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Cooperative MIMO with Data Aggregation: Impact on Energy Efficiency of Clustered Wireless Sensor Networks

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Abstract − In wireless sensor networks, battery's life is the main constraint in their deployment and working. Hence, many techniques have been developed to improve the energy efficiency of wireless sensor networks which in turn increases their network lifetime. In this paper, we use cooperative communication jointly with data aggregation to reduce the energy consumption of batteries. For this purpose, we use cooperative multiple-input multiple-output (MIMO) to reduce the energy consumption during transmission of data bits and data aggregation to reduce the redundant data bits for transmission by correlating neighbor nodes data. In this paper, variation in average energy consumption per node is analyzed by varying cluster size in the sensor network. We have also compared this technique with cooperative MIMO without data aggregation, data aggregation without cooperative MIMO and single-input single-output (SISO) technique. Also variation in energy saving gain is shown with variation in average distance of two neighboring nodes considering different spatial correlation.

Keywords– Cooperative multiple-input multiple output, data aggregation, network lifetime, wireless sensor networks (WSNs), energy efficiency

INTRODUCTION

Wireless sensor networks (WSNs) have emerged as one of the most important field in wireless communication as they are having countless applications such as surveillance, intelligence, targetingsystems, intrusion detection, patient monitoring, product quality monitoring and monitoring disaster areas [1]. As size of sensors have become very small over the period of time, so is their power source i.e. batteries and it is very difficult to recharge or replace them in most applications. So, some techniques should be used to reduce the amount of energy consumed in transmission of data between the clusters. It can be further reduced by eliminating the redundant data between the neighboring nodes by correlating them. Therefore, less the data for transmission, less will be the energy consumed.

For reducing the transmission energy, we are proposing the cooperative MIMO (CMIMO) technique. The efficiency of cooperative transmission under space-time block code encode (STBC) is discussed and the synchronization requirements are analyzed in [2]. In a clustered sensor network where sensors cooperate with each other on signal transmission or reception in a deterministic way, energy efficiency points have been investigated in [3]. The overall energy consumption can further be reduced by properly balancing the power allocation between intra-cluster (local) and inter-cluster (long-haul) transmissions [4]. If the long-haul transmission distance is large enough and cluster size is optimally chosen, the energy efficiency of cooperative MIMO can be significantly increased [3]. The energy consumed during inter-cluster transmission can be saved by using data aggregation (DA) technique to reduce the amount of data in transmission.

Of late, approaches have been presented that combines cooperative MIMO with data aggregation (CMIMO-DA) [3], [4]. [3] presents effect of the distance of long-haul transmission on the energy efficiency of the network and concluded that the total energy consumption can further be reduced by combining both cooperative MIMO and data aggregation techniques. But results limited with maximum two sensor nodes in a cluster makes it difficult to distinguish between different aggregation schemes. Where as in [4], average energy consumption per node versus cluster size has been examined for cooperative MIMO with data aggregation scheme and compared with three other schemes. It has been compared with SISO, cooperative MIMO without data aggregation and data aggregation without CMIMO. In this paper, research of [4] has been extended by varying some parameters involved and presenting that more number sensor nodes can exist with negligible compromise on the average energy consumption per node.

Remaining paper is organized as follows. Section II proposes energy consumption model for CMIMO-DA for centralized data aggregation scheme (CDAS). In Section III, optimal cluster size is obtained for minimized average energy consumption per node. Energy saving gain is also obtained for different spatial correlation. Section IV finally concludes the paper.

SYSTEM MODEL

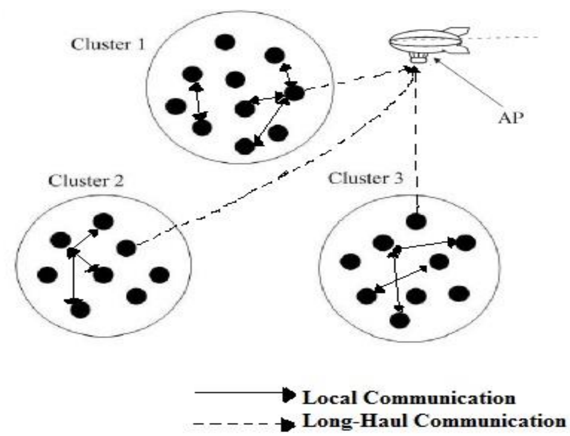

Fig.1. CMIMO-DA Communication

In Fig.1, the sensor nodes are uniformly distributed with nodal density and self organized into clusters. These nodes transmit data to the AP (access point) by cooperative communication. Let us assume that cluster size is n (i.e. each cluster contains n sensors nodes). Such nodes sense L bits of data in given period of time. Data sensed by the nodes in a cluster are correlated as they are closely spaced. Data aggregation condenses the redundant data using the correlation property and hence reduced amount of data is to be transmitted to the AP.

