show that the proposed scheme outperforms the STBC based scheme.
- We analyze the diversity order of the proposed scheme through pairwise error probability. We also derive the upper bounds for the BER and FER of the proposed scheme. Simulations as well as numerical results are presented to show the effectiveness of the proposal.

For the rest of this paper, we consider only two CHs in a cluster ($M=2$) for simplicity, unless otherwise stated. This paper is organized as follows. In section 2 we describe the proposed cooperative LEACH protocol and the system model for our proposal. Section 3 describes the cooperative transmission strategy for our proposed system. Pairwise error probability and end to end error analysis is done in section 4. In section 5 we support our idea with some numerical simulations and finally we conclude this paper in section 6.

2. System Description

The first order radio model, proposed in [11], shows that radio electronics dissipates *50* nJ/bit to run the transmitter or receiver circuitry; whereas, transmit amplifier takes *100* pJ/bit/m^2 to achieve an acceptable signal to noise ratio. From these statistics, we can conclude that cooperation in sensor node to CH communication is completely inefficient. Because, it doubles the radio circuitry power dissipation even the same transmit power is maintained. Moreover, diversity is much needed at CH to destination channel where transmission is more vulnerable to fading and path loss. This point encourages us to propose a cooperative system model in this section that exploit transmit diversity in CH to destination level.

2.1. Protocol Description

The proposed cooperative LEACH protocol also operates in round by round fashion and each round has same three phases as LEACH protocol proposed in [11]. (Interested reader can find the details of the LEACH protocol in [11].) We propose some modification in second and third phase to select an additional CH that we termed as Cooperative-Cluster-Head (CCH). The advertisement phase of our proposed protocol is same as LEACH protocol. In the following, we describe the cluster formation and cluster setup including CH and CCH selection algorithms.

Cluster-head selection: Similar to LEACH protocol, each node decides whether or not to become a CH for current round. This decision is based on a prior percentage of CHs for the network and the number of times the node has been a CH so far [11]. After making this decision each node that has elected itself as a CH for the current round broadcasts an advertisement message to the rest of the nodes.

Cluster Setup: After receiving the advertisement messages, each non-CH node decides the cluster to which it will belongs, for this round. This decision is taken based on the received signal strength of the advertisement massage.

Cooperative Cluster-head Selection: The proposed cooperative CCH selection algorithm can be explained through the following steps

Step 1: At the end cluster setup, each node informs the selected CH node that it will be a member of the cluster as well as the node is a candidate to become a CCH or not. The decision to become a CCH is simply based on the number of times the node has been a CCH so far. This decision is same as the decision made for CHs selection in LEACH [11]. The overhead of this procedure is just transmitting one extra bit along with the cluster joining packet.

Step 2: The CH node receives cluster joining packets from nodes that want to be a member of the cluster.

Step 3: The CH selects a CCH from the interested candidates based on the received signal strength of cluster joining packets. The CH selects a CCH which has the highest signal strength (i.e., located in minimum communication distance) from the CH node. When there is no candidate for CCH within the cluster, The CH selects a CCH only on the basis of the received signal strength. If a pair of CH/CCH is in the same place or very close to each other (less than the half wave length) then the system will not achieve full diversity gain. Cluster-head can avoid this situation by setting a predefined threshold value of the received signal strength while selecting CCH.

Step 4: Depending on the number of nodes in the cluster, the CH creates a TDMA schedule and sends this schedule to CCH and all other sensor nodes. At the same time CH informs the selection of CCH and synchronization information for data processing and long haul transmission. The overhead of this procedure is about transmitting few extra bits along with the TDMA schedule. The major advantage of the proposed coded transmission scheme is CH and CCH do not need symbol level synchronization for long-haul transmission whereas, STBC encoded cooperative transmission requires strict symbol level synchronization. Proposed scheme only requires packet level synchronization to transmit the sub-packets N_1 and N_2 as explained in section 3. Such packet level synchronization requires only TDMA scheduling. Therefore, the overhead requires to achieve packet level synchronization is very small.

Data transmission: During steady-state phase of cooperative LEACH protocol, sensor nodes start transmitting data. Due to the broadcast nature of wireless transmission, both CH and CCH receive these transmissions. Similar to LEACH protocol, we consider all the sensor nodes transmit their information in different time slot allocated by the CH. We also consider that neighboring clusters are using different orthogonal channel to avoid the inter cluster interference. After receiving information from all sensor nodes, both CH and CCH transmit them to sink node using the proper signaling structure of cooperative communication. In this paper, we consider a code combining based cooperative protocol which is explained in the next subsection. All kinds of signal processing at CH nodes like, data fusion are beyond the scope of our physical layer analysis. Consequently, we avoid these processing in this paper. It is straight forward that additional signal processing does not affect our protocol when both CH and CCH use the same signal processing techniques.

