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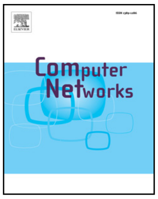

Energy efficient collaborative proactive routing protocol for Wireless Sensor Network

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ABSTRACT

A Wireless Sensor Network (WSN) is a group of tiny power-constrained nodes that cover a vast region of interest (ROI), sense and communicate it to the Base Station (BS). The main challenge encountered in WSNs is how to cover the ROI perfectly and transmit the monitored data to the BS for the longest possible time. Although many energy-efficient routing protocols for periodic monitoring applications were recently introduced, the dynamic nature and complex environments of WSN applications make building such protocols a considerable challenge. In this paper, the node degree of the Degree Constrained Tree (DCT) in homogeneous proactive WSN is studied analytically for the network with one BS that is outside the ROI. Since the node degree affects the network lifetime of these types of networks, the optimum node degree for minimum energy consumption in DCT is derived. Subsequently, the paper proposes a Collaborative Distributed Antenna (CDA) routing protocol that is based on distributed antenna theory to provide fair load distribution in terms of transmission energy. CDA is based on DCT with optimal node degree and is designed for periodic data monitoring in WSN applications. The experimental results prove our analysis to emphasize that using optimal node degree in DCT doubles its network lifetime compared to using other node degrees. Moreover, adding CDA to DCT with optimal node degree is proved to double the network stability period and reduce the ratio between instability period and the network lifetime to its half. It also shows 25% increase in network lifetime and minimum rate of node loss compared to its peers, such that the lifetime of half the nodes is preserved until few rounds before the end of network lifetime.

1. Introduction

A sensor network is a number of tiny sensor nodes of low costs that cover a certain Region of Interest (ROI) to measure data using different sensing capabilities and transmit them to the base station (BS). To minimize power consumption in data transmission, it is preferable to use multi-hop transmission to reach the BS instead of direct transmission, especially in large ROIs with only one BS. Consequently, the computational and communication tasks of sensor nodes may divide them into three main types according to their role in the ROI, which are sensor nodes, routers, and relay nodes. These three main types may vary physically as in the heterogeneous or hybrid networks; unlike homogeneous networks, as discussed by Abdul-Salaam et al. in [1].

The lack of energy fairness in multi-hop routing, especially when BS is far from the ROI that is monitored by homogeneous WSN, leads to losing the nodes that are responsible for ROI to BS transmission. Accordingly, the nodes in ROI become disconnected from the BS. Thus, the need for self-organized networks encourages researchers to introduce different dynamic routing protocols to avoid this issue. For example, Elsayed et al. introduced a distributed self-healing approach called DSHA that was designed for clustered network architecture in [2]. This recovery algorithm

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works at both network levels, sensor node levels, and cluster head levels. The authors utilized DSHA to overcome the challenge of energy loss and sudden failures of hardware components to extend WSN lifetime. However, these protocols produce relatively high network overhead, as studied in [3], unlike static routing protocols.

In contrast, static routing protocols with single setup phase suffer from the premature end of network lifetime. It is typical when BS is far from the ROI, due to losing the nodes that connect the BS to the ROI, which are the first nodes to drain their energy in the network. This problem was discussed in [3]; however, the choice of the degree of the DCT [4] that was the base of the energy-aware algorithms OHCR and OHA was not analytically justified. In literature, the end of WSN lifetime has been defined from the different point of views to describe network sustainability, which is a requirement in many WSN applications, as studied in [5]. In this paper, we will depend on the best case definition of network lifetime, which is the time until all nodes have been drained of their energy since the proposed protocol will be based on connectivity aware algorithm to avoid the premature end of network lifetime.

On the other hand, the distributed antenna system is a cooperative method that lets different information sources simultaneously transmit a packet and control the phase of their transmissions. In spite of the system complexity and synchronization issues of such Distributed and Collaborative Beamforming (DCBF) scheme, as discussed in [6,7], it has received a great attention from researchers in the last few years, as investigated in [8]. In DCBF, the signals constructively combined from antenna elements at the intended destination leading to power gain, which causes a dramatic increase in transmission range, Bit Error Rate (BER), and energy efficiency, as proven in [9]. Accordingly, adding the distributed antenna technique to an energy efficient routing tree like DCT with optimal node degree extends network lifetime effectively, especially by adding an energy-aware dynamic routing algorithm like OHCR [3].

In this paper, we introduce an analytical study of the effect of the degree of the DCT on the network lifetime. Additionally, our analytical derivation of the relation between node degree and the number of levels is proven by experimental results. On the other hand, the optimal node degree that leads to the highest network lifetime is proven by experiments as well as analytical derivation. Based on the results obtained from our analytical study, we introduce an energy-efficient routing protocol called Collaborative Distributed Antenna (CDA) for a single path, medium density network of sensor nodes. It is based on collaborative data transmission of antennas in distributed sensor nodes. It targets periodic data gathering applications, where the BS is outside the ROI. The protocol aims at avoiding energy depletion of a single node in the routing tree through preserving energy fairness. The energy efficiency of CDA is proved by being applied to a homogeneous DCT with optimal node degree. The results obtained from our work can be summarized in the following five points:

- The generalization of our node degree vs. the number of levels relationship for a DCT is derived by comparing the results of node-degree analytical relationship based on ideal network assumptions with the number of levels obtained by practical one on randomly deployed nodes.
- The relationship between network lifetime, node degree, and a number of levels in DCT of randomly deployed homogeneous WSN is studied to validate our optimal node degree derivation.
- A comparison between CDA and its peers in terms of percentage of node loss and percentage of energy overhead is shown to prove its energy efficiency.
- The gradient of energy decay E_{grad} and the breakdown energy E_b where the premature end of network lifetime occurs are introduced. We compare DCT with optimal node-degree with SPT and DCT with non-optimal node-degree in terms of the average energy of the network E_{avg}. Similarly, CDA is compared with the recent energy efficient routing protocols in terms of E_{avg} to show E_{grad}.
- The effect of the distance between ROI and BS on network lifetime and breakdown energy of DCT with optimal node degree is compared with SPT and DCT with non-optimal node degree. Similarly, the network lifetime of CDA is compared with that of its competitors.

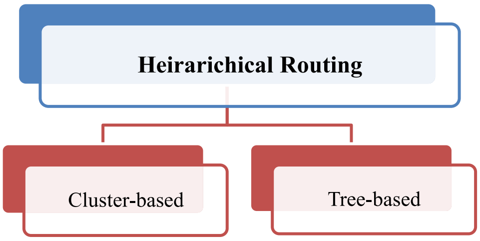

Fig. 1. Types of hierarchical routing protocols.

This paper is organized as follows; Section 2 shows the recent related works that aim to extend WSNs lifetime. Section 3 describes the network and radio transmission models used in our work. Section 4 shows our analytical derivation of the relationship between node degree and the number of levels as well as network lifetime. Section 6 illustrates the proposed routing protocol CDA with a detailed analysis of its energy efficiency. Finally, Section 6 presents the experimental results to support our analytical results and compares CDA with the recent energy efficient routing protocols. Finally, Section 7 describes our conclusions and future work in details.

2. Related work

Since WSN applications are normally in urban areas [10], the accessibility of the sensor nodes for network maintenance is difficult and costly. In this section, we summarize the previous efforts performed to study lifetime maximization of WSNs.

Asharioun et al. [11] introduced a detailed survey that focuses on energy-balancing methods and analytical research in Corona-based WSN. They discussed the relationship between the factors affecting network efficiency that include network lifetime, sensors coverage, the number of alive nodes, network connectivity, application quality of service requirement, and the energy hole problems. They also covered the basic mathematical modeling of network connectivity and coverage, energy consideration and optimum corona width. Similarly, Lui [12] performed an informative review covering typical hierarchical WSN routing protocols using a comprehensive comparison based on their general performances and application scenarios. He showed their effect on prolonging network lifetime. Additionally, he offered a classification of those protocols based on logical node topology to be divided into four types that are Chain-Based Routing, Tree-Based Routing, Grid Based Routing, and Area-Based Routing.

Several research efforts were performed to maximize network lifetime using different approaches; however, the most common energy efficient WSN protocols that are used in data gathering applications are hierarchal. Hierarchical routing is either cluster-based routing protocols or tree-based ones, as shown in Fig. 1. For cluster-based routing, the proactive routing protocols, where data are periodically reported to the BS, are the most suitable for monitoring applications. Accordingly, many cluster-based energy-efficient routing protocols outspread from LEACH [13] to provide higher network stability and lifetime. These protocols include

HEED [14], T-LEACH [13], IBLEACH [15], NEECP [16], and WCDA [17].

Using intelligent algorithms such as fuzzy logic, genetic algorithm (GA), and neural networks have also gained attention from researchers to extend the lifetime of dynamic WSN. Yuan et al. proposed a cluster-based protocol [18] that enhances the dynamic nature of WSNs using Genetic Algorithm (GA). Similarly, Elhoseny et al. [19] used different factors including the coverage range of each sensor to propose a K-coverage model based on Genetic Algorithm (GA) to extend the lifetime of a WSN. However, these methods suffer from energy drainage in multi-hop networks and usually are better within a single-hop clustering model framework. As a result, a new CH selection method based on GA for both single-hop and the multi-hop cluster models was introduced in [20], although it assumed that single-hop transmission is possible. Additionally, a GA based model was proposed for network coverage optimization for continuous monitoring applications in [21].

Data gathering applications of WSN is considered as one of the most energy draining types of WSN applications. Accordingly, Fujii et al. [22] proposed a clustering algorithm that is specifically designed for simultaneous data aggregation applications. This protocol addresses the very high power consumed by the relay station leading to the premature end of network lifetime. Additionally, various research directions used and analyzed aggregation techniques aiming at network lifetime maximization for data gathering WSN applications. For example, Dhand and Tyagi [23] showed the importance of data aggregation in data gathering applications of WSNs through a comparative survey that includes various Hierarchical energy efficient clustering approaches. The authors highlighted the effect of data fusion on lifetime maximization of data gathering WSNs.

