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Design of Energy-Efficient Wireless Sensor Networks Using Cooperative MIMO Techniques

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Abstract: To prolong the lifetime of wireless sensors network energy efficient transmission method is required so that energy consumption must be minimized while satisfying given throughput and delay requirements. In this context, we analyze the performance of cooperative multiple-input multiple-output (MIMO) based communication in wireless sensors networks. In this paper, we analyze the transmission method and best modulation to minimize the total energy consumption required to send a given number of bits. We then extend our energy efficiency analysis of MIMO system to individual single antenna nods that cooperate to form multiple antenna transmitters or receivers. We also show that over some distance ranges, Cooperative MIMO transmission and reception can simultaneously achieve both energy savings and delay reduction. Simulation results are included.

Keywords: Wireless Sensor Network (WSN), Cooperative multiple-input multiple-output, Energy efficiency, Alamouti diversity schemes.

1. INTRODUCTION

Recent hardware advances allow more signal processing functionally to be integrated into a fully functional wireless sensors node with small batteries. Such wireless nodes are deployment in many human inaccessible situations to provide a fast, reliable, fault tolerant, and energy-aware channel for monitoring applications [1]. Energy optimization is a critical issue in the design of low power, wireless sensors networks. Wireless nodes are operate with small batteries for which replacement, when possible, is a very difficult and very expensive. Thus, in many cases, the wireless node must operate without battery replacement for many years. Consequently, minimizing the energy consumption is a very important issue in design consideration and energy–efficient transmission schemes must be used for data transfer in wireless sensor networks. The total energy consumption includes both transmission energy and circuit energy consumption.

Motivated by information theoretic predictions on large spectral efficiency of Multiple-input multiple-output (MIMO) systems in fading channels [1]. It has been shown [1] that MIMO systems can support high data rates under the same transmit power budget, and bit error rate performance as a Single Input Single Output (SISO) systems. For the same throughput requirements, MIMO systems require less transmission energy than SISO systems. However, direct application of multiple-input multiple-output (MIMO) techniques to sensor networks is impractical due to the limited physical size of sensor node which typically can only support a single antenna. Therefore, by allowing individual single antenna nodes to cooperate on information transmission and reception, a cooperative MIMO system can be constructed such that Energy efficient MIMO schemes can be developed. Energy-efficiency consumption techniques typically focus on minimizing the transmission energy only, which is reasonable in long range applications where the transmission energy is dominant in the total energy consumption. However, in short range applications such as wireless sensor networks where the circuit energy consumption is comparable to or even dominates the transmission energy. The circuit energy consumption includes the energy consumed by all the circuit blocks along the signal path: Analog to Digital converter (ADC), Digital to Analog converter (DAC), Mixer, Frequency Synthesizer, Low Noise Amplifier (LNA), Power Amplifier, and baseband DSP. Some joint energy-minimizing techniques have been proposed for SISO systems in [2]-[6], where multimode operation with optimized system parameters is discussed.

The rest of this paper is organized as follows: In Section 2, model for MIMO system including energy consumption is discussed. In Section 3, MIMO with multi node cooperation is discussed. In Section 4, total energy consumption and total delay of cooperative MIMO systems are compares with that of non cooperative approach systems under the same throughput and bit error rate (BER) requirement. The energy efficiency is compared over different transmission distances with assumption that

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Alamouti diversity codes are used for MIMO systems. Section 5 summarizes our conclusion.

2. ENERGY EFFICIENCY OF MIMO SYSTEM

In this paper, Alamouti schemes are used to achieve diversity in the MIMO system. The Alamouti code with two transmit antennas, proposed in [8], as shown in Figure 1, uses two different symbols s_1 and s_2 that are transmitted simultaneously during the first symbol period from antennas 1 and 2, respectively , followed by signals $-s_2^*$ and s_1^* from antennas 1 and 2, respectively , during next symbol period. It has been shown [1] that for Raleigh fading channels MIMO system based on Alamouti scheme can achieve lower average probability of error than SISO systems under the same transmit energy budget due to the diversity gain and possible array gain (when $M_r > 1$) . In other words, under the same BER and throughput requirement, MIMO systems require less transmission energy than SISO systems.

2.1. Alamouti 2X1 Scheme

We consider a 2x1 MISO Alamouti scheme where H = $[h_1\ h_2]$.

