Energy efficient cooperative MIMO communication for uncorrelated data transmission at wireless sensor network

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Abstract

Energy efficient data transfer is one of the key factors for wireless sensor network (WSN). Cooperative MIMO explores the wireless communication schemes between multiple sensors emphasizing the multiple input multiple output (MIMO) structure. An energy efficient cooperative technique is proposed for a WSN where selected numbers of sensors at the transmitting end are used to form a MIMO structure wirelessly connected with selected number of sensors at the receiving end.
The selection of nodes in the transmitting end is based on a selection function which is a combination of channel condition, residual energy, inter sensor distance in a cluster and geographical location whereas the selection in receiving side is performed on the basis of channel condition. Energy and delay models are evaluated for uncorrelated data scenario and life time analysis is done. The selected MIMO structure outperforms the unselected MIMO.
The issue of cooperative node selection in MIMO communications for wireless sensor networks, where a source node is surrounded by multiple neighbors and all of them are equipped with a single antenna.
In order to optimize system performance, the optimization of all the parameters is considered, given the aforementioned system constraints. It is assume that the source node either has channel state information (CSI), or has no channel state information (CSI).
Keywords: Residual energy, Inter sensor distance, Cluster.

1. Introduction

Multiple-input multiple-output (MIMO) wireless uses different waveforms on typically two, but sometimes three or more transmitting antennas inputting to the channel carrying radio waves from Point A to Point B. Multiple antennas and radios (typically, two or three) also are applied to the output of the radio channel at the receiver, along with a lot of signal processing, which ideally improves range and throughput compared with simpler or traditional radio designs operating under similar conditions.

MIMO technology has attracted attention in wireless society because of significant increases in data throughput and link range without additional bandwidth or transmit power it brings. It achieves this by higher spectral efficiency (more bits per second per hertz of bandwidth) and link reliability or diversity (reduced fading).

MIMO can be sub-divided into three main categories, pre-coding, spatial multiplexing or SM, and diversity coding. Pre-coding is multi-layer beam-forming in a narrow sense or all spatial processing at the transmitter in a wide-sense. In (single-layer) beam-forming, the same signal is emitted from each of the transmit antennas with appropriate phase (and sometimes gain) weighting such that the signal power is maximized at the receiver input. Spatial multiplexing requires MIMO antenna configuration. Diversity Coding techniques are used when there is no channel knowledge at the transmitter [5].

Hardware advancements allow more signal processing functionality to be integrated into a single sensor chip. RF transceiver, A/D (analog to digital) and D/A (digital to analog) converters, base band processors and other application interfaces are integrated into a single device to be used as a smart wireless node. A wireless sensor network typically consists of a large number of sensor nodes distributed over a certain region. Monitoring node (MN) monitors its surrounding area, gathers application specific information and transmits the collected data to a data gathering node (DGN) or a gateway. Energy issues are more critical in the case of MNs rather than in the case of DGNs since MNs are remotely deployed and it is not easy to frequently change the energy sources.

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Therefore, the MNs have been the principal design issue for energy limited wireless sensor network design. MIMO is a potential candidate for energy efficient design for a targeted probability of bit error rate at the receiver.

There has been a great amount of research on various MIMO techniques (including MISO and SIMO) in wireless communication systems due to its diversity and BER (bit error rate) improvements [1]. But the fact that MIMO techniques could require complex transceiver circuitry and signal processing leading to large power consumptions at the circuit level has precluded the application of MIMO techniques to energy limited wireless sensor networks.

Moreover, physical implementation of multiple antennas at a small-size sensor node may not be feasible. The solution came in the form of cooperative MIMO. Cooperative MIMO is a kind of MIMO technique where the multiple inputs and outputs are formed via cooperation. The concept has been proposed to achieve MIMO capability in a network of single antenna nodes. The sensors cooperate with each other to form a multiple input multiple output structure.

