A Design of Energy-Efficient Receivers for Cluster-Head Nodes in Wireless Sensor Networks*

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Abstract. In wireless sensor networks, embedded sensor nodes equipped with sensing, computation, and communication resources are generally constrained in energy supply. An efficient way to save energy of the network is to partition the network into distinct clusters with specific nodes called cluster-head. Since, however, higher level of energy consumption at cluster-head nodes might cause more damage to the network, energy-saving in cluster-head nodes is critical. In this paper, we propose an energy-efficient receiver for cluster-head nodes in two-tiered wireless sensor networks. The receiver performs multiuser detection and channel decoding jointly in a CDMA system, where information about channel codes is utilized for multiuser detection. This receiver exhibits improved performance of the sensor networks in terms of overhead, delay and power, and its excellent performance is shown via simulation.

1 Introduction

Recent advances in MEMS (micro electro-mechanical system) technology and embedded software have resulted in cheap and small devices with sensing, computing and wireless communication capabilities. A network of these devices could be utilized for information gathering and distributed sensing in many civil, military and industrial applications. The use of wireless medium for communication provides the network operating to convey collected information to a sink node without any fixed infrastructure. Wireless sensor networks pose many new challenges primarily because the sensor nodes are resource constrained, where sensor nodes are powered by small batteries that cannot be replaced [1]. Under this hard energy constraint, sensor nodes can only transmit a finite number of bits in their lifetime. Consequently, reducing the energy consumption per bit for end-to-end transmissions becomes an important design consideration for such networks. Since all layers of the protocol stack contribute to the energy per bit consumed in its end-to-end transmission, energy minimization requires a joint design of the underlying hardware where the energy is actually expended. Another efficient way to save energy of the network is to partition the network into

* This work is supported by the ubiquitous Autonomic Computing and Network Project, the Ministry of Information and Communication (MIC) 21st Century Frontier R&D Program in Korea, and the Research Grant of Kwangwoon University in 2005.

distinct clusters with specific nodes called cluster-head, which is the multi-tiered wireless sensor network. However, higher level of energy consumption at cluster-head nodes might cause more damage to the network since such cluster-head nodes also limit accessibility of other sensor nodes. Therefore, the energy-saving mechanism in cluster-head nodes is critical issue and determines the performance and lifetime of such networks [2].

We only consider the simplified case where interference is eliminated by using direct sequence code division multiple access (DS-CDMA) schemes. DS-CDMA is a popular choice as a multiple access scheme within a cluster of wireless sensor networks, where nodes are assigned different spreading codes. The transmitter of each sensor node sends its data by modulation with its own sequence. The conventional DS-CDMA receiver consists of a bank of matched filters to obtain nodes' data from the received signal. However, in multiuser detection (MUD) receivers, interference from the other signals is removed by subtracting it from the desired signal. This is possible because the correlation properties between the signals are known at the cluster-head node. MUD provides a means of reducing the effect of multiple access interference (MAI), and hence increases the system capacity [3]. The error correction capability of channel codes plays an important role in achieving performance improvement in noisy and interference-limited environments. Therefore, the transmitted data from sensor nodes to the cluster-head node are usually protected against errors due to MAI and noise by employing channel codes in DS-CDMA systems, as depicted in Figure 1.

Fig. 1. K -node Cluster System with MUD and Channel Codes

New design approaches for MUD that include the consideration of channel codes were proposed in [4], where MUD provides soft outputs including reliability measurements to the channel decoder. Joint detection-decoding (JDD) receivers have been proposed recently to improve the performance of receivers [5]. These JDD receivers repeat multiuser detection and error correction in an iterative manner. Therefore, the complexity of receiver increases linearly with the number of iterations and the complexity of each stage depends on the frame size of the channel codes. In [6], a JDD receiver was proposed employing multistage parallel interference canceller (PIC), where each stage utilizes convolutional codes for estimation and cancellation. Multistage PIC is known to be a simple and effective technique for mitigating MAI in DS-CDMA systems. However, its performance can be significantly degraded due to incorrect interference decisions that are subtracted from the received signal. It minimizes the effect of incorrect cancellation with the aid of convolutional codes, and also

decreases the computation complexity. Cluster-head nodes with such receivers have interference and noise reduction, so that the nodes can operate with less overhead and less latency. The remainder of this paper is organized as follows. Section 2 presents the concept of JDD receivers employing PIC and convolutional codes, and the analysis of the JDD receiver performance. The application of the receivers in wireless sensor networks is evaluated by simulation in Section 3. Finally, concluding remarks are given in Section 4.