2.2. System model

Fig. 1 shows a cooperative LEACH protocol based wireless sensor network that can achieve spatial diversity in long haul data transmission. Each cluster has two heads (CH and CCH); therefore, we can compare our system model with LEACH protocol in two ways. Assume both LEACH and Cooperative LEACH environment has same number of sensor nodes. First, the number of clusters in cooperative LEACH based system is half of the LEACH based protocol. Hence, the number of nodes within a cluster is also double here. This effect results a larger size of clusters in proposed cooperative LEACH which increases the average local communication distance $d_{CL,local}$ compare with $d_{L,local}$. Here the subscript CL is used for cooperative-LEACH and *L* is used for LEACH. This increment in $d_{CL,local}$ also increases the path loss of local transmission. To make an exact comparison, we have to consider this extra path loss. To do this, we make an assumption that the clusters are circular in shape and the average local communication distance is equal to the radius of the circle. For a fixed network area of consideration, the relationship between the two local communication distances can be given as, $d_{CL,local} = \sqrt{2} \times d_{L,local}$. For relatively small cluster size this difference is minimal.

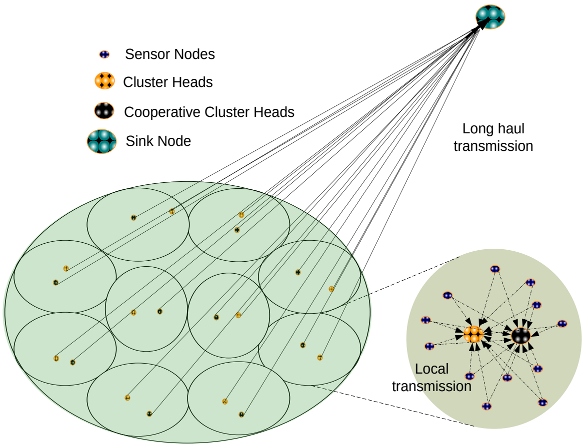


Fig. 1 System model of Cooperative LEACH protocol.

In other way, we can say that the numbers of CH in cooperative-LEACH is double than LEACH. Heinzelman et al in [11] also analyzes the percentage of CH with normalized energy dissipation. They showed that the optimal percentage of CH for LEACH protocol is 5% that dissipating about 16% of total energy. In our proposal, we consider 2 CHs in one cluster i.e. total CH becomes double. Hence, we need 10% CH to get the optimum performance that dissipate about 20% of total energy; therefore, we are only paying about 4% power overhead for cooperation (the approximated values of normalized total power are taken from figure. 8 of reference [11]). This power overhead is very small compare with diversity gain achieved by our proposal.

Another important point is spectral efficiency of the system. We consider the number of clusters in cooperative LEACH based system is half of the LEACH based protocol. Each cluster uses one orthogonal channel for coded cooperation based long haul transmission. As the number of clusters reduces in cooperative LEACH protocol, it also required a less number of orthogonal channels for long whole transmission. In proposed system model, the number of cluster is half in comparison with LEACH based system i.e., we need only half of the orthogonal channel. But the increase in sensor nodes in each cluster reduces the spectral efficiency of the system. Therefore the total utilization of communication resource for LEACH and Cooperative LEACH is same.

We consider a quasi-static multipath fading channel for both sensor node to CH (Local communication) and CH to sink node (Long haul communication). To take path loss into account, we can follow the same approach as [12] to model the variance of channel fading coefficient between node *i* and *j* as a function of distance between two nodes and given by

$$\sigma_{ij} = d_{ij}^{-a} \tag{1}$$

where α is so called pathloss exponent that vary from 2 to 6 on the basis of channel environment and d_{ij} is the distance between node *i* and *j*. Consider, each node has a single half duplex radio and a single antenna. The baseband equivalent received signal at node *j* owing to the transmission of node *i* for symbol *n* is given by

$$r_{ij}(n) = g_{ij}s(n) + \eta_j(n) \tag{2}$$

where $\eta_j(n)$ is AWGN noise sample with variance $N_0/2$ per dimension at terminal *j*, g_{ij} is fading coefficient between node *i* and *j*. $s(n)$ are BPSK modulated samples. In practical cases, CHs are very close to the sensor node in comparison with the distance from destination to CH so, it is realistic to assume that the fading effect in CH to destination channel is much severe than sensor node to CH channel. Throughout this paper, we consider multipath fading. In the signal model of Eq. (2) the fading coefficient (g_{ij}) represents the small scale multipath fading [14]. The variance of g_{ij} represents the distance dependent path-loss.