The cooperative MIMO based sensor networks may in fact lead to better energy efficiency and smaller end to end delay. Since all the nodes are transmitting the data, energy is utilized inefficiently. One approach to the node selection is the nodes are selected on the basis of geometric locations of the MNs. Another approach for node selection is the node selection is done on the basis of channel gain parameter.

Approach of a selection based cooperative communication for energy-limited wireless sensor networks where the multiple sensors in input and output cluster form the MIMO structure is done. The selection of nodes in the input cluster is based on a selection function which is a combination of channel condition, residual energy, inter sensor distance in a cluster and geographical location of the sensors whereas the nodes in the output cluster is selected on the basis of channel condition only [2-4].

2. System Model

System model is a centralized wireless sensor network, where many clusters with several sensors are connected wirelessly with the DGN using multi-hop communication. Design is concentrated on cluster to cluster communication which is an intermediate hop between the clusters to DGN data transmission.

The system model is shown in figure 1. It is assume a system with narrowband, frequency-flat Rayleigh fading channels and perfectly synchronized transmission/reception between wireless sensor nodes. Consider N_t transmitted and N_r received antennas which are placed at N_t sensors at the transmitting side and N_r sensors at the receiving side. So, each sensor contains one antenna. Assume each element in H is a zero-mean circulant symmetric complex Gaussian random variable with unit variance. The fading is assumed to be constant during the transmission of each frame [1]. Unless otherwise specified, the terms node, sensor and MN are considered as synonyms to each other.

In this model, a sensor with high residual energy is deployed as a cluster head and it remains the cluster head until the network die. The cluster head broadcasts its status to the other sensors in the network. Each sensor node determines to which cluster it wants to belong by choosing the cluster head that requires the minimum communication energy. Once all the nodes are organized into clusters, each cluster head creates a schedule for the nodes in its cluster. This allows the radio components of each non cluster head node to be turned off at all times except during it's transmit time, thus minimizing the energy dissipated in the individual sensors.
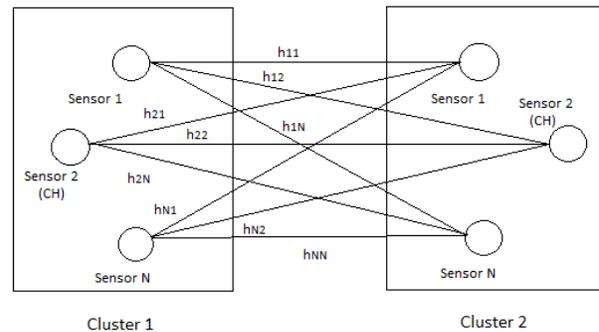

Fig. 1 System model for cluster to cluster communication in wireless sensor network

2.1 Proposed Model

Cooperative MIMO works with multiple sensors and it is possible to choose better sensors contributing to energy minimization. To achieve the near optimal solution, several selection parameters need to be considered in the form of a selection function. If the cluster head can dynamically select the sensors with better selection parameters, it can help to reduce the overall energy consumption. The overall energy consumption largely varies due to several parameters: i) channel condition ii) residual energy iii) inter-sensor distance in a cluster and

iv) geographical location of the sensors. These parameters are the potential candidates for node selection [1].

Selected number of sensors from available active sensors to transmit the data of all the sensors in a cluster is used. Channel condition parameter h is a critical issue in transmitting data to a distant receiver. The signal power drops off due to three effects: mean propagation path loss, macroscopic fading and microscopic fading [4]. To represent the channel condition, only microscopic fading is used since the other effects can be easily minimized using controlled transmission.

