An Energy Efficient Relay Selection Algorithm for Clustered Wireless Sensor Networks

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Abstract— **In this paper we propose an energy-efficient relay selection algorithm for clustered Wireless Sensor Networks (WSNs). In contrast to conventional multi-hop transmission schemes adopted in clustered WSNs, where only cluster heads (CHs) participate in the transmission, in our method the relay is selected from a set of candidate nodes within the source transmission range, subject to predefined desired transmission power at the source and the relay. The fundamental of this method is to forward the source signal using the node which minimizes the end-to-end total path distance, such that the total energy cost per bit is reduced at the relay and at the source. Thus, the node that satisfies the signal-to-noise ratio (SNR) distance-based threshold of both links participates in the transmission. Taking into consideration the circuit energy cost, the modulation strategy and its impact on energy cost are investigated and the optimal choice of the number of bits per symbol is considered to optimize the total energy cost per transmission. The proposed method is shown to be more energy efficient compared to the traditional multi-hop transmission and random relay selection in terms of energy cost for a target bit error rate at the destination. Additionally, the proposed method also outperforms both methods in terms of the network lifetime.**

Keywords— Clustering, Cooperative Communication, Wireless Sensor Network, Relay Selection

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of a huge number of tiny low-power sensor nodes. These networks are deployed for various application purposes such as military, control, monitoring, forecast, etc. [1]. In WSNs, nodes operate autonomously, collect data and report periodically to a central base station. Although the main power source is a small-capacity battery, nodes are expected to serve for long period without maintenance and access to a backup charger. With the unimpressive battery improvement, energy efficiency has attracted more attention and several strategies have been proposed to overcome this issue [2]. Clustering schemes mainly adopted to improve network reliability have been intensively studied and numerous protocols have been proposed and modified to be more energy efficient (EE) [3]. In these schemes, the network is divided into sub-regions, where nodes cooperate and elect their Cluster Head (CH) responsible for forwarding aggregated data towards the destination using multiple-hop, single-hop, or even direct transmission. Although clustering is shown to be an EE technique, the drawbacks are notable due to the limitation of relay number as only CH forwards signal, which may lead to incorrect message decoding in case of poor channel condition, or/and additional transmit power at the source or the CH to overcome this issue [4][5].

In this regard, relay selection has been introduced to improve the network performance in terms of energy consumption. Thus, several relay selection methods have been proposed, where the selection metrics revolve around maximizing the SNR at the destination, choosing the hop with the best channel condition, or selecting the nearest node to the source [6,7]. However, relay selection schemes and the impact in terms of the additional energy cost per transmission have been triggered from battery life perspective in [8,9]. Moreover, relay selection based on the Channel State Information (CSI) is proposed in [10], while in [11], finite CSI is feedback to the transmit cluster to select a node with the best channel condition. Additionally, energy efficiency has been addressed by a minimum distance relay selection method in [12]. In addition to that, a relay selection method based on the relay location has been suggested to minimize Symbol Error Probability in [13]. Correspondingly, energy efficiency was approached through power allocation in [14], where the authors propose minimizing the transmit power subject to the mean square error target, while in [15] the authors allocate transmit power based on bit error rate (BER) requirement. Comparatively, relay selection based on the optimal transmission distance and the residual energy of the nodes has been proposed as a routing technique to extend the network lifetime in [16]. Maximizing the SNR is the core of the relay selection method in [17], by using virtual Multiple-input multiple-output (MIMO) transmission between clusters. Likewise, the impact of the relay location on energy efficiency has been studied in [18]-[22], from the power minimization perspective by using fair power allocation at the involved nodes in the transmission.

We propose an energy-efficient single relay selection algorithm at the relay, where the node with the minimum two paths distance subject to a predefined target BER at the destination forwards the source message. The contribution of this paper can be summarized as follows:

- In the literature, the energy saving problem has been addressed at the relay or at the source, while we minimize the energy cost at the relay and at the source which minimize the total energy cost.
- We consider all the signal processing blocks to illustrate the trade-off between transmission energy cost and the circuit energy cost. Therefore, we choose the best modulation strategy.
- We consider the channel gain and its impact on the total energy cost, thereby allowing the relay and the source to adjust the transmit power. We assume an AWGN channel for local transmission and Rayleigh fading channel for long range transmission, while in literature the ideal channel has been implemented.

- We offer a less complex solution, as the selection is made at the relay without the need of additional signaling that can increase the energy cost.
- As the selection is made at the relay in a non-centralized fashion, the proposed method is adaptive to the channel condition and enhances the network lifetime as it offers diversity of path for each transmission.

