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Two Slot MIMO Configuration for Cooperative Sensor Network

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Abstract

Sensor networks are used in various applications. Sensors acquire samples of physical data and send them to a destination node in different topologies. Multiple Input Multiple Output (MIMO) systems showed good utilization of channel characteristics. In MIMO Sensor Network, multiple signals are transmitted from the sensors and multiple sensors are used as receiving nodes. This provides each sensor multiple copies of the transmitted signal and hence, array processing techniques help in reducing the effects of noise. In this paper we devise the use of MIMO sensor network and array decision techniques to reduce the noise effect. The proposed system uses a transmission time diversity to form the MIMO system. If the number of sensors is large then groups of sensors will form the MIMO system and benefited from the diversity to reduce the required transmitted power from each sensor. Enhancing the BER reduces the required transmitted power which results in longer battery life for sensor nodes. Simulation results showed an overall gain in SNR that reaches 11 dB in some sensor network scenarios. This gain in SNR led to the opportunity of reducing the transmitted power by similar amount and hence, longer battery life is obtained.

Keywords: Wireless Sensor Networks (WSN), Cooperative Sensor Network (CSN), MIMO, Diversity

1. Introduction

Wireless Sensor Network (WSN) is defined as spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions. The development of wireless sensor networks is motivated by military applications and is used in many industrial and civilian application areas, such as environmental, pollutants, medical, vehicles, energy management, inventory control, home and building automation, homeland security and others [1-3].

A collection of sensors, actuators, controllers or other elements that communicate with each other and are able to achieve, more or less autonomously, a common goal are defined as cooperating objects. Thus, sensors and actuators form the hardware interfaces with the physical world, where the sensors retrieve information from the physical environment and the actuators modify the environment in response to appropriate commands. Controllers process the information gathered by sensors and issue the appropriate commands to the actuators, in order to achieve control objectives.

Performance of WSN is measured and optimized based on various criteria such as: capacity; bit error rate; SNR; Cross-layer Optimal Scheduling; power requirements; security and robustness.

Power consumption of WSN is an important issue, because if batteries are to be changed constantly, a lot of potential applications will be lost and widespread adoption will not occur. The power consumption must be minimized when the sensor node is designed. The power consumption can be reduced by, reduce the amount of data transmitted through the use source encoding, compression, lower the transceiver duty cycle and the repetition rate of data transmissions, reduce the frame overhead, managing power by using power-down and sleep modes. Implement an event-driven transmission strategy; only transmit data when a sensor event occurs. Turn power on to sensor only when sampling, Turn power on to signal conditioning only when an event occurs. Lower sensor sampling rate to the minimum required by the application.

Virtual MIMO has been studied in a wide range in recent years, in order to advise energy-efficient schemes, constrained by allowed physical size and battery. An individual sensor is allowed to contain only one antenna.

Previous studies showed that if these individual sensors jointly form a MIMO system, tremendous energy is saved while satisfying the required performance. However the disadvantages of the virtual MIMO are the increased complexity and the cost of multiple Radio Frequency (RF) chains.

Since wireless transceivers usually consume a major portion of battery power [3], it is critical to improve their power efficiency. Nevertheless, one of the major difficulties comes from the harsh communication environment with multipath propagation and severe fading [4,5]. Sophisticated and yet computationally efficient techniques is used for reliable and efficient signaling [6]. Moreover, optimization techniques have been used to solve problems arising in wireless networks. Achievable rate combinations were computed in [7,8]. Also, cross-layer optimizations to maximize throughput have been considered in [9].

In this work, we consider a wireless sensor network in which nodes are distributed in a certain region; each node can vary its transmission power to maintain the energy-constraint. A group of sensors may sample one physical quantity forming multi input to the transmission channel and at the Central Node (CN) receiver we employ multiple antenna elements to form the MIMO system. The use of MIMO system creates parallel channels that can be used for independent transmissions [10,11]. This will provide a promising solution to enhance the received signal quality and hence reducing the BER that leads to power saving.

2. System Description

In this paper we devise a solution to implement a MIMO system in wireless sensor networks by having a group of sensor nodes repeat transmitting the same signal that originally initiated by some sensor and another group of nodes acts as a multiple receivers. This architecture of cooperative sensor network will enhance the received signal error rate and hence, improves the network performance. The main idea is that; each sensor will transmit its own signal and repeats other sensors signals. The sensor selects the best K signals received and retransmits them once again as shown in **Figure1**.

Transmitting the same signal twice from the same node is not allowed, and hence a transmission convergence is reached.