In CMIMO-DA, communication can be divided into two steps:

a) Local Communication
b) Long-Haul Communication.

In Local communication, sensor nodes exchange their data with each other through a central node and correlated data are compressed by appropriate aggregation scheme and then distributed to individual sensor nodes. In Long-Haul communication, compressed data from previous step is transmitted by each individual node to the AP through the wireless channel using a Space Time Block Coding (STBC) scheme.

For Local communication, a Square Law Path loss with additive white Gauss Noise (AWGN) is assumed. A Rayleigh fading channel with Square-Law path loss is assumed for long-haul communication. We adopt orthogonal STBC (OSTBC) codeword. Rayleigh fading channel gain between a transmitting and a receiving node is a scalar. Hence, the fading factors of CMIMO channel can be represented as a scalar matrix [2].

Let us assume E_{total} (Total Energy Consumption for transmitting L bits from each of the n nodes in a cluster to the AP) can be divided into two components:

- The energy consumed in long-haul communication by the sensor nodes in a cluster to the AP for cooperatively transmitting the compressed data E_{lh}.
- The energy consumed in local communication for exchange of data and compression E_{lc}, which is given by:

$$E_{total} = E_{lh} + E_{lc} \quad (1)$$

A. Energy Consumption of Long-Haul Communication E_{lh}:

The energy consumed in long-haul communication CMIMO-DA, $E_{\text{lh}}^{CMIMO-DA}$ is given by:

$$E_{\text{lh}}^{CMIMO-DA} = [\, P_{\text{DMIMO}} + (nP_T + P_R)]\, \frac{I_n}{R_{lh}} \quad (2)$$

where sensor nodes in a cluster encode the compressed data with the OSTBC scheme and cooperatively transmit them to the AP. P_{DMIMO} is the power consumption of the power amplifiers on the transmitting side, and R_{lh} denotes the transmission bit rate defined as $R_{lh} = R_b.b.B$, with b being the constellation size (bits per symbol), B being the modulation Bandwidth and R_S being the spatial rate of the encoding scheme. Here, R_S =1/2, because OSTBC with code rate of ½ is used, I_n is the total amount of data after compression in a cluster with n nodes and the general expression of I_n is application dependant. General expression for I_n is calculated according to rainfall model [7]. The total amount of compressed data generated by a set of n nodes after lossless compression can approximately be calculated by an iterative formula as follows:

$$I_i = I_{i-1} + \left[1 - \frac{1}{(d_i/c+1)}\right] L, \qquad i = 2,3, \dots, n \quad (3)$$

where c is a constant and represents the degree of spatial correlation in the data, and d_i is the minimum distance between the new source node (the i^{th} node) and the existing set of nodes. The initial set of nodes consists of only one source node; thus, we have $I_1 = L$. At each iteration, the new source node makes a certain amount of contribution to the total compressed data, which is equal to $[1 - (1/(d_i/c + 1))]L$. Furthermore, we can conclude, based on (3), that the amount of compressed data contributed by the new source node, i.e., $\Delta I_i = I_i - I_{i-1}$, increases as the total number of the nodes involved increases.

In Long-Haul communication, distance between AP and the cluster is usually much larger than the maximum separation of the clusters which is denoted by D. we assume that this distance is same for all the sensor nodes. The Power consumed by power amplifiers in one cluster when the channel experiences only a square-low path loss is denoted as P_{DMIMO} and can be given by [5].

$$P_{\text{DMIMO}} = (1 + \alpha) E_{lh}^{b}\, R_{lh} \frac{(4\pi)^2 D^2}{G_t G_r \lambda^2} M_l N_f \quad (4)$$

where E_{lh}^{b} is the average energy per bit required for a given BER requirement. $\alpha = (\xi/\eta) - 1$, with ξ being the peak-to-average ratio (PAR) and η being the drain efficiency of the RF power amplifier. Here, G_t and G_r are the transmitter and receiver antenna gains, respectively, λ is the carrier wavelength, M_l is the link margin that compensates for the hardware process variations and other additive background noise or interference, and N_f is the receiver noise level defined as $N_f = N_r/N_0$, with N_r being the power spectral density (PSD) of the total effective noise at the receiver input and N_0 being the single-sided thermal noise PSD at room temperature. ξ (PAR) is given as:

$$\xi = 3\left(\frac{2^{\frac{b}{2}} - 1}{2^{\frac{b}{2}} + 1}\right) \quad (5)$$