2 Joint Detection-Decoding Receiver

MUD receivers jointly estimate the transmitted signals of all nodes in the system. A JDD receiver performs multiuser detection and channel decoding jointly, where information about channel codes is utilized during multiuser detection. Let us assume a DS-CDMA system employing channel codes, where a sequence of information bits $\mathbf{b}_k$ is encoded into the sequence of channel symbols $\mathbf{d}_k$ and the sequence of channel symbols is transmitted via the multiuser channel resulting in the matched filter bank output $\mathbf{y}_k$, for a node k . The outputs $\mathbf{y}_k$ include MAI due to the other $k-1$ nodes and are correlated over a frame of channel codes. Therefore, the symbol estimates $\hat{\mathbf{d}}_k$ from the matched filter bank output $\mathbf{y}_k$ can be jointly detected over nodes and decoded in time to obtain the information estimates $\hat{\mathbf{b}}_k$. The error correction capability of channel codes increases the probability of correct estimates of symbols by performing detection and decoding jointly. This, in turn, improves mitigation of MAI.

2.1 Multistage Parallel Interference Cancellation Receiver

Multistage parallel interference cancellation (PIC) receivers attempt to remove the MAI through signal processing at multiple stages for all nodes. They have much lower complexity than linear MUD receivers. As depicted in Figure 2, each stage of PIC receivers consists of two steps: estimation and cancellation, where estimates of all nodes' signals are generated and MAI for all nodes are constructed and canceled from the received signal based on the estimates. As the accuracy of the estimates improves through the multiple stages, the performance of receiver also improves [5].

The estimation step computes the estimates of symbols $\hat{d}_k(l|l-1)$ from the *a posteriori* signal of the previous stage $y_k(l-1)$ for a node k , where l is the number of stage. The estimates $\hat{d}_k(l|l-1)$ are treated as *a priori* information for the next stage. The cancellation step tries to remove MAI present in the node's signal $y_k(l)$ using the correlation matrix $\mathbf{R}$,

$$y_k(l) = y_k(0) - \sum_{i \neq k} \rho_{ik} \hat{d}_i(l|l-1) \quad (1)$$

The final decision is made based on the *a posteriori* signal of the last stage, $y_k(L)$. In a conventional multistage PIC receiver, the estimation step makes a hard decision on the *a posteriori* signal of the previous stage $y_k(l-1)$ to decide the estimate of

symbols $\hat{d}_k(l|l-1)$. However, this estimation step may lead to an incorrect decision that may cause an incorrect cancellation of interference. Such incorrect cancellation is propagated to the subsequent stages of the receiver. Therefore, the performance of multistage PIC receivers improves as the probability of correct decision on the estimates of symbols $\hat{d}_k(l|l-1)$ increases at each estimation step. In order to improve the performance of such receivers, JDD receivers that utilize channel codes at estimation steps are described in the next subsections.

Fig. 2. Multi-stage PIC Receiver

Performance evaluation of the JDD receivers is shown in [6]. These results show the obvious performance improvement of JDD receivers, where it is shown that the systems employing JDD schemes increase the user capacity remarkably or decrease the bit error rate.

