An Algorithm for Energy Efficient Cooperative Communication in Wireless Sensor Networks

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Abstract

In this paper, we propose an algorithm for energy efficient cooperative communication in wireless sensor network (WSN). The algorithm computes the appropriate transmission distance corresponding to optimal broadcast bit error probability, while taking the circuit energy consumption and the number of cooperating nodes into consideration. The algorithm guarantees minimum energy consumption by choosing higher value of bit error probability for cooperative phase and lower value of bit error probability for broadcast phase while maintaining the required end-to-end reliability. The simulation results show that the proposed algorithm provides significant energy saving gain when compared with traditional fixed distance schemes and is suitable for applications demanding energy efficiency with high quality of reception.

Keywords: cooperative communication, sensors, C-MISO, WSN, energy efficiency, energy-delay product

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1. Introduction

Wireless Sensor Networks (WSNs) have drawn more attention from researchers recently because they find applications spanning over vast and varied areas such as fire detection, habitat sensing and target tracking etc., The sensor nodes deployed in WSNs usually consists of sensing, data processing and communicating components, which make them fully functional wireless node. The sensor nodes are tiny and typically powered by small batteries, for which replacement, even if possible, is highly expensive and intricate [1]. Hence, energy efficiency in WSN has become the practical challenge and design focus recently, besides the other requirements such as reliability and throughput.

The Multiple Input Multiple Output (MIMO) technique is a low power long distance communication method [2] which has the potential to support higher data rate and dramatically reduces transmit energy consumption over multipath fading channels. The MIMO technique deploys multiple antennas, both at the transmitter and receiver, and provides diversity gain [3]-[5]. The MIMO provides coding gain also, when it is used in conjunction with appropriate space time coding (e.g. space time trellis code). These gains can be utilized to conserve the energy of the sensor nodes. However, direct pertinence of MIMO technology in WSN is highly impractical due to the small physical size of a sensor node which may only be able to support single antenna. WSN nodes are usually designed to communicate using Single Input Single Output (SISO) technology through a single antenna.

As a solution to the problem, Cooperative Communication (CC) concept has been proposed in [6]. In CC, multiple nodes which have only single antenna, cooperate and coordinate among them, simultaneously transmit, receive, decode and retransmit the data. The CC establishes a Virtual MIMO (V-MIMO) system, so that energy efficient MIMO schemes can be utilized. In wireless environments, the received power falls off as the k^{th} power of distance, with $2 \le k \le 6$, where k is the channel path loss exponent. Hence, the transmit energy is conserved by using multi-hop routing [7] and smaller transmission distance ($d \le 100$ m) is chosen for each hop. The smaller transmission distance makes the transmit energy comparable with the circuit energy along the signal path. Hence, both transmit energy and circuit energy consumption needs to be considered in determining the optimal transmission distance.

In [8], the authors investigated the energy consumption of Multiple Input Single Output (MISO) in WSN. The authors assumed same bit error probability of the broadcast phase and the bit error probability of the cooperative phase. In addition, the authors used fixed distance d =100 m. In [9], the authors investigated the energy efficiency of cooperative communication in WSN. The authors used optimal broadcast bit error probability and optimal number of cooperating nodes. In addition, the authors used fixed distance d =200 m.

In the proposed work, an algorithm for energy efficient co-operative communication in WSN is proposed with optimal distance and optimal number of nodes.

The main contributions of the paper are

(i) The equations for optimal broadcast bit error probability and the optimal long haul distance that maximizes the energy efficiency is derived.

(ii) An algorithm for energy efficient cooperative communication in WSN is proposed.

The rest of the paper is organized as follows. The related work is presented in section 2. Section 3 describes the system model. Simulation results are given in section 4. Finally, section 5 concludes the paper.

2. Related Work

Most of the pioneering research in the area of network lifetime prolongation has focused on transmission schemes to reduce the total energy required per bit. The total energy required per bit per hop includes both the circuit energy consumption and transmit energy consumption and is directly proportional to the transmission distance, reliability and the number of nodes participating in the CC. On the other hand, the total energy required per bit per node is directly proportional to the transmission distance, reliability and inversely proportional to the number of nodes participating in the CC.

In [6], the authors analyzed the energy consumption profiles of V-MIMO and SISO for single hop and showed that significant energy conservation can be obtained when the transmission distance exceeds 25 m. With the system parameters given in [6], when the distance between the transmitter and receiver is greater than 25 m called threshold distance, MIMO is energy efficient than SISO. The dependency of energy efficiency on propagation parameters and extra training overhead is investigated in [10].

In [11], the authors proposed an energy efficient algorithm to address the node selection problem in MIMO-based sensor networks. They investigated the effect of circuit power consumption on the performance of MIMO-based sensor networks. They demonstrated the energy efficiency of V-MIMO even for smaller distances, provided the circuit power consumption is small. The authors proposed a metric which is a function of channel conditions and remaining battery energy for selecting the cooperating nodes. They also analyzed the influence of number of cooperating nodes on network lifetime. They achieved additional energy saving and improved network lifetime by selecting the cooperating nodes.

In [12], the authors proposed an energy efficient multi-hop cooperative MIMO scheme for limited number of available cooperating nodes in wireless sensor networks. They analyzed the energy consumption of SISO, multi-hop SISO and cooperative MIMO schemes. They also investigated the optimal number of transmitting and receiving cooperating nodes for a given transmission distance. The authors demonstrated the energy efficiency of proposed scheme and its demand for less network resource over conventional SISO, multi-hop SISO and cooperative MIMO schemes.

In [13], the authors analyzed the energy efficiency of cooperative schemes and showed that the cooperation is more energy efficient than non-cooperative single hop and multi-hop schemes. In [14] and [15], the authors proposed a space-time coded cooperation to reduce energy consumption. In [16], the authors proposed a scheme to exploit transmit diversity in multi-hop WSN and showed the improvement in energy saving as the number of hops increased when end-to-end outage probability is fixed.

In [17], the authors proposed an energy efficient chain based routing protocol for wireless sensor networks to minimize energy consumption, transmission delay and energy-delay cost. In [18], the authors proposed an Energy Balancing Cluster Head (EBCH) in WSN to maintain minimum inter cluster energy consumption of the network by balancing the intra cluster load among the cluster heads.