3. Cooperative Strategy

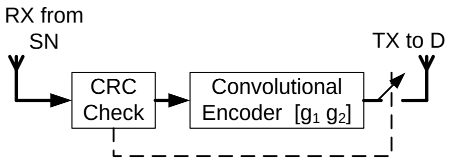
The main contribution of this paper is to exploit cooperative diversity in the physical layer to combat against the adverse effect of the channel fading. In this section, we describe the proposed cooperative strategy. We integrate the cooperative transmission with the channel coding which can achieve coding gain along with the diversity gains. In our proposal, we divide the whole codeword in two parts that are transmitted by CH and CCH. As a result, the sink-node achieves spatial diversity because the channels form CH and CCH to sink-node are independent fading channels. Moreover, instead of transmitting the same codeword from CH and CCH, the CCH transmits incremental redundancy to achieve coding gain. Due to this coding gain the proposed scheme outperforms the other STBC based cooperative schemes of [6][7][8][9].

The most popular cooperative communication protocols are Amplify-and-forward, decode-and-forward and coded cooperation. Among these protocols coded cooperation performs better [2] than others. Another interesting point of coded cooperation is that, it always performs better than direct transmission even in very low interuser and uplink channel SNR. This observation is very important in terms of wireless sensor network as it works in very low power transmission range. The major disadvantage of conventional coded cooperation [4] is that the processing at partner node is much complex than amplify-and-forward and decode-and-forward protocol. It required a Viterbi decoding to detect the partner's information. Since cooperative LEACH protocol does not require interuser transmission, we are free from this complexity of coded cooperation. Therefore, coded cooperation is the best choice for our system. In this work, we implement the coded cooperation by using the concept of code combining proposed in [18]. Code combining technique was proposed for combining several repeated codewords. In this paper we combine two different codewords to produce a lower rate code.

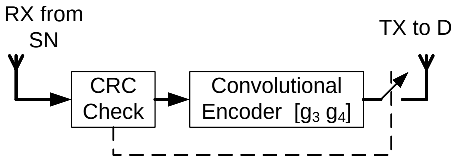
For the convenience of coded cooperation, we consider all the sensor nodes are equipped with convolutional encoder, cyclic redundancy check (CRC) encoder and decoder. Convolutional encoders are used only for long haul communication. Sensor nodes sense the environment and encode each event with a CRC encoder to check the reliability of the event at cluster-heads (CH and CCH). These CRC encoded events are transmit towards both CH and CCH in their own time slot. Both CH and CCH decode the information from all sensor nodes using maximum likelihood detection and check the reliability of the packet using CRC check. The CH and CCH also do some signal processing job like data fusion which is beyond the scope of our physical layer analysis. We consider they perform the same signal processing job; therefore, they have the same data to transmit towards destination. Conventional cooperative communication protocol can utilize the half of total allocated bandwidth due to their half-duplex operation. Our proposed protocol gives us the freedom of utilizing the full bandwidth; therefore, we can obtain higher order diversity with full rate.

Fig. 2 shows the block diagram of cooperative scenario among the CH, CCH and destination. For simplicity, we omitted the basic blocks of communication like modulator, demodulator, detector, channel estimator etc. The block diagram shows only the convolutional encoding and decoding blocks which is offering forward error correction (FEC) capability as well as the signaling structure of proposed cooperative transmission. In our cooperative strategy, we use a similar two frame structure proposed in coded cooperation protocol in [4] but the technique we used to generate two frames is different. Coded cooperation technique uses RCPC encoder to divide the total codeword (N) in two parts (N_1 and N_2) and these two part of the codeword are transmitted through independent fading channel to get spatial diversity.

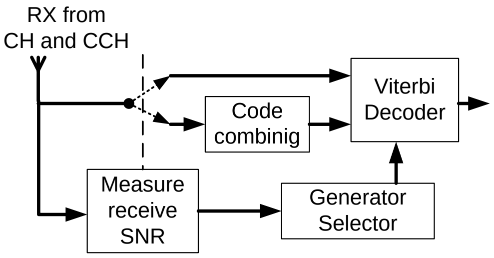
In this work, we proposed a different way to divide the total codeword in two parts. First we divide the generator polynomial G of our desired code in two parts G_1 and G_2. Assign these two parts of generator polynomial to CH and CCH, respectively. Cluster-head encode its gathered data using generator polynomial G_1 to generate N_1 and send toward the destination. Similarly, cooperative-cluster-head encode its gathered data using generator polynomial G_2 to generate N_2 and send toward the destination. Consider CH and CCH are transmitting on orthogonal channel, so that destination can separately detect two frames without interference. In this paper, we consider time division multiplexing for CH and CCH. Destination performs a code combining operation [18] to combine these two parts of codeword from CH and CCH. Finally, a maximum likelihood Viterbi decoding is done on the combined codeword to decode the transmitted signal from CHs. An example based on figure 2 will clarify the idea. First we chose a code with rate 1/4 with generator $G=[g_1\ g_2\ g_3\ g_4]$. We divide the generator that yields two generator $G_1=[g_1\ g_2]$ and $G_2=[g_3\ g_4]$ of rate 1/2 . CH encodes its data using generator G_1 and produce codeword N_1 of rate ½ . Similarly, CCH encodes its data using generator G_2 and produce codeword N_2 of rate ½ . That is, total codeword with rate ¼ is divided into two parts and these two portions of codeword are transmitted from CH and CCH respectively to achieve a diversity of order *2*. The destination performs a code combining also known as Chase combining [18] on two parts of the codeword which gives the codeword N with rate 1/4.