Node 4 will receive the signal from node 1 and replicas from nodes 2, 3 and 5. Then at node 4 multiple versions of the signal produced from node 1 will arrive, each from different direction and goes different channel conditions. Node 5 will receive node 1 signal from node 1, 2 and 4. Node 2 will receive the signal from nodes 1, 4

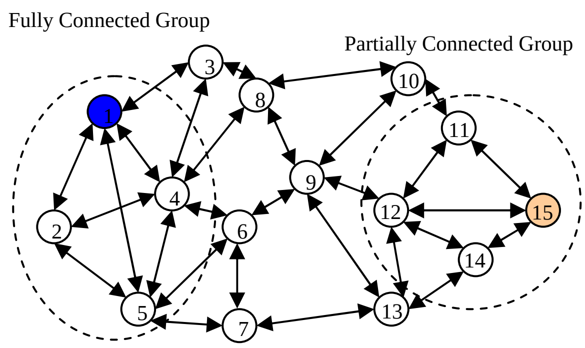

Figure 1. Cooperative sensor network as MIMO system.

and 5. Node 3 also receives node 1 signal from two paths (node 1 and node 4) but this node does not receive the signal from nodes 5 and 2, therefore, it is not in the first group.

To form MIMO system we first need to define the nodes forming each group, these nodes will have wireless connectivity among each others. This can be seen by forming the connectivity matrix as follows:

$$\Omega = \left[\begin{array}{ccccccc} & C_1 & C_2 & C_3 & C_4 & C_5 & \cdots & C_{N_T} \\ C_1 & 1 & 1 & 1 & 1 & 1 & & \\ C_2 & 1 & 1 & 0 & 1 & 1 & & \\ C_3 & 1 & 0 & 1 & 1 & 0 & & \\ C_4 & 1 & 1 & 1 & 1 & 1 & & \\ C_5 & 1 & 1 & 0 & 1 & 1 & & \\ \vdots & & & & & & \ddots & \\ C_{N_T} & 0 & 0 & 0 & 0 & 0 & & 1 \end{array}\right] \quad (1)$$

When the entry ji=1 it means an RF channel from node C_i to node C_j is possible. A fully connected group will have all ones in its corresponding sub matrix as the case of C_1, C_2, C_4 and C_5. A partially connected group will have ones in most of its sub matrix elements as the case of C_{11}, C_{12},C_{14} and C_{15}. A MIMO system can be constructed from a fully connected group, for example the group $\boldsymbol{G}$ having N points fully connected forms an N-1 × N-1 MIMO system. That means each sensor transmits its data to N-1 other sensors. This transmission will be fully available at the second transmission interval, since each sensor will repeat all other sensors signals after it receives them. If the destination node for the data is not a member of the current group, the border nodes (C_1, C_4 and C_5) (C_{11}, C_{12} and C_{14}) will be associated with other groups and hence transfer the data to the next group.

The whole network will be constructed from many groups; each group will be formed from a sub matrix that contains all ones. This can be done by omitting some rows and columns in the matrix as well as performing some permutation to create groups in the matrix. Usually, sensors forming a subgroup are close to each others in space.

For each group the data is transferred by group cooperation and the signal from node C_i will be transmitted in the ith time slot. Each sensor will store the signals corresponding to all group members and then process the received signals to obtain the best detection. The signals R_j^n arrived at sensor j corresponding to sensor n data can be written as:

$$R_j^n = \begin{bmatrix} r_{j1}^n \\ r_{j1}^n \\ \vdots \\ r_{jN-1}^n \end{bmatrix} \quad where \;\; r_{ji}^n = h_{ji} x_{ni} + w_{ji} \tag{2}$$

where r_{ji}^n is the signal arrived at sensor j corresponding to sensor n from sensor i, x_{ni} is the n^{th} sensor signal transmitted by sensor i, h_{ij} is the channel coefficient from sensor i to sensor j and w_{ji} is an *iid* $N(0,\ \sigma_w^2)$ white Gaussian noise. In matrix form we can write all the arrived signals at sensor j as:

$$R_j = H_j X_n + W_j \tag{3}$$

where:

$$H_j = \begin{bmatrix} h_{j1} & 0 & \cdots & 0 \\ 0 & h_{j2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{jN-1} \end{bmatrix} \quad X_n = \begin{bmatrix} x_{n1} \\ x_{n2} \\ \vdots \\ x_{nN-1} \end{bmatrix}$$

$$and \;\; W_j = \begin{bmatrix} w_{j1} \\ w_{j2} \\ \vdots \\ w_{jN-1} \end{bmatrix} \tag{4}$$

At the j^{th} sensor a Weighted Least Square (WLS) detector can be used to recover the data for each transmitting sensor as:

$$\hat{X}_n = \left[H_j^T V_{ww}^{-1} H_j \right]^{-1} H_j^T V_{ww}^{-1} R_j \tag{5}$$

V_{ww} is the noise covariance matrix.