The reference SISO system is treated as a special case of MISO systems with H = $[h_1]$. As shown in [1], the instantaneous received SNR is given by

$$\gamma_b = \frac{\|H\|_F^2}{M_t}\frac{\overline{E_b}}{N_o}, \qquad M_t = 1,2 \tag{1}$$

Where the M_t in the denominator comes from the fact that the transmit power is equally split among transmitter antennas. The average BER is given by [1]

$$\overline{P_b} = \varepsilon_H\left\{Q(\sqrt{2\gamma_b})\right\} \tag{2}$$

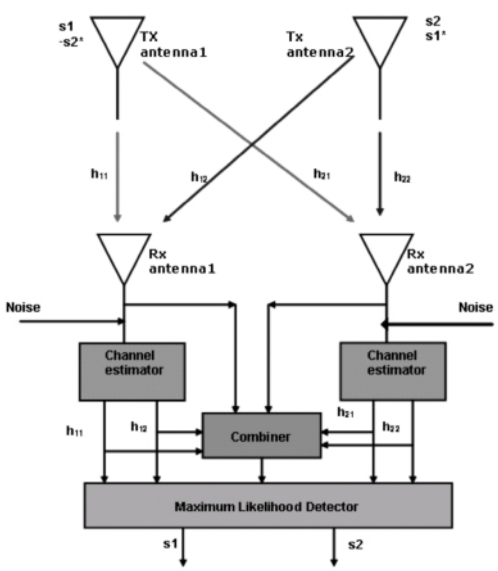

Figure 1: MIMO System

According to the Chernoff bound [1] (in the high SNR regime)

$$\overline{P_b} \le \left(\frac{\overline{E_b}}{M_t N_o}\right)^{-M_t} \tag{3}$$

We can derive an upper bound for the required energy per bit:

$$\overline{E_b} \le \frac{M_t N_o}{\overline{P_b}^{-1/M_t}} \tag{4}$$

By approximating the bound as equality, we can calculate the total energy consumption per bit for both the MISO system and the reference SISO system according to Equation (1) and Equation (4). Thus, we can obtain

$$E_{bt} = (1+\alpha)\frac{M_t N_o}{\overline{P_b}^{-1/M_t}} x \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + P_c / R_b \tag{5}$$

2.2. Alamouti 2X2 Scheme

We now consider a 2x2 MIMO system based on Alamouti code where the channel matrix is given by:

$$H = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix} \tag{6}$$

According to [1], this MIMO system can achieve a diversity order of 4 and array gain of 2, which means that even less transmission energy, is required compared with the 2 x 1 MISO system under the same performance requirement.

3. MIMO WITH MULTI-NODE COOPERATION

For sensor networks, maximizing the network lifetime is the main concern. Since sensor networks are mainly designed to cooperate on some joint task where per node fairness is not emphasized, the design intention is to minimize the total energy consumption in the network instead of minimizing energy consumption of individual nodes. In this section, we propose a strategy to minimize the total consumption of multiple nodes from network perspective.

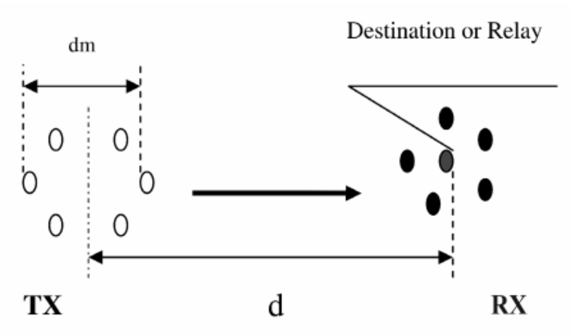

Figure 2: Information Flow in a Sensor Network

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In a typical sensor network, information collected by multiple local sensors need to transmitted to a remote central processor. If the remote processor is far away, the information will first be transmitted to relay node, then multihop based routing will be used to forward the data to its final destination; This scenario is illustrated in Figure 2.

Since MIMO can provide energy saving in fading channels. Thus if we allow Cooperative transmission among multiple nodes, we can treat them as multiple antennas to destination node such that an equivalent MISO system can be constructed. By using this equivalent MISO system, the requirement on transmission energy for long haul transmission can be reduced. However in order to make the cooperative transmission possible, local data exchange is necessary before the long haul transmission. The local information flow costs energy, which should be less than the energy saved by using the MISO structure. Another tradeoff is the transmission delay since the MISO approach has different delay characteristics than non cooperative approaches.

Cooperation can explore on the transmission side and receiving side. On the receiving there may also be multiple nodes around the destination node such that cooperative reception is possible. Therefore, an equivalent SIMO or MIMO system can be constructed. Similarly, local energy consumption is necessary due to the data aggregation among receiving nodes. The total delay requirement is accordingly altered.