II. System Model

We consider a WSN shown in Figure 1, where nodes report their data to the CH responsible for forwarding the aggregated packet to the sink. In the proposed scenario, 100 nodes are randomly deployed over 150m^2 square area with the sink at the location with coordinates of (200m,200m) on the network grid. Nodes operate in half-duplex mode and channels between nodes are reciprocal and similar in both directions. We adopt cluster formation, so at each round different nodes with dissimilar path conditions to the sink perform the CH role and cluster members experience different links towards the CH. The cluster number is given by

$$k = \sqrt{\frac{N}{2\pi}}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}\frac{X}{d_{BS}^2} \quad (1)$$

where d_{BS} is the average distance to base station, N is the number of nodes in the network, X represents the side of thesquare grid network,$\varepsilon_{fs}$and $\varepsilon_{mp}$are the free space and multipath model transmit amplifier circuit energy consumption respectively. The sink broadcasts a "HELLO" message, allowing all nodes to gather network information, estimate the path distance to the sink, and determine the required transmit power.

A. Local Transmission

In this phase, nodes report their data to their CH, and the signal received at the CH is given by

$$S_{CH} = \sum_{i=1}^{m} h_i\sqrt{E_i}S_i + n_i \quad (2)$$

where $m$is the number of nodes per cluster, while $S_{CH}, h_i, \sqrt{E_i}, S_i$ and n_i are the received signal at the CH, channel coefficient from the sending node to the CH, the transmit energy per symbol at the source, the node symbol and the white noise at the CH receiver respectively. The total energy consumption is given by

$$E_{Int} = \sum_{i=1}^{m} L(E_C^i + E_{Tx}^i + E_{Rx}^i + E_{DA}^i) \quad (3)$$

where i is the node index, and $L, E_C^i, E_{Tx}^i, E_{Rx}^i, E_{DA}^i$are the packet size, circuit energy cost, transmission energy cost, receive energy cost and data aggregation energy cost respectively.

B. Long Haul Transmission

We consider the cooperative scenario where the CH as source (S), communicate with the sink as destination (D) through the help of a relay(R).The communication implements time division multiple access (TDMA) as shown in Figure 2, where S broadcasts the message and the relay retransmits the signal, and the signals received at R and D are given by

$$S_R = h_{SR}\sqrt{E_{S_1}}S_1 + n_{SR}$$

$$S_D = h_{RD}\sqrt{E_{S_2}}S_2 + n_{RD} \quad (4)$$

where h_{SR}, h_{RD} are the channel complex gain of the $S-R$and $R-D$ links respectively, $n_{SR}, n_{RD}$are the additive white Gaussian noise with average power spectral density N_0, and $\sqrt{E_{S_1}}$ and $\sqrt{E_{S_2}}$are the energy per symbol at S and R, respectively. The total energy cost is given by

$$E_{Intra} = \sum_{i=1}^{m} L(2E_C^i + 2E_{Tx}^i + 2E_{Rx}^i) \quad (5)$$

where $L, E_C^i, E_{Tx}^i, E_{Rx}^i$ are the packet length, circuit energy cost, transmission energy cost and receive energy cost respectively. The total energy cost is given by

$$E_t = E_{Int} + E_{Intra} \quad (6)$$

III. TRANSMISSION ENERGY COST

A. Energy Cost Affecting Factors

The energy consumption in a typical RF transceiver consists of the power amplifier P_{PA} and the circuit power P_C. It is also related to the system operation time T_{On}. Therefore, the energy cost per bit is given by

$$E_b = (P_c + P_{PA})T_{On} \quad (7)$$

where $P_c$is the sum of the DAC power P_{DAC}, ADC power P_{ADC}, mixer power P_{MIX}, synthesizer power P_{SYN}, low noise amplifier power P_{LNA}, intermediate frequency amplifier P_{IFA}, receiver filter power $P_{FILR}$and transmitter filter P_{FILT}. T_{On} and P_{PA} are given as by (8) and (9) respectively.

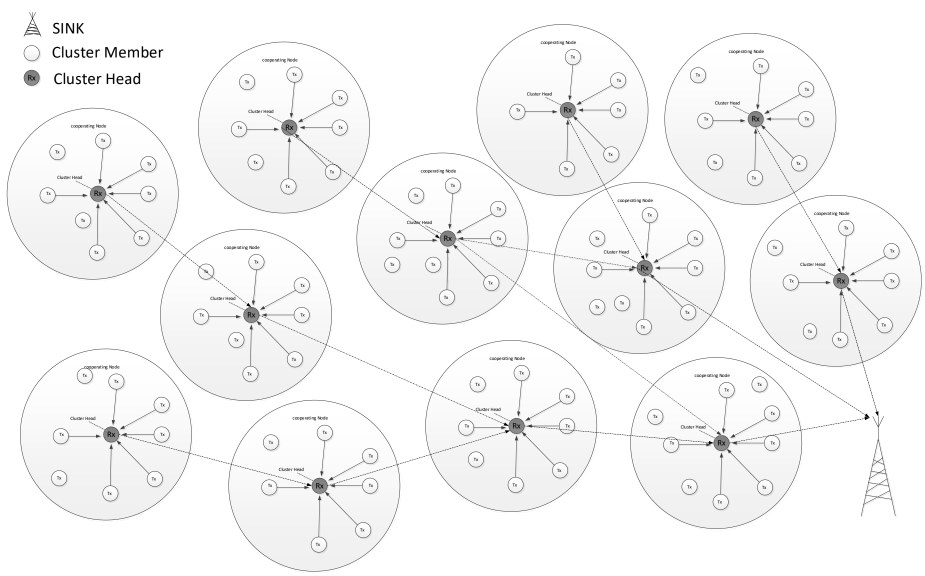

Figure. 1. Clustered Wireless Sensor Network

$$T_{on} = \frac{L}{Bb} \quad (8)$$

where b and B are the number of bit and the system bandwidth respectively.