However, the dynamic routing protocols suit dynamic environments, like target tracking, and monitoring applications, as studied in [24]. They suffer from communication overhead, as studied in [3]. Thus, single phase routing protocols are preferred to minimize this source of energy drainage, especially in static environments. Wan, Zhang, and Chen designed a tree-based routing protocol for large-scale WSNs [25]. Another tree-based routing and data aggregation protocol that reduces the network traffic, the SEcure sharing of TAsks (SETA) [26], was designed to fulfill confidentiality and integrity issues while minimizing communication overhead. Similarly, OHCR and OHA [3] maximize network lifetime while minimizing communication overhead significantly. Nguyen et al. [27] proposed Maximum Lifetime Data Aggregation Tree Scheduling (MLDATS) problem for scheduling virtual data aggregation trees to maximize the network lifetime. Brown [28] extends their work [27] to consider the reliability and energy efficiency of lossless data delivery with the semi-scalable aggregation function APPEND. He proved that in applications where all data must be delivered with a high level of reliability, significant improvements in energy efficiency occurs if all the data from a particular branch of the tree can fit in a single packet. Moreover, Lin and Chen [29] studied the minimum spanning directed data aggregation tree in sensor networks to extend its lifetime that ends on losing the first node, which matches our aim of extending the network stability period. However, we focus on fairly distributing data transmission load rather than data aggregation load distribution approach through partial node rearrangement that is proposed in [29].

On the other hand, two group of researchers in [30,31] studied the feasibility of a distributed beamforming approach. Master-slave approach was proposed. In Master-slave approach, packets are shared among a cluster of transmitters to be sent and combined constructively in the transmission medium, thus received coherently. The authors in [30] developed a mathematical model to compute the system performance for the cases of the stationary and the non-stationary receive antenna. The authors in [31], present stochastic analysis that demonstrates the robustness of beamforming gains with imperfect synchronization, and demonstrate a tradeoff between synchronization overhead and beamforming gains to solve the expensive communication with a distant Base Station receiver using a cluster of distributed transmitters emulating a centralized antenna array to transmit a common message signal coherently. Their simulation results proved that even in the presence of phase error that reaches 60^o and the suboptimal analog PLL, it is possible to achieve SNR gains of 70% of the maximum. Although their work focuses on timing synchronization algorithms, their findings are the base of our proposed energy conservative routing protocol.

3. Radio transmission and network model

For the purpose of our study, we use the energy model and analysis used in [32] where the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics. For the experiments described here, both the free space (d^2 power loss) and the multipath fading (d^4 power loss) channel models were used, depending on the distance between the transmitter and receiver. Power control can be used to invert this loss by appropriately setting the power amplifier—if the distance is less than a threshold d_o, the free space (*fs*) model is used; otherwise, the multipath (*mp*) model is used. Thus, to transmit an *l*-bit message across a distance *d*, the radio consumes

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) \tag{1}$$

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 \; d < d_o \\ lE_{elec} + l\varepsilon_{mp}d^4 \; else \end{cases} \tag{2}$$

For finding the estimated value of d_o, make $d = d_o$

$$d_o = \sqrt{\frac{\varepsilon_{fs}}{\epsilon_{mp}}} \tag{3}$$

To receive this packet, the radio consumes energy that is calculated from Eq. (4)

$$d_o = \sqrt{\frac{\varepsilon_{fs}}{\epsilon_{mp}}} = E_{Rx-elec}(l) = l\ E_{elec} \tag{4}$$

Our study is based on randomly distributed nodes $N = 100$ in 100×100 area between $(x = 0,\ y = 0)$ and $(x = 100,\ y = 100)$ and the BS is at location $(x = 50,\ y = 200)$ using the data gathering process in [33] that each node receives and transmits one packet in each round. The initial energy of each node is 0.5 J. The electronics energy,E_{elec} depends on factors such as the digital coding, modulation, filtering, and spreading of the signal, whereas the amplifier energy, $\varepsilon_{fs}d^2$ or $\varepsilon_{mp}d^4$, depends on the distance to the receiver and the acceptable bit-error rate. The notations that are used throughout the analysis are defined in Table 1.

4. Analysis of the Degree Constrained Tree

The energy consumed in tree setup phase at the beginning of network operation time is mainly of the operational type, first in location discovery algorithm, then in parent selection; however, the operational energy consumption is not addressed here. For simplicity, we assume that each node consumes energy in nearest node joining for topology setup, ignoring the type of algorithm used in the tree formation step. In this section, the DCT tree is covered in a detailed analysis of energy consumption in data gathering phase, since the number of children/parent is predefined as shown in Fig. 2.

Table 1
Mathematical notations.