(a) Cluster-head



(b) CooperativeCluster-head



(c) Destination

Fig. 2 Block diagram of CH, CCH and Destination

On the basis of the CRC check results at CH and CCH, there are 4 possible cases for long haul transmission. Case-1: both CH and CCH successfully detect the information. In this case both CH and CCH transmit and destination performs code combining operation on receive signals to produce a 1/4 rate code corresponding to generator G. Case-2: only the CH successfully detects and the CCH failed to detect the information packet. In this case, the CH transmits and destination receives a 1/2 rate code corresponding to generator G_1. Case-3: only the CCH successfully detect and the CH failed to detect the information packet. In this case, the CCH transmits and destination receives a 1/2 rate code corresponding to generator G_2. Case-4: both CH and CCH fail to detect information block. In this case all the CH, CCH and destination remain silent during long haul communication.

The destination works independently and can be recognize which case has happened by measuring the instantaneous received SNR of the time slot of the CH and CH. The destination performs code combining before Viterbi decoding only for case 1. For other cases, it passes the received information directly to Viterbi decoder. Based on the received SNR destination selects the proper generator corresponding to each case as shown in **Fig. 2(c)**.

4. Performance Analysis

First, we consider the error probability of long haul communication. In this case, we use convolutional code as a forward error correction code. To develop Bit Error Rate (BER) and Frame Error Rate (FER) bounds, we employ the so-called pairwise error probability (PEP), the probability of choosing one symbol sequence over another for a given pair of possible transmitted symbol sequences. BER and FER of convolutionally coded sequence can be calculated by performing a weighted summation over all pairwise events.

4.1. Pairwise Error Probability

Assume Viterbi decoder chooses the coded sequence $\hat{c} = (c_1, \hat{c}_2, \ldots, c_n)$ when the transmitted codeword was $c = (c_1, c_2, \ldots, c_n)$, given that these are the only two possible choices. The PEP for convolutionally encoded a BPSK modulated signals conditioned on instantaneous signal to noise ratio (SNR) can be written as [14]

$$P(c \to \hat{c} | g) = Q\left(\sqrt{2 \sum_{n \in \eta} \gamma(n)}\right) \tag{3}$$

where the set η is the set of all n for which $\hat{c} \neq c$, $Q(x)$ is Gaussian Q function and $\gamma(n)$ is the instantaneous SNR of received signal at instance n.

We consider slow fading i.e., fading coefficients of each channel are constant over the channel coherent time. For linear codes the PEP depends on the Hamming distance d between c_n and $\hat{c}$ not on codewords. Total codeword N is recombination of N_1 and N_2 according to **Fig. 2**. So, we can assume that the hamming distance between transmitted and received codewords (c_n and $\hat{c}_n$) is divided over 2 frames as $d = d_1 + d_2$, where

$$\frac{d_1}{d_2} = \frac{N_1}{N_2}. \tag{4}$$

To calculate the end to end error analysis we have to consider all possible cases of long haul transmission.

Case-1: In this case the destination receives a codeword corresponding to generator G=[g_1 g_2 g_3 g_4] and two portion of the received codeword experience independent fading path. The conditional PEP of this case can be simply written as [15],

$$P(d | \gamma_1, \gamma_2) = Q\left(\sqrt{2d_1\gamma_1 + 2d_2\gamma_2}\right). \tag{5}$$

Here, γ_i is instantaneous signal to noise ratio (SNR) and defined as

$$\gamma_i = \frac{E}{N_0} |g_i|^2 \tag{6}$$

where *i* indicate two channels (for CH to destination channel, *i=1* and for CCH to destination channel, *i=2*), *E* is energy per coded symbol, N_0 is variance of white noise and g_i is instantaneous fading coefficient of *i*-th channel.