$$P_{PA} = (1+\theta)P_{out} \quad (9)$$

where θ is the amplifier drain efficiency and P_{out} is the transmit power given by

$$P_{out} = \frac{(4\pi)^2 d^{\alpha} M_t N_f}{G_r G_t (\lambda)^2}\overline{E_b}R_b \quad (10)$$

where M_t, N_f, R_b, G_r, G_t, and λ are the link margin, receiver noise figure, bit rate, receiver antenna gain, transmitter antenna gain and wavelength respectively. α and $\overline{E_b}$ are the pass loss attenuation exponent and the required energy per bit at the receiver respectively. α is evaluated based on the distance d between transceivers and given by

$$\alpha = 2 if d \leq d_0$$
$$\alpha = 3 if d_0 \leq d \quad (11)$$

where the threshold distance d_0 is given by

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (12)$$

B. Communication Energy Cost

For local transmission within the cluster, we assume an additive white Gaussian noise (AWGN) channel. The probability of error is calculated and given by

$$P_e \approx 4\left(1-\frac{1}{2^b}\right)e^{-\frac{y}{2}\frac{3}{2^b-1}} \quad (13)$$

where the signal to noise ratio y is given by

$$y = \frac{P_r}{2B\sigma^2 N_f} \quad (14)$$

and the required received power for a target BER is given by

$$P_{rl} = \frac{4}{3}N_f B\sigma^2(2^b-1)\log 2\frac{4(1-\frac{1}{2^b})}{P_e} \quad (15)$$

The transmission energy cost per bit E_{bl} and the total transmission energy cost at CH E_{btl} are given in (16) and (17), respectively.

$$E_{bl} = ((1+\theta)\frac{4}{3}N_f B\sigma^2(2^b-1)\log 2\frac{4(1-\frac{1}{2^b})}{P_e}M_l T_{on})/L + (P_c T_{on})/L + E_{DA} \quad (16)$$

$$E_{btl} = \frac{4}{3}N_f B\sigma^2(2^b-1)\log 2\frac{4(1-\frac{1}{2^b})}{P_e}M_l T_{on} \quad (17)$$

For the CH and relay transmission, we consider a Rayleigh fading channel, where the average probability of error P_e follows the Rayleigh distribution given in (18), and P_e is approximated using (19).

$$f_y(y) = \frac{1}{\bar{y}}e^{\frac{-y}{\bar{y}}} \quad (18)$$

$$P_e \approx \frac{1}{2}\left(1-\sqrt{\frac{x\bar{y}}{1+x\bar{y}}}\right) \quad (19)$$

where $x = \frac{3}{2(M-1)}$ and the constellation size $M = 2^b$, and y is the instantaneous SNR. And the average SNR $\bar{y}$ is given by

$$\bar{y} = \frac{2^b-1}{6P_e} \quad (20)$$

The required received power P_{rl} for the target BER is given by

$$P_{rl} = N_f B\sigma^2\frac{(2^b-1)}{3P_e} \quad (21)$$

The energy cost per bit at CH, E_{C_b} and the total transmission cost at CH, E_{C_T} are given in (22) and (23) respectively. The energy cost per bit E_{R_b} and the total energy cost E_{R_T} at the relay are given in (24) and (25) respectively. And the total transmission energy cost is given in (26).

$$E_{C_b} = ((1+\theta)N_f B\sigma^2\frac{2^b-1}{3P_e}M_s T_{on} + P_c T_{on})/L \quad (22)$$

$$E_{R_b} = ((1+\alpha)N_f B\sigma^2\frac{2^b-1}{3P_e}M_R T_{on})/L + P_c T_{on}/L \quad (23)$$

$$E_{C_T} = N_f B\sigma^2\frac{2^b-1}{3P_e}M_S T_{on} \quad (24)$$

$$E_{R_T} = N_f B\sigma^2\frac{2^b-1}{3P_e}M_R T_{on} \quad (25)$$

$$E_a = E_{Cbt} + E_{Rbt} + E_{bl} \quad (26)$$

where M_s, M_R are the path power gain factors.