An example of a fully connected group from the network shown in **Figure 1** will be:

(1,2,4,5), (4,5,6), …, (11,12,14), (11,12,15). And a partially connected groups could be: (4,6,8,9), (6,7, 9, 13), …, (11,12,14,15). Data propagation is done via the boundary nodes, where the decision is made.

In the following we consider an example of a 5 nodes sensor network, the close sensors will have communication channels between each other and groups are formed to propagate data between different sensors. Each sensor will repeat the data once, and the boundary sensors will make a decision when the data is fully available for all sensors.

Example:

Figure 2 shows a 5 nodes simple sensor network, if

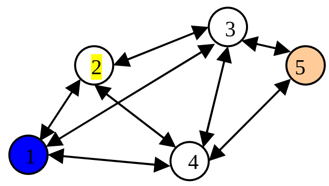

Figure 2. A simple 5 sensor example.

sensor 1 sends a packet to sensor 5, it transmits its signal first to its neighbouring sensors (2, 3 and 4). Then in the second transmitting interval sensors 2, 3 and 4 resends the signal received from sensor 1 again and after the second signalling interval sensor 2 will have the following received signals (corresponding to sensor 1) $r_{21}^1,\ r_{23}^1\ and\ r_{24}^1$, sensor 3 will have the following received signals $r_{31}^1,\ r_{32}^1\ and\ r_{34}^1$ and sensor 4 will have the following received signals $r_{41}^1,\ r_{42}^1\ and\ r_{43}^1$. The combined signals at sensors 2, 3 and 4 form a 3x3 MIMO system. The received signals at sensor 2 are given by:

$$\begin{bmatrix} r_{21}^1 \\ r_{23}^1 \\ r_{24}^1 \end{bmatrix} = \begin{bmatrix} h_{21} & 0 & 0 \\ 0 & h_{23} & 0 \\ 0 & 0 & h_{24} \end{bmatrix} \begin{bmatrix} \hat{x}_{12} \\ \hat{x}_{13} \\ \hat{x}_{14} \end{bmatrix} + \begin{bmatrix} w_{21} \\ w_{23} \\ w_{24} \end{bmatrix} \tag{6}$$

where;

$$\hat{x}_{12} = x \quad \hat{x}_{13} = h_{31} x \;\; and \;\; \hat{x}_{14} = h_{41} x \tag{7}$$

x is the transmitted signal from sensor 1. We can combine equations 10 and 11 for each sensor as:

$$\begin{bmatrix} r_{21}^1 \\ r_{23}^1 \\ r_{24}^1 \end{bmatrix} = \begin{bmatrix} h_{21} & 0 & 0 \\ 0 & h_{23}h_{31} & 0 \\ 0 & 0 & h_{24}h_{41} \end{bmatrix} \begin{bmatrix} x \\ x \\ x \end{bmatrix} + \begin{bmatrix} w_{21} \\ w_{23} \\ w_{24} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} r_{31}^1 \\ r_{32}^1 \\ r_{34}^1 \end{bmatrix} = \begin{bmatrix} h_{31} & 0 & 0 \\ 0 & h_{32}h_{21} & 0 \\ 0 & 0 & h_{34}h_{41} \end{bmatrix} \begin{bmatrix} x \\ x \\ x \end{bmatrix} + \begin{bmatrix} w_{31} \\ w_{32} \\ w_{34} \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} r_{41}^1 \\ r_{42}^1 \\ r_{43}^1 \end{bmatrix} = \begin{bmatrix} h_{41} & 0 & 0 \\ 0 & h_{42}h_{21} & 0 \\ 0 & 0 & h_{43}h_{31} \end{bmatrix} \begin{bmatrix} x \\ x \\ x \end{bmatrix} + \begin{bmatrix} w_{41} \\ w_{42} \\ w_{43} \end{bmatrix} \tag{10}$$

Sensor j will decide for the received signal $\hat{x}_j$ using equations 3 and 8. The network creates a diverse transmission system. This diversity will enhance the BER performance of the over all data transmission. If a diversity order of L_d is used then the BER will be reduced exponentially by a factor of L_d [15]. In the proposed structure and for a group of N nodes, we retransmit the signal N times (lets call it power repetition L_p=N) and the diversity order is $L_d = (N-1)^2$. The power repetition is the cost we pay for retransmitting the signal and the gain we achieve is the reception diversity L_d. For the above example we have $L_d = 9$ and $L_p = 4$. As N grows larger we can achieve better gain compared to one transmission scenario. The overall diversity gain we achieve using the proposed structure can be written as:

$$G_d = \frac{(N-1)^2}{N} \text{ dB} \tag{11}$$

This means that, for a preset BER performance we can reduce the average transmitted power from each sensor by a factor related to G_d.

