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Specifying the Optimal Transmission Manner in WSNs: Analysis and Simulation

Abd Elwahab Fawzy[1] · **Mona Shokair**[1] · **Waleed Saad**[1]

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Abstract Employing multi-hop transmission (MH) in wireless sensor networks achieves the uniform distribution of energy cost between nodes. However, the minimum energy cost isn't completely guaranteed. Therefore, in several cases, the total energy cost might be greater than direct transmission (DT). In this paper, we are interested in determining the factors that influence choosing the efficient transmission manner. It's assumed that there is a judging metric, called characteristic distance d_{char} that specifies whether to use DT or MH. If the transmission distance is greater than d_{char} MH is used, else DT is preferred. The previous conclusion is obtained through the following three steps: The first step is to analyze the relation between the radio hardware parameters and the consumed energy of the different transmission techniques. Hence, a general law for d_{char} will be deduced. Secondly, a supplementary analysis will be performed to understand the effect of these parameters on d_{char}. Finally, a great concern is paid to estimate efficient design of cluster size in cluster-based routing protocols. Therefore, d_{char} and the radio hardware parameters are exploited in specifying the optimum size of the cluster. The proposed design consumes the least energy cost and minimizes the variance of nodes residual energy in comparison with DT, MH and normal clustering. This helps in avoiding energy hole problem and enhancing the network lifetime.

Keywords WSNs · Routing · Direct transmission · Multi-hop transmission · Hardware parameters · Cluster design

✉ Abd Elwahab Fawzy
abdelwabfawzy@el-eng.menofia.edu.eg

Mona Shokair
mona.sabry@el-eng.menofia.edu.eg

Waleed Saad
waleed.saad@el-eng.menofia.edu.eg

[1] Faculty of Electronic Engineering, Menofia University, Menouf, Egypt

1 Introduction

WSNs are composed of small size, low cost and limited resources sensing nodes which work together to acquire information from the sensing field. These nodes are equipped with capabilities of sensing the surrounding environment, processing the sensed data, and wireless communication. They send the sensed data to a central node called Base Station (BS). BS is a master node with high capabilities and unlimited power source. It acts as a gateway between the nodes and the end user [1]. WSNs have been exploited as effective data gathering tool in several applications such as monitoring, military surveillance, industrial, agricultural producing, healthcare, intelligent home furnishing, security and safety applications [2, 3].

Mostly, WSN applications are employed in hostile environments. Therefore, the deployed nodes have to be battery powered devices. These Portable batteries are integrated into nodes during the fabrication process. From an economical and practical point of view, replacing or recharging of batteries is not an available option. Hence it is important for these nodes to achieve the optimum use of their energy to live a long time without any external assistance. WSNs have to be designed to operate in an efficient manner to save energy as much as possible. Routing data between nodes can play a vital role in achieving this objective. How to achieve the efficient utilization the available energy during routing process so as to prolong network lifetime and enhance its performance, is an important research issue. There are several routing protocols proposed for WSN [4, 5]. These protocols can be classified according to different parameters. In terms of participation style of the nodes, they can be classified to; DT, MH and clustering protocols.

Several transmission manners for conventional computer networking such as DT and MH have been employed for WSN [6, 7]. DT is convenient for small-scale networks. Due to the exponential increase of the consumed energy with distance, DT is not preferable for either far nodes or large-scale networks. In MH, the total distance is partitioned into small parts and the nodes work cooperatively to relay data. In [8–10], CBRP concept was introduced to overcome the problems of DT and MH such the energy efficiency and the delay respectively. In CBRP, the sensor nodes are grouped into a number of separated clusters. Each cluster has a Cluster Head (CH) which is responsible for receiving the sensed data from Member Nodes (MNs), fusing and aggregating it in a single block message before sending it to BS. Cluster-based Protocols are more efficient in satisfying the WSNs needs. In initial clustering approaches, cluster members communicate to their designated CH using single-hop communication. Recently, MH intra-cluster communication is employed when the sensing nodes have limited communication range [11]. Hence, the nodes within the same cluster collaborate to relay the data packets to the CH. This is convenient when there are a large number of non-CH nodes and restricted numbers of CHs.

Assuming that a far node needs to send data to its CH. Due to the exponential increment of energy consumption with distance, this node will avoid DT and begin to search for an intermediate node to relay data. The relay node will spend two terms of energy; the relay cost plus the transmission cost to send data to CH. Hence the total expended energy may be much higher than DT cost. Moreover, nodes closer to CH will be overloaded with much more data compared to distant ones. This leads to unbalanced energy consumption within clusters. From previous, the distances between nodes and their related CHs have a direct impact on the energy consumption within each cluster. Hence limiting cluster size will balance energy consumption. Unlike traditional routing protocols where optimum cluster size plays a minor role, this paper focus on maximizing the outcomes of DT in cluster size design.

The main contributions of this paper lie in three main sections as follows:

- A comprehensive analysis of different transmission manners will be performed to determine the maximum allowable distance between two nodes at which DT needs least cost in comparison with MH. This distance is called characteristic distance d_{char}.
- The influence of some parameters that affected on d_{char}, are carefully studied.
- The optimum size of a cluster in CBRP can be deduced relative to d_{char}. Hence a fixed and minimum number of clusters can be obtained.

The rest of this paper is organized as follows: Related work will be presented in Sect. 2. The system model and the problem will be discussed in Sect. 3. In Sect. 4, compressive analysis to deduce a formula for characteristic distance d_{char} will be performed. In Sect. 5, the influence of radio hardware parameters on characteristic distance will be studied in a detailed manner. The optimum size of CH will be derived in terms of d_{char} in Sect. 6. The efficiency of our proposed design will be verified using MATLAB simulator in Sect. 7. Finally, conclusions will be accomplished in Sect. 8.

2 Related Work

In 2002, Heinzelman et al. introduced Low Energy Adaptive Clustering Hierarchy (LEACH) as a standard model for CBRP in homogenous WSN where all nodes have the same initial energy [12]. LEACH operation is divided into rounds. Each round is separated into two phases, called Setup and Steady state.

2.1 Setup Phase

It is concerned with CHs election strategy and cluster formation. There is an optimal percentage p (specified a priori) for nodes to be CH. It guarantees that each node will become CH exactly once every $1/p$ rounds. At each round, every non-CH node generates a random number which compared with threshold value $T\ (si)$. The node will be CH only if this number is less than $T\ (si)$ which is given by,

$$T(si) = \left\{ \begin{array}{ll} \dfrac{p}{1 - p\left(r * \bmod \dfrac{1}{p}\right)} & if\ \ si \in G \\ 0 & else \end{array} \right\} \tag{1}$$

where r is the round number. $si \in$ G refers to that node si hasn’t been selected as CH in recent rounds. Once CHs are selected, non-CH nodes make a decision to join one of these CHs depending on the Received Signal Strength Indication (**RSSI**).