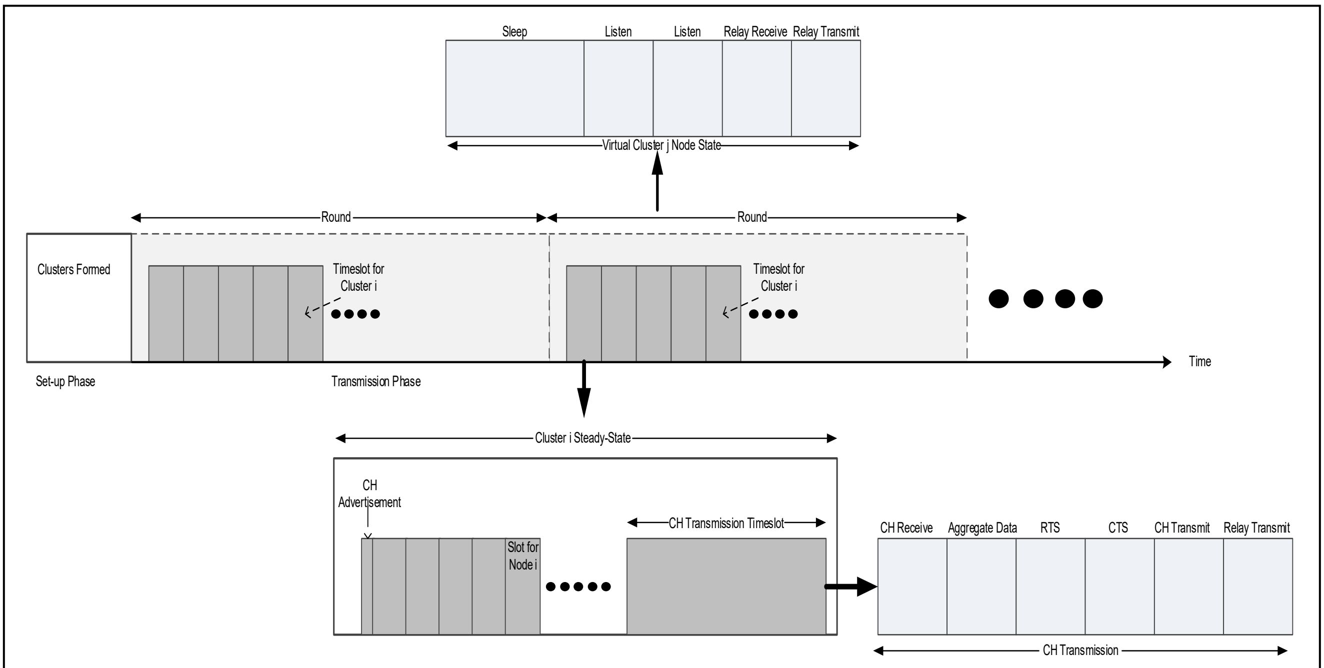

Figure. 2. Cooperative TDMA Time Slots

IV. PROPOSED RELAY SELECTION ALGORITHM

A. The Impact of Relay Location

In typical wireless network, the relay location is not within line of sight between S and D, which leads to an increase of the end-to-end transmission distance from S to D compared to the direct path length given in (27), and the increase of the total transmission distance compared to the direct transmission is given in (28).

$$d_t = d_l = d_1 + d_2 \quad (27)$$

$$d_t \neq d_l$$

$$d_1 + d_2 \neq d_t \quad (28)$$

where d_1, d_2 and d_l are the $S-R, R-D$ and $S-D$ path length and d_t is the sum of $S-R, R-D$ path lengths.

Since power decreases with transmission range, the relay's location is crucial to ensure the destination receives the signal with sufficient power for correct decoding, minimizing additional energy costs. To examine that, we plot the transmit energy cost per bit using equation (26) for different relay locations with respect to total path distance.

From Figure 3, it can be clearly observed that the energy cost decreases monotonically with the relay moving toward the midpoint. Moreover, the energy costs at the distance ratios of 0.4 and 0.6 are the same. Thus, from this observation, a node is considered as a potential relay candidate, if the following condition is satisfied.

$$\frac{d_1}{d} > 0.4 \text{ and } \frac{d_1}{d} < 0.6 \quad (29)$$

Although higher modulation decreases the amount of time spent on signal processing, as T_{On} decrease, the transmission energy cost escalates significantly to meet the required desired power at destination. Thus, the constellation size is another optimization factor.

B. Optimal Modulation Strategy

To examine the impact of the modulation strategy on energy consumption, we use a specific numerical example with total transmission distance of 150 meters and plot the energy cost using different values of constellation size M.

