Cooperative Technique Based on Sensor Selection in Wireless Sensor Network

Mohammad R. ISLAM, Jinsang KIM
Department of Electronics and Radio Engineering,
Kyung Hee University, Suwon, South Korea
rakibultowhid@yahoo.com

***Abstract*—An energy efficient cooperative technique is proposed for the IEEE 1451 based Wireless Sensor Networks. Selected numbers of Wireless Transducer Interface Modules (WTIMs) are used to form a Multiple Input Single Output (MISO) structure wirelessly connected with a Network Capable Application Processor (NCAP). Energy efficiency and delay of the proposed architecture are derived for different combination of cluster size and selected number of WTIMs. Optimized constellation parameters are used for evaluating derived parameters. The results show that the selected MISO structure outperforms the unselected MISO structure and it shows energy efficient performance than SISO structure after a certain distance.**

***Index Terms*—Cooperative technique, energy efficiency, IEEE 1451.5, channel estimation, wireless sensor networks**

I. Introduction

Energy minimization now a day is a burning issue for remotely clustered Wireless Sensor Networks. Recent hardware advancements allow more signal processing functionality to be integrated into a single chip. RF transceiver, A/D and D/A converters, base band processors, and other application interfaces are integrated into a single device to be used as a fully-functional wireless node. SOC (System on Chip) and NOC (Network on Chip) are being developed for integrated system design. These SOC or NOC based wireless nodes typically operate with small batteries for which replacement, when possible, is very difficult and expensive. Thus, in many scenarios, the wireless nodes must operate without battery replacement for many years. Consequently, minimizing the energy consumption is a very important design consideration.

The Instrumentation and Measurement Society's Sensor Technology Technical Committee TC-9 in the Institute of Electrical and Electronics Engineers (IEEE) has been working to establish a group of smart sensor interface standards called IEEE 1451 [17]. The IEEE 1451 standard provides a set of protocols for wired and wireless distributed applications. The IEEE 1451.5 is the wireless standard under IEEE 1451 family promises to integrate a wide variety of sensors with a number of different wireless radio implementations using standards based protocols to communicate between the application and the sensor. 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 gateway. The DGN processes the data and takes appropriate actions if needed. Energy issues are more critical in the case of MNs (WTIM in IEEE 1451.5 standard) rather than in the case of DGNs (NCAP in IEEE 1451.5 standard) since MNs are remotely deployed and it is not easy to frequently change the energy sources. For this purpose we are concentrating on the MNs rather than DGNs.

However, in a wireless sensor network, unlike in cellular mobile communications, the circuit energy consumption may not be negligible compared to the actual transmit power. Thus, usual energy optimization techniques that minimize transmission energy may not always guarantee to be effective in the case of wireless sensor networks. Motivated by information theoretic predictions on large spectral efficiency of multiple-input-multiple-output (MIMO) systems, recently there has been a great amount of research on various MIMO techniques for wireless communication systems [1], [2]. However, 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 node may not be feasible. As solutions to the latter problem cooperative MIMO [3] and virtual antenna array [4] concepts have been proposed to achieve MIMO capability in a network of single antenna (single-input/single-output or SISO) nodes. A closer look at the total energy and delay comparisons between cooperative MIMO and SISO communications was taken in [3]. The results showed that in some cases cooperative MIMO based sensor networks may in fact lead to better energy optimization and smaller end-to-end delay. Later this idea has been improved in [5] considering channel estimation (training overhead). Further analysis have been done in [23] on cooperative MIMO using sensor selection based on channel gain parameter. Constellation size used here is not optimized and hence total energy consumption can be further minimized.

It is known that the energy required to transmit a certain amount of information is exponential to the inverse of the transmission time [8]. Several energy-efficient packet-scheduling protocols for single-user communication links [9], [10], [11], which perform smoothing or filtering on the packet arrival-time intervals, resulting in an output packet traffic that is less burst than the input traffic, and leading to significant energy savings. One straight approach towards energy efficiency would be the use of long transmission time intervals, however many applications impose hard

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delay constraints. This energy-efficiency delay tradeoff has been recently studied in [12]. Another different approach [13] examines single-hop sensor communications using time division multiple access (TDMA), proposing optimal and suboptimal algorithms to minimize the energy to transmit data with a given capacity in the adequate time. Theoretical energy gains are thus obtained for optimal and suboptimal schemes as compared to the TDMA ideal capacity. Another energy optimization technique [1] recently proposes a cross layer approach where the signal-to-noise ratio gap approximation is used in order to jointly handle required bit rates, transmission energies, and symbol error rates. Both of the last two papers used Lagrangean's multipliers method to optimize the total energy. To encourage the first time users, virtual lab for wireless sensor networks is proposed in [24].