As the cooperative MIMO is based on the distributed antennas, and the channel parameter is different from one node to another, this feature can be used to optimize the data transmission. Residual energy r_e is the amount of energy present in a sensor at a particular time. Inter sensor distance in a cluster d_m is the distance between a cluster head and the other sensors inside a cluster. The closer the sensors, the less are the energy consumption for local communication. Geographical location of the sensors, d is the distance of the sensors from the receiving cluster. Total energy consumption increases with the increase in this distance [2]. Node selection is based on the previous four parameters and a sensor is selected on the basis of the following node selection function,

$$N_s = \frac{d\,d_m}{h\,r_e}$$

(1)

The node selection function is chosen in a way that all the required choices of selection parameters for energy efficient transmission lead to a smaller value of selection function. For example, higher value of h and r_e are desirable and lower value of d and d_m are desirable for lower energy consumption which lead to a smaller value of proposed selection function. The parameters in the node selection function are normalized.

2.2 Selection Procedure

Figure 2 shows the detailed procedure for selection. There are many sensor networks where the data are rarely correlated or fully uncorrelated for which we do not need to transmit the sensor data to the cluster head for data aggregation purpose because if the data are uncorrelated, there will be no reduction of data size after data aggregation. The sensors will broadcast their data to all the other sensors and every sensor will have the data of the other sensors.

In this case, inter sensor distance is considered as an average distance from a sensor to the other sensors. The sensors periodically estimate the channel, determine the distance from the receiving cluster, d, using the training bits and determine the distance from other sensors, d_m, using the broadcasted data and keep the cluster head updated regarding residual energy. At the same time, the transmitting cluster head sends the channel estimation results to the receiving cluster head. Cluster head at the receiving side selects receiving sensors on the basis of channel estimation result performed at the transmitting end and send a command signal to remain active. The transmitting cluster head selects the sensors with better selection function and sends a command signal to start transmitting data. After receiving the data, selected sensors at the receiving cluster transmit them to their cluster head locally.
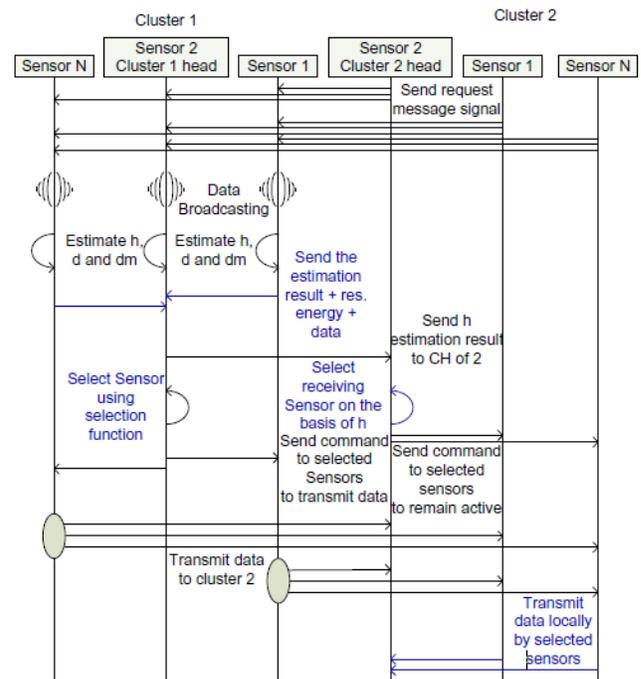

Fig. 2 Cooperative Communication

3. Energy Model

The developed energy model is based on the system model shown in Figure 1. The problem is stated from the receiver point of view and estimates the received energy. To estimate the total energy consumption, both circuit and transmitter powers are taken into consideration. Source

coding, pulse shaping, modulation and error correction coding blocks are omitted for simplicity. The total power consumption for a single node consists of two main parts, namely, the power consumption of all the power amplifiers P_{PA} which is a function of transmission power P_{out}, and the power consumption of all other circuit blocks P_C.

$$P_T = P_{PA} + P_C$$

(2)

The amplifier power can be calculated using the following equation

$$P_{PA} = (1 + \alpha)P_{out}$$

(3)

where $\alpha = (\frac{\xi}{\eta} - 1)$, where η is the drain efficiency and ξ is the peak average ratio. When the channel only experiences a kth power loss with additive white Gaussian noise (AWGN), P_{out} can be calculated using the link budget relationship as follows.