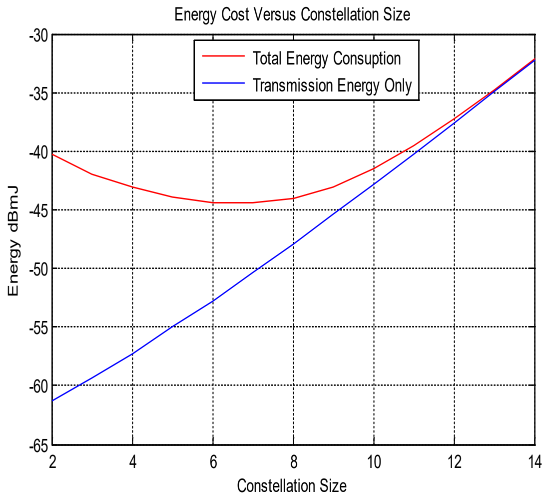

Figure. 3. Transmission Energy Cost vs Total Energy

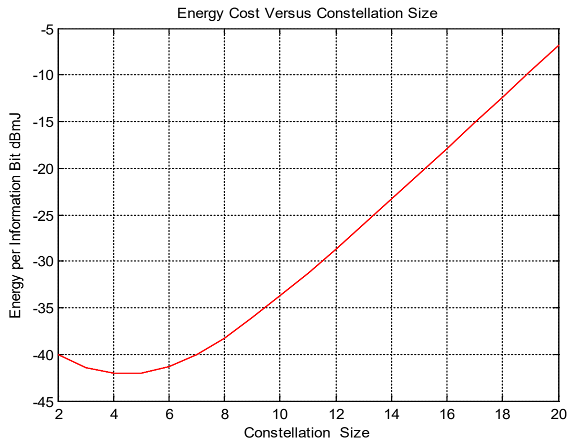

Figure 4. Energy Cost Constellations Size

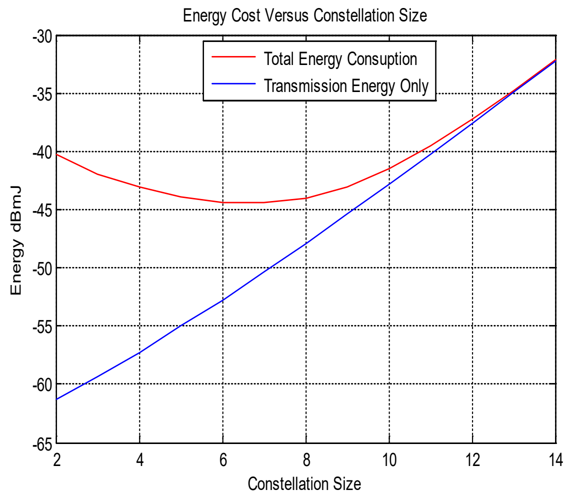

Fig. 5. Transmission Energy Cost vs Total Energy Cost

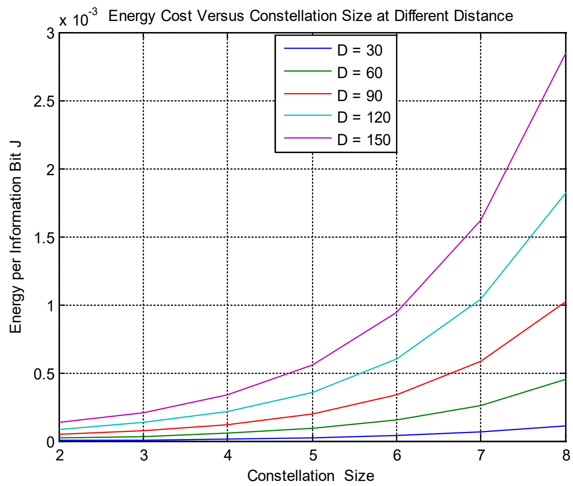

Fig. 6. Energy Cost Vs Constellations Size at Different Distances

From Figure 4, the transmission energy cost increases linearly with M greater than 6. Additionally, it can be seen from Figure 5 that the total energy cost increases slowly for M greater than 6 while a drastic increase in the transmission energy cost is observed at the same value. Moreover, from Figure 6, at different transmission distances, the total energy cost drastically increases with M greater than 6. Thus, the best choice of M is 8 which is obtained by using a b value of 3.

C. Relay Selection Algorithm

In the proposed method, all the nodes within the source transmission range are considered as potential relay candidate subject to satisfying the following condition:

$$\gamma_1 > T_1$$
$$\gamma_2 > T_2 \qquad (30)$$

where γ_1 and γ_2 are the instantaneous SNR of both links at the node, while T_1 and T_2 are the SNR threshold for both links. From the RTS/CTS message of the MAC protocol, potential relays estimate the SNR of both links and compete to win the relay role if the condition in (30) is satisfied. The optimization policy is given by

$$Minimize\ E_1, E_2$$
$$subject\ to P_e \leq P_{req}$$
$$d_1 \geq d_{Min} and d_1 \leq d_{Max}$$
$$d_1^2 + d_2^2 \leq d^{\alpha}$$
$$P_t < P_{Max} \qquad (31)$$

where E_1 and E_2 are the total energy cost per bit at the source and the relay respectively.

Table I. Units for magnetic properties.