We can get the unconditional PEP over the pdf by averaging the equation (5). By following the same procedure as [4], we can find the exact unconditional PEP for Rayleigh distribution as

$$P(d)=\frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{d_1\bar{\gamma}_1}{\sin^2\theta}\right)^{-1}\left(1+\frac{d_2\bar{\gamma}_2}{\sin^2\theta}\right)^{-1}d\theta \tag{7}$$

where $\bar{\gamma}$ represents the average SNR of the corresponding links. Equation (7) is the exact expression of the unconditional PEP and can easily be evaluated with numerical integration technique. We can obtain the upper bound by setting $\sin\theta=1$ and performing the integration of (7) as

$$P(d)\le\frac{1}{2}\left(\frac{1}{1+d_1\bar{\gamma}_1}\right)\left(\frac{1}{1+d_2\bar{\gamma}_2}\right). \tag{8}$$

In (7) and (8), PEP is inversely proportional to the product of link average SNR values of the channels. Since there are 2 statistically independent channels, a diversity of order 2 is achieved when d_1 and d_2 not equal to zero.

Case-2: In this case the destination receives a codeword corresponding to generator G=[g_1 g_2]. The conditional PEP of this case can be given by

$$P(d|\gamma_1)=Q\left(\sqrt{2d_1\gamma_1}\right). \tag{9}$$

We can obtain the unconditional exact PEP and upper bound similar to (7) and (8) as

$$P(d)=\frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{d_1\bar{\gamma}_1}{\sin^2\theta}\right)^{-1}d\theta \tag{10}$$

$$P(d)\le\left(\frac{1}{1+d_1\bar{\gamma}_1}\right). \tag{11}$$

In this case a diversity order of 1 is also achieved.

Case-3: only the CCH successfully detect and the CH failed to detect the information packet. In this case destination receives a codeword corresponding to generator G=[g_3 g_4]. The unconditional exact PEP and upper bound for this case is similar with case-2 with d_1 and $\bar{\gamma}_1$ replace by d_2 and $\bar{\gamma}_2$,

$$P(d)=\frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{d_2\bar{\gamma}_2}{\sin^2\theta}\right)^{-1}d\theta \tag{12}$$

$$P(d) \leq \left(\frac{1}{1+d_2\bar{\gamma}_2} \right). \tag{13}$$

Case-4: both CH and CCH fail to detect information block. In this case, there is no long haul transmission i.e,

$$P(d) = 1. \tag{14}$$

4.2. Bit and Frame Error Rate

For a code having rate 1/n with Viterbi decoder the error event probability for case C = {1, 2, 3, 4} can easily be calculated using the well known Viterbi's upper bound as [15]

$$P_E(\gamma, C) \leq \sum_{d=d_{free}}^{\infty} a_d P(d|\gamma, C) \tag{15}$$

where d_{free} is the free distance of the code and a_d is the number of error evens with Hamming distance *d*. Conditional Frame Error Rate (FER) probability in terms of error event probabilities of a decoded block of length *B* can be calculated using the approach of [16] as

$$\begin{aligned} P_{FER}(\gamma, C) &\leq 1-(1-P_E(\gamma, C))^B \\ &\leq BP_E(\gamma, C) \\ &\leq B \cdot \sum_{d=d_{free}}^{\infty} a_d P(d|\gamma, C) \end{aligned} \tag{16}$$

where a_d is the information error events on all paths with $d \geq d_{free}$. The conditional Bit Error Rate (BER) of case C = {1, 2, 3, 4} is also can be calculated using Viterbi's upper bound for bit error probability [15] as

$$P_{BER}(\gamma, C) \leq \sum_{d=d_{free}}^{\infty} c_d P(d|\gamma, C) \tag{17}$$

where c_d is the information error weight on all paths with $d \geq d_{free}$.

To find the unconditional BER and FER, we can simply use the unconditional PEP $P(d)$ calculated in section 4.1. This approach gives a sufficient tight bound for fast fading case but for slow fading case this bound is very loose. For slow fading case, we use the limit before averaging technique introduced in [16] as

$$P_{FER}(C) \leq \int_{\gamma} \min[1, P_{FER}(\gamma, C)] \cdot p(\gamma) d\gamma \tag{18}$$

$$P_{BER}(C) \leq \int_{\gamma} \min\left[\frac{1}{2}, P_{BER}(\gamma, C)\right] \cdot p(\gamma) d\gamma \cdot \tag{19}$$

To evaluate equation (18) and (19) the order of integration and summation cannot be changed and a two-fold integration has to be carried out since we use two independent fading channels to transmit the entire codeword.

4.3. End-to-end error analysis

End-to-end error analysis is dependent on both local communication and long haul communication. In the previous subsection, we derive the error probability of long haul communication condition on four possible cases. Now we need to calculate the probability of individual cases C = {1, 2, 3, 4}. In our proposed protocol CH and CCH forward information on the basis of the frame error at local communication. So the probability of each individual case is a function of frame error rate at both CH and CCH. Bit error rate of a simple fading channel (local communication is considered as simple fading channel) is available in literature. We develop a relationship between bit error rate and frame error rate to calculate the probability of all possible cases.