The average BER $\mathcal{E}_{lh}$ of a MIMO with MQAM when b=2 is given by [5].

$$\mathcal{E}_{lh} = \mu_h\left[Q\left(\sqrt{2\gamma_{lh}}\right)\right] = \int_0^\infty Q\left(\sqrt{2\gamma_{lh}}\right) f(\gamma_{lh})\, d\,\gamma_{lh} \quad (6)$$

where $\mu_h(x)$ denotes the expectation of x with channel vector h, and γ_{lh} is the instantaneous received SNR for the CMIMO system.

E^b_{lh} can be given by chernoff bound [6]. So, upper limit for the required energy per bit in the high SNR region is given as

$$E^b_{lh} \leq \frac{nN_0}{(\mathcal{E}_{lh})^{1/n}} \quad (7)$$

By taking equality in (7) and putting into (4), we can calculate P_{DMIMO}.

B. Energy Consumption of Local Communication E_{lc}:

In [4] two data aggregation schemes have been proposed in CMIMO-DA to exchange and compress their data and result in different forms of energy consumption in Local communication. One scheme is CDAS, in which central node collects the data sensed by all the nodes in the cluster, compresses the data and then distributes the compressed data back to the nodes. The other scheme as DDAS (Distributed Data Aggregation Scheme) in which each node exchange its data with all other nodes in a cluster and then separately compress the data. In [4], it is shown that CDAS is more energy efficient than DDAS when the degree of spatial correlation is above a threshold value (c=1740 in this case). So, we will consider CDAS in this paper for CMIMO-DA. CDAS works in there phase:

a) Gathering Phase
b) Compressing Phase
c) Broad Casting Phase as given in [4].

The energy consumption of CDAS in a cluster is the sum of the energy consumed in above mention three phases, which is given by:

$$E_{lc} = E_{gath} + E_{cmprsn} + E_{broad} \quad (8)$$

where E_{gath}, E_{cmprsn} and E_{broad} are the energy consumption of the gathering, compressing and broadcasting phases in CDAS, respectively.
Some parameters are omitted here that consumes energy to maintain the efficiency of the model. The energy dissipated in the gathering phase is given as

$$E_{gath} = [(n-1)P_{dSISO} + (n-1)(P_T + P_R)]\frac{L}{R_{lc}} \quad (9)$$

where P_{dSISO} denotes the power consumption of the power amplifier at the transmitter side, and P_T and P_R are the power consumption of circuit blocks at the transmitter side and the receiver side, respectively. The transmission data rate is given by $R_{lc} = b.B$.

P_{dSISO} can be calculated when the channel experiences only a Square-Law Path Loss based on the link budget relationship [5].

$$P_{dSISO} = (1+\alpha)E^b_{lc}\, R_{lc}\frac{(4\pi)^2 d^2}{G_t G_r \lambda^2} M_l N_f \quad (10)$$

where E^b_{lc} is the energy per bit required for a given BER requirement. For simplicity, all the clusters are assumed of circular area of the same size as in [4], and the radius of the circular area is used as the transmission distance, which is denoted by *d*, for all the nodes in a cluster to exchange their data through a central node. To obtain P_{dSISO}, the energy per bit E^b_{lc} required for a given BER $\mathcal{E}_{lc}$ needs to be determined. The average BER of a SISO with MQAM when b= 2 is given by [5].

$$\mathcal{E}_{lc} \approx Q(\sqrt{2\gamma_{lc}}) \quad (11)$$

where $Q(x)$ is the Q-function, which is defined as $Q(x) = \left(1/\sqrt{2\pi}\right)\int_x^\infty e^{-t^2/2}\,dt$ and γ_{lc} denotes the instantaneous received signal-to-noise ratio (SNR), which can be written as

$$\gamma_{lc} = \frac{E^b_{lc}}{N_0} \quad (12)$$

Hence E^b_{lc} can be obtained for the given $\mathcal{E}_{lc}$ by substituting (12) into (11). The energy dissipated in the compression phase is given by [4].