Step	*Algorithm*
1.	***set***$D_{Max}, D_{Min}, P_{Max}$
2.	***for*** *i: N-M;*
3.	***if*** *(29&30):* ***do*** *(36);*
4.	***else****:* ***do*** *sleep;*
5.	*end* ***if****;*
6.	*end* ***for****;*
7.	***set*** *Timer(36);*
8.	***for*** *i: N-M;*
9.	***if*** *(ACK):* ***do*** *R =I, break;*
10.	*end* ***for****;*
11.	***If****(R!=0):* ***do*** *R (24), S(25);*
12.	***else****:* ***do*** *S(sleep);*
13.	*end* ***if****;*

The cooperation procedure is given in Figure 7 and the proposed algorithm is given in Table 1, where the relay selection is completed in an un-centralized manner. Candidate relay sets their timer Δ using equation (32), and the node with the minimum sum distance of both links has the smaller timer value and has the priority to send the flag to win the relay role.

$$\Delta = \frac{d_i^1 + d_i^2}{d_l} T \qquad (32)$$

where d_i^1 and d_i^2 are the candidate relay distance to the source and the destination, respectively, and i is the node index, and d_l is the path length from source to destination, while T is the transmission time. In Table 1, N, M, S and R represent the number of nodes outside the source cluster listening to the source transmission, the nodes within the source cluster to the source transmission, the source, and the successful relay respectively. While D_{Min}, D_{Max} and P_{max} are the minimum distance threshold from S to R, the maximum distance threshold from S to R and the maximum transmit power calculated based on $S - D$ path length. As nodes have network information, they estimate D_{Min} and D_{Max}, and if the node satisfies the condition in (29) and (30), it listens to the RTS/CTS messages to calculate the transmission power using (36). If the SNR threshold is satisfied, the node sets the timer based on equation (32). The node with the minimum two link path length sends the ACK FLAG declaring winning the relay role. S and R use equation (24) and equation (25) to calculate the required energy and adjust the transmit power. In case of unsuccessful cooperation, the source transfers to sleep mode, and waits for the next round to transmit.

D. Performance Evaluation

The probability of n out of m nodes $Pr(n/m)$ satisfying the condition in (30) is correlated with the desired SNR and the received SNR at the node and is given in by

$$Pr(n/m) = \frac{m!}{n!(m-n)!} e^{m\beta} (1 - e^{\beta})^{m-n} \qquad (33)$$

where $\beta = P_{re} P_r^{-1}$, and P_{re}, P_r are the required power at the receiver and received power at the receiver respectively. Thus, the probability of successful transmission is given by

$$P(S) = P(\gamma_1 > T_1) P(\gamma_2 > T_2) \qquad (34)$$

where T_1 and T_2 are evaluated using (19) and given by

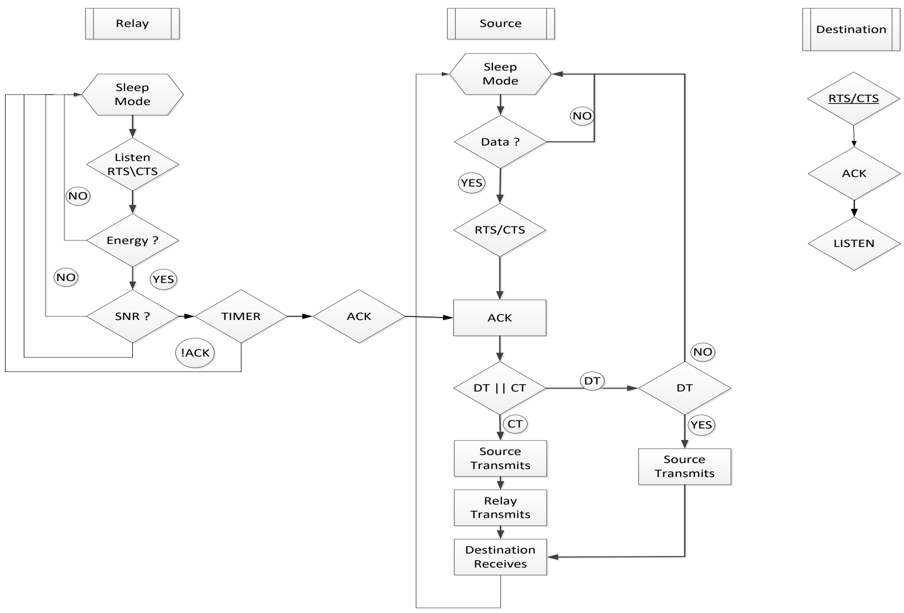

Figure. 7. Cooperative Transmission Procedure

$$T_1 = T_2 = \frac{(1-2P_e)^2}{x(1-(1-2P_e)^2)} \quad (35)$$

The required power P_{Tr} at the relay is given by.

$$P_{Tr} = \frac{(1-2P_e)^2 2B\sigma^2 N_f}{x(1-(1-2P_e)^2)} \quad (36)$$

To examine the effect of the relay location with respect to the total path length of 150 meters, we set the transmit power to $P_{Max}/2$ at the relay and the source. Thus, we use different value of b and we assume an ideal channel and the destination drops the received packet if the BER is below 10^{-3}.