In [19], the authors proposed a scheme to find the optimal relay nodes and their corresponding radio interfaces that minimize energy consumption while satisfying the end-to end packet deadline requirement. In [20], the authors jointly optimized the hop distance and the number of cooperating nodes to improve the energy efficiency in wireless ad hoc networks. They showed that the Cooperative Multiple Input Single Output (C-MISO) transmission is energy efficient compared with SISO transmission for higher values of path loss exponent. However, the authors considered the end-to-end bit error probability as the error probability for both the broadcast phase and cooperative phase. The authors ignored the impact of channel gain on the energy consumption. Though the authors addressed the effect of bit error probability, they obtained a fixed number of cooperating nodes and optimal distance for a given bit error probability requirement and thus lack flexibility.

In [21], the authors proposed an energy-efficient network cooperation scheme to reduce the power consumption of secondary transmissions while maintaining the performance of primary transmissions. In [22], the authors proposed a protocol using cognitive relaying to provide continuous connections for target users and to minimize the outage probability of transmissions though optimal allocation of time slots.

In [23], the authors proposed efficient spectrum sensing strategies to reduce sensing overhead and to mitigate the interference to primary users in cognitive radio network. In [24], the authors proposed an energy efficient cooperative model for multicell multiantenna cooperative cellular networks. They analyzed the model under different cooperative transmission scenarios, channel conditions and interference levels. The authors achieved significant improvement in energy efficiency and outage probability performance.

In [25], the authors proposed an energy efficient cooperative algorithm to effectively take the relaying decision. They investigated the influence of transmission distance, number of receive nodes on the energy consumption of cooperative MIMO. The authors also demonstrated the influence of number of relay nodes on the energy consumption and saved energy about 10% than direct transmission.

In [26], the authors proposed a metric to select an appropriate next relay cluster for energy efficient CC in WSN. The authors have taken the circuit energy consumption into consideration for optimizing the energy consumption per unit transmission distance. However, the authors have neglected the influence of intra cluster error probability by assuming it as error free. The authors also failed to address the network life time issue by selecting a far away cluster. In [8], the authors investigated the energy consumption of various configurations such as SISO, Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO) and MIMO in WSN. The authors configured a route which consumes minimum energy by selecting the best configuration for each hop. However, the authors assumed same bit error probability for intra cluster and inter cluster transmission to maintain the end to end reliability. Moreover, the authors fixed the inter hop distance irrespective of the cooperating nodes, leading to inefficient utilization of energy.

In [9], the authors investigated the energy efficiency of cooperative communication in WSN. The authors used optimal broadcast bit error probability and optimal number of cooperating nodes to minimize the energy consumption. However, the authors fixed the inter hop distance irrespective of the cooperating nodes. Hence, a strategy which determines the optimal transmission distance which minimizes the total energy consumption by taking the bit error probability of broadcast and cooperative phase and circuit energy consumption into account while satisfying the end to end reliability and data rate requirements is yet to be proposed.

3. System Model

3.1 Multihop C-MISO Scheme

A densely populated WSN which consists of thousands of sensor nodes is considered. The nodes are stationary and each node has single omni directional antenna with communication range of radius d . The nodes are randomly located according to a uniform distribution with a node density ρ . It is further assumed that the transmission between WSN nodes are perfectly synchronized [14] and the channel is a flat Rayleigh fading channel. The data are modulated by 4-QAM and transmitted to a remote sink through multi-hop cooperative transmission.

The **Fig. 1** shows the system model and describes a typical dual hop C-MISO communication. The transmission in each hop can be divided into two phases: broadcast phase (i.e local communication) and cooperative phase (i.e. long haul communication). During broadcast phase, the Source Node (SN) broadcasts its data to the neighbouring nodes. The nodes which are within the broadcast distance d_b ($d_b \leq 8$ m [8]) are regarded as neighbours and those neighbour nodes which are willing to participate in the cooperative transmission are regarded as Cooperating Nodes (CNs). During cooperative phase, the CNs encode the received data using distributed STBC and simultaneously transmit to the relay node (i.e. inter hop node).

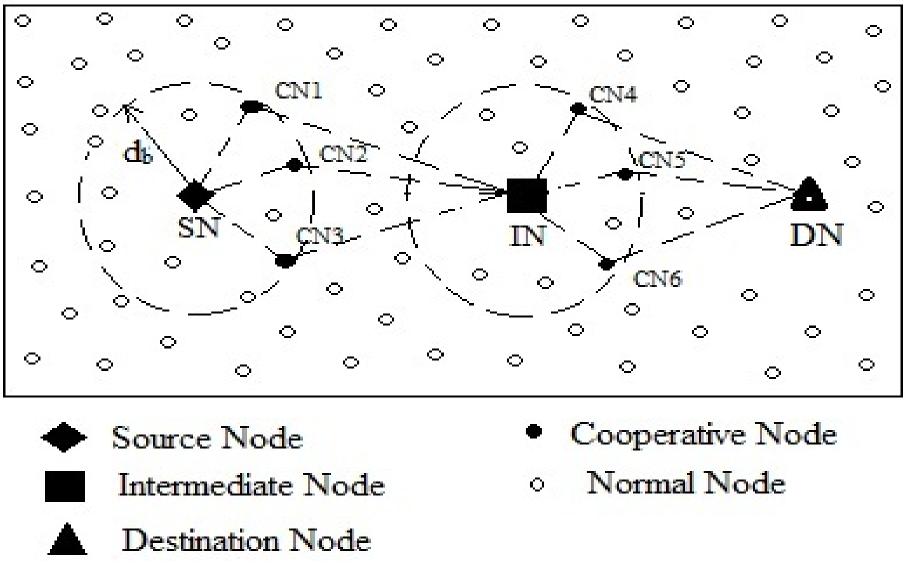

Fig. 1. System Model

The Inter hop Node (IN) decodes the information and broadcasts to the neighbor nodes that are willing to take part in the cooperative transmission. The Inter hop nodes are selected, such that the hop distance d is equal to 100 m in the existing work. However, in the proposed work the Inter hop nodes are selected based on the derived optimal distance equation. Out of the many sensor nodes available in the cooperation range, the cooperative nodes are selected randomly. The CNs of the IN encode the received data using distributed STBC and simultaneously transmit to the next relay node. This process is repeated until the Destination Node (DN) is reached. Nodes CN1, CN2 and CN3 are the CNs of SN and CN4, CN5 and CN6 are the CNs of IN.