In order to compare the performance between the non cooperative approach and the MIMO approach, some assumptions need to be made. We assume that there are M_t transmitting nodes and each has N_i bits to transmit, where Ii = 1, 2,……, M_t. For non cooperative approach, we assume that each transmitting node uses a different time slot to transmit the information to the remote node with uncoded MQAM. For MIMO approach, the M_t nodes on transmitting side will cooperate. Each node first broadcast its information to all the other local nodes using different time slots. After each node receives all the information bits from other nodes, they encode the transmission sequence according to the Alamouti diversity codes [1]. Since each node has a preassigned index i, they will transmit the sequence which the i^{th} antenna should transmit in an Alamouti MIMO system. On the receiving side, there are M_r nodes joining the cooperative reception. The (M_r-1) assisting nodes first quantize each symbol they receive into n_r bits then transmit all the bits using uncoded MQAM to the destination node to do the joint detection.

The total energy consumption in each node is summation of the transmission energy and energy consumption by analog circuit of MIMO systems. For local transmission, we assume a K^{th} power path loss (loss α $1/d^k$) with AWGN. For long haul transmissions, we assume a Rayleigh fading channel with square law path loss. Within local cluster (for both Tx side and Rx side), if the maximum separation is d_m meter, we assume each node is optimize their constellation size according to this worst case distance. Since usually long haul distance between the remote node and local cluster is much larger than d_m, we assume the long haul transmission distance, denoted as d, is same for each transmitting node.

The energy cost per bit for local information flow on the TX side, denoted as E_i^t, i = 1, 2,……, M_t, and the energy cost per bit for local information flow on the *Rx* side, denoted as E_j^r, j = 1, 2,……, M_r -1. Since there are always M_t-1 receivers listening during the local transmission, the total circuit energy consumption on the receiver side should be the total energy consumption of M_t-1 set of receiver circuits. The energy cost per bit for MIMO long haul transmission, can be denoted as E_b^r. For the SISO long haul transmission used by the non cooperative approach, the energy per bit denoted as E_i^0can be calculated as a special case of MIMO system can be calculated as a special case of MIMO systems where we set $M_t = M_r = 1$.

The total energy consumption E_{tra} for the non-cooperative approach is given by

$$E_{tra} = \sum_{i=1}^{M_t} N_i E_i^0, \qquad (7)$$

While the total energy consumption E_{MIMO} for the cooperative MIMO approach is given by

$$E_{MIMO} = \sum_{i=1}^{M_t} N_i E_i^t + E_b^r \sum_{i=1}^{M_t} N_i + \sum_{j=1}^{M_r - 1} E_j^r n_r N_s, \qquad (8)$$

Where $N_s = \dfrac{\sum_{i=1}^{M_t} N_i}{b_m}$ is the total number of symbol received with b_m the constellation size (bits per symbol) used in the Alamouti code.

The total delay required is defined as the total transmission delay, for a fixed transmission bandwidth B; we assume the symbol period is approximately $T_s \approx 1/B$, for the non cooperative approach, the total delay T_{tra} is given as

$$T_{tra} = \sum_{i=1}^{M_t} \frac{N_i}{b_i^0} T_s \qquad (9)$$

Where b_i^0 is the constellation size used by node i, for the MIMO approach, the total delay T_{MIMO} includes both the local transmission delay and long haul transmission delay. Accordingly, T_{MIMO} is given by

$$T_{MIMO} = T_s \left(\sum_{i=1}^{M_t} \frac{N_i}{b_i^t} + \frac{\sum_{i=1}^{M_t} N_i}{b_m} + \sum_{j=1}^{M_r - 1} \frac{n_r N_s}{b_j^r} \right) \qquad (10)$$

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Where b_i^t and b_j^r are the constellation sizes used during the local transmission on the Tx side and the Rx side, respectively. The first and third terms in the total delay are the local delay values contributed by the Tx side and Rx side, respectively, and the seconds terms is the delay caused by the long haul MIMO transmission.

4. PERFORMANCE EVALUATION AND SIMULATION EXPERIMENTS

4.1. The Simulation Environment

We assume a flat Rayleigh fading channel, i.e., the channel gain between each transmitter antenna and each receiver antenna is a scalar. Therefore, the fading factors of the MIMO channel can be represented as a scalar matrix. In addition, the path loss is modeled as a power falloff proportional to the distance squared. In other words, on top of the square law path loss, the signal is further attenuated by a scalar fading matrix H, in which each entry is a Zero Mean Circulant Symmetric Complex Gaussian (ZMCSCG) random variable with unit variance [1]. The fading is assumed constant during the transmission of each Alamouti codeword. For simulation experiments, we assume that d_m = 1 meter, B = 10 KHz, n_r = 10, and all the transmitting nodes have the same number of bits to transmit, i.e. N_i = 20 Kb. The related circuit and system parameters are defined in Table 1.