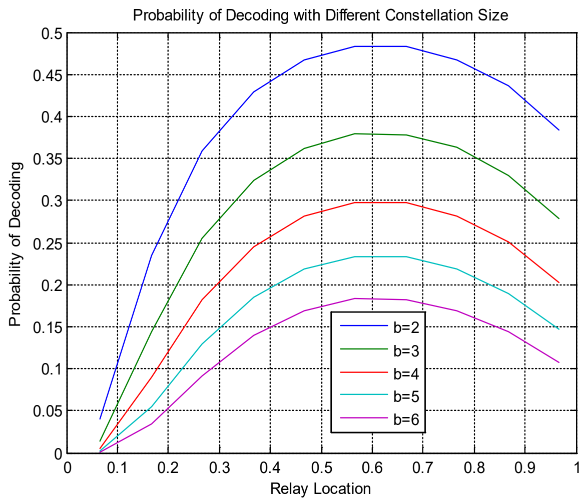

Figure. 8. Probability of Successful Transmission

In Figure 8, with the relay falling toward the midpoint, the probability of correct decoding at the destination increases which leads to a higher probability of successful transmission.

V. SIMULATION RESULTS

Table II. Simulation Parameters

Parameters	Annotation	Value
Drain Efficiency	η	0.35
Thermal Noise PSD	N_0	-171dBm
Target Bit Error Rate	P_e	10^{-3}
Carrier Frequency	f_c	2.5GHz
Bandwidth	B	$1MHz$
Packet Length	L	$200Kb$
Link Margin	M_l	$40dB$
Transmission Deadline	T	$100ms$
Mixer Power	P_{MIX}	$30.3mW$
ADC & DAC Power	P_{DAC}, P_{ADC}	$15.4mW$
LNA Power	P_{LNA}	$20mW$
Active Filter Power	P_{FILR}, P_{FILT}	$2.5mW$
Frequency Synthesizer Power	P_{SYN}	$50mW$
Receiver Noise Figure	N_f	$10dB$
Intermediate Frequency Amplifier Power	P_{IFA}	$3mW$