Symbol	Definition
N	The number of currently alive sensors
l_s	Data packet size in bits
l_c	Control packet size in bits
E_{elec}	Transmitter/Receiver Electronics
E_{DA}	Energy consumed in data aggregation
ε_{mp}	Multi-path propagation loss
ε_{fs}	Free space propagation loss
d_o	The threshold distance of wireless propagation energy model
E_o	Initial energy of sensor node
r_s	Stability period, the number of rounds taken till the first node is dead
r_N	Network lifetime, the number of rounds taken till the ROI is disconnected from BS
$E\mathcal{G}$	The energy consumed in data gathering phase
Δ	The node degree
c	The number of children per parent $c = \Delta - 1$
$\mathcal{J}$	The level number in the tree
$\mathcal{P}^{\mathcal{J}}$	Pendant nodes at level $\mathcal{J}$
$\mathcal{P}$	Parent nodes with $\Delta \geq 2$
$d_{to\ \mathcal{P}}$	Distance from child to its parent
$E\mathcal{G}_{\mathcal{P}}(r, j)$	Energy consumed in data gathering phase by parent node in level j through round r in the DCT
$E\mathcal{G}_{\mathcal{P}}(r, j)$	Energy consumed in data gathering phase by pendant node in level j through round r in the DCT
DAE	Distributed Antenna Elements; the set of sensor nodes that collaborate with VBS for ROI to BS data transmission
TM	Topology Maintenance algorithm
$VBS.id$	The node ID of the currently selected VBS
$VBS.E$	The residual energy of the current VBS
E_{BS}	The threshold energy of VBS
$s(i).id$	The ID of sensor node i
$[M]$	The set of IDs of prospected nodes to be VBS
$s(i).p$	The priority of node i to become a new VBS
$[P]$	The set of probabilities of each of the prospected nodes to become the new VBS
P_{avg}	Average transmitted power
P_{Tx}	Power consumed in data transmission
η	The number of distributed antenna elements
a	Relative attenuation constant
$s(i).d$	The displacement between sensor node i from the BS
$s(i).E$	Residual Energy of sensor node i
η_{unif}	The ratio of nodes within the circle of radius d_o, assuming uniform node distribution in the ROI
n_{VBS}	The number of nodes that were selected as VBS throughout
E_{CDA}	The total energy cost of CDA protocol
E_i	The maximum average energy consumed in data transmission by node i in one round
d_{nn}	The distance between every two nodes in the ROI
$\triangle E$	The maximum load difference in terms of the energy difference between nodes in ROI within one round
$\%\mathcal{O}$E	Percentage of energy overhead
$\%r_{is}$	The percentage of time that the network spends out of the stability period with respect to the whole network lifetime
E_{grad}	The average amount of energy consumed by the whole network in every round

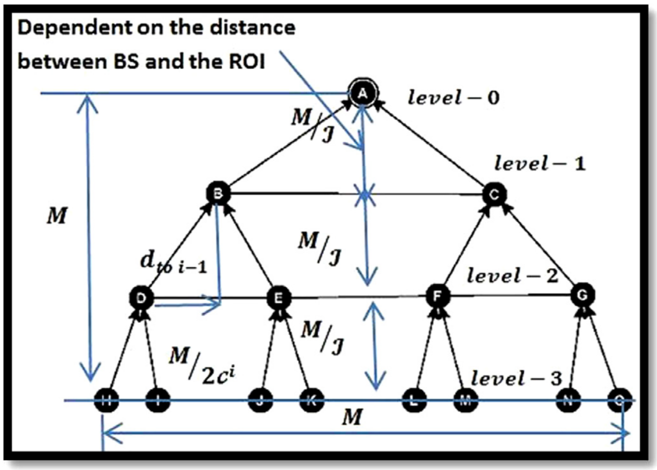

Fig. 2. Uniform displacement tree.

4.1. Data gathering phase E_G

For measuring the energy consumed during the data gathering process, we divide the nodes into two categories, which are as follows:

- Parent nodes $\mathcal{P}$ with $\Delta \geq 2$ having children$c = \Delta - 1$. Thus, they need to perform data aggregation and may be in any level $j \geq 1$ in the network.
- Pendant nodes $\mathcal{P}^{\mathcal{J}}$ that are children of the BS or the last level children, so the data aggregation is not needed, they can be in any level in the tree, but normally in the last level.

We build this total energy consumption derivation on a symmetrical tree, such that each parent $\mathcal{P}$ has c children and each two consecutive levels of the tree are separated by constant displacement, as shown in Fig. 2. Thus, each parent $\mathcal{P}$ in level $\mathcal{J}$ consumes energy in receiving data packets from its c children and aggregates these packets to transmit them to its parent at level $\mathcal{J} - 1$. On the other hand, each pendent node $\mathcal{P}$ consumes energy in transmitting data packets to its $\mathcal{P}$, which can be the BS if $\mathcal{P}$ is at $\mathcal{J} = 1$. The amount of energy consumed by each node in the DCT in the data gathering process during each round is dependent on its role in the tree and its level number. This amount of energy can be calculated from the given two Eqs. (5) and (6)

$$E\mathcal{G}_{\mathcal{P}}(r,j)=\begin{cases} l_s\left[\Delta E_{elec}+cE_{DA}+\varepsilon_{mp}\ d^4_{to\ \mathcal{P}}\right] & d_{to\ \mathcal{P}}>d_o\&\ j>1\\ l_s\left[\Delta E_{elec}+cE_{DA}+\varepsilon_{fs}\ d^2_{to\ \mathcal{P}}\right] & d_{to\ \mathcal{P}}<d_o\&\ j>1\\ l_s\left[\Delta E_{elec}+cE_{DA}+\varepsilon_{mp}\ d^4_{to\ BS}\right] & d_{toBS}>do\&j=1\\ l_s\left[\Delta E_{elec}+c\ E_{DA}+\varepsilon_{fs}\ d^2_{to\ BS}\right] & d_{to\,BS}<d_o\&j=1 \end{cases} \tag{5}$$

$$E\mathcal{G}_{\mathcal{P}}(r,j)=\begin{cases} l_s\left[(E_{elec}+\varepsilon_{mp}\ d^4_{to\ \mathcal{P}}\ \right] & d_{to\ \mathcal{P}}\geq d_o\\ l_s\left[E_{elec}+\varepsilon_{fs}\ d^2_{to\ \mathcal{P}}\right] & else \end{cases} \tag{6}$$