2.2 Steady State Phase

In Steady State Phase, data transmission either between MNs and CHs or between CHs and BS is achieved. The sensed data by MNs are processed and aggregated locally by CHs before sending it to BS. MNs use TDMA schedules to communicate with CHs while CHs use CDMA keys to reach BS. LEACH network structure is shown in Fig. 1.

To some extent, CHs selection in LEACH is a random process. Hence remarkable drawbacks appear such as:

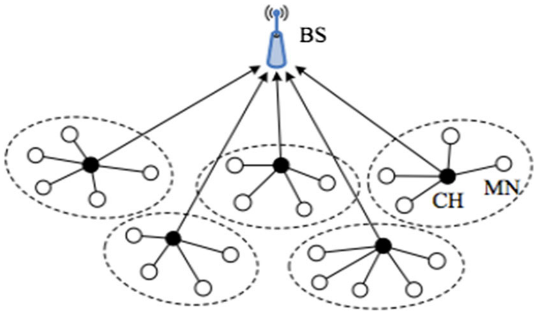


Fig. 1 Network structure in LEACH prtocol

- Number of CHs in each round is not equal.
- The uniform distribution of CHs through the sensing field is not guaranteed.
- Different cluster sizes are obtained, which means that some CHs will serve a small number of nodes while the rest CHs will have to deal with a large number of nodes. This causes unbalance energy consumption.
- Nodes' residual energies are not considered during CHs selection.

Several approaches for enhancing LEACH had been introduced. Some of these protocols are interested in improving the CHs selection process [13–16], the cluster formation process [17–19] or the transmission process itself [20–23].

In [13], Energy-LEACH was introduced to improve the CH selection process. Node residual energy became the main factor to decide whether this node becomes CH or not. Hence, nodes with more residual energy become CHs in future rounds, and so on. Sadat et al. presented a distance aware CH selection protocol in [14], where the probability of CH selection p was modified depending on the node's distance from BS. Smaller p was assigned to faraway nodes, hence they would be CHs fewer times than closer ones. WSN can be categorized into homogeneous or heterogeneous on the basis of the initial energy of nodes. If nodes' initial energies are equal, then it is homogenous, else it is heterogeneous. Various types of routing protocols have been presented to suit heterogeneous networks [15, 16]. Authors in [15] introduced Stable Election Protocol (SEP) for two energy level WSN where the nodes are classified into normal and advanced. Advanced nodes have more initial energy than normal ones. In SEP, CH election probability relies on the initial energy of nodes, therefore advanced nodes are exposed to be CH more times than the normal ones. For multilevel heterogeneous WSN, Distributed Energy Efficient Clustering algorithm (DEEC) was introduced in [16]. The probability of a node to be selected as CH is not fixed as LEACH or depend only on the initial energy of nodes such as SEP, but instead, the ratio between the residual energy and the average energy of the whole network plays a vital role in CH selection. As result nodes with higher energies are exposed to be CH more than lower ones. SEP and DEEC enhanced the lifetime of the network using a heterogeneous aware clustering algorithm.

In [17], Energy Efficient Clustering Scheme (EECS) was discussed. Cluster formation is dependent on the distance from BS. Due to the direct communication between CH and BS, far clusters consume larger energy than near ones. In EECS, far nodes construct smaller size clusters than near ones to balance the consumed energies in Intra and Inter Cluster communications. On the other hand, Energy Efficient Unequal Clustering (EEUC) mechanism was introduced in [18, 19]. EEUC used MH transmission between CHs to reach BS, therefore closer CHs to BS were exposed to heavy relay traffic and tends to die early. To overcome this problem, the network was portioned into unequal size clusters. Hence near clusters have a smaller size than closer ones.

According to the nature of the interesting application, WSNs were classified into reactive or proactive. In the reactive network, nodes have to sense then transmit their respective data to BS in a periodic manner while in proactive one, nodes send to BS only if the sensed data overcomes threshold values that are specified previously [20, 21]. In Most CBRP, there are two modes of transmissions [22, 23]: Intra and Inter cluster Transmission. Intra-cluster transmission deals with the communication between nodes within the cluster while Inter-Cluster Transmission interests in the communication between CHs and BS. There is no doubt that Cluster size affects the energy cost of both modes.

In [24, 25], MH transmission to send data from a source node to BS was investigated briefly, then the optimum number of hops to decrease the expended energy was deduced. Depending on the deduced optimum number of hops, Hob-based Energy Aware Routing (HEAR) algorithm was introduced to enhance the energy efficiency and the lifetime of the network. From the discussion above, we conclude that the transmission manner and cluster size play an important role in minimizing the energy consumption through the network [8].

3 System Model and Problem Statement

3.1 Network Model

Let us consider a number of sensors are randomly deployed within the interesting sensing field. These nodes are used to measure a locative function (say temperature, radiation or pressure), then the sensed data are sent to BS. Moreover, the following assumptions are taken into consideration:

- BS is an unlimited resource device.
- As soon as the sensor nodes are deployed, their locations are maintained fixed.
- All nodes know its location using GPS or any other location determination device.
- All sensor nodes work in proactive mode.
- Nearby sensors have correlated data.
- The communication channel is symmetric (i.e. The energy cost for transmitting a message between two nodes is the same in both directions).

Each sensor node is a multi-tasking device which able to perform a variety of tasks such as sensing, processing, transmitting, and receiving data. The energy consumed for sensing and processing is relatively small, periodic and identical for all nodes. Hence they are given less concern in comparison with the transmit and receive cost [26]. As result, the total expended energy becomes dependent on the transmit and receive costs. Therefore, they have a direct influence in choosing the transmission policy of nodes.