$$P_{out} = B_a r_b \times \frac{(4\Pi)^2 d^k}{G_t G_r \lambda^2} M_l N_f$$

(4)

where $\bar{E}_b$ is the average energy per bit required for a given bit error rate (BER) specification, R_b is the transmission bit rate, d is the transmission distance, G_t and G_r are the transmitter and receiver antenna gains respectively, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other background noise, N_f is the receiver noise figure defined as $N_f = \frac{N_r}{N_0}$ where N_r is the power spectral density (PSD) of the total effective noise at the receiver input and N_0 is the single-sided thermal noise PSD at the room temperature [1].

The circuit power includes transmitter and receiver circuit power P_{ct} and P_{cr} respectively. This power consumption is due to several power blocks such as P_{mix}, P_{syn}, P_{filt}, P_{filr}, P_{LNA}, P_{IFA}, P_{DAC}, and P_{ADC} which are the power consumption values of the mixer, the frequency synthesizer, the active filters at the transmitter and at the receiver side, the low noise amplifier, the intermediate frequency amplifier, the D/A and A/D converter,

respectively. The total energy consumption per bit can be written as

$$E_{bt} = \frac{(P_{PA} + P_C)}{R_b}$$

(5)

where R_b is the actual bit rate and can be replaced by $R_b^{eff} = \frac{F - pN_T}{F} R_b$, when pN_T training symbols are inserted in each block to estimate the channel at the receiving cluster or DGN side. The block size is equal to F symbols and can be obtained by setting $F = [T_C R_S]$, where R_S is the symbol rate and T_C is the fading coherence time. The fading coherence time can be estimated from $T_c = \frac{3}{4f_m \sqrt{\Pi}}$ where the maximum doppler shift fm is given by $f_m = \frac{v}{\lambda}$ with v being the velocity and λ being the carrier wavelength. The total energy consumption is estimated by multiplying E_{bt} by the number of bits L to be transmitted [6].

3.1 Total Energy Consumption

The total energy consumption in cooperative case is

$$E_{CO}^{C-C} = \sum_{i=1}^{N_t} \frac{L_i}{F} E_{ch} + L_{ch} \sum_{i=1}^{N_{t-1}} \frac{L_i}{F} E_i^t + L_{ch} \frac{L_i}{F} E_s^l$$

$$+ \sum_{i=1}^{N_t} L_i E_i^{br} + L_{cps} \frac{L_i}{f} \sum_{i=1}^{x} E_i^{t0} + E_M^l \sum_{i=1}^{N_t} L_i$$

$$+ \frac{1}{b_{mimo}} \sum_{i=1}^{N_t} L_i \sum_{i=1}^{y} b_{i_r} E_j^t$$

(6)

where E_{ch} is the channel estimation energy. Data size L_i is divided by the frame size F to find out the number of channel estimations required for the transmitted data size L_i as channel estimation is performed once in frame duration. The second term is due to the transfer of channel estimation result to their own cluster head. E_i^t is the energy per bit required to transmit the channel estimation result from a sensor to the cluster head. L_{ch} is the number of bits needed to transmit the channel