2.2 Joint Detection-Decoding Receiver with Partial Decoding Information

The JDD receiver employs a generalized version of the decoding method in that it minimizes the probability of error in partial words consisting of one or more channel symbols. In the trellis diagram of the Viterbi algorithm, a path consists of states and branches representing state transitions. Each entire codeword $\mathbf{d}_k = [\mathbf{d}_k^{(1)}, \dots, \mathbf{d}_k^{(N+l)}] = [d_k^{(1)}, \dots, d_k^{(n(N+l))}]$ can be represented by a unique state sequence $\mathbf{S}_k = [S_k^{(0)}, \dots, S_k^{(t)}, \dots, S_k^{(N+l+1)}]$, where $S_k^{(0)} = 0$ and vice versa. The partial codeword $\mathbf{d}_k^{(t)} = [d_k^{((n-1)t+1)}, \dots, d_k^{(nt)}]$ corresponds to each state transition (branch) from the state $S_k^{(t-1)}$ at time $t-1$ to the state $S_k^{(t)}$ at time t , where $t=1, \dots, N+l$. Therefore, the entire codeword of channel symbols $\mathbf{d}_k$ and the partial codeword of channel symbols $\mathbf{d}_k^{(t)}$ correspond to the path and branches of convolutional codes, respectively. The

partial codeword $\mathbf{d}_k^{(t)}$ also contains partial decoding information about the transmitted symbols. It can reduce the complexity of the receiver at the expense of suboptimum decoding at estimation steps.

The estimation steps in the proposed JDD receiver employ $\mathbf{y}_k^{(t)}$, i.e., the *a posteriori* signal corresponding to the partial codeword of channel symbols $\mathbf{d}_k^{(t)}$. Then they obtain the estimates of the partial codeword $\hat{\mathbf{d}}_k^{(t)}$ based on the signal $\mathbf{y}_k^{(t)}$ and the probabilities of starting states $S_k^{(t-1)}$, and calculate the probabilities of ending states $S_k^{(t)}$ for the next signal $\mathbf{y}_k^{(t+1)}$. In [8], the probability functions are defined as

$$\begin{aligned} \alpha_t(s_t) &= \Pr\{S_k^{(t)} = s_t; \mathbf{y}_k^{(1)}; \dots; \mathbf{y}_k^{(t)}\} \text{ and} \\ \gamma_t(s_{t-1}, s_t) &= \Pr\{S_k^{(t)} = s_t; \mathbf{y}_k^{(t)} \mid S_k^{(t-1)} = s_{t-1}\}, \end{aligned} \quad (3)$$

where s_t and s_{t-1} are the states at time t and time $t-1$, respectively.

By the Markov property of convolutional codes as shown in Equation (5) of [8],

$$\alpha_t(s_t) = \sum_{s_{t-1}} \alpha_{t-1}(s_{t-1}) \gamma_t(s_{t-1}, s_t), \quad (4)$$

where the boundary conditions are $\alpha_0(0) = 1$, and $\alpha_0(i) = 0$ for $i \neq 0$.

The probability $\gamma_t(s_{t-1}, s_t)$ can be obtained from Equation (3),

$$\gamma_t(s_{t-1}, s_t) = \Pr\{\mathbf{y}_k^{(t)} \mid \mathbf{d}_k^{(t)}\} \cdot \Pr\{S_k^{(t)} = s_t \mid S_k^{(t-1)} = s_{t-1}\}, \quad (5)$$

where $\Pr\{S_k^{(t)} = s_t \mid S_k^{(t-1)} = s_{t-1}\}$ is the state transition probability defined as

$\Pr\{S_k^{(t)} = s_t \mid S_k^{(t-1)} = s_{t-1}\} = 1$, if there is a trellis transition from s_{t-1} to s_t , and $\Pr\{S_k^{(t)} = s_t \mid S_k^{(t-1)} = s_{t-1}\} = 0$, otherwise. From Equation (4), the MAP decoding problem on a state transition (branch) becomes the procedure to maximize the probability of the next state based on $\alpha_{t-1}(s_{t-1})$ and $\gamma_t(s_{t-1}, s_t)$,

$$\hat{S}_k^{(t)} = \arg \max_{s_t \in S} [\log \Pr(\alpha_t(s_t))] \text{ for } t = 1, \dots, N+l, \quad (6)$$

where S is the set of states, and s_t and s_{t+1} at time t and time $t+1$, respectively.