3.2 Energy model

A commonly used energy model, known as the first order radio model is shown in Fig. 2. This model is used to clarify the expended energy by nodes over the network operation time. As the transmission cost increases exponentially with the α-*th* power of distance, there are two models of losses depending on distance d between TX and RX; Free Space ($\alpha = 2$) and Multipath fading ($\alpha = 4$). Here, it is also worth mentioning that the value of distance power gradient α can be other values rather than 2 or 4. Table 1 lists some other

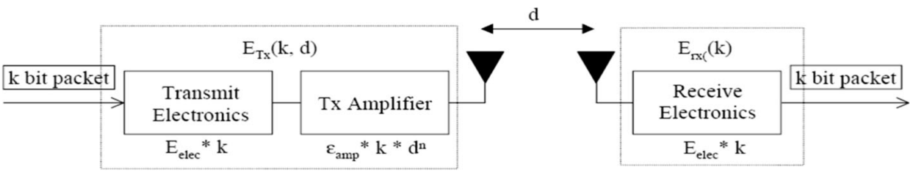


Fig. 2 Radio model [12]

Table 1 Values of distance power gradients [24]

Parameter	α
Urban area	2.7–3.5
Indoor line-of-sight (LOS)	1.6–1.8
Indoor no line of sight	4–6

values used in practical wireless communication environment [24]. Other radio hardware parameters and their definitions are given in Table 2 [12].

The energy cost expended by radio unit for transmitting *k* bits message over a distance *d*, and receiving it is given by:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ &= k \cdot E_{elec} + k \cdot \varepsilon_{amp} \cdot d^{\alpha} \\ &= \begin{cases} k \cdot E_{elec} + k \cdot \varepsilon_{fs}.d^2, & if \ d \le do \\ k \cdot E_{elec} + k \cdot \varepsilon_{mp} \cdot d^4, & if \ d > do \end{cases} \end{aligned} \tag{2}$$

$$E_{Rx}(k) = E_{Rx-elec}(k) = k.E_{elec} \tag{3}$$

where E_{elec} is the electronic energy that counts on the filtering, modulation the digital coding and spreading of the signal, ε_{fs} is the free space loss coefficient, and ε_{mp} is the multipath loss coefficient. To the best of our knowledge, E_{elec} has fixed value equals 50 nJ/bit while the other parameters ε_{fs} and ε_{mp} can take different values by switching through dual transmitting power levels as proposed in [22, 23]. If a node works as an intermediate node to relay data from source to destination, its radio expends:

Table 2 Radio parameters [12]

Parameter	Definition	Value/unit
E_{elec}	Energy dissipation in electronic circuits	50 nJ/bit
ε_{amp}	Energy dissipation rate to run amplifier ε_{amp} may equal ε_{fs} or ε_{mp}	ε_{fs} = 10 pJ/bit/m^2 ε_{mp} = 0.0013 pJ/bit/m^4
k	Data length	4000 bits
d	Transmission distance	m
d_o	Threshold distance	$d_o = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$ = 87.7 m

$$E_{Fx}(k,d) = E_{Rx}(k) + E_{Tx}(k,d)$$
$$= 2k \cdot E_{elec} + k \cdot \varepsilon_{amp}.d^{\alpha}$$
$$= \begin{cases} 2 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d^2, & if\, d \le do \\ 2 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{mp} \cdot d^4, & if\, d > do \end{cases} \tag{4}$$

3.3 Problem Statement

From the former network and radio models, assume there are a several numbers of nodes that have already sensed the sensing field and needs to send data to remote BS. The following questions will be suggested which are answered through the rest of the paper:

a. *Whether to send data directly (DT) or use another node as a relay?* There is always a threshold distance or characteristic distance d_{char} which is used for solving this urgent question. The mathematical formula for d_{char} is needed to be obtained.
b. Based on the previous answer, *which parameters does d_{char} depend on?* Influence of the various parameters needed to be studied rigorously with analysis and figures.
c. *To which degree we can exploit this distance to optimize the cluster size? d_{char}* will be employed to estimate the optimum size of a cluster.

4 Deduction of Characteristic Distance

MH is convenient for far nodes while DT adequate for near nodes. In this section, it is assumed that there is a threshold distance which is used as a judging criterion for answering the following question (whether to transmit the data directly or through MH?). In most real environments, nodes are not placed at equal intervals in often. Hence, in contrast to the network assumptions in [6], the uniform distribution of nodes in our model isn't considered. The relation between the expended energies by DT and two-hop transmission will receive considerable attention in the following sections. To illustrate this point, consider the linear network shown in Fig. 3. Node 2 is a source node which needs to send data to BS. Node 1 is a relay node which able to receive data from node 2, then transmit it to BS. According to previously discussed energy model, there are three possible scenarios for distances $d_1, d_2, (d = d_1 + d_2)$. Each case will be analyzed in detail in the following subsections.

1. The free space model $(d \le d_o)$.
2. The multipath model $(d \ge 2d_o)$.
3. The hybrid model $(d_o < d < 2d_o)$.

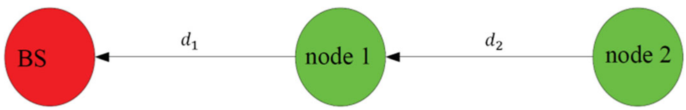


Fig. 3 Relay node network model

4.1 The Free Space Model

Small distances scenario ($d \leq d_o$) is convenient for small area networks where the free space loss dominates. Hence the free space model is used during transmission process [6, 24]. The consumed energies using DT, and 2-hop transmission through node 1 are;

$$E_{DT} = k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d^2 \tag{5}$$

$$\begin{aligned} E_{2-hop} &= \underbrace{k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d_2^2}_{Expended\ energy\ by\ node2} + \underbrace{2 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d_1^2}_{Expended\ energy\ by\ node1} \\ &= 3 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot \left(d_1^2 + d_2^2\right) \end{aligned} \tag{6}$$

DT will consume less energy than 2-hop transmission if;

$$\begin{aligned} &\Delta\mathrm{E} = E_{DT} - E_{2-hop} \leq 0 \\ &k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d^2 - (3 \cdot kE_{elec} + k \cdot \varepsilon_{fs} \cdot (d_1^2 + (d - d_1)^2)) \leq 0 \\ &\Delta\mathrm{E} = d_1 \cdot (d - d_1) - \left(\frac{E_{elec}}{\varepsilon_{fs}}\right) \leq 0 \\ &\frac{d\Delta\mathrm{E}}{dd_1} = d - 2d_1 = 0 \\ &d_1 = d_2 = {}^{d}\!/_{2} \end{aligned} \tag{7}$$