In this paper, we propose a MISO based cooperative communication for energy-limited wireless sensor networks. The proposed scheme is based on channel estimated selected nodes. We first estimate the energy consumption of a MISO system and then compare it with that of a SISO system. Constellation size is optimally chosen to make the energy consumption efficient. Then we analyze energy efficiency and delay for different combination of active and selected number of WTIMs. We show that selected number of WTIMs is more energy efficient than the use of all active WTIMs.

The remainder of this paper is organized as follows: In section II, Energy model of IEEE 1451.5 based MISO system is introduced. In section III we show our simulation results with comparisons. Section IV concludes the paper.

II. ENERGY MODEL OF 1451.5 BASED MISO SYSTEMS

A. System Model

Our system model is a centralized wireless sensor network shown in Figure 1, where there is a Data Gathering Node called NCAP and a cluster with several Transducer Interface Modules connected wirelessly with the NCAP. Sensors connected in a WTIM transmit data to the NCAP. We state our problem from the receiver point of view, so a loss model is used to estimate the received energy. To calculate the total energy consumption, both the circuit and transmitter power is taken into count. We are using the same transmitter and receiver block shown in [3]. Source coding, pulse shaping, modulation and error correction coding block is as well omitted from the design. Our model can be extended to a MIMO case considering multiple antennas in the receiving side when the information will be relayed. Throughout the paper, we assume a system with narrowband, frequency-flat Rayleigh fading channels and perfectly synchronized transmission/reception between wireless sensor nodes. The system considers N number of transmitted antenna each placed at a WTIM and NCAP contains a single antenna.

For the MISO system, Na number of WTIMs being active, the received discrete-time signal is attenuated by a $Na \times 1$ channel matrix $\mathbf{H}$ of scalar fading coefficients. We assume each element in $\mathbf{H}$ is a zero-mean circulant symmetric complex Gaussian random variable with unit variance. The fading is assumed constant during transmission of each frame.

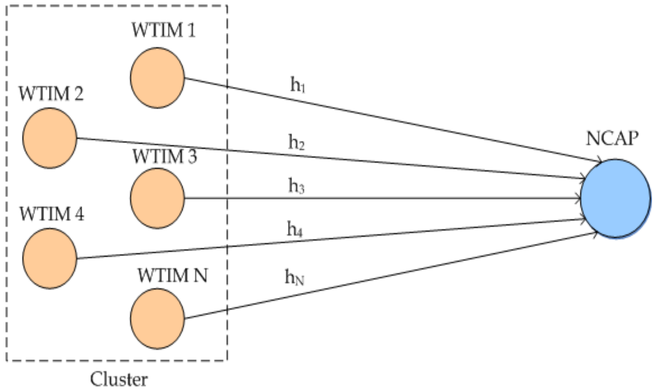

Figure 1. System model for IEEE 1451.5 based Sensor Network.

Channel condition is a critical issue in transmitting data to a distant receiver. When it comes to the case of multiple inputs, there are always options to choose among the inputs. If the cluster head can dynamically select the sensors with better channel condition and let them transmit, it can help reducing the overall energy consumption.

The total power consumption can be categorized into two main parts, namely, the power consumption of all the power amplifiers P_{PA} which is function of the transmission power P_{out}, and the power consumption of all other circuit blocks P_C

$$P_T = P_{PA} + P_C \quad (1)$$

where P_{PA} is the amplifier power and P_C is the circuit power.