Table 1
System Parameters

$f_c = 2.5\ GHz$	$\eta = 0.35$
$G_tG_r = 5\ dBi$	$\sigma^2 = -174\ dBm/Hz$
$B = 10\ KHz$	$\beta = 1$
$P_{mix} = 30.3\ mW$	$P_{syn} = 50\ mW$
$P_b = 10^{-3}$	$P_{LNA} = 20\ mW$
$P_{filt} = 2.5\ mW$	$M_L = 40\ dB$
$N_f = 10\ dB$	$T_s = 1/B$

4.2. Simulation Result

In Figure 3, we are comparing the total energy consumption per bit with transmission distances between cooperative MIMO system and non-cooperative approach system in wireless sensor networks. From Figure 3, we can conclude that MIMO requires less transmission energy for the long haul transmission, the total energy consumption will becomes smaller compared with non cooperative approach.

In Figure 4 we are comparing the total dealy performance with transmission distances between cooperative MIMO system and non cooperative approach in wireless sensor networks. Total delay of cooperative approach is less than non cooperative approach upto 200 meter transmission distances. Hence, Cooperative MIMO system provides a sweet window (from 30 m to 200 m) where we can reduce both energy consumption and delay.

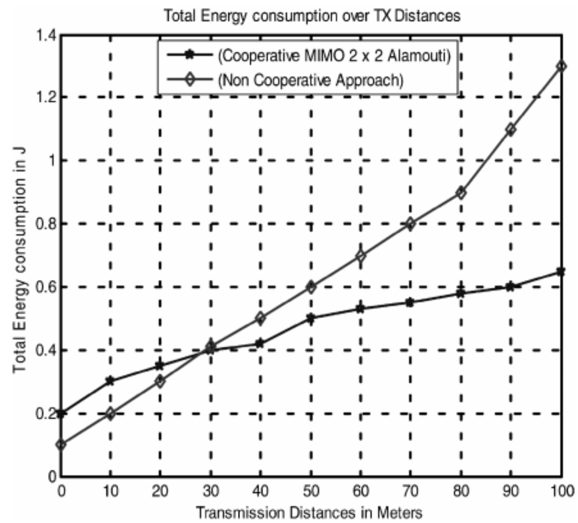

Figure 3: Total Energy Consumption Over Transmission Distances

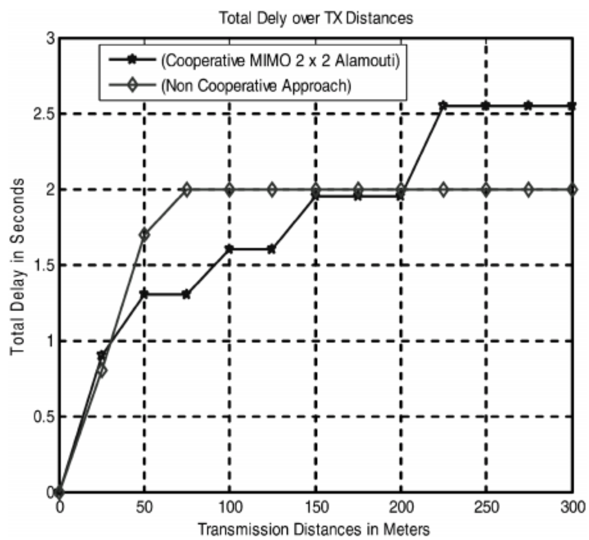

Figure 4 : Total Delay Over Transmission Distances

5. CONCLUSION

In this paper, we described the MIMO system for wireless sensor networks which can save total energy when it is compared with non cooperative approach system. Through computer simulation, it is justified that proposed system is more energy efficient than non cooperative approach for long haul transmission. We also investigate the energy efficiency of cooperation among nodes for both transmission and reception. By allowing cooperation, we can treat the equivalent system as a MIMO system. By applying the energy minimization result to MIMO system , we show that over certain distance ranges both the total energy consumption and the total delay can be reduced, even when we take into account the energy and delay cost associated with the local information exchange. Our results shows that the proposed cooperative-multi input multi output based

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communication architecture can offer substantial energy savings in wireless sensors network provided that the system is designed judiciously for e.g. careful consideration of transmission distance requirements, rate optimization as well as end to end delay constraints.

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