Finally, the estimates of partial code $\hat{\mathbf{d}}_k^{(t)}$ for $t = 1, \dots, N+l$ can be obtained as

$$\hat{\mathbf{d}}_k^{(t)} = \arg \max_{s_t, s_{t-1} \in S} [\log \Pr(\alpha_{t-1}(s_{t-1}) \gamma_t(s_{t-1}, s_t))] \text{ for } t = 1, \dots, N+l. \quad (7)$$

Once the estimates of partial codeword $\hat{\mathbf{d}}_k^{(t)}$ are obtained, they are fed to the cancellation step in the same stage to eliminate MAI. In the cancellation step, MAI is constructed using the correlation matrix $\mathbf{R}$ and partial codewords $\hat{\mathbf{d}}_k^{(t)}$ of nodes. Then the MAI is subtracted from the output of matched filter $\mathbf{y}_k^{(t)}$. These new output signals form the input to the estimation step in the next stage.

3 JDD Receivers for Cluster-Head Nodes in Sensor Networks

Two-tiered wireless sensor networks, where the network is partitioned into distinct clusters with specific nodes called cluster-head, usually uses CDMA technology for a

multiple access scheme as described in [9]. In such networks, the higher level of energy consumption at cluster-head nodes might cause more damage to the network since such cluster-head nodes also limit accessibility of other sensor nodes. Therefore, the energy-saving mechanism in cluster-head nodes is critical issue and determines

Fig. 3. Simulation Results of Receivers in Wireless Sensor Networks

the performance and lifetime of networks. The receiver of the cluster-head node within a dense cluster, however, suffers from MAI due to non-orthogonal PN codes. MAI in addition to noise causes the bit errors and results in frame retransmissions or information losses from sensor nodes. In the receiver of cluster-head nodes, MUD can be employed to eliminate MAI, while channel codes are utilized to cope with bit errors. Therefore, JDD receivers are expected to improve the performance of cluster-head nodes and decrease the number of bits to be delivered between a cluster-head node and its sensor nodes. As a result, the JDD receiver help such networks save the energy consumption in the delivery of sensed data from sensor nodes to the cluster-head node.

To evaluate the effectiveness of the receiver for cluster-head nodes, we perform simulations to compare the performance of different receivers with different multiple access schemes. Two types of multiple access schemes are evaluated; one is DS-CDMA and the other is TDMA. In particular, for a DS-CDMA system, the conventional receiver and the JDD receiver are compared. The main objective of the simulation is to compare the performance of three types of receivers in terms of average delay, average overhead and total energy consumption.

Experiments are performed on simulations with 100, 200, 300, or 400 sensor nodes randomly distributed in a 100×100 square meter area. Each sensor node is assumed to have data to send with 2-state MMPP (markov-modulated Poisson process) traffic. The maximum transmission range of the sensor nodes is set to 10m. It is assumed that the channel has AWGN (additive white Gaussian noise) and ARQ (automatic repeat request) scheme is employed to recover frame errors.

In order to capture the performance of different receivers and multiple access schemes we use the metrics, average delay, average overhead and energy consumption. Figure 3 shows the results about the average delay at the cluster-head nodes, the average overhead between sensor nodes and a cluster-head node, and the amount of energy consumption at the cluster-head node according to the number of nodes. It shows that CDMA systems outperform a TDMA system in terms of delay in cluster-head nodes. Furthermore, the CDMA system utilizing the JDD receiver has less average delay than the one with separate MUD and channel codes at cluster-head nodes. It also indicates the JDD receiver decrease the amount of average overhead remarkably between sensor nodes and a cluster-head node. As the number of nodes increases, however, the overhead amount of TDMA system becomes less. At last, the receiver with JDD dissipates less energy to forward data from sensor nodes to parent cluster-head nodes than other schemes due to less overhead and the low bit error rate.

4 Conclusions

In this paper, we have proposed a design of the receiver employing PIC and convolution codes, and its application to cluster-head nodes in multi-tiered wireless sensor networks. Utilizing the state-transition information of convolutional codes, our proposed approach estimates partial codeword of channel symbols corresponding to branches of state transition in convolutional decoding at each estimation step in PIC. We have evaluated the performance of the receiver and the performance of the wireless sensor network when the receiver is used for cluster-head nodes. It is shown that

the receiver outperforms the existing receiver when CDMA is used for a multiple access scheme. Furthermore, the receiver experiences much less delay than a TDMA scheme. In particular, the proposed JDD receiver is quite attractive when a number of users (nodes) exist within a cluster in terms of delay and energy consumption.

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