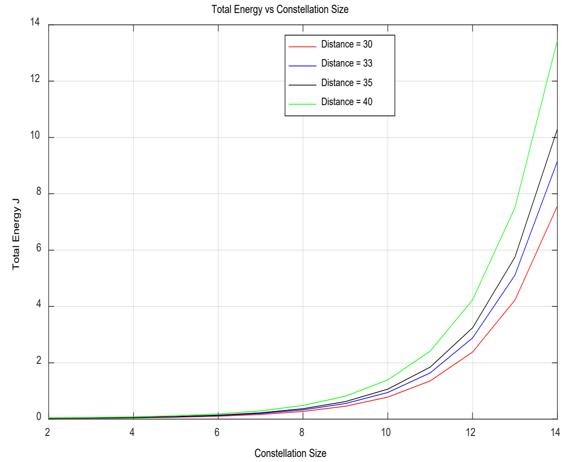

Figure. 9. Total Energy Cost with Different Relay Locations

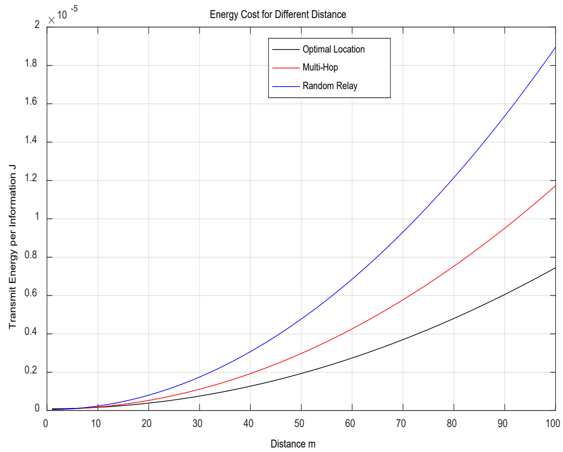

Figure. 10. Energy Cost of Three Methods in Ideal Scenario

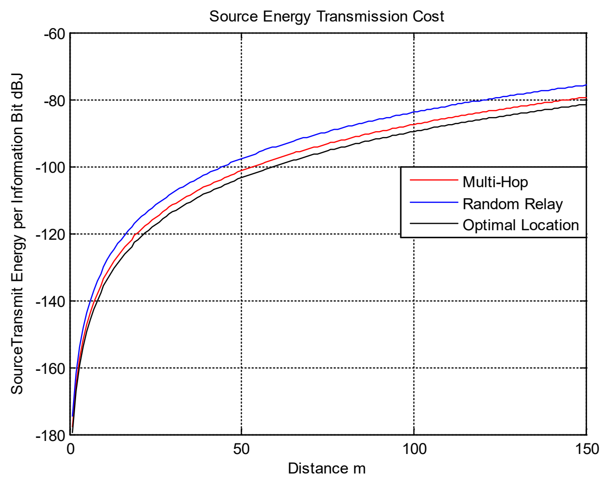

Figure. 11. Source Transmit Energy Cost per Information Bit

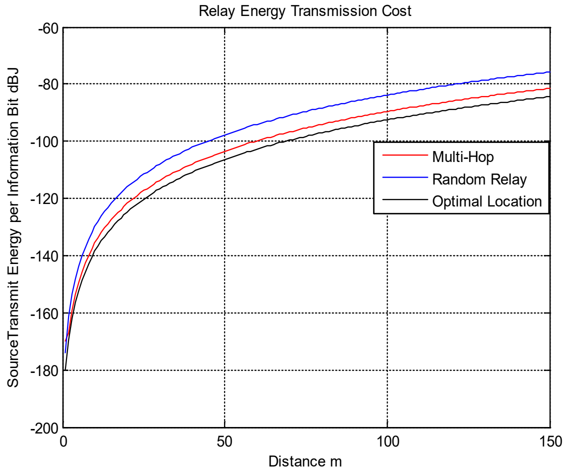

Figure. 12. Relay Transmit Energy Cost per Information Bit

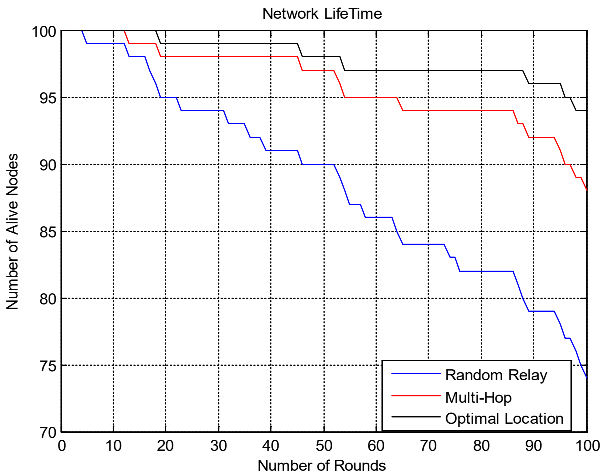

Figure. 13. Network Lifetime of Three Schemes

The performance of the proposed method is evaluated using the parameters given in Table II, the power consumption for sleep mode and transient between different states is ignored, while the data aggregation cost at CH is set to 5 Nano joule per bit. To illustrate the performance of the proposed method (Optimal Location), we compare the transmit energy cost per bit with Multi-Hop routing and Random Relay selection, and the direct transmission is set as a comparison benchmark. In Multi-Hop, CH relays the source packet while in Random Relay selection, all the nodes within the source transmission range are considered as relay candidates. The successful relay adjusts transmit power using (36) to achieve P_e at the destination, while the source uses half ofP_{Max}.In Multi-Hop and Random Relay selection methods, the relay is selected randomly. In the proposed scenario, it is assumed that candidate relay transmits ACK message with sufficient power to reach all candidate relays, thus the collision is avoided. For the proposed method, we investigated the relation between the constellation size and the relay location, and we examined 4 different scenarios.

In Figure 9, the relay within 45, 50, 55 and 50 meters' distance from the source consume the minimum energy with constellation size lower than 8, while the energy cost increases with constellation size greater than 8. This observation supports the choice of constellation size of 8. Thus, we use a constellation size of 8 and we compare the performance of the three methods in terms of total energy consumption per bit. We consider the ideal scenario where the relay falls within the line of sight of the source and the destination, with a $S-D$path length of 100 meters. In Figure 10, the proposed method outperforms Random Relay selection method and Multi-Hop selection method in terms of the total energy cost per bit as it balances both link distances. Moreover, at a transmission range of 100 meters, the proposed method consumes $0.4*10^{-5}$and $1.2*10^{-5}$ joules less energy compared to Multi-Hop and Random Relay respectively. Moreover, as the selected relay in the proposed method the proposed method outperforms both methods in term of energy consumption at the source as seen in Figure 11. Similarly, in Figure 12, the proposed method outperforms both other methods.

As seen in Figure 13, the total energy cost per information bit of the proposed method is inferior by 3 dB, and around 5 dB to both methods at distance of 50 meters. Moreover, the network performance in term lifetime is illustrated in Figure 13, where we assumed that nodes have an initial energy of 0.5 Joule. The proposed method outperforms both methods. The result shows 93 alive nodes after 100 rounds, while in Multi-Hop and Random Relay selection the number of alive nodes is 87 and 74 respectively. As the energy consumption is balanced in the network, nodes deplete their energy slower when the proposed method is adopted in comparison to both other methods.

VI. CONCLUSION

In this paper, an energy efficient relay selection algorithm for clustered WSNs was proposed. An SNR distance-based threshold is used, whereby only nodes that fulfill the criterion of having both links SNR above the required threshold compete to participate in the transmission. Therefore, the node with minimum distance to source and destination is selected as relay. Consequently, the overall transmission path is minimized, which decreases the energy cost per transmitted bit. The constellation size has been investigated through numerical example. The proposed method outperforms the traditional multi-hop relaying and Random Relay selection in terms of energy cost per bit at the source and relay. Furthermore, the proposed method also outperforms the two methods in terms of the network lifetime.

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