estimation result. $L_{ch}\frac{L_i}{F}E_s^i$ is the term required to transmit the channel estimation result to the receiving cluster head due to channel estimation purpose. E_i^{br} is the broadcasting energy per bit needed to broadcast the data to all the other sensors. E_i^{t0} is needed to transmit a command signal from the cluster head to the selected sensors. L_c denotes the bit length of a command signal and $x = N_{Bt}-1$ for the cluster head being a selected sensor and $x = N_{Bt}$ otherwise where N_{Bt} denotes number of selected sensors at the transmission end. p_s is the probability that a selected sensor is changed in the next frame and is chosen as $\frac{1}{N_t}$. After receiving all the bits, the selected nodes encode the transmission sequence according to some diversity scheme, such as the STBC. E_M^i denotes the energy cost per bit for the long-haul MIMO transmission $\sum_{i=1}^{N_t} L_i$ is divided by the optimal bit size of the longhaul transmission b_{mimo} to find the number of symbols present in the received signal. The number of symbols is then multiplied by the optimal bit size of the local transmission b_{l_r} to find the total bit length. E_j^t is the energy per bit required to transmit the data from a sensor to the cluster head at the receiver side. $y = N_{Br}- 1$ is used for the cluster head being a selected sensor and $x = N_{Br}$ otherwise where N_{Br} denotes number of selected sensors at the receiving end [1].

In the SISO approach. the total energy consumption becomes

$$E_{SISO}^{C-C} = \sum_{i=1}^{N_t} L_i E_i^{br} + E_{S_{C-C}}^i \sum_{i=1}^{N_t} L_i \qquad (7)$$

$E_{S_{C-C}}^i$ denotes the SISO long haul transmission and can be calculated as a special case of MIMO transmission with $N_{Bt}= 1$ and $N_{Br}= 1$ where N_{Bt} and N_{Br} are the selected number of antennas at the transmitting and receiving end respectively [3].

4. Issues and Discussion

In order to get the total communication energy consumption, the average energy per bit required for a given BER P_b, $\bar{E}_b$ needs to be determined. The value of $\bar{E}_b$ by using a numerical search is identified. Ten thousand randomly generated channel samples are taken and

averaged to find the desired bit error rate at each transmission distance. The value of the constellation size is optimized for each transmission distance.
Several issues are experimented: energy issue, delay issue and network life time issue.
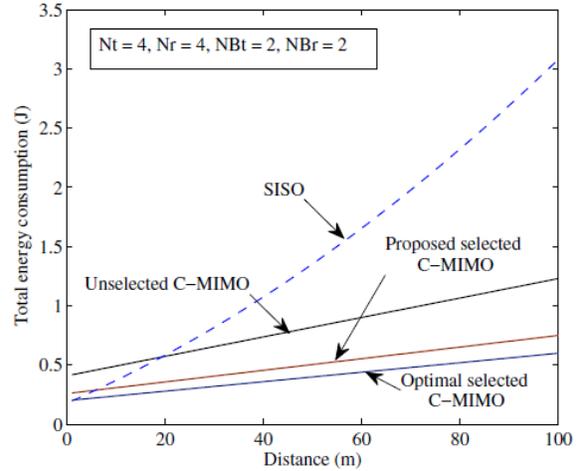

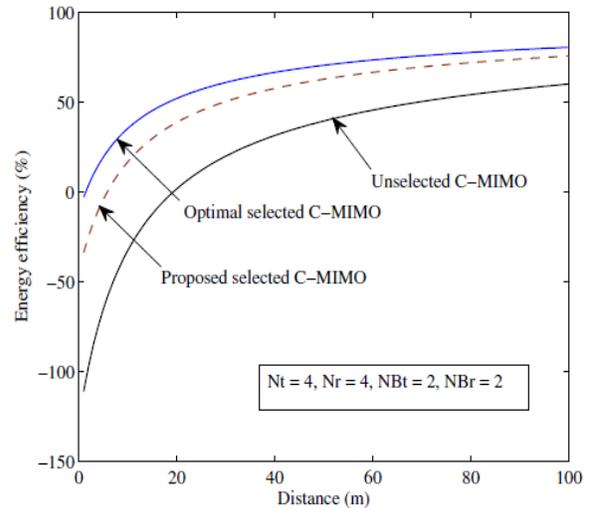Fig. 3 Total energy consumption over distance for cluster to cluster transmission

Fig. 4 Energy efficient over distance for cluster to cluster transmission

4.1 Energy Issue

Total energy consumption and energy efficiency are the key terms to evaluate the energy efficient performance. For simulation, consider all the sensors in a cluster are transmitting the same data size $L_i= 10\ kb$. In simulation,

the unselected approach is taken as a special case of selected approach where all the sensors in a cluster are selected for transmission. While choosing all the sensors from a cluster, consider not including the extra overhead taken by the selective approach.