3.2 Minimization of Energy Consumption

In this paper, the energy model proposed in [6] and followed in [8] is used. Based on [6], the power consumption of the power amplifier is given by

$$P_{ampl} = (1+\alpha)P_{tx} \tag{1}$$

where P_{ampl} is the power consumption of all the power amplifiers, P_{tx} is the power required for transmission and α is the modulation and power amplifier dependent parameter which is given by

$$\alpha = \left(\xi / \eta \right) - 1 \tag{2}$$

where η is the drain efficiency of the power amplifier and ξ is the modulation dependent peak to average ratio which is given by

$$\xi = 3\frac{M - 2\sqrt{M} + 1}{M - 1} \tag{3}$$

where $M = 2^b$ is the size of the constellation and b is the number of bits used to represent a symbol. The transmission power P_{tx} of equation (1) is given by

$$P_{tx} = \bar{E}_{bt} R_b \times \frac{(4\pi)^2 d^k}{G_t G_r \lambda^2} M_l N_f \tag{4}$$

where $\bar{E}_{bt}$ is the energy required per bit at the receiver for a given bit error probability requirement, R_b is the bit rate, d is the transmission distance, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, M_l is the link margin and N_f is the receiver noise figure. The total power consumption by all other circuit blocks except power amplifier is given by

$$P_{ckt} \approx N_t \left(P_{DAC} + P_{mix} + P_{filt} \right) + 2P_{syn} + N_r \left(P_{LNA} + P_{mix} + P_{IFA} + P_{ADC} + P_{filr} \right) \tag{5}$$

where N_t is the number of transmitting nodes and N_r is the number of receiving nodes. **Table 1** lists the system parameters as in [6].

Equation (5) is represented in terms of energy consumption of the transmitter circuit blocks $E_{Ckt_{TX}}$ and energy consumption of the receiver circuit blocks $E_{Ckt_{RX}}$ as

$$P_{ckt} = \left(N_t E_{Ckt_{TX}} + N_r E_{Ckt_{RX}} \right) bB \tag{6}$$

where B is the transmission bandwidth and

$$E_{Ckt_{TX}} = \frac{P_{DAC} + P_{mix} + P_{filt} + \frac{P_{syn}}{N_t}}{bB} \tag{7}$$

$$E_{Ckt_{RX}} = \frac{P_{LNA} + P_{mix} + P_{IFA} + P_{ADC} + P_{filr} + \frac{P_{syn}}{N_r}}{bB} \tag{8}$$

The value of N_t is considered as 1 for broadcast phase and as N for cooperative phase. The value of N_r is considered as N for broadcast phase and as 1 for cooperative phase. The bit

Table 1. System Parameters

Symbol	Parameter	Value
f_c	Carrier frequency	2.4 GHz
$G_t \times G_r$	Product of antenna gain	5 dBi
B	Bandwidth	10 KHz
N_f	Receiver noise figure	10 dB
η	Drain efficiency of RF amplifier	0.35
k	Channel path loss exponent	2 & 3.5
P_{syn}	Power consumption of frequency synthesizer	50 mW
P_{DAC}	Power consumption of DAC	15.4 mW
P_{ADC}	Power consumption of ADC	6.7 mW
P_{mix}	Power consumption of mixer	30.3 mW
P_{LNA}	Power consumption of LNA	20 mW
P_{IFA}	Power consumption of IFA	3 mW
P_{filt}	Power consumption of filter at transmitter	2.5 mW
P_{filr}	Power consumption of filter at receiver	2.5 mW
$N_0/2$	Noise power	-174 dBm/Hz
M_l	Link margin	40 dB

error probability for M-ary QAM P_{MQAM} with transmit and receive diversity is given by equation (9) as in [8]

$$P_{MQAM} \approx 0.2e^{\frac{-1.6\left\|H_{N_r\times N_t}\right\|^2 \bar{E}_{bt}}{(M-1)N_t N_0}} \tag{9}$$

where $\|\ .\ \|^2$ is the Frobenius norm, $H_{N_r\times N_t}$ is the channel gain matrix and N_0 is the noise power. By substituting equation (4) in equation (9) and after making necessary rearrangements, the energy consumption per bit E_{bt} is given by equation (10) as in [8]

$$E_{bt}=\frac{(4\pi)^2(2^b-1)\xi M_l N_t N_0 N_f d^k}{1.6\left\|H_{N_r\times N_t}\right\|^2 \eta G_t G_r \lambda^2}\ln\left(\frac{0.2}{P_{MQAM}}\right) \tag{10}$$

In C-MISO system, during local transmission, the source node or inter hop node transmits its data to the cooperating nodes with the transmit energy consumption $E_{Loc_{TX}}$, which is computed using equation (10) by considering $d = d_b$, $P_{MQAM} = P_b$, $E_{Loc_{TX}} = E_{bt}$ and $N_t = 1$, and is given by

$$E_{Loc_{TX}} = \frac{(4\pi)^2 (2^b - 1)\xi M_l N_0 N_f d_b{}^k}{1.6\left\|H_{b,N_r \times N_t}\right\|^2 \eta G_t G_r \lambda^2} \ln\left(\frac{0.2}{P_b}\right) \tag{11}$$

where d_b is the broadcast distance, P_b is the bit error probability of the broadcast phase, $\left\|H_{b,N_r \times N_t}\right\|^2$ is the channel gain of the broadcast phase with $N_t = 1$ and $N_r = 1$. When the number of sensor nodes participating in the cooperation is N, then the total energy consumption for local communication is given by

$$E_{TE_{Loc}} = E_{Loc_{TX}} + E_{Ckt_{TX}} + NE_{Ckt_{RX}} \tag{12}$$

where $E_{Ckt_{TX}}$ and $E_{Ckt_{RX}}$ are given by equations (7) and (8).