The amplifier power can be calculated using the following equation

$$P_{PA} = (1+\alpha)P_{out} \quad (2)$$

Here $\alpha = (\xi/\eta) - 1$, where η is the drain efficiency [14] and ξ is the peak to average ratio. For the rest of the paper, unless otherwise stated, all the statements about modulation are referring to the uncoded MQAM. For MQAM, $\xi = 3\frac{\sqrt{M}-1}{\sqrt{M}+1}$ and the number of bits per symbol for optimal constellation size is defined as $b = log_2 M$. When the channel only experience a k^{th}-power path loss with Additive White Gaussian Noise (AWGN), P_{out} can be calculated according to the link budget relationship as follows.

$$P_{out} = \overline{E}_b R_b \times \frac{(4\pi)^2 d^k}{G_t G_r \lambda^2} M_l N_f \quad (3)$$

where $\overline{E}_b$ 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 $N_f = N_r/N_0$ 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.

The second term in the total power consumption is the circuit power which consist of two parts

$$\begin{aligned} P_{ct} &= P_{mix} + P_{syn} + P_{filt} + P_{DAC} \\ P_{cr} &= P_{mix} + P_{syn} + P_{LNA} + P_{filr} + P_{IFA} + P_{ADC} \end{aligned} \quad (4)$$

where P_{ct} and P_{cr} are circuit powers for the transmitter and the receiver respectively. P_{mix}, P_{syn}, P_{filt}, P_{filr}, P_{LNA}, P_{IFA}, P_{DAC} and P_{ADC} 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 the A/D converter, respectively. The total energy consumption per bit can be written as

$$E_{bt} = (P_{PA} + P_C)/R_b \quad (5)$$

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. The block size is equal to F symbols and can be obtained by setting $F = floor(T_C R_S)$, where R_S is the symbol rate and T_C the fading coherence time. The fading coherence time can be estimated as $T_c = \frac{3}{4 f_m \sqrt{\pi}}$ where the maximum Doppler shift f_m is given by $f_m = \frac{v}{\lambda}$ with v being the velocity and λ being the carrier wavelength [21]. The total energy consumption is estimated by multiplying E_{bt} by the number of bits L to be transmitted.

B. Cooperative Communication with selected number of transmitting antenna

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. To minimize the total energy consumption of multiple nodes from a network perspective cooperative MIMO was proposed in many papers.

In a typical sensor network, information collected by multiple local sensors need to be transmitted to a remote central processor. If the remote processor is far away, the information will first be transmitted to a relay node, then multi hop-based routing will be used to forward the data to its final destination. As we know that MIMO (including MISO, SIMO, and MIMO) can provide energy savings in the fading channels, we can allow cooperative transmission among multiple sensor nodes and treat them as multiple antennas to the destination node. Cluster head acts as the coordinator for cooperative transmission in this cluster based WSN.

In this paper we propose an idea using selected number of transmitting antenna out of a number of available active antennas which will transmit the data of all the other antennas. Selected antennas will be chosen on the basis of channel condition. According to Figure 2, NCAP continuously send training bit to all the available WTIMs. WTIM receives the training bit and estimates the channel and then sends the result to the cluster head which is responsible to select the WTIMs among the available active WTIMs on the basis of channel estimation result. The channel estimation result from different WTIM is sent to the cluster head along with the transmitting data. Cluster head then aggregate the data [16] and select the superior WTIMs (whose channel condition is better) using the channel estimation result. It then sends the aggregated data to the other active WTIMs and sends a command to the superior WTIMs to start transmitting the data.