In figure 3 and figure 4, the total energy consumption and energy efficiency are compared for uncorrelated data. The selected approach outperforms the unselected approach. This is because the unselected approach is using all the available sensors to transmit the data without considering their parameter conditions and therefore remains inefficient. It is considered equal number of transmitted and received antenna throughout our simulations. In these figures, selected approach is also compared with the optimal selection.

To find the optimal selection, the exhaustive search technique is used. For choosing 2 sensors out of 4 sensors, 6 combinations are available. All these 6 combinations of selected sensors are used to find out the total energy consumption and hence energy efficiency. Selection function is not the optimal one but is close to optimum.

4.2 Delay Issue

Delay issue is another key issue in data transfer at the wireless sensor network. The total delay required is defined as the total transmission delay. For a fixed transmission bandwidth B, assume that the symbol period is approximately $TS \approx 1/B$. The total delay in the case of SISO communication is defined as

$$T_{SISO}^{C-C} = \left(\sum_{i=1}^{N_t} \frac{L_i}{b_{l_t}} + \frac{1}{b_{SISO}} \sum_{i=1}^{N_t} L_i \right) \qquad (8)$$

where b_{l_t} is the transmission bit size at the transmitter side local communication and b_{SISO} is the transmission bit size for longhaul SISO transmission.

The total delay in the case of cooperative MIMO communication is defined as

$$T_{CO}^{C-C} = t_{ch} + T_s \left(\sum_{i=1}^{N_t} \frac{L_i}{b_{l_t}} + \frac{1}{b_{MIMO}} \sum_{i=1}^{N_t} L_i \right)$$

$$+ T_s \sum_{i=1}^{NB_r - 1} \frac{1}{b_{l_r}} \left\{ \frac{n_r}{b_{MIMO}} \sum_{i=1}^{N_t} L_i \right\} \qquad (9)$$

where t_{ch} is the channel estimation delay. The term $T_s \sum_{i=1}^{N_t} \frac{L_i}{b_{l_t}}$ is for the delay due to the broadcasting among the sensors to deliver their data to each other. $T_s \frac{1}{b_{MIMO}} \sum_{i=1}^{N_t} L_i$ term is caused by the long-haul MIMO transmission [1]. The next term is due to the local transmission at the receiver side. On the receiving side, there are N_r sensor nodes out of which NB_r nodes will be allowed to join the cooperative reception.
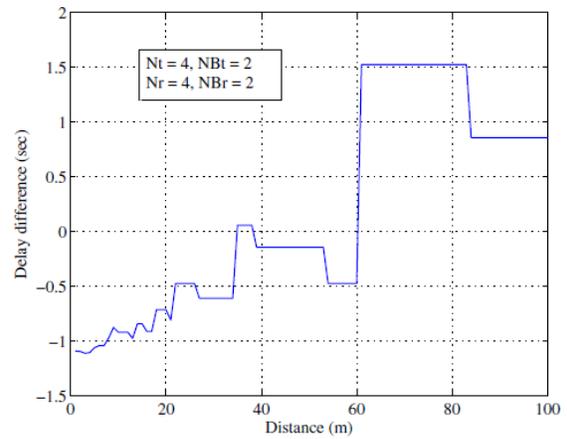

Fig. 5 Delay difference over distance

The assisting nodes first quantize each symbol they receive into nr bits, then transmit all the bits using uncoded MQAM to the destination node to do the joint detection.