During the long haul communication, all the N CNs transmit their data to the next inter hop node or destination node with the transmit energy consumption $E_{Lng_{TX}}$, which is computed using equation (10) by considering $d = d_c$, $P_{MQAM} = P_c$, $E_{Lng_{TX}} = E_{bt}$ and $N_t = N$ and is given by

$$E_{Lng_{TX}} = \frac{(4\pi)^2 (2^b - 1)\xi M_l N_t N_0 N_f d_c{}^k}{1.6\left\|H_{c,N_r \times N_t}\right\|^2 \eta G_t G_r \lambda^2} \ln\left(\frac{0.2}{P_c}\right) \tag{13}$$

where d_c is the long haul transmission distance, $\left\|H_{c,N_r \times N_t}\right\|^2$ is the channel gain of the cooperative phase with $N_t = N$ and $N_r = 1$, and P_c is the bit error probability of the cooperative phase. Thus, the total energy consumption for long haul communication is given by

$$E_{TE_{Lng}} = E_{Lng_{TX}} + NE_{Ckt_{TX}} + E_{Ckt_{RX}} \tag{14}$$

The total energy consumption for a single hop ($E_{CC_{hop}}$) is the sum of the energy consumption for local communication and long haul communication. Hence, $E_{CC_{hop}}$ is obtained by adding equations (12) and (14) as

$$E_{CC_{hop}} = E_{Loc_{TX}} + E_{Lng_{TX}} + C_1(N+1) \tag{15}$$

where $C_1 = E_{Ckt_{RX}} + E_{Ckt_{TX}}$.

By substituting equations (11) and (13) in equation (15) and rearranging, we get the total energy consmption for a single hop $E_{CC_{hop}}$ as

$$E_{CC_{hop}} = C_2[ln(0.2)] - C_2 ln(P_b) + C_3 ln(0.2) - C_3 ln(P_c) + C_1(N+1) \tag{16}$$

where

$$C_2 = \frac{(4\pi)^2 (2^b - 1)\xi M_l N_0 N_f d_b{}^k}{1.6\left\|H_{b,N_r \times N_t}\right\|^2 \eta G_t G_r \lambda^2}$$

$$C_3 = \frac{(4\pi)^2 (2^b - 1)\xi M_l N_t N_0 N_f d_c{}^k}{1.6\left\|H_{c,N_r \times N_t}\right\|^2 \eta G_t G_r \lambda^2}$$

Based on [9], the end to end bit error probability P_e is represented in terms of P_b and P_c as

$$P_e = 1-(1-P_b)(1-P_c) \tag{17}$$

$$\approx P_b + P_c \tag{18}$$

$$\approx P_b + (P_e - P_b) \tag{19}$$

By substituting $P_c = P_e - P_b$ in equation (16), the total energy consumption for a single hop $E_{CC_{hop}}$ is given by

$$E_{CC_{hop}} = C_2[ln(0.2)] - C_2 ln(P_b) + C_3 ln(0.2) - C_3 ln(P_e - P_b) + C_1(N+1) \tag{20}$$

The total energy consumption $E_{CC_{hop}}$ is minimized by taking partial derivation of equation (20) with respect to P_b and equating it to zero

$$\frac{\partial E_{CC_{hop}}}{\partial P_b} = -\frac{C_2}{P_b} + \frac{C_3}{P_e - P_b} = 0 \tag{21}$$

$$-\frac{C_2(P_e - P_b) - C_3 P_b}{P_b(P_e - P_b)} = 0$$

$$C_2 P_c = C_3 P_b$$

$$C_2 P_c = C_3(P_e - P_c) \tag{22}$$

By substituting the values of C_2 and C_3 in equation (22) and cancelling the like term yields,

$$\frac{d_b^k}{\left\|H_{b,N_r \times N_t}\right\|^2} P_c = N_t \frac{d_c^k}{\left\|H_{c,N_r \times N_t}\right\|^2} P_b \tag{23}$$

The number of nodes within a circle of radius d with a WSN of node density ρ is given by $N = \pi d_b^2 \rho$

$$\text{i.e.} \quad d_b{}^2 = \frac{N}{\pi\rho} \tag{24}$$

On substituting equation (24) in equation (23), with $N = N_t$ and $k = 2$, since the broadcast distance is small, the equation (23) becomes

$$\frac{N_t P_c}{\pi\rho\left\|H_{b,N_r \times N_t}\right\|^2} = \frac{N_t d_c^k}{\left\|H_{c,N_r \times N_t}\right\|^2} P_b \tag{25}$$

From equation (25), the optimal broadcast bit error probability P_b is given by

$$P_b = \frac{\left\|H_{c,N_r \times N_t}\right\|^2}{\left\|H_{b,N_r \times N_t}\right\|^2} \frac{P_c}{\pi\rho d_c^k} \tag{26}$$

From equation (25), the optimal long haul distance d_{Pbopt} is given by

$$d_c = \left(\frac{\left\| H_{c,N_r \times N_t} \right\|^2}{\left\| H_{b,N_r \times N_t} \right\|^2} \frac{P_c}{\pi \rho P_b} \right)^{1/k} \tag{27}$$

The d_{Pbopt} is the long haul distance d_c with optimal broadcast bit error probability and minimum total energy consumption. The d_{Pbopt} also depends on the channel path loss exponent, the node density and the number of cooperating nodes which determines the size of the channel gain matrix.

The **Fig. 2** shows effect of number of nodes N on the total transmit energy, total circuit energy and total energy consumption per bit for fixed distance case with $d_c = 100$ m.

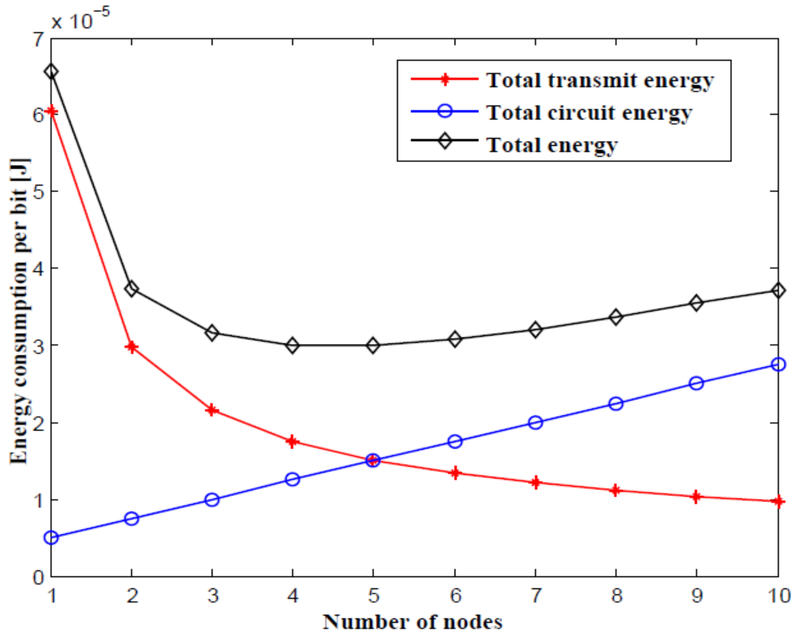

Fig. 2. Energy consumption per bit over number of cooperating nodes for $d_c = 100$ m