$$E_{cmprsn} = nLE_{comp} \quad (13)$$

where E_{comp} denotes the energy cost per bit for data compression.
The energy dissipated in the broadcasting phase is given by [4].

$$E_{broad} = [P_{dSISO} + (q(n)P_T + (n-1)P_R)]\frac{l_n}{R_{lc}} \quad (14)$$

For (14) to be valid when n is any positive integer, a binary function $q(n)$ is defined as

$$q(n) = \begin{cases} 0, & n = 1 \\ 1, & n \geq 2 \end{cases}$$

So, energy consumption during local communication under CDAS can be obtained by combing (8),(9),(13) and (14). It is expressed as

Parameter	Symbol	Value
Drain Efficiency	η	0.35
Transmitter and Receiver Antenna Gain	$G_t G_r$	5 dBi
Link Margin	M_l	40 dB
Receiver noise level	N_f	10 dB
Single sided thermal Noise Power Spectral Density at room temperature	N_0	-171 dBm/Hz
Modulation Bandwidth	B	10 KHz
Power Consumption at transmitter side	P_T	150 mW
Power Consumption at receiver side	P_R	100 mW
Energy cost per bit for data compression	E_{comp}	5 nJ/bit/signal
Length of data in bits	L	2000 bits
Distance between clusters and access point	D	10000 m
Constellation size	b	2
Nodal Density	ρ	$10^{-6}/m^2$
Degree of spatial correlation in data	c	2500
Carrier Wavelength	λ	0.12 m

$$E_{lc} = \frac{1}{R_{lc}}\{[(n-1)L + I_n]P_{dSISO} + [(n-1)L + q(n)I_n]P_T + [(n-1)(L+I_n)]P_R\} + nLE_{comp} \quad (15)$$

Now, the total energy consumption for all nodes in a cluster to transmit their sensed data to the AP, E_{total} can be obtained as

$$E_{total} = E_{lh} + E_{lc}$$

The average energy consumption per node will be used as an indicator for evaluating the energy efficiency of CMIMO-DA [4], which is expressed as

$$E^{CMIMO-DA} = \frac{E_{total}}{n} \quad (16)$$

Therefore,

$$E^{CMIMO-DA} = \frac{1}{nR_{lc}}\{[(n-1)L + I_n]P_{dSISO} + [(n-1)L + q(n)I_n]P_T + [(n-1)(L+I_n)]P_R\} + LE_{comp} + \frac{I_n}{nR_{lh}}[P_{DMIMO} + (nP_T + P_R)] \quad (17)$$

ANALYSIS AND COMPARATION OF CMIMO-DA WITH OTHER TECHNIQUES

In this section, firstly we will compare the performance of CMIMO-DA with CMIMO, data aggregation with CMIMO (DAW), and SISO system. Average energy consumption per node for CMIMO, DAW and SISO system can be given by [4] and they are denoted as E^{CMIMO}, E^{DAG} and E^{SISO} respectively.

Therefore,

$$E^{CMIMO} = \frac{L}{nR_{lc}}[(2n-1)P_{dSISO} + q(n)(2n-1)P_T + (n^2-1)P_R] + \frac{L}{R_{lh}}[P_{DMIMO} + nP_T + P_R] + LE_{comp} \quad (18)$$

$$E^{DAG} = \frac{L}{nR_{lc}}(n-1)(P_{dSISO} + P_T + P_R) + LE_{comp} + \frac{I_n}{nR_{lh}}[P_{DSISO} + P_T + P_R] \quad (19)$$

$$E^{SISO} = [P_{DSISO} + P_T + P_R]\frac{L}{R_{lc}} + LE_{comp} \quad (20)$$

where P_{DSISO} is the power consumption of the power amplifier during data transmission from the cluster to the AP, which is the same as P_{dSISO} expressed by (10), but replacing d with D. Some assumptions are made in the simulation of these four techniques just as in [4]. We compare the results for average energy consumption per node versus cluster size as given in [4] for different average BER (both long-haul $\mathcal{E}_{lh}$ and local $\mathcal{E}_{lc}$). So, we demonstrate the effect of cluster size on average energy consumption per node for four analytical models derived in (17)-(20) for a given parameter settings given in Table I.