The delay difference is calculated using the following equations. Assume the value of $t_{ch} \approx 0$.

$$DD = T_{SISO}^{C-C} - T_{CO}^{C-C}$$

$$= T_s \left(\frac{1}{b_{SISO}} \sum_{i=1}^{N_t} L_i - \frac{1}{b_{MIMO}} \sum_{i=1}^{N_t} L_i \right)$$

$$-T_S \sum_{i=1}^{NB_r-1} \frac{1}{b_{i_r}} \left\{ \frac{n_r}{b_{MIMO}} \sum_{i=1}^{N_t} L_i \right\}$$

(10)

The value of n_r is chosen at the receiver based on the optimized transmitted constellation size. The delay difference is a measure of delay performance by which the cooperative MIMO can be compared with SISO. Positive delay difference indicates the SISO is facing larger delay compared to CMIMO. In figure 5, delay difference is compared where proposed C-MIMO outperforms SISO after 60 meters.

4.3 Network life time Issue

Network lifetime is the time span from the deployment to the instant when the network is considered non-functional. The criterion of non-functionality of the network is application specific. In some literatures, the network is said to be "dead" if the target SNR at the destination cannot be achieved with a certain probability [6]. For simplicity, consider that the network dies when at least one sensor dies. Consider that the cluster head starts with a residual energy of 3 joules and normal nodes start with 1 joule.
Figure 6 shows the network lifetime against longhaul distance. Network lifetime is measured as the number of rounds before it dies. Consider one round as the transmission of one frame. Channel parameter remains static throughout the frame.
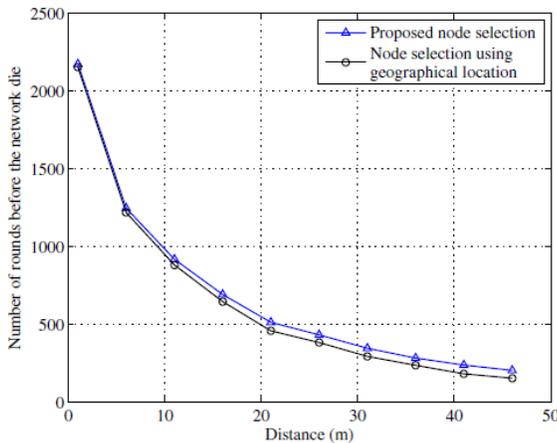

Fig. 6 Life term in terms of number of round over distance

From the figure it is seen that the network lifetime increases when the longhaul distance decreases. This is because, smaller longhaul distance needs smaller transmission energy. Comparison of the proposed selection algorithm with a single parameter selection is also done. This single parameter selection is performed using geographical location of the sensors. When the clusters are closely located, geographical location plays a key role for selection since the distance from sensors in one cluster to the sensors in other cluster varies a lot. But when the clusters are distantly located, this distance varies little and selection using geographical location becomes ineffective.

5. Results and Conclusion

Table 1: Total energy consumption over distance for cluster to cluster transmission

	Distance (m)	Total Energy (J)
Optimal selected C-MIMO	100	0.6
Proposed selected C-MIMO	100	13 mm (0.51 in)
Unselected C-MIMO	100	1.2
SISO	100	3.1

Table 2: Energy efficiency over distance for cluster to cluster transmission

	Distance (m)	Energy efficiency (%)
Optimal selected C-MIMO	100	75
Proposed selected C-MIMO	100	74
Unselected C-MIMO	100	55

An energy efficient cooperative technique for cluster based wireless sensor networks is proposed where the sensors participating in cooperative transmission are chosen in the selective way. A mathematical model developed and simulated them. Delay models for both SISO and proposed C-MIMO are developed.

The result shows that the selected cooperative MIMO structure outperforms the unselected cooperative MIMO. Model can be considered as a special case of multi hop wireless sensor structure where consider only the cluster to cluster communication. So, the proposal can well be extended to the multi hop wireless sensor network considering both the cluster to cluster and cluster to DGN transmission.

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