From the figure, it is clear that as the number of nodes N increases, the total circuit energy consumption increases linearly with N, the total transmit energy consumption decreases exponentially with N. The total energy consumption decreases and reaches a minimum value at $N = 5$, and then increases. At $N = 5$, the total transmit energy consumption is approximately equal to the total circuit energy. From **Fig. 2**, it is clear that cooperative communication is energy efficient if total transmit energy consumption is approximately equal to the total circuit energy.

3.3 Algorithm for Energy Minimization

The algorithm can be initiated by the source node or any other controller node of the network. For the given P_e, the algorithm selects a P_b which is lower than P_e and roughly in the range - from 1/10th of P_e to 1/100th of P_e. Choosing a value for P_b above 1/10th of P_e results in more number of CNs (greater than 10) and choosing a value below 1/100th of P_e results in CNs less than 2. The P_c is determined using equation (18). The algorithm for energy minimization in the form of pseudocode is given below.

Algorithm : Total energy minimization

1. **Initialize** the parameters required for energy calculation such as end to end bit error probability P_e, broadcast bit error probability P_b which is slightly lower than P_e and bit error probability of the cooperative phase P_c
2. **For** $i \leftarrow 2$ to N
   Do calculate the total circuit energy as $\left(\left(E_{Ckt_{TX}} + E_{Ckt_{RX}}\right) \times (i+1)\right)$ using (7) and (8)
   (i) Calculate the local transmission distance d_b using (24)
   (ii) Calculate the local transmit energy $E_{Loc_{TX}}$ using (11)
   (iii) Calculate the long haul distance d_c using (27)
   (iv) Calculate the long haul transmit energy $E_{Lng_{TX}}$ using (13) with $N_t = i$
   (v) Compare the total circuit energy with the total transmit energy
   If the total circuit energy is approximately equal to the total transmit energy
   Then choose the N as N_{Pbopt}, choose the d_c as d_{Pbopt}
   Else go to step 2
   End
   End

Algorithm: Pseudocode for energy minimization.

Initially, by considering the value of N as 2, the algorithm calculates the total circuit energy, local transmit energy, long haul transmission distance and long haul transmit energy. It then compares total transmit energy with the total circuit energy. If the total transmit energy is approximately equal to the total circuit energy, the algorithm stops. The value of N is N_{Pbopt} and the corresponding d_c is the d_{Pbopt}. Otherwise, the value of N is incremented by one and the whole process of energy computation and comparison is repeated.

4. Simulation Results

The CMISO system is simulated using the simulation parameters listed in **Table 2**. The nodes are randomly deployed according to uniform probability distribution and the source and destination are randomly selected.

Table 2. Simulation Parameters

Parameter	Value
Node density (ρ)	0.08
Distance between source and destination (d_{SD})	300 m
Number of bits to be transmitted (N_i)	20 Kbits
Deployed Area	1000×1000 m^2
Initial energy of a node	100 J

For a given broadcast error probability $P_b = 0.73 \times 10^{-4}$ and end to end bit error probability $P_e = 10^{-3}$, the number of CNs N is varied from 2 to 10 and total circuit energy and total transmit energy per bit is computed and shown in **Fig. 3**. N_{Pbopt} is the minimum value of N for which total transmit energy is approximately equal to the total circuit energy.

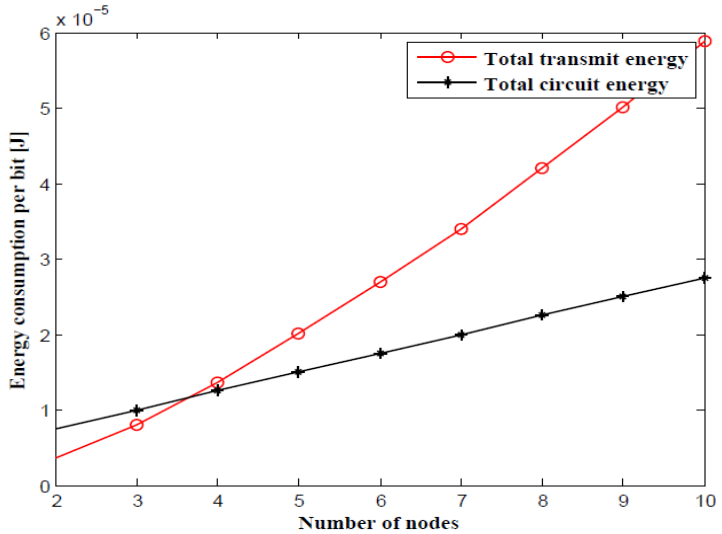

Fig. 3. Energy consumption per bit over number of cooperating nodes for $P_e = 10^{-3}$ and $P_b = 0.73 \times 10^{-4}$ for a hop.

From **Fig. 3**, the optimum number of co-operating nodes N_{Pbopt} is equal to 4. For N_{Pbopt} = 4, the optimal distance d_{Pbopt} is computed and is given by d_{Pbopt} = 75 m. For d_{Pbopt} = 75 m, the total energy consumption per bit for both SISO & C-MISO is calculated and tabulated in **Table 3**.

Table 3. Comparison of per bit total energy consumption between SISO & C-MISO for d_{Pbopt} = 75 m

Total Energy Consumption per bit in J	
SISO	**C-MISO**
4.784×10^{-5}	2.595×10^{-5}

From the **Table 3**, it is evident that C-MISO is energy efficient than SISO.