Assuming a complete tree, the total energy consumed per level in data gathering process can be calculated from Eq. (7)

$$E\mathcal{G}(r,j)=\begin{cases} c^jE\mathcal{G}_{\mathcal{P}}(r,j)\\ c^{\mathcal{J}}\ E\mathcal{G}_{\mathcal{P}}(r,j) \end{cases} \quad 1\leq j\leq \mathcal{J}-1\ and\ j=\mathcal{J} \tag{7}$$

For $\mathcal{J}$ levels, the total energy consumed in data gathering process can be calculated from Eq. (8)

$$E\mathcal{G}(r,j)=c^{\mathcal{J}}\ E\mathcal{G}_{\mathcal{P}\mathcal{J}}(r,j)+\sum_{i=1}^{\mathcal{J}-1}c^iE\mathcal{G}_{\mathcal{P}\ i}(r,j) \quad c\in\{1,2,\ldots,N-1\} \tag{8}$$

In our proposed DCT model, the total number of nodes N is divided into $\mathcal{J}$ levels where the BS is the root at level 0 and the rest of the nodes are uniformly distributed. Since the DCT form a symmetrical complete tree of nodes in the ROI, the relation between the number of children c and the node degree Δ is $c=\Delta-1$. On the other side, the relation between c and $\mathcal{J}$ in the DCT can be simplified as a geometrical series forming the total number of nodes N and their BS as given in Eqs. (9) and (10)

$$N=(c+1)\sum_{j=0}^{\mathcal{J}}c^j=\frac{(c+1)\left(c^{\mathcal{J}+1}-1\right)}{(c-1)}=\frac{\Delta\left((\Delta-1)^{\mathcal{J}+1}-1\right)}{\Delta-2} \tag{9}$$

$$\mathcal{J}=\frac{\log(N((\Delta-\ 2)/\Delta+\ 1)}{\log\left(\Delta-\ 1\right)-1} \tag{10}$$

Assuming a uniform distribution of nodes over the RoI, and a complete tree where all the pendant nodes are in the last level only, the relationship between the distances from each child to its parent $d(j)_{to\mathcal{P}}$ and the ratio between the ROI dimension and the number of levels is given in Eqs. (11) and (12)

$$d(j)^2_{to\ \mathcal{P}}\leq\left(\frac{M}{\mathcal{I}}\right)^2+\left(\frac{Mc^{\mathcal{I}-j}}{c^{\mathcal{I}}-1}\right)^2 \quad \text{For } j=\{1,2,3,\ldots,\mathcal{J}\}\ \&\ c\geq 2 \tag{11}$$

$$d(j)^2_{to\ \mathcal{P}}|_{min}=\left(\frac{M}{\mathcal{I}}\right)^2 \tag{12}$$

Knowing that BS is outside the RoI, which is $M\times M$, the nodes are distributed in a prism shape with bottom base $b=M$, vertical height $h=M$, and upper base $b1$ can be calculated from Eq. (13). Thus, the area of deployment $Area$ can be calculated from Eq. (14). Accordingly, the total energy consumed in data transmission from all the children in the ROI to their parents can be calculated from Eq. (15). Due to the omnidirectional transmissions used, the radiation density is spread in a sphere. Accordingly, the total energy consumed in data transmission from N nodes in the ROI to their parents can be calculated from Eqs. (16)–(18)

$$b1=(c-1)\frac{Mc^{\mathcal{I}-j}}{c^{\mathcal{I}}-1} \tag{13}$$

$$Area=\frac{M^2}{2}\left((c-1)\frac{c^{\mathcal{I}-1}}{c^{\mathcal{I}}-1}+1\right) \tag{14}$$

$$E\left[d(j)^2_{to\ \mathcal{P}}\right]=\oiint\left(x^2+y^2\right)\rho(x,y)dx\ dy \tag{15}$$

$$E\left[d(j)^2_{to\ \mathcal{P}}\right]=\frac{2N}{M^2\left((c-1)\frac{c^{\mathcal{I}-1}}{c^{\mathcal{I}}-1}+1\right)}\int_0^{2\pi}\int_{\left(\frac{M}{\mathcal{I}}\right)}^{\sqrt{\left(\frac{M}{\mathcal{I}}\right)^2+\left(\frac{Mc^{\mathcal{I}-j}}{c^{\mathcal{I}}-1}\right)^2}} r^2\ rdr\ d\theta \tag{16}$$

$$E\left[d(j)^2_{to\ \mathcal{P}}\right]=\frac{2N}{M^2\left((c-1)\frac{c^{\mathcal{I}-1}}{c^{\mathcal{I}}-1}+1\right)}\int_0^{2\pi}\int_{\left(\frac{M}{\mathcal{I}}\right)}^{\sqrt{\left(\frac{M}{\mathcal{I}}\right)^2+\left(\frac{Mc^{\mathcal{I}-j}}{c^{\mathcal{I}}-1}\right)^2}} r^3\ dr\ d\theta \tag{17}$$

$$\begin{aligned} &E\left[d(j)^2_{to\ \mathcal{P}}\right]\\ &=\frac{N\ \pi}{M^2\left((c-1)\frac{c^{\mathcal{I}-1}}{c^{\mathcal{I}}-1}+1\right)}\left(\sqrt{\left(\frac{M}{\mathcal{I}}\right)^2+\left(\frac{Mc^{\mathcal{I}-i}}{c^{\mathcal{I}}-1}\right)^2}-\left(\frac{M}{\mathcal{I}}\right)\right)^4 \end{aligned} \tag{18}$$