The optimum distance of d_1 can be excluded by setting the derivative of ΔE with respect to d_1. It is easy to prove that the maximum allowable distance to use DT (d_{char}) takes place when the total distance is halved. In such case, it is important to point out that, the 2-hop energy cost equals DT cost. Substituting of d_1 and d_2 by *d/2,* a formula for d_{char} can be deduced as follows:

$$\begin{aligned} &\frac{d_{char}^2}{4} \leq \frac{E_{elec}}{\varepsilon_{fs}} \\ &d_{char} \leq 2 \cdot \sqrt{{}^{E_{elec}}\!/_{\varepsilon_{fs}}} \end{aligned} \tag{8}$$

4.2 The Multipath Model

The calculations in the previous case are suitable for small area WSNs. Otherwise, large distances scenario ($d \geq 2\ do$) is more acceptable for wide area WSNs where the multi path fading dominates. Hence the multi-path model is used. The disbursed energies using DT and 2-hop transmission are given as follows:

$$E_{DT} = k \cdot E_{elec} + k \cdot \varepsilon_{mp}.d^4 \tag{9}$$

$$\begin{aligned} E_{2-hop} &= \underbrace{k \cdot E_{elec} + k \cdot \varepsilon_{mp} \cdot d_2^4}_{Expended\ energy\ by\ node2} + \underbrace{2 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{mp} \cdot d_1^4}_{Expended\ energy\ by\ node1} \\ &= 3 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{mp} \cdot \left(d_1^4 + d_2^4\right) \end{aligned} \tag{10}$$

DT will consume less energy than 2-hop transmission if;

$$\Delta \mathrm{E} = E_{DT} - E_{2-hop} \leq 0$$

Substituting of d_1 and d_2 by $d/2$, as explained in Eq. (7),

$$\begin{aligned} & k \cdot E_{elec} + k \cdot \varepsilon_{mp} \cdot d^4 - \left(3 \cdot k \cdot E_{elec} + 2 \cdot k \cdot \varepsilon_{mp} \cdot \left(\frac{d}{2}\right)^4\right) \leq 0 \\ & \varepsilon_{\mathrm{mp}} \cdot \frac{7}{8} \cdot d^4 \leq 2 \cdot E_{elec} \\ & d_{char} = 2 \cdot \sqrt[4]{E_{elec}/7 \cdot \varepsilon_{mp}} \end{aligned} \tag{11}$$

4.3 The Hybrid Model

Calculations in previous two subsections are appropriate for small and large transmission distances, respectively. However, more specific analysis for intermediate distances ($d_o < d < 2d_o$) is highly required in this subsection. In the hybrid model, the energy exhausted in DT and 2-hop are:

$$E_{DT} = k \cdot E_{elec} + k \cdot \varepsilon_{mp}.d^4 \tag{12}$$

$$\begin{aligned} E_{2-hop} &= \underbrace{k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d_2^2}_{Expended\ energy\ by\ node2} + \underbrace{2 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d_1^2}_{Expended\ energy\ by\ node1} \\ &= 3 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot \left(d_1^2 + d_2^2\right) \end{aligned} \tag{13}$$

The same derivation is as in Eq. (7),

$$E_{2-hop} = 3 \cdot k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot 2 \cdot \left(d/2\right)^2$$

DT will consume less energy than 2-hop transmission if.

$$\begin{aligned} & \Delta E = E_{DT} - E_{2-hop} \leq 0 \\ & \varepsilon_{mp} \cdot d^4 - \frac{\varepsilon_{fs}}{2} \cdot d^2 - 2 \cdot E_{elec} \leq 0 \end{aligned}$$

By solving this fourth order equation, the characteristic distance can be calculated

$$d_{char} = \sqrt{\frac{\frac{\varepsilon_{fs}}{2} + \sqrt{\left(\frac{\varepsilon_{fs}}{2}\right)^2 + 8 \cdot \varepsilon_{mp} \cdot E_{elec}}}{2\varepsilon_{mp}}} \tag{14}$$

A general formula for d_{char}:

$$d_{char} = \begin{cases} 2 \cdot \sqrt{E_{elec}/\varepsilon_{fs}}, & d_{char} \le do \\ \sqrt{\dfrac{\frac{\varepsilon_{fs}}{2} + \sqrt{\left(\frac{\varepsilon_{fs}}{2}\right)^2 + 8 \cdot \varepsilon_{mp} \cdot E_{elec}}}{2\varepsilon_{mp}}}, & (do < d_{char} \le 2do) \\ 2 \cdot \sqrt[4]{E_{elec}/7 * \varepsilon_{mp}} & d_{char} > 2do \end{cases} \tag{15}$$

5 The Effect of Radio Hardware Parameters

Equation (15) shows that d_{char} is totally dependent on the radio hardware Parameters $\varepsilon_{fs}, \varepsilon_{mp}$ and E_{elec}. Normally these parameters are related to the hardware components. To the best of our knowledge, E_{elec} has fixed value equals 50 nJ/bit while the other parameters ε_{fs} and ε_{mp} can take different values within the range of 100 pJ/bit/m^2. In [6, 24] a simple model is assumed where the radio dissipates ε_{amp} = 100 pJ/bit/m^2 (doesn't differentiate between ε_{fs} and ε_{mp}) for the transmit amplifier to achieve an acceptable E_b/N_o. While in [12–16] more specific model is used with the parameters values given in Table 2. In [22, 23], ε_{fs} and ε_{mp} can take different values by switching through dual transmitting power levels for intra-or inter-cluster transmission. From previous, it's inferred that both ε_{fs} and ε_{mp} can take different values within the range of 100 pJ/bit/m^2. Varying ε_{fs} and ε_{mp} have a direct impact on d_{char} value. Each one of the aforementioned three cases for d_{char} will be studied in detail, each separately.

5.1 Free Space Model

From Eq. (8), d_{char} depends only on E_{elec} and ε_{fs}. In Fig. 4, d_o and d_{char} are simulated and evaluated verses different values of ε_{fs}, where $\varepsilon_{mp} = 0.0013$ pJ/bit/m^4, $E_{elec} = 50$ nJ/bit.