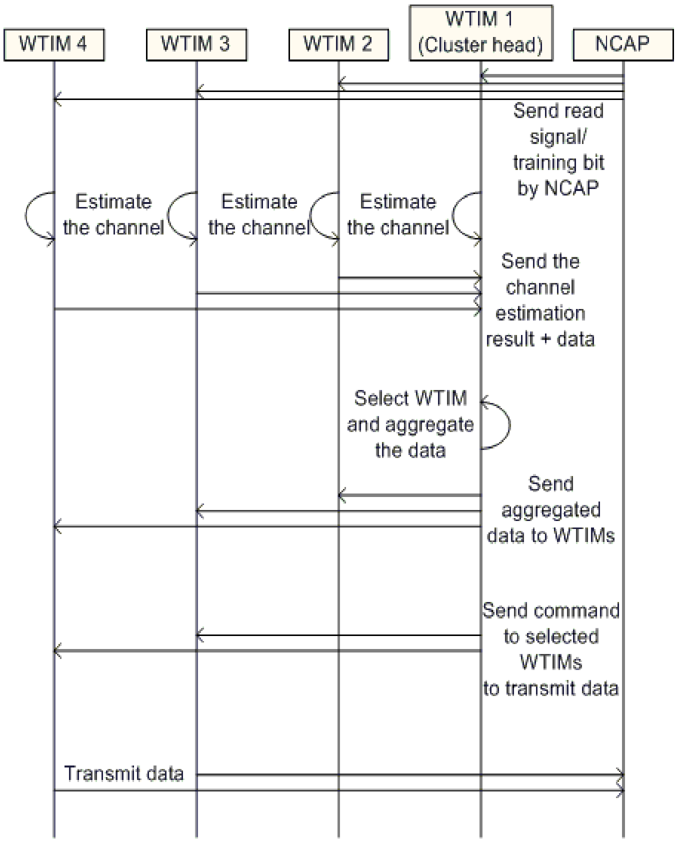

Figure 2. Cooperative communication.

C. Mathematical model for Selected MISO

As described in Figure 2, the total energy in cooperative case is

$$E_{CO} = \left[\begin{aligned} & E_{CE} + \sum_{i=1}^{Na-1} L_i E_i^t + E_{da} \sum_{i=1}^{Na} L_i \\ & + \sum_{i=1}^{x} E_i^{t0} \sum_{i=1}^{Na} L_i \gamma_i + E_M^l \sum_{i=1}^{Na} L_i \gamma_i \end{aligned} \right] \quad (6)$$

Here $x = Nb\text{-}1$ if the cluster head is a member of superior WTIMs and $x = Nb$ otherwise. E_{CE} is the channel estimation energy and is modeled as

$$E_{CE} = \left\{ \sum_{i=1}^{Na} \frac{L_i}{F} E_{Ch} + \sum_{i=1}^{Na-1} \frac{L_i}{F} E_i^t \right\} \quad (7)$$

where data size L_i is divided by the frame size F to find the number of channel estimations required for the transmitted data size as channel estimation is performed once in frame duration.. E_{Ch} is the channel estimation energy and is using 28 μJ/bit/signals in our simulation experiment [18]. The second term E_i^t in the channel estimation energy is due to the transfer of channel estimation result to the cluster head. The same energy per bit is needed to transmit the data from WTIMs to the cluster head. E_{da} is the energy dissipation per bit required in the cluster head for data aggregation. It depends on the algorithm complexity.

$$E_{da}(L) = C_0 + C_1 \times L + C_2 \times L^2 \quad for\ O(n^2)$$
$$= C_0 + C_1 \times L \quad for\ O(n) \tag{8}$$

where L is the number of transmission bits and C_0, C_1 and C_2 are coefficients depending on the software and CPU parameters. In our model, we are using beam forming algorithm and are using 5 nJ/bit/signals in simulation experiment [19]. E_i^{t0} denotes the local transmission energy cost per bit for transferring the aggregated data to the remaining active WTIMs, γ is the percentage of remaining data after aggregation, which reflects the correlation between data amongst different sensors or WTIMs. After each superior node receives all the bits, these *Nb* (Number of superior nodes) nodes encode the transmission sequence according to some diversity scheme, such as the STBC scheme. E_M^l denotes the energy cost per bit for the long-haul MISO transmission. As we are concerned about the WTIM side due to its energy constraint nature, we are ignoring the energy consumption in the NCAP side.

For the SISO approach, there is no burden for channel estimation and the cluster head will transmit all the aggregated data directly to the destination node without any cooperation. So the total energy consumption becomes

$$E_{SISO} = \sum_{i=1}^{Na-1} L_i E_i^t + E_{da} \sum_{i=1}^{Na} L_i + E_S^l \sum_{i=1}^{Na} L_i \gamma_i \tag{9}$$

where E_S^l denotes the SISO long haul transmission and can be calculated as a special case of MISO transmission where *Nb*=1 with the calculated optimized constellation size for this particular case. The optimal constellation size is determined simulating the program for a set of constellation sizes in different communication distance so that at any given distance, the communication energy consumption is minimized under its constellation size. In Figure 3 and Figure 4, the constellation size is shown for different combination of active WTIMs (*Na*) and superior WTIMs (*Nb*).