For a given $N_{Pbopt} = 2$, the end to end error probability P_e is varied and the corresponding d_{Pbopt} and long haul transmit energy $E_{Lng_{TX}}$ is computed. The long haul transmit energy, $E_{Lng_{TX}}$ signed as ($E_{Lng_{TX}}$ $(\times 10^{-5})$ J) in **Fig. 4**.

The simulation is repeated for N_{Pbopt} = 4, 6 and 8. From **Fig. 4**, it is evident that for a given N_{Pbopt}, the long haul transmit energy $E_{Lng_{TX}}$ remains constant even if we decrease the end to end bit error probability P_e.

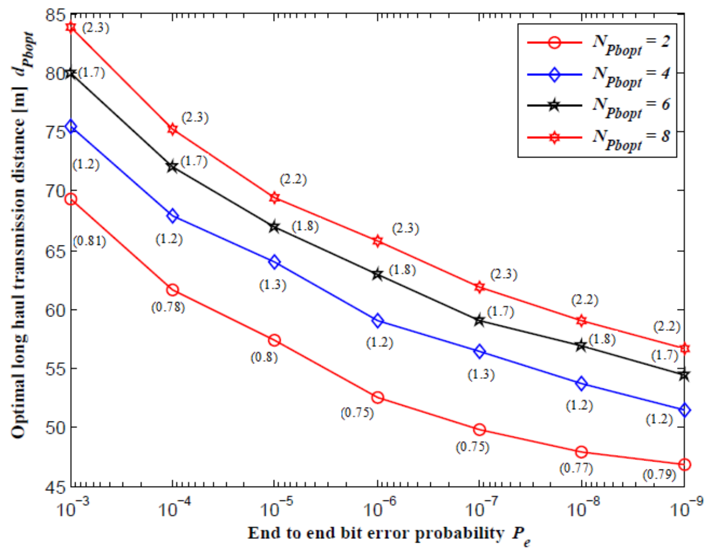

Fig. 4. Optimal long haul transmission distance over end to end bit error probability P_e under different number of optimal cooperating nodes.

For a fixed N_{Pbopt} = 2, the P_e is varied and the long haul transmit energy consumption is calculated for a bit through single hop using equation (13) and is shown in **Fig. 5**. For a given P_e, P_b is selected such that N_{Pbopt} = 2. The experiment is repeated for N_{Pbopt} = 4 and 6. It is observed that the energy required for transmission remains almost constant with decrease in P_e, since the transmission distance is decreased inorder to compensate for increase in transmit energy due to decrease in P_e. It is also observed that for a given P_e, the transmit energy increases with N_{Pbopt}. The reason is that the transmission distance increases as per equation (27) with increase in N_{Pbopt} for a given P_e.

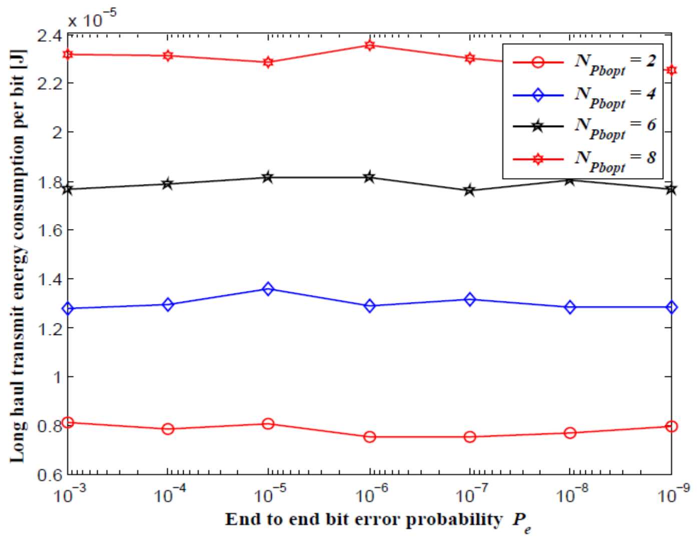

Fig. 5. Long haul transmit energy consumption over end to end bit error probability P_e under different number of optimal cooperating nodes.

The variation in optimal broadcast error probability P_b with respect to P_e for a given N_{Pbopt} is shown in **Fig. 6**. For a fixed N_{Pbopt} = 2, the P_e is varied and corresponding optimal broadcast error probability P_b is selected such that N_{Pbopt} = 2. The experiment is repeated for N_{Pbopt} = 4 and 6. It is clear from the figure that the P_b decreases with decrease in P_e for a given N_{Pbopt}. It is also clear from the figure that for a given P_e, decrease in P_b cause the N_{Pbopt} to decrease.

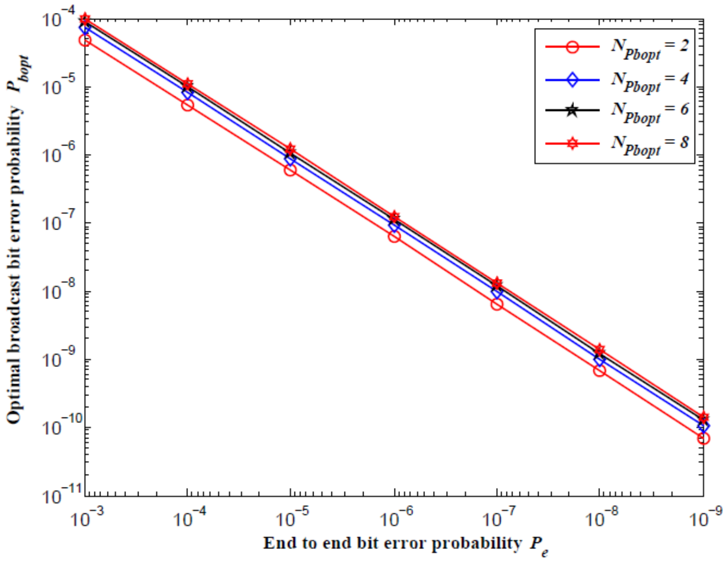

Fig. 6. Optimal broadcast bit error probability P_b over end to end bit error probability P_e under different number of optimal cooperating nodes.

The **Table 4** gives the simulation results for the total energy consmption for two different cases by varying the end to end bit error probability P_e. For both the cases 20,000 bits are transmitted from source to destination with d_{SD} = 300 m.