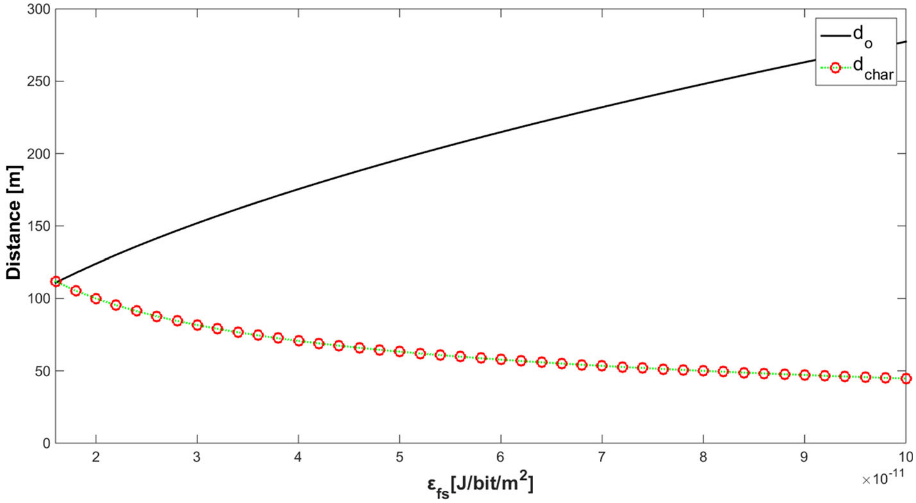


Fig. 4 d_{char} versus ε_{fs} for free space model, $\varepsilon_{fs} \in 16 - 100$ pJ/bit/m^2

The values of ε_{fs} are chosen carefully to achieve our assumption that $(d_{char} \leq do)$, hence it varies from 16 to 100 pJ/bit/m^2.

Firstly, since d_o is directly proportional to $\sqrt[2]{\varepsilon_{fs}}$, it is noticed that as ε_{fs} increases, d_o increases. Moreover, from (9), d_{char} is inversely proportional to $\sqrt[2]{\varepsilon_{fs}}$, hence d_{char} decreases with the increment of ε_{fs}. As ε_{fs} increases, the transmission cost $(k \cdot \varepsilon_{fs} \cdot d^2)$ increases compared to the relay cost of the possible intermediate node. Therefore, transmitting the signal over long distances is avoided. Then, it is preferred to use MH than DT for more smaller ranges. This is obvious with the decrease of d_{char} from 111 to 45 m when ε_{fs} increase from 16 to 100 pJ/bit/m^2, as shown in Fig. 4.

5.2 Multi-path Model

As given in Eq. (11), d_{char} depends only on E_{elec} and ε_{mp}. In Fig. 5, 2 d_o and d_{char} are simulated and evaluated verses different values of ε_{mp}, where $\varepsilon_{fs} = 10$ pJ/bit/m^2,$E_{elec} = 50$ nJ/bit. The values of ε_{mp} are chosen carefully to achieve our assumption that $(d_{char} \geq 2do)$, hence it varies from 0.02 to 0.12 pJ/bit/m^4.

At first, since d_o is inversely proportional to $\sqrt[2]{\varepsilon_{mp}}$, it is noticed that as ε_{mp} increases, 2 d_o decreases. Moreover, from (11), d_{char} *is* inversely proportional to $\sqrt[4]{\varepsilon_{mp}}$. Hence,$d_{char}$ decreases slowly as long as ε_{mp} increases. As ε_{mp} increase, the transmit cost $(k \cdot \varepsilon_{mp} \cdot d^4)$ increase compared to the relay cost. Transmitting the signal to long distance is avoided. Therefore, it becomes more reliable to use MH than DT for a wider range of small distances. This is evident in Fig. 5, d_{char} decreases from 49 to 31 m, as ε_{mp} varied from 0.02 to 0.12 pJ/bit/m^4.

5.3 Hybrid Model

As noticed in Eq. (14), d_{char} depends on E_{elec}, ε_{mp} and ε_{fs}. In this subsection, one of the hardware parameters, ε_{mp} or ε_{fs} will be varied while the other is kept fixed. It must be

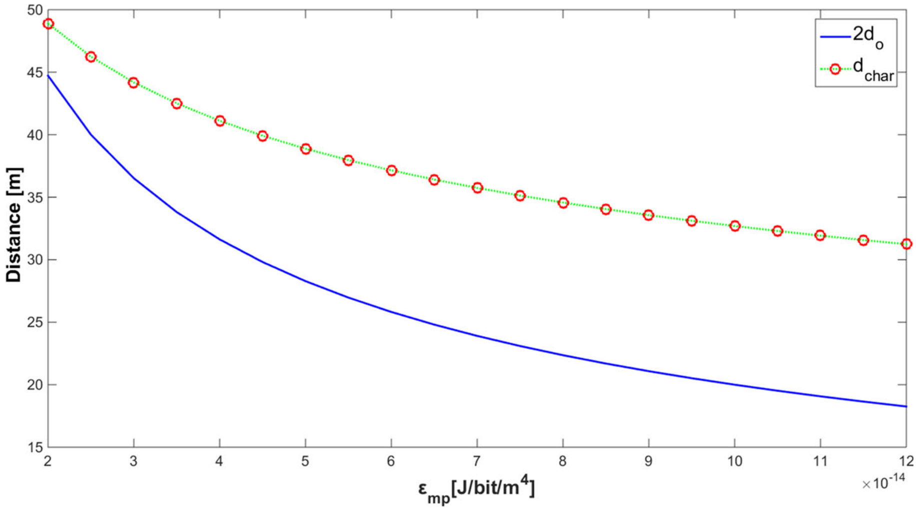


Fig. 5 d_{char} versus ε_{mp} for multi path model, $\varepsilon_{mp} \in 0.02 - 0.12$ pJ/bit/m^4

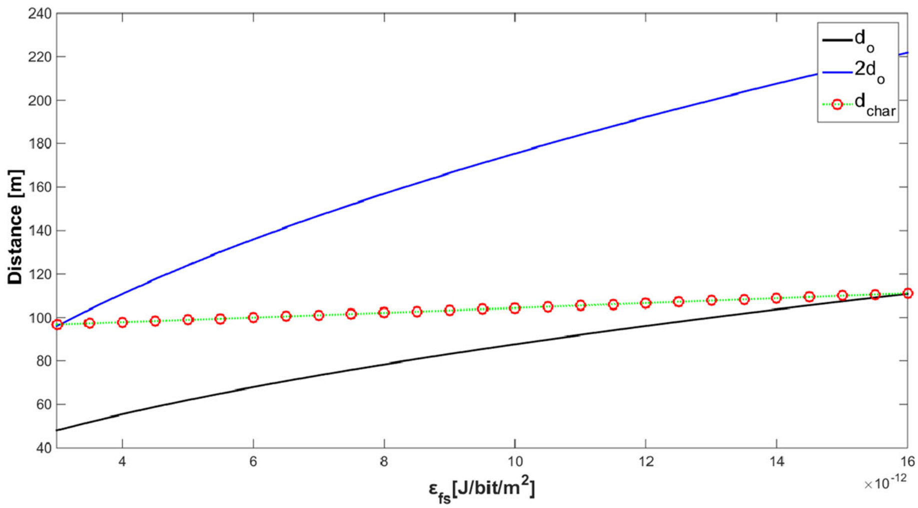


Fig. 6 d_{char} versus ε_{fs} for Hybrid model, $\varepsilon_{fs} \in 3 - 16$ pJ/bit/m^2

emphasized that the ranges of ε_{fs} and ε_{mp} are chosen carefully in order to be committed to the assumption of the hybrid scenario $(d_o < d_{char} < 2d_o)$. Then, we get two cases:

1. E_{elec} = 50 nJ/bit, ε_{mp} = 0.0013 pJ/bit/m^4 and $\varepsilon_{fs} \in 3 - 16$ pJ/bit/m^2.
2. E_{elec} = 50 nJ/bit, ε_{fs} = 10 pJ/bit/ m^2 and $\varepsilon_{mp} \in 0.0006 - 0.0096$ pJ/bit/m^4.

First case: In Fig. 6, d_o, $2d_o$ and d_{char} are simulated and evaluated verses ε_{fs}. As ε_{fs} increases, d_o and $2d_o$ increases respectively. From Eq. (14), d_{char} is approximately directly proportional to $\sqrt[2]{\varepsilon_{fs}}$. Therefore, d_{char} slightly increases from 98.9 to 110.08 m, as ε_{fs} varied from 3 to 16 PJ/bit/m^2. Hence, the efficiency of DT increases to include more wide ranges of large distances.

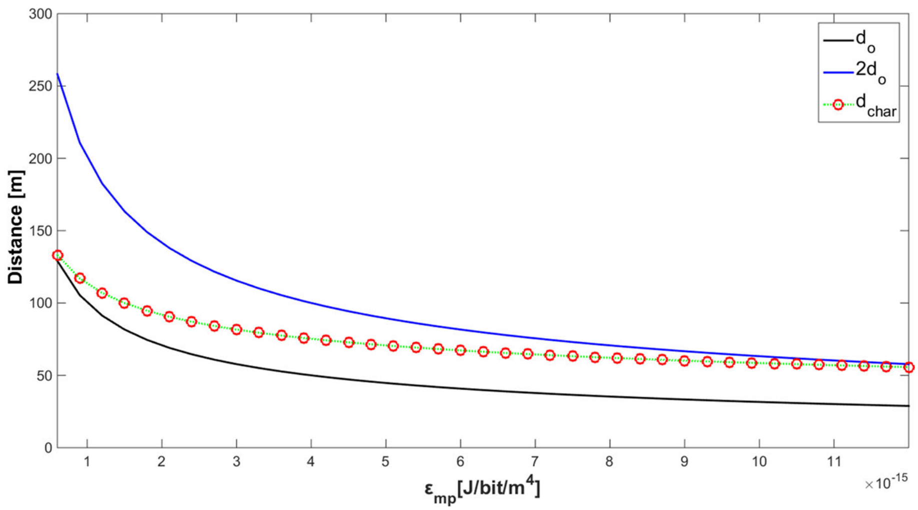


Fig. 7 d_{char} versus ε_{mp} for free space model, $\varepsilon_{mp} \in 0.0006 - 0.0096$ pJ/bit/m^4

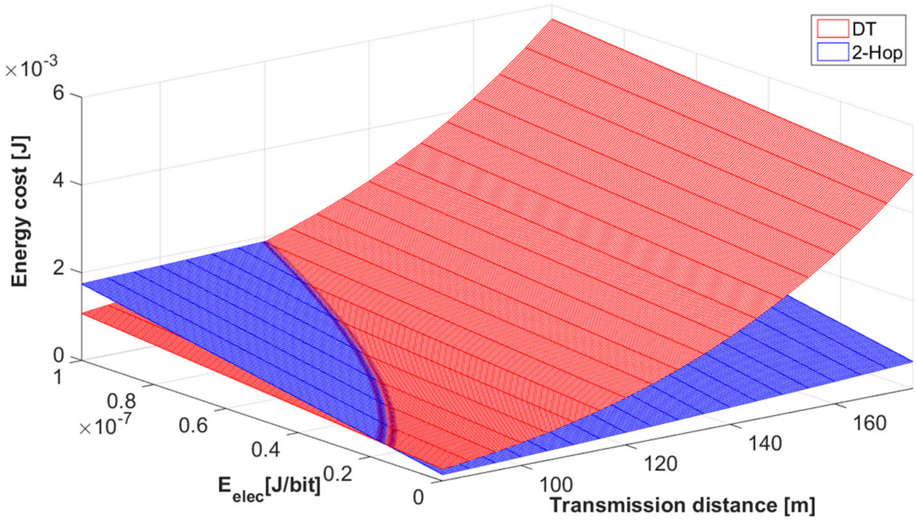


Fig. 8 3D plot for the Total energy consumption by DT and 2-hop routing ($d_o < d < 2d_o$)

Second case: In Fig. 7, d_o, $2d_o$ and d_{char} are simulated and evaluated verses $\varepsilon_{\mathrm{mp}}$. As $\varepsilon_{\mathrm{mp}}$ increase, d_o and $2d_o$ decrease accordingly. From (14), d_{char} is approximately inversely proportional to $\sqrt[2]{\varepsilon_{\mathrm{mp}}}$. Therefore d_{char} decreases from 133.16 to 59.14 m, as $\varepsilon_{\mathrm{mp}}$ varied from 0.0006 to 0.0096 PJ/bit/m^2. Hence, the efficiency of DT is restricted to small distances while MH becomes more convenient for larger distances.