For feasibility, we apply the Alamouti schemes for distributed cooperative MISO transmission participated by the supreme nodes. As proposed in [13,20], Alamouti code with two transmitting antennas uses two different symbols s_1 *and* s_2 to transmit simultaneously during the first symbol period, followed by $-s_2^*$ *and* s_1^* during the next symbol period.

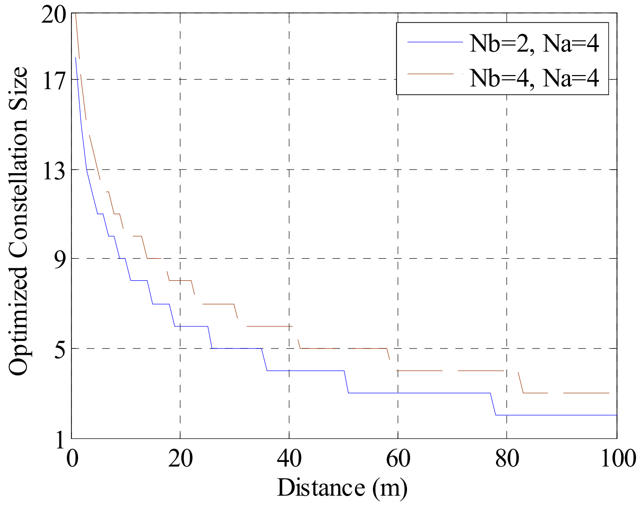

Figure 3. Optimized constellation size over distance for Na=4.

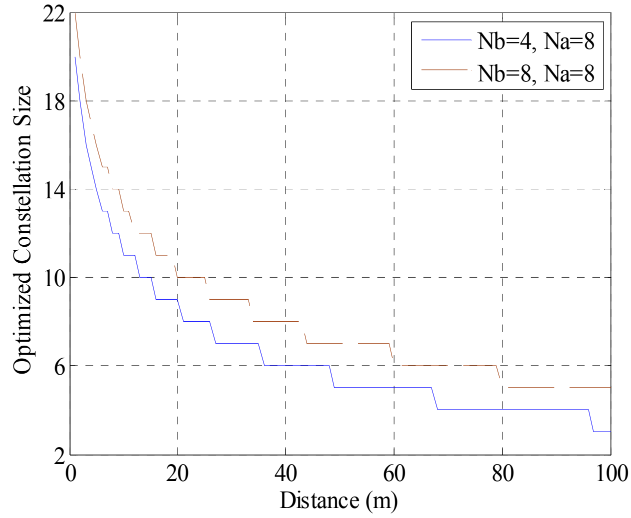

Figure 4. Optimized constellation size over distance for Na=8.

III. SIMULATION RESULTS

A. Simulation parameters

In order to get the total communication energy consumption, the average energy per bit required for a given BER, $\overline{E}_b$ need to be determined. The average BER of a MISO system using Alamouti schemes with MQAM is given by [15]

$$\overline{P}_b \approx E_H\left[\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right)\right] \quad for\ b \geq 2\ and$$
$$\approx E_H\left[Q\left(\sqrt{2\gamma_b}\right)\right] \quad for\ b = 1 \tag{10}$$

where $E_H[\cdot]$ denotes the expectation with variable **H**, and $Q(\cdot)$ is the Q-function defined as $Q(x) = 1/\sqrt{2\pi}\int_x^{\infty} e^{-t^2/2}dt$. In our approach we get the value of $\overline{E}_b$ by using numerical search.

In the case of local communication the distance d_m between the WTIMs within a cluster is chosen 1 m to avoid complexity. It is assumed that the long haul distance is same from the WTIMs within a cluster. For the long haul communication, SISO can be a special case of MISO system.

The channel matrix of MISO system can be written as $H = [h_1 \quad h_2 \quad h_3 \cdots \quad h_{Na}]$. Out of the Na available WTIM, Nb number of channels will be chosen to transmit the data of all the active WTIMs. The system parameters used in simulation are shown on Table 1.