TABLE I. SYSTEM PARAMETERS

Fig. 2, Fig. 3 and Fig. 4 shows the effect of different average BER on average energy consumption per node versus cluster size for CMIMO-DA, CMIMO, DAW and SISO. For Fig. 2, Fig. 3 and Fig. 4, we have taken the average BER as 10^{-2}, 10^{-3} and 10^{-4} respectively. As clearly shown in these three figures, CMIMO-DA outperforms all other three systems mentioned in terms of energy efficiency in most cases. From these figures, we can show that after proper clusterization, CMIMO-DA will become most energy efficient system in WSNs.

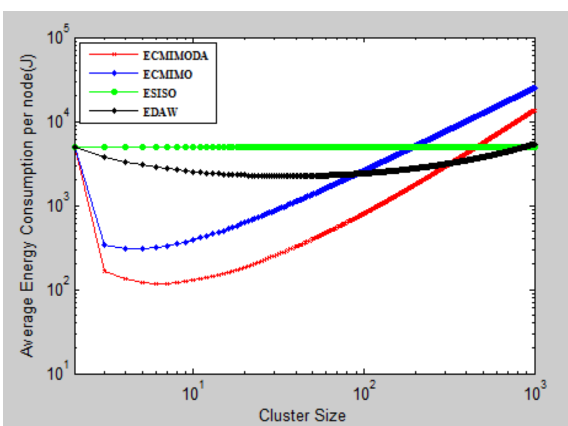

Fig. 2. Average energy consumption per node against cluster size for CMIMO-DA, CMIMO, DAW, and SISO with average BER=10^{-2}

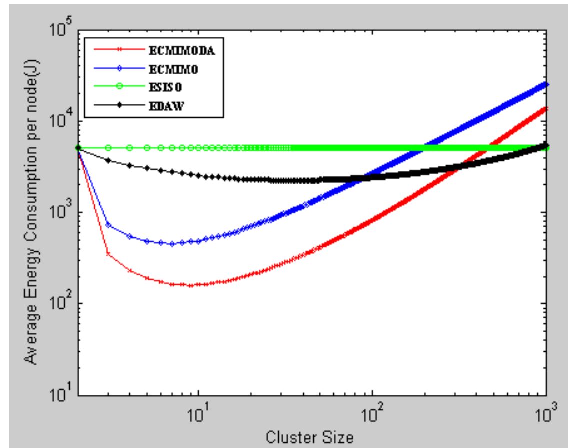

Fig. 3. Average energy consumption per node against cluster size for CMIMO-DA, CMIMO, DAW, and SISO with average BER=10^{-3}

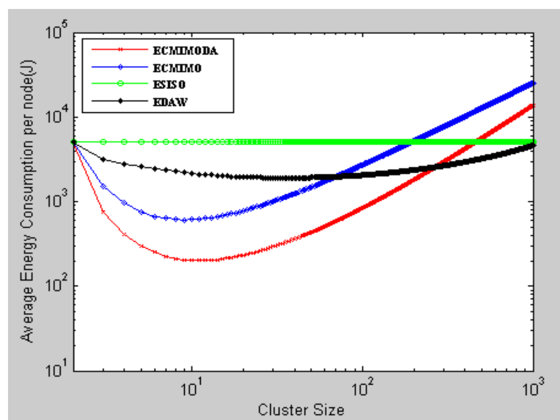

Fig. 4. Average energy consumption per node against cluster size for CMIMO-DA, CMIMO, DAW, and SISO with average BER=10^{-4}

Here, we compare CMIMO-DA system's average energy consumption per node and accordingly optimal cluster size for different average BER values. Fig. 2 shows average energy consumption per node against cluster size for CMIMO-DA, CMIMO, DAW, and SISO with average BER=10^{-2}. For this setting, we get $E^{CMIMO-DA}$=103J and n=5. Fig. 3 shows average energy consumption per node against cluster size for CMIMO-DA, CMIMO, DAW, and SISO with average BER=10^{-3}. For this setting, we get

$E^{CMIMO-DA}$=108J and n=8. Fig. 4 shows average energy consumption per node against cluster size for CMIMO-DA, CMIMO, DAW, and SISO with average BER=10^{-4}. For this setting, we get $E^{CMIMO-DA}$=110J and n=10. For the settings given in Table I and average BER of 10^{-2}, CMIMO-DA achieves minimum average energy consumption for a cluster size of 5.