Bit error probability for a BPSK modulated fading channel is given in [13] as

$$P_b(\gamma_l) = Q(\sqrt{2\gamma_l}) \tag{20}$$

where γ_l is the local communication SNR. Now, the relationship between conditional BER and FER of local communication can be given as

$$P_f(\gamma_l) = \sum_{k=1}^{B} \binom{B}{k} (P_b(\gamma_l))^k (1 - P_b(\gamma_l))^{B-k}. \tag{21}$$

To get the unconditional FER, we need to average the equation (21) over the pdf of fading coefficient as,

$$P_f = \int_{\gamma_l} \sum_{k=1}^{B} \binom{B}{k} (P_b(\gamma_l))^k (1 - P_b(\gamma_l))^{B-k} p(\gamma_l) d\gamma_l \tag{22}$$

where *p(x)* is probability density function of *x*. One important point to note here, due to the minimization the order of integration and summation cannot be changed for slow fading case. For slow fading, the fading coefficients are constant over all the symbols of a packet. Consequently, the integration should be taken over many packets to get the average frame error probability. So, the order of integration and summation cannot be changed in (22). For the same reason the order of integration and summation cannot be changed in (18) and (19). This phenomenon is well explained in [16] and termed as limit before averaging approach. Now, we can find the probability of each individual cases and be express as,

Probability of case-1,

$$\Pr(C = 1) = \left(1 - P_f^{(ch)}\right)\left(1 - P_f^{(cch)}\right) \tag{23}$$

Probability of case-2,

$$\Pr(C = 2) = \left(1 - P_f^{(ch)}\right) P_f^{(cch)} \tag{24}$$

Probability of case-3,

$$\Pr(C=3)=\left(1-P_f^{(cch)}\right)P_f^{(ch)} \tag{25}$$

Probability of case-4,

$$\Pr(C=4)=P_f^{(ch)}P_f^{(cch)} \tag{26}$$

here $P_f^{(ch)}$ is FER at CH and $P_f^{(cch)}$ is FER at CCH and can be calculated using equation (22).

Finally, the overall unconditional BER and FER is the average over the four possible case of transmission and given by

$$P_{FER}=\sum_{i=1}^{4}P_{FER}(C)\cdot\Pr(C=i) \tag{27}$$

$$P_{BER}=\sum_{i=1}^{4}P_{BER}(C)\cdot\Pr(C=i)\,. \tag{28}$$

5. Results and Discussions

We consider all sensor nodes have data of block size 128 bits. These data blocks are assumed as information events, we termed as frame. In our simulation, the performance measurement unit is frame error rate (FER) with respect to transmit SNR values i.e. rate of correct event received at destination. Similar analysis for bit error rate is also possible. For both local and long haul communication, we assume that the channels are subjected to a flat Rayleigh fading with additive white Gaussian noise (AWGN). AWGN noise is modeled as zero mean complex random variable with variance 0.5 per dimension. The fading coefficients between node *i* and *j* are modeled as uncorrelated samples of Rayleigh fading. The values are generated by zero mean complex random variables with variance $\sigma_{ij}/2$ per dimension where σ_{ij} is given in equation (1) with $\alpha=3$. We normalize the average distance between CHs and sink node (long haul distance) is equal to *1*. We assume the average local communication distance (distance from SNs to CH/CCH) is one tenth of the long haul communication distance (distance from CH/CCH to Sink node).

We use 1/4 rate convolutional code with polynomial generator G=(15 17 13 15). Eventually, the generator polynomial for CH is G_1=(15 17) and generator polynomial for CCH is G_2=(13 15). We chose this group of code because all G, G1 and G2 are best code in this group [13] i.e. has the maximum free distance. For sensor node to CH transmission, we consider an uncoded transmission. Throughout the simulation, we consider a flat slow fading. For both local and long haul communication channels, fading coefficients are constant over the transmission of one frame and identically independent from next. We also assume that perfect channel state information is available at each of the receiver so that a coherent detection is possible. The simulation parameters are summarized in **Table 1**.

We analyze the FER performance against CH to destination Channel SNR of our proposed protocol with LEACH protocol based direct transmission. For a fair comparison, we have to maintain equal total power transmission and data rate. Local communication is same for both LEACH based direct transmission and our proposal. In long haul communication, the CH of LEACH based direct transmission transmits a 1/4 rate convolutional code. On the other hand, in our proposed cooperative LEACH protocol, CH and CCH divide the 1/4 rate codeword in two equal parts as shown in **Fig. 2**.