Table 4. Comparison of total energy consumption between SISO and C-MISO under different end to end bit error probability P_e for end to end transmission of N_i = 20,000 bits through multiple hops with N_{Pbopt} = 4 and d_{SD} = 300 m.

End to end bit error probability P_e	Total energy consumption for end to end transmission in Joules					
	Traditional case : $d > d_{Pbopt}$ per hop (d = 100 m)			Proposed case : $d = d_{Pbopt}$ per hop (d = 75 m, 64 m and 56 m)		
	SISO	C-MISO 4×1	Energy Saving	SISO	C-MISO 4×1	Energy Saving
10^{-3}	50	32	18	40	21	19
10^{-5}	95	47	48	65	27	38
10^{-7}	139	64	75	66	30	36

Traditional fixed distance case :

The total energy consumption is calculated for SISO and CMISO (4×1) with fixed hop distance $d = 100$ m [8] ($d > d_{Pbopt}$). The simulation is repeated by varying the end to end bit error probability P_e.

Proposed optimal distance case :

For each P_e, the optimal distance d_{Pbopt} is computed (i.e. $d = 75$ m, 64 m and 56 m for $P_e = 10^{-3}$, 10^{-5} and 10^{-7} respectively). The total energy consumption is calculated for SISO and CMISO (4×1) with d_{Pbopt}. **Fig. 7** shows the energy consumption for these two cases.

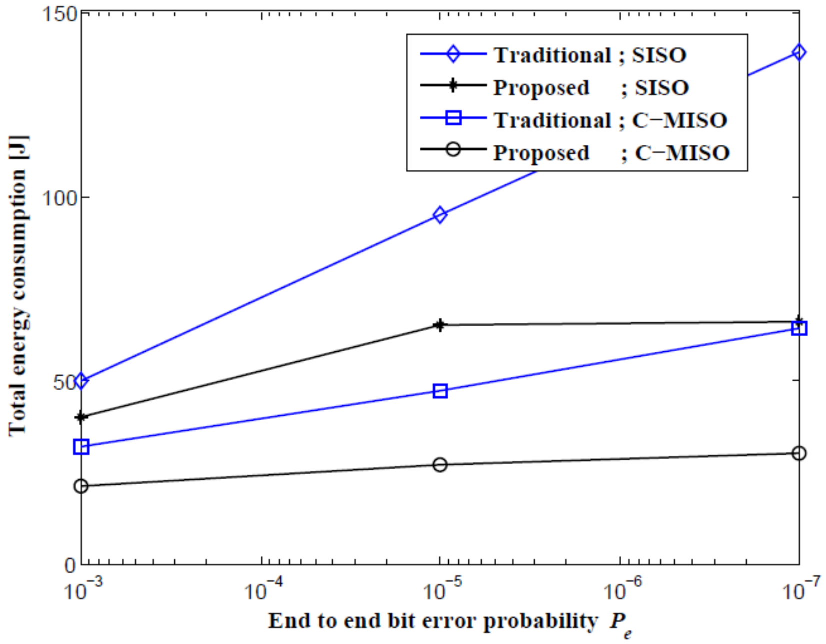

Fig. 7. Total energy consumption comparison between SISO and C-MISO under proposed and fixed distance cases for end to end transmission through multiple hops over different end to end bit error probability P_e for $N_{Pbopt} = 4$ and $N_i = 20{,}000$ bits.

Fig. 8 compares the number of times a relay node can participate in the transmission of 20000 bits of data for the traditional fixed hop distance and the proposed case with optimal hop distance. It is clear from the **Fig. 8** that the number of participations for the proposed case is higher than traditional case.

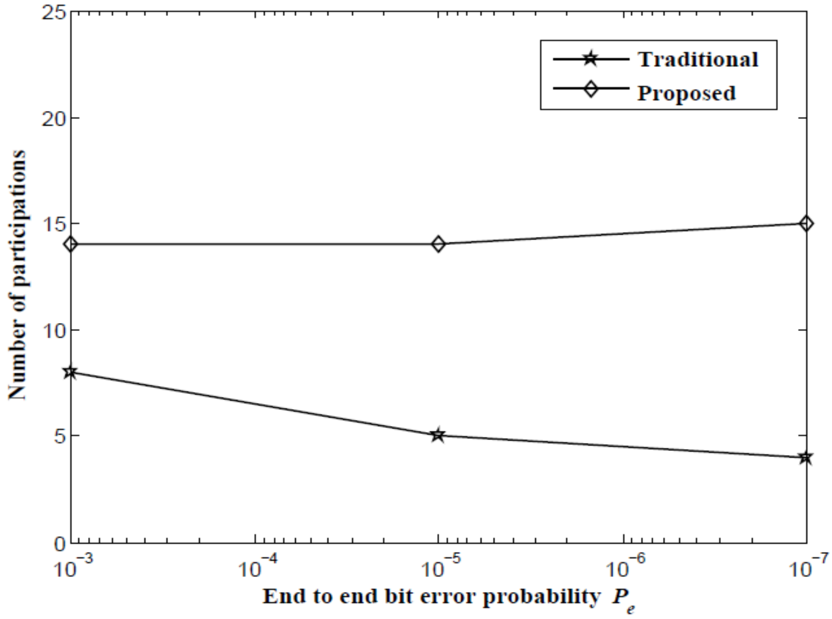

Fig. 8. Comparison of number of participations by a relay node in the transmission of 20000 bits between proposed and fixed distance cases over different end to end bit error probability P_e for $N_{Pbopt} = 4$.

Finally, the performance of the proposed case is compared with the traditional fixed distance case using energy delay product as the metric in **Fig 9**. The energy delay product is the product of the total energy consumed in the process of transmitting the data from source to the destination and the number of hops required to reach the destination from source.