Using the radio Parameters in Table 2, the total consumed energy for both DT and 2-hop transmission at different transmission distances and E_{elec} are calculated and showed in Fig. 8. The values of the transmission distance are chosen ($d_o < d < 2d_o$), to achieve the assumption of the hybrid model. The cross-sectional line which interconnects the two

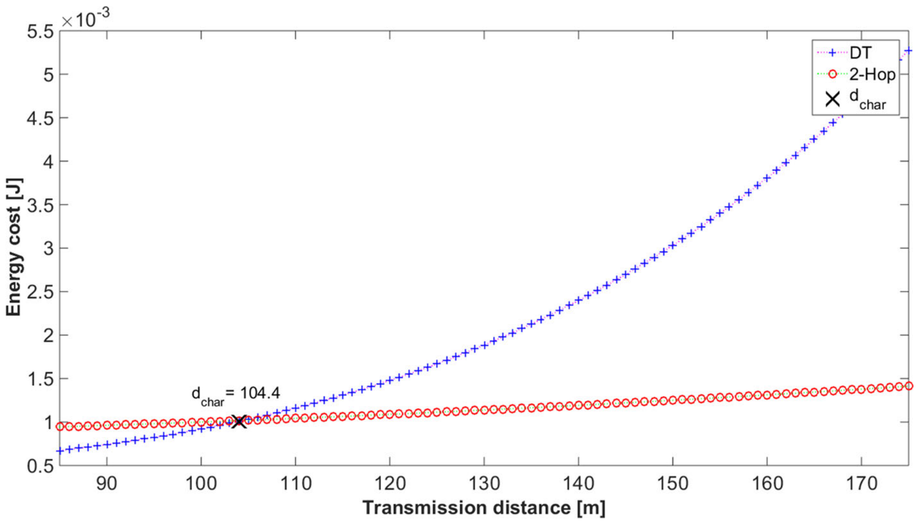


Fig. 9 The Energy cost by DT and 2-hop versus distance ($d_o < d < 2d_o$)

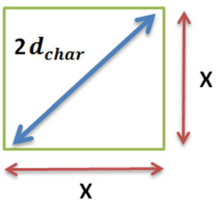
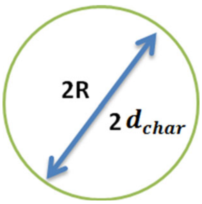
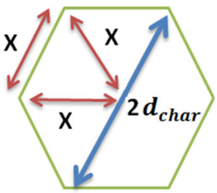
planes represents d_{char} at different E_{elec}. For distances less than d_{char}, DT cost is lower than either 2-hop or MH techniques. It is observed that for small values of E_{elec} (< 20 nJ/bit), MH is more efficient than DT. This is due to the large decrease in the relay cost with the decrement of E_{elec}. Hence the energy part saved by partitioning the transmission distance into small parts in MH is greater than the cost of relaying. From the above, it is clear that great attention must be paid to reduce E_{elec} during the practical design of nodes transceiver. This should be considered in the WSN for future works.

Figure 9 represents the energy cost for DT and 2-hop at different transmission distances, according to the hardware parameters in Table 2. It represents a slice from Fig. 8 also when E_{elec} = 50 nJ/bit as estimated in the practical radio model in [12]. The intersection point of DT and 2-hop curves represents the value of the judging metric d_{char} that specifies whether to use DT or MH. If the transmission distance is greater than d_{char} MH is used, else DT is preferred. The value of d_{char} can be estimated either from Fig. 9 by 104.4 or calculating it using Eq. (14).

6 Cluster Design

In CBRP, each CH collects the information from its MNs. In this section, we are interested in employing d_{char} as the maximum allowable distance, hence the distance between any MN and the CH doesn't exceed d_{char}. As result, MH transmission policy is avoided in Intra-cluster communication. Furthermore, a common range transmission strategy for MNs

Table 3 Area and dimensions of different cluster shapes in terms of d_{char}

Cluster shape	Cluster area	Cluster dimensions
	$A_{square} = 2 * d_{char}^2$	(length) × $\leq \sqrt{2} * d_{char}$
	$A_{circular} = \pi * d_{char}^2$	*(Radius) R* $\leq d_{char}$
	$A_{hexagonal} = \left(\frac{3\sqrt{3}}{2}\right) * d_{char}^2$	(Side length) × $\leq d_{char}$

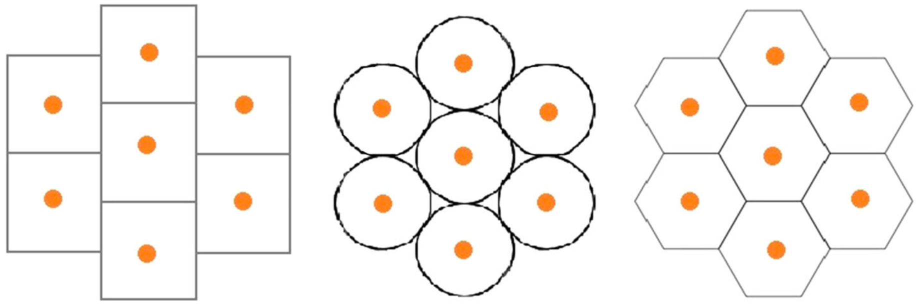


Fig. 10 Different network structures using various cluster shapes

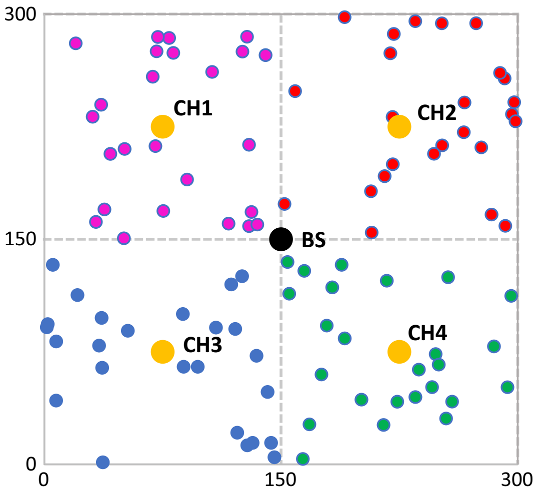
within a cluster can be achieved, where the node transmits with the same power level without any power control. This reduces the energy dissipation within each cluster and enhances the performance of the whole network. Depending on the desired cluster shape, the area and sides of the cluster can be calculated in terms of d_{char}. Area and dimensions of most conventional shapes such as, square, circular and hexagonal are calculated in Table 3. Moreover, different network structures which are related to the various cluster shapes, are shown in Fig. 10.

Exploiting d_{char} in cluster design would lead to optimizing the transmission energy for each node. Moreover, close nodes will not be overloaded with any additional cost. Then, the variance of nodes energy is supposed to be minimized. Then the energy cost is balanced for all nodes in the network.