Table 1. Simulation Parameters

Nodes	100
Normalized Network size	1 × 1
Normalized Average d_{local}	0.1
Normalized Average d_{long}	1
Pathloss Exponent	3
Packet size	128 bit
Percentage of CHs	10%
Convolution code Polynomial in octal	G = (15 17 13 15). G_1 = (15 17). G_2 = (13 15).
CRC code polynomial in hexadecimal	15935
Modulation	BPSK
Number of rounds (repeat time)	10^6
Simulation tool	MATLAB

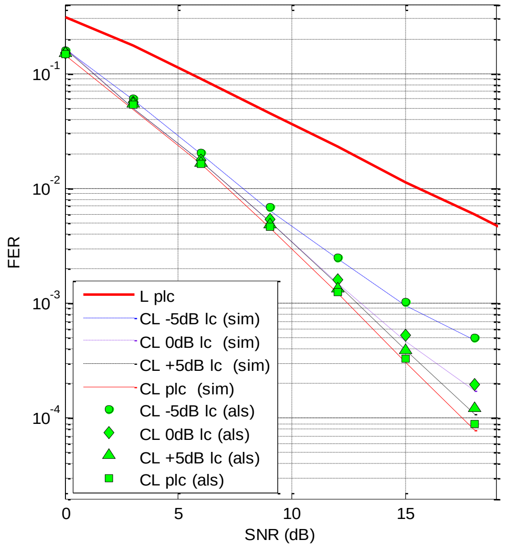


Fig. 3. FER performance comparison of our proposed protocol with conventional LEACH protocol.

Fig. 3 shows the performance of our proposed cooperative LEACH protocol with conventional LEACH protocol. With a perfect local communication (plc) our proposed protocol outperforms the conventional LEACH protocol. We also observe the effect on local communication channel condition. **Fig. 3** confirmed that, 5dB local communication (lc) channel performs very close to the perfect local communication. Performance of our proposal gets worse when local communication channel SNR degrades, but it is much better than LEACH based direct transmission even at -5 dB local communication SNR. In this figure, we also verify our simulation results with analytical FER computation. All the simulation results (sim) are evaluated through MonteCarlo simulation. The numerical simulation is used to evaluate the analytical results (als). The lines are the simulation (sim) results and the points represent the approximation found by numerical analysis (als). We truncate the simulations of equation (16) and (17) to the first 5 terms of a_d and c_d. We use MATLAB function ‘distspec’ to evaluate the values of a_d and c_d. In all cases the analytical approximations agree very well with the simulations. A similar result for BER performance is given is **Fig. 4**. From **Figs. 3** and **4**, we can say that the BER performance of the proposed scheme is exactly same with the FER performance except some scaling factor. Therefore, in the rest of our comparison, we only consider the FER performance.

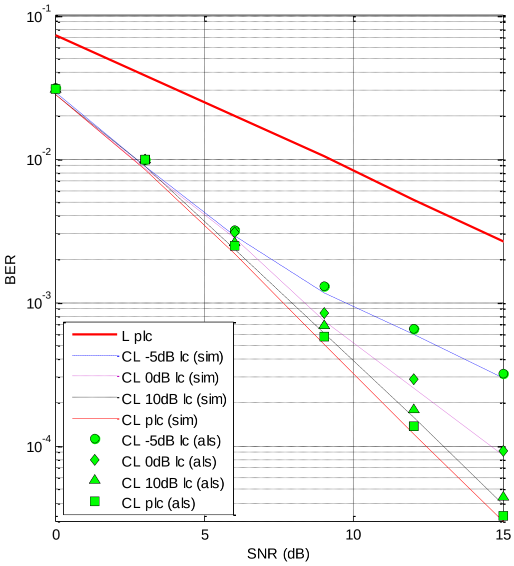


Fig. 4. BER performance comparison of our proposed protocol with conventional LEACH protocol.

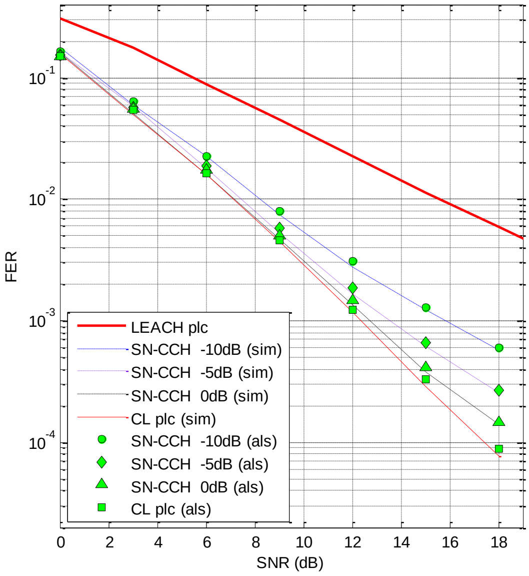


Fig 5. FER performance with CCH selection.