If $M=100$, then $M/2<do$, and $d_{to\,BS}>d_o$, then the energy consumed by each parent node $\mathcal{P}$in communication is given in Eq. (19)

$$\begin{aligned} &E\mathcal{G}_{\mathcal{P}}(r,j)\\ &=\begin{cases} l\left[(c+1)E_{elec}+\ cE_{DA}+\ +\ \varepsilon_{mp}\ d^4_{to\ BS}\right] & d_{BS}\geq do\ \&\ j=1\\ l\left[(c+1\ )E_{elec}+\ cE_{DA}+\ \varepsilon_f\ E\left[d(j)^2_{to\ \mathcal{P}}\right]\right] d_{to\mathcal{P}}<d_o\ \&\ j=\{2,\ldots,\mathcal{J}\} \end{cases} \end{aligned} \tag{19}$$

The energy consumed by each pendant node $\mathcal{P}$ in communication with node j in a round r can be calculated from Eq. (20)

$$E\mathcal{G}_{\mathcal{P}\mathcal{J}}(r,j)=l\left[(E_{elec}+\varepsilon_{fs}\ E\left[d(j)^2_{to\ \mathcal{P}}\right]\ \right] \qquad d_{to\ \mathcal{P}}<d_o \tag{20}$$

By assuming a uniform distribution of children over$\mathcal{P}$, such that each $\mathcal{P}$ has $c=\Delta-1$ children and no $\mathcal{P}$ nodes directly connected to the BS. The total energy consumed in the network in one round r can be calculated from Eq. (22)

For one round

$$E\mathcal{G}=c^{\mathcal{I}}\ E\mathcal{G}_{\mathcal{P}\mathcal{J}-1}+cE\mathcal{G}_{\mathcal{P}\ j=1}+\sum_{j=2}^{\mathcal{I}-1}\ c^jE\mathcal{G}_{\mathcal{P}\ \mathcal{J}>1} \tag{21}$$

$$\begin{aligned} E\mathcal{G}=\ l\ \Big[&c^{\mathcal{I}}\ \left[E_{elec}+\ \varepsilon_{fs}\ E\left[d(i)^2_{to\ \mathcal{P}}\right]\ \right]\\ &+c\left[(c+1)E_{elec}+c\ E_{DA}\ +\ \varepsilon_{mp}\ d^4_{to\ BS}\ \right]\\ &+\sum_{j=2}^{\mathcal{I}-1}c^j\left[(c+1)\ E_{elec}+c\ E_{DA}\ +\ \varepsilon_{fs}\ E\left[d(j)^2_{to\ \mathcal{P}}\right]\right]\Big] \end{aligned} \tag{22}$$

To find the optimum number of levels $\mathcal{J}_{opt}$ and the optimum number of children c_{opt} that minimize the total energy consumed in the tree, we need to differentiate Eq. (22) with respect to any of its dependent variables. Then, we compensate in it to find the other variable knowing the total number of nodes N. Thus, the objective of this optimization process is given in Eq. (23)

$$\min_c\left\{E\mathcal{G}\left(c,\mathcal{I},E_{elec},\ E_{DA,}\varepsilon_{mp},\varepsilon_{fs},M,N\right)\right\} \tag{23}$$

This type of optimization problems is solved using nonlinear programming, Integer-Constrained methods [34], the objective equation has been solved to give the optimal $c = 2$; thus, $\Delta = 3$. However, for simplicity, we refer to the number of children as the node degree (Δ).

4.2. Stability period and estimation of network lifetime

Since each node is connected to its parent once at the beginning of network lifetime, the total energy consumed in data transmission by relay, parent and pendant nodes throughout the network lifetime r_N based on the radio transmission model in Section 3 are given in Eqs. (24)–(26), respectively. Whereas, the relay node receives data packets from its $\Delta = 1$ children that were connected to it through control packet aggregates them with its data packet to transmit the aggregated data to the BS. Similarly, parent node receives data from its connected children, but transmits the aggregated data to its parent. However, pendant doesn't receive data, but only transmit control information to its parent to connect to it and then transmits the data packet.

$$E_{n\mathcal{P}\ {}_{j=1}} = \begin{cases} (\Delta-1)l_c E_{elec} + l_s\ \left(\Delta E_{elec} + \varepsilon_{mp} d_{toBS}^4 + \Delta E_{DA}\right) & d_{toBS} \geq d_o \\ (\Delta-1)l_c E_{elec} + l_s\ \left(\Delta E_{elec} + \varepsilon_{fs} d_{toBS}^2 + \Delta E_{DA}\right) & else \end{cases} \tag{24}$$

$$E_{n\mathcal{P}} = \begin{cases} l_c\left(\Delta E_{elec} + \varepsilon_{mp} d_{nn}^4\right) + l_s\ \left(\Delta E_{elec} + \varepsilon_{mp} d_{nn}^4 + \Delta E_{DA}\right) & d_{nn} \geq d_o \\ l_c\left(E_{elec} + \varepsilon_{fs} d_{nn}^2\ \right) + l_s\ \left(\Delta E_{elec} + \varepsilon_{fs} d_{nn}^2 + \Delta E_{DA}\right) & else \end{cases} \tag{25}$$

$$E_{n\mathcal{P}} = \begin{cases} l_c\left(E_{elec} + \varepsilon_{mp} d_{nn}^4\right) + l_s\ \left(E_{elec} + \varepsilon_{mp} d_{nn}^4\right) & d_{nn} \geq d_o \\ l_c\left(E_{elec} + \varepsilon_{fs} d_{nn}^2\ \right) + l_s\ \left(E_{elec} + \varepsilon_{fs} d_{nn}^2\right) & else \end{cases} \tag{26}$$