The performance of this network is calculated by BER and average power transmitted from each sensor. The main goal is to achieve minimum BER at minimum transmitted power from each sensor. The power constraint imposed in equation 6 makes sure that each sensor will remain under its maximum allowable transmitted power and hence, maximizes its battery life. The BER performance depends on the MIMO sub groups formulated in the network; therefore, a simulation program is used next to determine the BER performance under the power constraint.

3. Simulation Results

In this section we used a MATLAB routine to simulate different sensor networks and results was obtained at different SNR's. The simulation flow is implemented as follows:

1) Initialize the network topology, the power constraint and calculates the groups.

2) Generate random data for each sensor.

3) Transmit the first packet from each sensor, setting the second transmission to all zeroes.

4) Receive the packets at each sensor, append new data to the received packet and retransmit it again (The receiving is done by using equation 3 and the detection is done by using equation 5, then the BER performance is calculated).

5) Repeat (4) until all data is transmitted.

The MIMO part is constructed from the received second transmission from other sensors and the current received signal from the current sensor. This means that we construct the multiple output from the received signal vector arrived from other sensors and the multiple input from the transmitted signals arrived from other sensors.

Four sensor networks were simulated for 5, 10, 15 and 20 sensors. Each simulation uses 1 million runs to calculate the BER performance for the proposed system and the system without MIMO construction. **Figures 3** to **5** shows the BER vs SNR for both with and without MIMO. The system with MIMO has better BER in all cases but to calculate the overall gain in power we select the required BER and the overall gain is found as:

$$G_T = (SNR - SNR_{MIMO}) - 10\log(N_{av} - 1) \ dB \tag{12}$$

where the last term represents the average extra power needed to be transmitted to form the MIMO system in

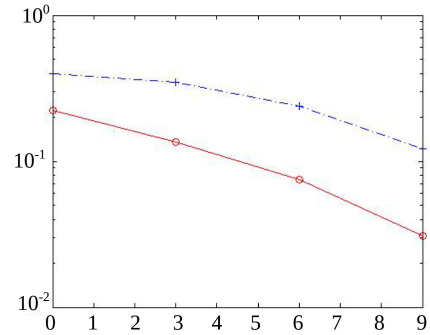

Figure 3. BER vs SNR performance for the proposed network with 5 sensors (cont. line) and one transmission network (dotted line).

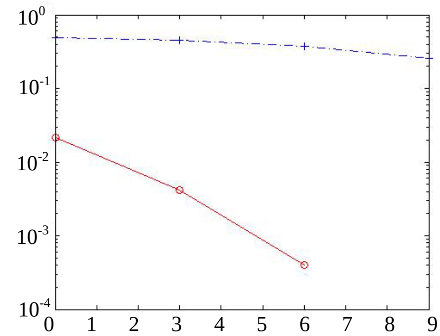

Figure 4. BER vs SNR performance for the proposed network with 10 sensors (cont. line) and one transmission network (dotted line).

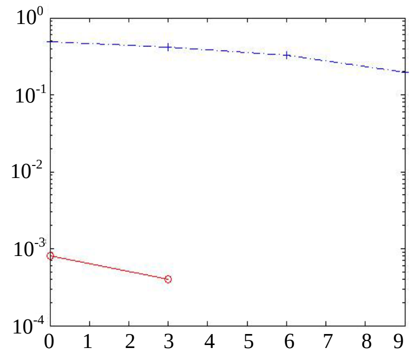

Figure 5. BER vs SNR performance for the proposed network with 15 sensors (cont. line) and one transmission network (dotted line).

the proposed solution.

As the number of nodes increases, the overall gain increases also. This can be seen in **Table 1** where we calculate the overall gain at different network sizes.

The shown results suggests that the sensor power can be reduced to smaller values even with signal repetition and still get the same BER performance as without repetition.

Tabel 1. Total Gain as a Function of Network Size.

N_T	SNR_{MIMO}	SNR	N_{av}	G_T
5	0 dB	6 dB	4	1.2 dB
10	0 dB	13 dB	5	6.0 dB
15	0 dB	19 dB	6	11.2 dB

4. Conclusions

The proposed system has showed an opportunity to enhance the wireless sensor network life by constructing a MIMO system from signal repetition emitted from each sensor. In MIMO structure we can use statistical detection techniques. This provides better signal detection and at the same time makes sure that the transmitted power from each sensor does not exceed a certain preset value. The proposed method requires more signal processing and it will delay the reception by one packet time interval.

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