Energy efficiency is calculated using the following formula

$$Energy\ efficiency = \frac{E_{SISO} - E_{CO}}{E_{SISO}} \tag{11}$$

Total delay in the case of SISO and Cooperative transmission is shown in equation (12) and (13) respectively. Channel estimation delay t_{ch} is ignored compared to the other delays.

$$T_{SISO} = T_S\left(\sum_{i=1}^{Na}\frac{L_i}{b_i^b} + \frac{1}{b^l}\sum_{i=1}^{Na} L_i\right) + t_{da} \tag{12}$$

$$\begin{aligned} T_{CO} &= t_{ch} + T_S\left(\sum_{i=1}^{Na}\frac{L_i}{b_i^b} + \sum_{i=1}^{Na}\frac{L_i\gamma_i}{b_i^b} + \frac{1}{b^l}\sum_{i=1}^{Na} L_i\gamma_i\right) + t_{da} \\ &= T_S\left(\sum_{i=1}^{Na}\frac{L_i}{b_i^b} + \sum_{i=1}^{Na}\frac{L_i\gamma_i}{b_i^b} + \frac{1}{b^l}\sum_{i=1}^{Na} L_i\gamma_i\right) + t_{da} \end{aligned} \tag{13}$$

The delay difference is calculated in the following way

$$Delay\ difference = T_{SISO} - T_{CO}$$

$$= T_S\left(\frac{1}{b_{SISO}^l}\sum_{i=1}^{Na} L_i\gamma_i - \sum_{i=1}^{Na}\frac{L_i\gamma_i}{b_i^b} - \frac{1}{b_{MIMO}^l}\sum_{i=1}^{Na} L_i\gamma_i\right) \tag{14}$$

B. Simulation results

For simulation we consider that all the WTIMs in a cluster are transmitting the same data size L_i = 10 kb. We experimented on 2 types of cluster size Na = 4 and Na = 8 where Na is the number of active WTIMs. Then we compare MISO with SISO for different number of superior WTIMs.

TABLE 1. SYSTEM PARAMETERS

f_c = 2.5 GHz	η = 0.35
G_tG_r = 5 dBi	N_0 = – 171 dBm/Hz
B = 10 KHz	k = 2 for local comm.
$P_b = 10^{-3}$	k = 3 for long haul com.
N_f = 10 dB	p = 0
γ = 1	P_{mix} = 30.3 mW
M_l = 40 dB	$P_{filt} = P_{filr}$=2.5 mW
E_{Ch} = 28 μJ/bit/signals	P_{syn} = 50.0 mW
E_{da} = 5 nJ/bit/signals	P_{LNA} = 20 mW

Figure 5 shows the comparison between SISO and MISO. MISO with Nb = 2 outperform SISO after 42 meter where the distance is 48 meter in the case of Nb = 4. Figure 6 and Figure 7 shows the energy efficiency for different combinations of Na and Nb. For both Na = 4 and Na = 8, combination of 2 (two) superior sensors shows energy efficient performance.

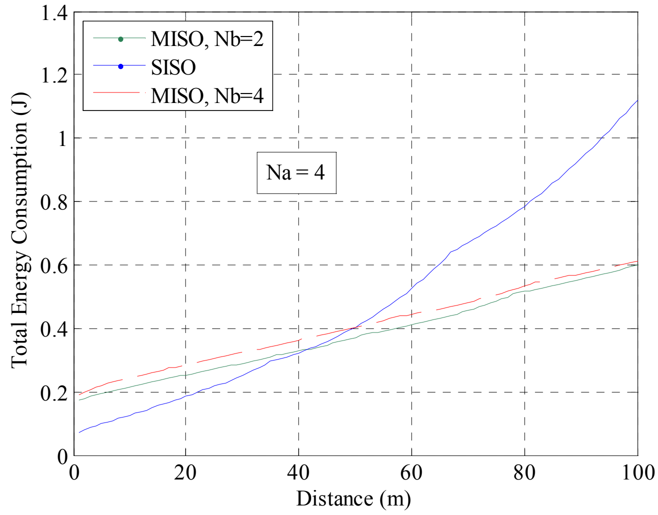

Figure 5. Total energy over distance for varying number of superior WTIMs.