In static trees, each node remains as it is throughout the network lifetime. Thus, there is no change in node role. Accordingly, the node lifetime in terms of its initial energy E_o can be estimated for relay, parent and pendant nodes from Eqs. (27)–(29) respectively, according to the node role

$$E_o = \begin{cases} r_{\mathcal{N}}\left[(\Delta-1)l_c E_{elec} + l_s\ \left(\Delta E_{elec} + \varepsilon_{mp} d_{toBS}^4 + \Delta E_{DA}\right)\right] & d_{toBS} \geq d_o \\ r_{\mathcal{N}}\left[(\Delta-1)l_c E_{elec} + l_s\ \left(\Delta E_{elec} + \varepsilon_{fs} d_{toBS}^2 + \Delta E_{DA}\right)\right] & else \end{cases} \tag{27}$$

$$E_o = \begin{cases} r_{\mathcal{N}}\left[l_c\left(\Delta E_{elec} + \varepsilon_{mp} d_{nn}^4\right) + l_s\ \left(\Delta E_{elec} + \varepsilon_{mp} d_{nn}^4 + \Delta E_{DA}\right)\right] & d_{nn} \geq d_o \\ r_{\mathcal{N}}\left[l_c\left(E_{elec} + \varepsilon_{fs} d_{nn}^2\ \right) + l_s\ \left(\Delta E_{elec} + \varepsilon_{fs} d_{nn}^2 + \Delta E_{DA}\right)\right] & else \end{cases} \tag{28}$$

$$E_o = \begin{cases} r_{\mathcal{N}}\left[l_c\left(E_{elec} + \varepsilon_{mp} d_{nn}^4\right) + l_s\ \left(E_{elec} + \varepsilon_{mp} d_{nn}^4\right)\right] & d_{nn} \geq d_o \\ r_{\mathcal{N}}\left[l_c\left(E_{elec} + \varepsilon_{fs} d_{nn}^2\ \right) + l_s\ \left(E_{elec} + \varepsilon_{fs} d_{nn}^2\right)\right] & else \end{cases} \tag{29}$$

Thus, the stability period is when the first node depletes all its initial energy in data transmission $r_{\mathcal{N}}|_{min} = r_{\&}$.

5. Collaborative Distributed Antenna protocol

The Collaborative Distributed Antenna CDA routing protocol is an energy efficient routing protocol that aims at achieving energy fairness among all the sensor nodes in the ROI. At the beginning of network operation, a random node is selected to act as a Virtual Base Station VBS within the RIO by being the root of the tree. The data is then aggregated from all nodes in the tree to reach the selected root VBS for a number of rounds until its energy level reaches a threshold energy level, called E_{BS}. Then VBS selects another root and the tree is re-built rooted at the new VBS. The VBS responsibilities includes both collecting data as a root of the tree and also distributing the aggregated data packet on a selected group of nodes called Distributed Antenna Elements DAEs with control information for synchronization. Thus, it cooperates with the DAEs to form the distributed antenna system in ROI to BS transmission.

For this collaborative data transmission operation, VBS selects η DAEs within a distance $d_{o,}$ in order to minimize the network overhead, and multicast the aggregated packet that will be sent to the BS (PTB) to the selected DAEs. The DAEs form a distributed antenna system and send the PTB to the BS in a cooperative way, as shown in Fig. 3. The responsibilities of the VBS can be summarized in the following five points:

1. In the first round only, the node with ID = 1 broadcasts itself to the whole ROI as a VBS to be the root of the tree in the upcoming rounds, as shown in Fig. 3(a).
2. It selects $\eta - 1$ Distributed Antenna Elements within d_o; the selected nodes form the distributed antenna system and are called Distributed Antenna Elements DAEs, as shown in Fig. 3(b).
3. It multicasts PTB to the $\eta - 1$ DAEs containing the synchronization control information, as shown in Fig. 3(b).
4. It cooperates with the $\eta - 1$ DAEs in data transmission to the BS, as shown in Fig. 3(c).
5. When $VBS.E \leq E_{BS}$, it selects the new VBS and broadcasts the new VBS information to the whole network, as shown in Fig. 3(d).

5.1. The proposed protocol design

The Collaborative Distributed Antenna CDA routing protocol is based on DCT. Using DCT with optimal node degree energy-efficient data aggregation is ensured and the aggregated packet that is sent to the BS PTB is sent to DAEs with minimal energy overhead. The protocol accepts an input for topology maintenance (TM), which can be OHCR or OHA [3]; however, OHCR has been proven to be more energy efficient.