7 Simulation Results

In this section, MATLAB simulator is used to evaluate our proposed approach for cluster design. The simulation environment consists of 104 sensing nodes, 100 of them are randomly deployed through 300 × 300 sensing field, while the other 4 have pre-determined

Fig. 11 Proposed network structure



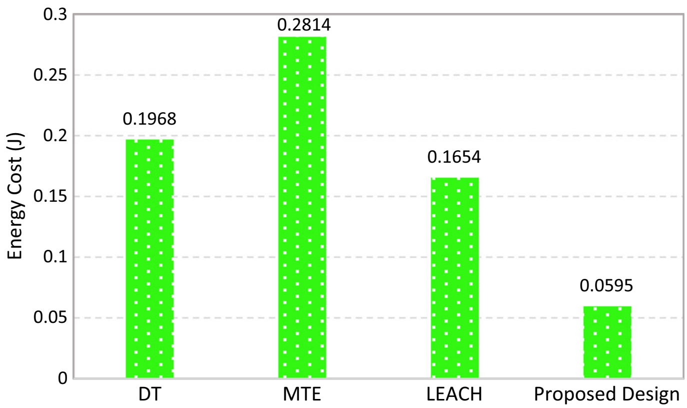


Fig. 12 Total consumed energy

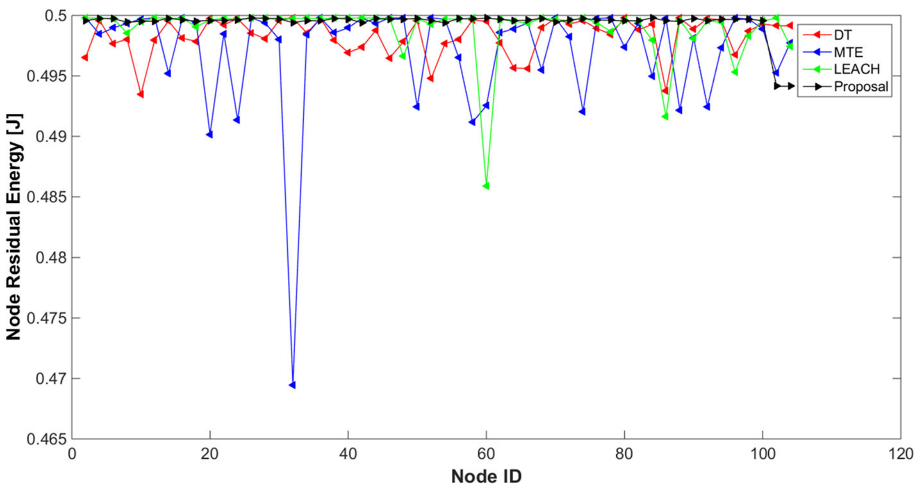


Fig. 13 Residual energy of nodes

locations (75, 75), (225, 75), (75, 225) and (225, 225), respectively. Furthermore, these four are assigned as CHs. BS is located in the center. Using square shape cluster design in Table 3, the network is divided into 4 identical clusters as shown in Fig. 11. The side length of the cluster is calculated $x = d_{char}\sqrt{2} \approx 150$. The initial energy of each node equals 0.5 J. Other radio Parameters are set to those in Table 2. Data transmission using DT, MH, LEACH and our Proposed Design is simulated for only one round.

The total consumed energy by nodes and their residual energy after the simulated round are shown in Figs. 12 and 13, respectively. In MH, Minimum Transmission Energy (MTE) is employed. It is a greedy algorithm where each MNs searches for its nearest neighbor node in its path to CH, regardless either the total cost of the path or the residual energy of the relay nodes [7]. Hence, MH consumes the maximum energy. Moreover, as shown in Fig. 13, the variance of nodes residual energy is maximum. In DT, due to the exponential increase of the energy cost with distance, far nodes consume a larger amount of energy than near nodes. The existence of BS in the center makes the total energy cost of DT remarkably lower than MH. Furthermore, the variance of the residual energy is lower than that of MH. Clustering concept in LEACH increases the energy efficiency and reduces the variance by larger a degree than DT and MH. It is observed that our proposed design consumes the least energy cost compared to others. As it maximizes the outcomes of DT within clusters. This, of course, plays important role in enhancing the network lifetime after several future rounds. Moreover, the residual energy of nodes is nearly constant compared to the others. This achieves the minimum variance of nodes residual energy over the network lifetime, then energy hole problem is avoided. To demonstrate the operation of the proposed design in most of the clustering protocols, we developed in [27] centralized energy aware grid clustering protocol (CEAG) which attains maximum network lifetime and throughput in comparison with other existing protocols.

8 Conclusions

In this work, it's assumed that there is always a threshold distance called characteristic distance d_{char} which used as a judging metric to specify the efficient transmission manner between two points. It is not allowable to use MH transmission with distances smaller than d_{char}. After a comprehensive analysis of energy cost of different transmission manners, a mathematical formula for d_{char} is obtained. It's concluded that d_{char} is totally dependent on the radio hardware parameters. Thereafter the effect of these parameters is deeply studied. Finally, d_{char} is exploited in the cluster design. Hence the dimensions of clusters can be estimated initially depending on the radio Parameters. Simulation results show that using our proposal, the transmission energy of nodes within clusters is minimized. Furthermore, no additional cost is overloaded to the nearest nodes to CH hence the energy cost is balanced over the whole network. As result the variance of nodes' residual energy is minimized. This, of course, enhances its performance of CBRP and prolongs the network lifetime.

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Abd Elwahab Fawzy has received his B.Sc. (Hons) and M.Sc. degrees from the Faculty of Electronic Engineering, Engineering, Menoufia University, Menouf, Egypt, in 2013 and 2017, respectively. Currently, he is a teaching assistant at the Department of Electronics and Electrical Communications Engineering, his major research interests include D2D communication, mobile communications, wireless sensor networks, and routing protocols.

Mona Shokair has received the B.Sc. and M.Sc. degrees in electronics engineering from El Menofia University, El-Menofia, Egypt, in 1993 and 1997, respectively. She received Ph.D. from Kyushu University, Japan, 2005. She was lecturer in El-Menofia University from 2006 to 2011. Since 2016, she is Professor in El-Menofia University. She received VTS chapter IEEE award from Japan in 2003. Her current area of interest include OFDM system, WiMAX system and cognitive radios.

Waleed Saad has received his B.Sc. (Hons), M.Sc. and Ph.D. degrees from the Faculty of Electronic Engineering, Engineering, Menoufia University, Menouf, Egypt, in 2004, 2008 and 2013, respectively. He joined the teaching staff of the Department of Electronics and Electrical Communications of the same faculty since 2014. In 2005 and 2008. His research areas of interest include mobile communication systems, computer networks, cognitive radio networks, D2D communication, OFDM systems, interference cancellation, resource allocations, PAPR reduction, physical and MAC layers design, and implementation of digital communication systems using FPGA.