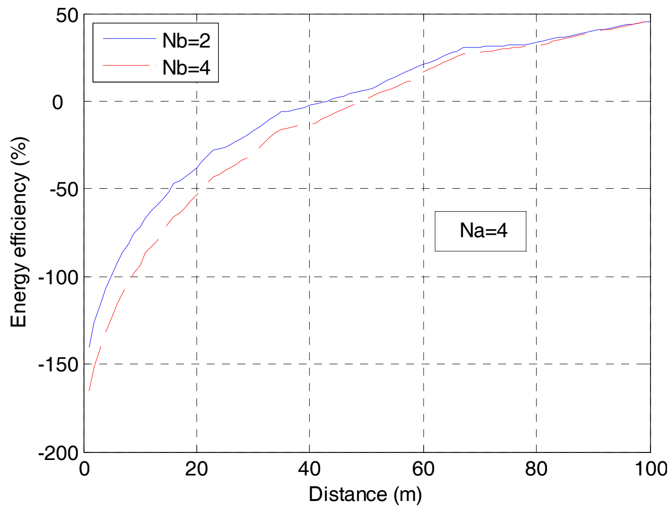

Figure 6. Energy efficiency over distance for Na = 4 with varying Nb.

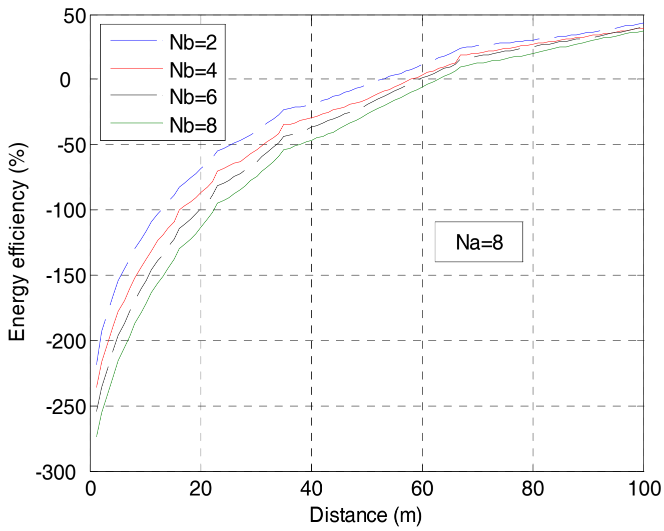

Figure 7. Energy efficiency over distance for Na = 8.

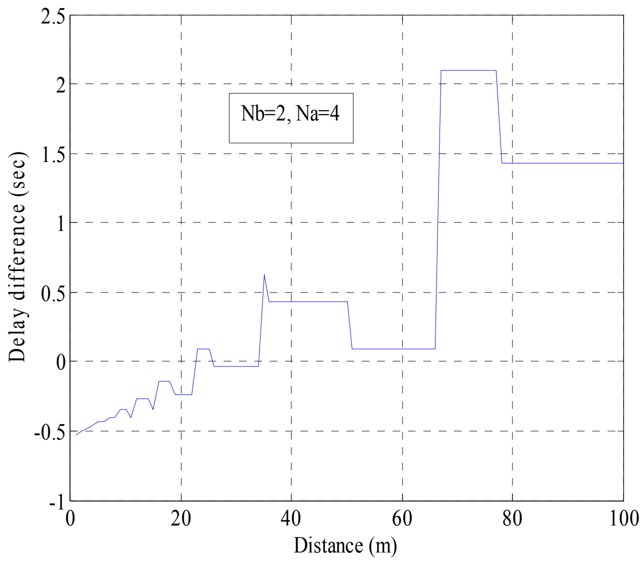

Figure 8. Delay difference over distance.

Hence we can say that selected MISO shows better performance in terms of energy efficiency. Figure 8 shows the difference in delay for $Na = 4$ and $Nb = 2$. When the delay is positive, it means $T_{SISO} \geq T_{CO}$. MISO performs better than SISO after 37 meter in terms of delay as the delay difference remains positive.

Energy efficiency is also compared in terms of channel estimation energy and is plotted in Figure 9. We see that the less the energy needed for estimating a channel, the more is the energy efficiency. Again another analysis is shown varying the distance between the sensors in a particular cluster. Result shows that increasing the distance between the sensors among a cluster makes the cooperative technique outperform SISO later in distance. It is shown in Figure 10 and Figure 11 in terms of total energy consumption and energy efficiency. In Figure 11, it shows that compact cluster is more energy efficient than the loosely distributed cluster.