As we can see from our results, CMIMO-DA and CMIMO are the two most effective techniques to save energy in WSNs for optimal cluster size and average BER. Here, we will compare both techniques for long-haul communication as most part of the energy is consumed in transmitting data from sensor nodes to AP [4]. Fig. 5 shows that CMIMO-DA consumes less energy than CMIMO for all cluster sizes as there are much less data to transmit from sensor nodes to AP due to data aggregation. The energy consumed in long-haul communication of CMIMO-DA is given by (2). The energy consumed in long-haul communication of CMIMO, E_{lh}^{CMIMO} is given by:

$$E_{\mathrm{lh}}^{CMIMO} = \frac{L}{R_{lh}}[\mathrm{P_{DMIMO}} + nP_T + P_R] \qquad (21)$$

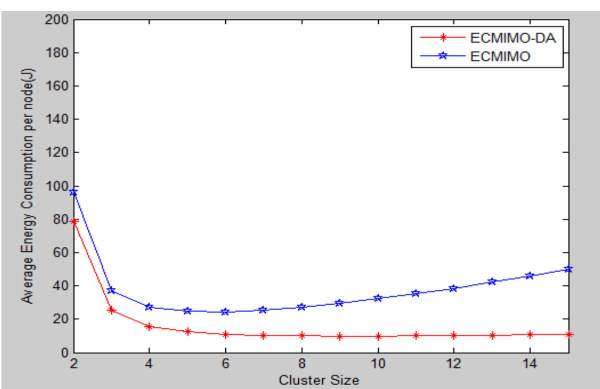

Fig. 5. Energy consumption comparison between CMIMO-DA and CMIMO for long-haul communication.

Lastly, we will show how spatial correlation affects energy saving in CMIMO-DA. For this, energy saving gain of CMIMO-DA is compared with CMIMO versus average distance of two neighboring nodes when ϕ= 0, 0.25, 0.5, 0.75 and 1. Here, energy saving gain is defined as the ratio of the reduction in energy consumption per node between CMIMO and CMIMO-A versus the energy consumption per node of CMIMO, i.e.,

$$\psi_{energy} = \frac{E_{node}^{CMIMO} - E_{node}^{CMIMO-DA}}{(1+\phi)E_{node}^{CMIMO}}, \quad \phi \geq 0 \qquad (22)$$

Fig. 6 shows energy-saving gain of CMIMO-DA compared with CMIMO versus average distance of two neighboring nodes when ϕ= 0, 0.25, 0.5, 0.75 and 1. It can be deduced from Fig. 6 that spatial correlation in the data produced by sensor nodes will decrease for the increased average distance, so the energy saving gain decreases with the increase in the average distance. In Fig. 6, the degree of spatial correlation is taken as c=100. It is also shown that all the nodes in the network will duplicate data and the energy consumed by CMIMO-DA is fractional compared with that of CMIMO when any two neighboring nodes in a sensor network are close enough.

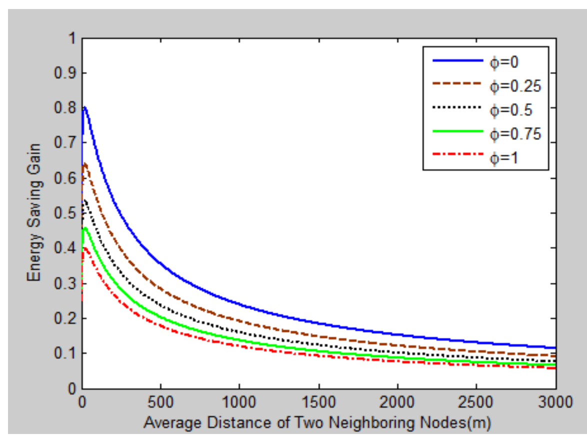

Fig. 6. Energy-saving gain of CMIMO-DA compared with CMIMO versus average distance of two neighboring nodes with degree of spatial correlation is taken as c=100.

CONCLUSION

In this paper, a combined approach of cooperative MIMO and data aggregation (CMIMO-DA) is used to increase the network lifetime of a clustered WSN by increasing its energy efficiency. The CMIMO-DA is compared with SISO, cooperative MIMO without data aggregation and data aggregation without CMIMO and the

CMIMO-DA became the most energy efficient model for different cluster sizes. It is also shown that CMIMO and CMIMO-DA are more energy efficient for optimally clustered network. But it can consume even more energy than other schemes if the cluster size is taken too big. It is also shown that energy consumption and optimal cluster size depends on average BER, and the energy saving gain decreases with the increase in the average distance.

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