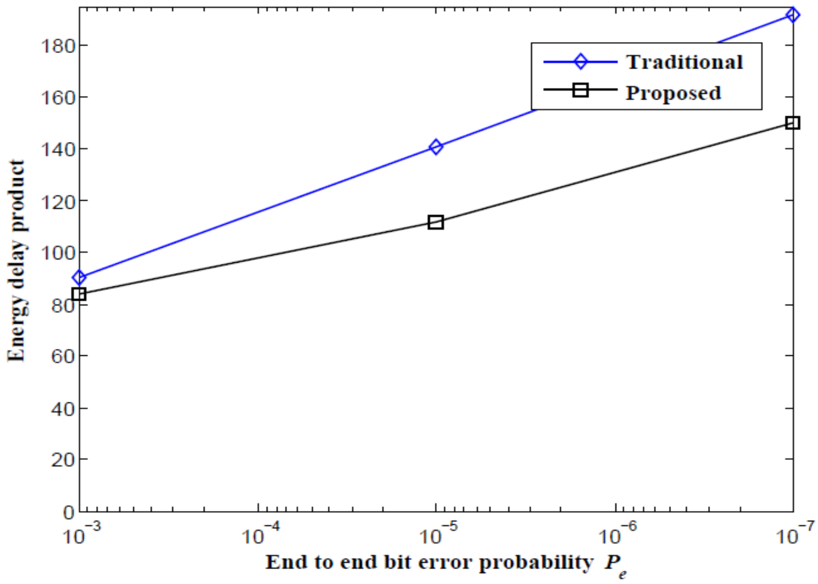

Fig. 9. Comparison of energy delay product between proposed and fixed distance cases over different end to end bit error probability P_e for $N_{Pbopt} = 4$ and $N_i = 20{,}000$ bits.

The delay incurred is dependent on the number of hops. More number of hops results in more amount of delay. The delay cost associated with the local information exchange also increases. Hence, for the cooperative transmission to be energy efficient and delay efficient, it requires lower EDP. The figure shows the EDP for two cases. The case (i) is the traditional fixed distance with $d > d_{Pbopt}$ (i.e. $d = 100$ m [8] irrespective of P_e) and case (ii) is the proposed work with $d = d_{Pbopt}$ (i.e. $d = 75$ m, 64 m and 56 m for $P_e = 10^{-3}$, 10^{-5} and 10^{-7} respectively). For a fixed $N_{Pbopt} = 4$, the P_e is varied and corresponding optimal broadcast error probability P_b is selected such that $N_{Pbopt} = 4$. To transmit the data through the source to destination distance d_{SD} of 300 m, traditional case requires 3 hops. Whereas the number of hops required for the proposed case is 4 for $P_e = 10^{-3}$ and 5 for $P_e = 10^{-4}$ and $P_e = 10^{-5}$. Though the traditional case requires less number of hops, it consumes more energy than the proposed case and results in higher EDP. From the figure, it is clear that the proposed case results in lower EDP and hence it is energy and delay efficient.

Fig. 10 shows the energy consumption of CMISO for the proposed and traditional fixed distance [[8], Jong-Moon Chung et al.] case. As in [8], the node density is varied from $\rho = 3\times 10^{-3}$ to 7×10^{-3}. The source to destination distance is fixed as $d_{SD} = 500$ m. From source to destination, 20000 bits are transmitted with four cooperating nodes $N_{Pbopt} = 4$. The bit error probability is fixed as $P_e = 10^{-3}$ for both broadcast and cooperative transmission. From the figure, it is clear that for all the node densities, the total energy consumption of the proposed case is significantly less when compared to the traditional fixed distance case [8] and hence proves to be energy efficient.

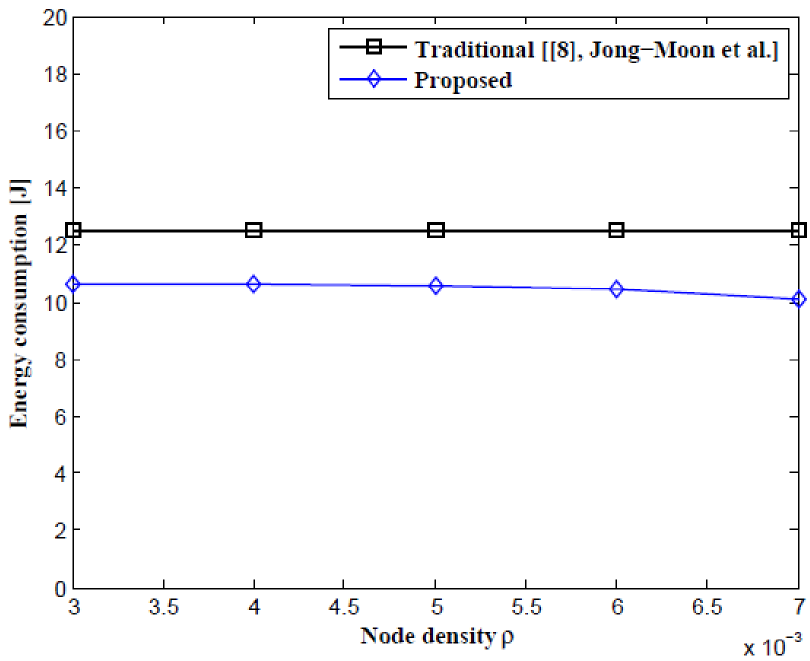

Fig. 10. Comparison of energy consumption between traditional fixed distance [[8], Jong-Moon Chung] and proposed case through multiple hops for $N_{Pbopt} = 4$ and $N_i = 20{,}000$ bits.

The proposed case achieves a marginal reduction in the energy consumption with increase in node density and the variation is significant between the node density $\rho = 6 \times 10^{-3}$ and 7×10^{-3}, where as the energy consumption remains constant for the traditional fixed distance case. The increase in node density increases the possibility of availability of nodes in best locations and decreases the average distance between the nodes. The amount of reduction in the average distance value between the nodes is insignificant when compared with the larger hop distance of the traditional case. Whereas, the amount of reduction in the average distance value between the nodes is marginally significant when compared with the comparatively smaller hop distance of the proposed case. In WSN, usually the nodes are deployed in larger numbers leading to higher node densities. Therefore, it is clear that the proposed case is energy efficient than the traditional case at all the node density values considered. It is also clear that the proposed case is more energy efficient at higher node densities when compared to lower node densities.

5. Conclusion

In this paper, an algorithm for energy efficient cooperative communication in WSN is proposed. The equations for optimal broadcast bit error probability and hence the optimal long haul distance that maximizes the energy efficiency is derived. The performance of the proposed scheme is evaluated in terms of energy and delay. The proposed scheme is compared with the traditional case. The simulation results show that the proposed scheme is both energy and delay efficient compared with traditional case. Since the proposed scheme is energy and delay efficient, it is suitable for real time applications.

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