In our proposed cooperative LEACH protocol, the CCH selection is not optimal; because, CCH is selected by CH without considering the sensor node to CCH (SN-CCH) channel condition. On the other hand selection of CH is optimal, because, sensor nodes select a CH depending on the signal strength of advertisement phase. We observe the effect of changing sensor node to CCH channel condition while sensor node to CH channel is fixed at 5 dB (which is very close to perfect local communication). From **Fig. 5**, it can be observed that, at low SNR region, the performance is very robust with CCH selection. At the high SNR region, a 0 dB SN-CCH channel shows the BER performance is very close to the perfect local communication (plc) channel. That means a suboptimal selection of CCH offers almost same performance as optimal selection. When the CCH selection is very poor (-10 dB SN-CCH) BER performance is also much better than conventional LEACH based transmission. Hence, our proposed Cooperative LEACH protocol always performs better than LEACH based direct transmission. In all cases of this figure, the analytical approximations agree very well with the simulations results.

Our proposed cooperative Leach protocol is also suitable for Alamouti signaling structure [17] because both CH and CCH receive information from all sensor nodes at the same time. Therefore they can synchronize each other for STBC based transmission. The Alamouti scheme (2×1) is considered as lower bound for the transmit diversity [2] with two antenna when each antenna knows the information exactly. In this multi hop cooperative LEACH protocol, this assumption is not realistic, because, the local communication may not be perfect due to the adverse environment of the area where sensor nodes are deployed. In this paper, we argue that in noisy local communication environment, our proposed coded scheme for cooperation performs better than Alamouti scheme [17]. In Alamouti scheme, if any one of the CH or CCH fails to detect a frame from sensor node then destination also fails to receive that packet correctly; because, CH and CCH work independently. In our proposal, if any one of the CH or CCH receives sensor node's information correctly and long-haul communication channel is good then a correct detection at destination is possible.

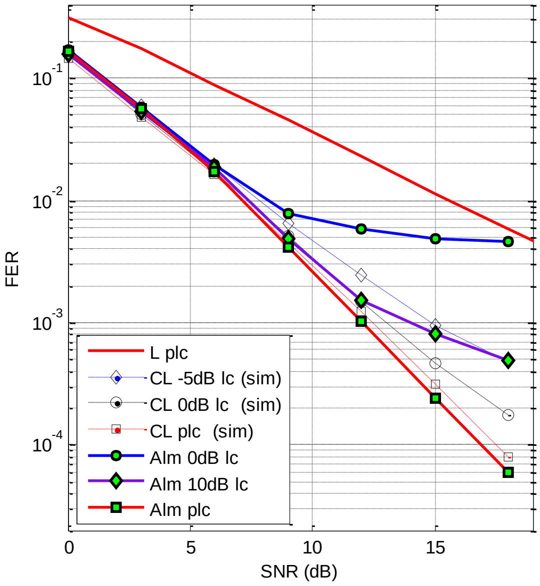


Fig. 6. Cooperative LEACH protocol with coded cooperation and Alamouti signaling

Fig. 6 shows the comparison between coded cooperation based transmission and Alamouti structure based transmission. For fair comparison, we consider both CH and CCH encode the information frame with a 1/4 rate convolutional code with generator G=[15 17 13 15] before transmission with Alamouti signaling structure. The solid lines represent the Alamouti signaling based cooperative LEACH and the dashed lines represent coded cooperation based cooperative LEACH. At perfect local communication (i.e., error free local communication channel) Alamouti scheme performs a little better than coded cooperation. But, this is not the case that happened in reality. In reality the local communications channel is also affected by fading and AWGN. For noisy local communication, coded cooperation performs much better than Alamouti scheme. Figure shows that Alamouti scheme with 10 dB local communication performs almost same as codec cooperation with -5 dB local communication.

6. Conclusions

In this paper, we proposed a novel cooperative wireless sensor network protocol. Proposed cooperative LEACH protocol can reduce huge energy consumption with same event error rate, spectral efficiency, data rate and delay requirements. Saving energy equivalently prolongs the network life time. We restrict our analysis for a diversity order of 2 i.e., we consider 2 CHs in a cluster. It is possible to increase the diversity order if we increase the number of CHs of a cluster, but in this case the normalized energy over head increases as the total number of CHs are increases. Performance analysis of the proposed scheme for $M > 2$ is left for future work. The proposed CCH selection technique is not optimal because this technique does not give a guaranty of having the similar link between SN to CH and SN to CCH. This is an open problem to find an optimal CCH. In this proposal, we only restrict our analysis on the physical layer to obtain transmit diversity. But a combination with other higher layer design criterion by including node mobility is a vast scope for further research.

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