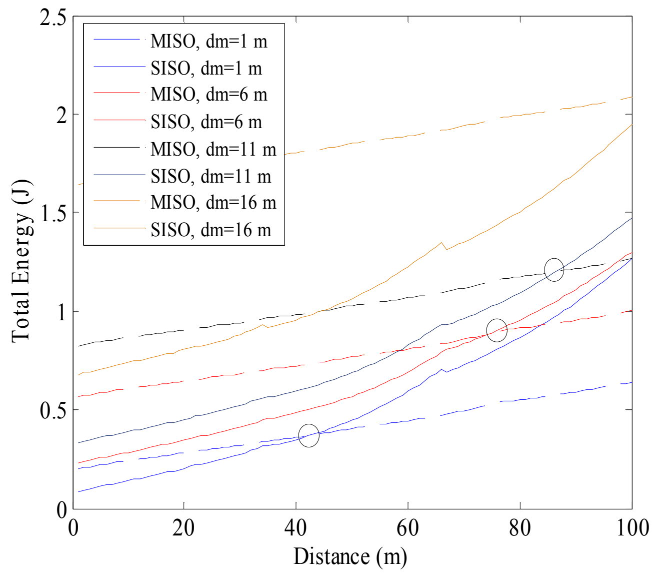

Figure 10. Total energy consumption over distance for varying inter sensor distance.

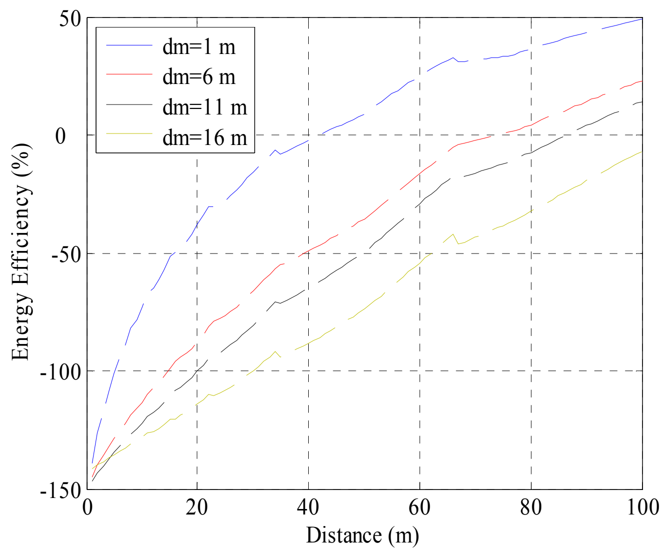

Figure 11. Energy efficiency over distance for varying inter sensor distance.

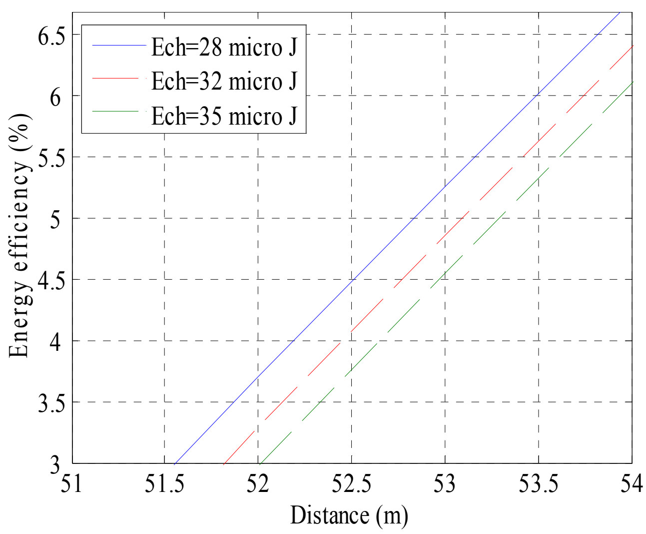

Figure 9. Channel estimation energy variation.

IV. CONCLUSION

An Energy efficient cooperative technique is proposed for the IEEE 1451.5 based Wireless Sensor Networks. Selected numbers of WTIMs are used on the basis of channel condition criteria to form a MISO structure. Energy efficiency and delay difference is evaluated for selected approach and is compared with the existing model. The results show that the selected MISO structure outperforms the unselected MISO structure both in terms of energy efficiency and delay after some distance. Our model can be extended to the MIMO case considering multiple antennas in the NCAP.

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