Since the VBS selects $\eta - 1$ sensor nodes for the distributed antenna system and selects the new VBS when its energy level reaches E_{BS}, it acts as a centralized processing unit that has to collect the information about all the sensor nodes in the ROI included in the data packets. This control information includes the node ID, its location and, its current residual energy. Accordingly, the current VBS performs the suitable calculations to select the most suitable $\eta - 1$ nodes for DAE roles. Moreover, when the energy of the VBS reaches its threshold value E_{BS}, it selects the new VBS for the next round and broadcasts its selection to the whole ROI. To ensure energy distribution throughout the VBS lifetime, when a DAE is lost, it no longer transmits packets to the VBS. Consequently, the VBS replaces it with another DAE. The size of data packets that are routed through the tree and the size of multi-casted PTB are greater than the size of a data packet sent to BS due to the added node information and the additional synchronization control information, respectively. For simplicity, this increase in packet size can be neglected compared to the large size of data packets used in our simulation environment. The VBS Algorithm is illustrated in Algorithm 1.

5.2. Analysis of the proposed protocol

The average radiated power P_{av} in a distributed antenna system is related to the power transmitted P_{Tx} and the number of antenna elements and the attenuation a, according to Paper and Mediatek [30]. However, the power is the energy per unit time and the en-

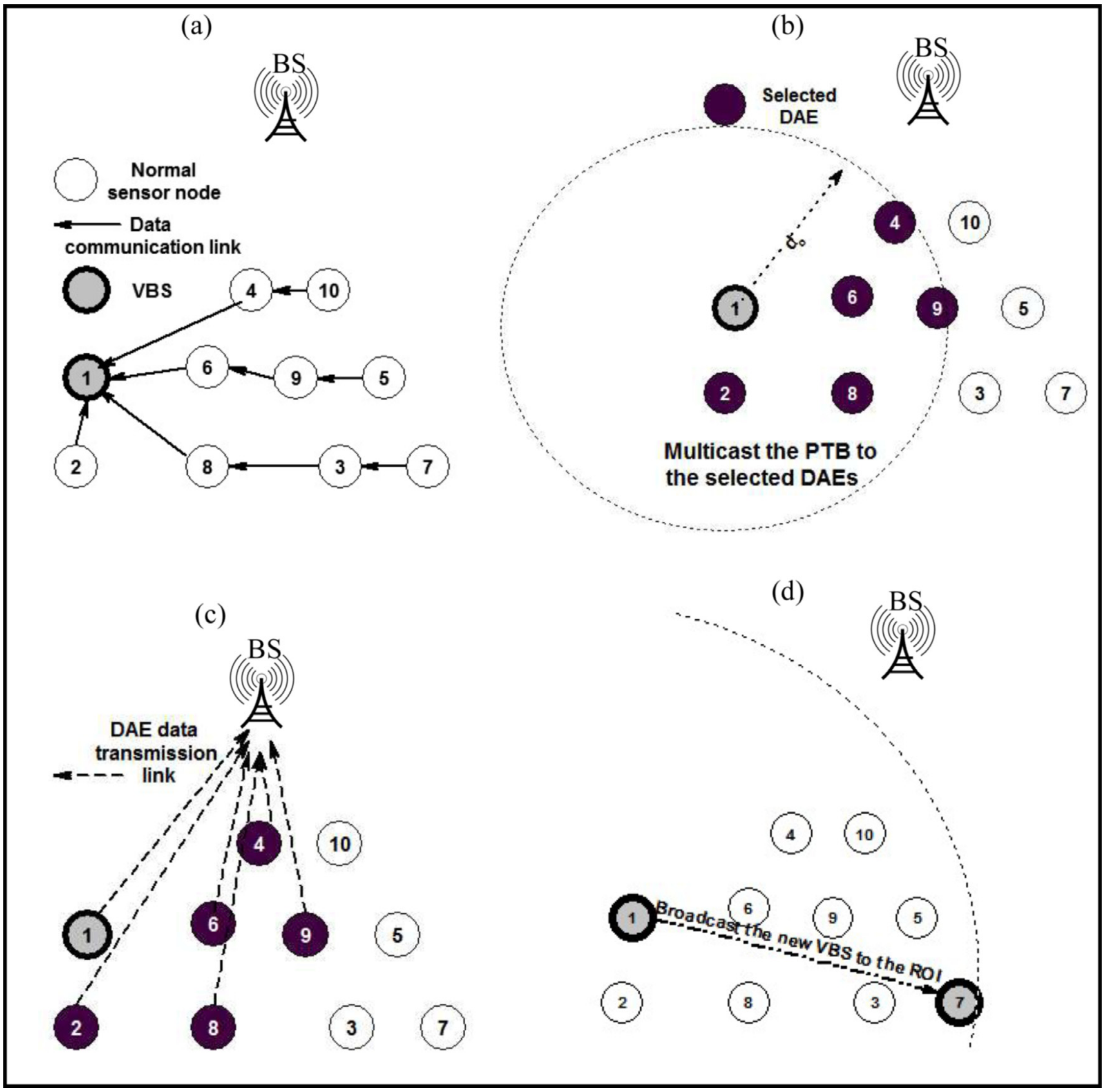

Fig. 3. CDA Protocol operation.

ergy consumed by each node for transmitting l bit packet to distance d is $E_{Tx}(l,\ d)$. Thus, assuming the attenuation $a = 1$ and applying our CDA the transmission energy of each node in the DAE is reduced by a factor of $1/\eta$. However, if signals combine coherently the transmission energy of each node in the system is reduced by a factor of $1/\eta^2$ as shown in Eqs. (30) and (31).

$$P_{avg} = \begin{cases} a\eta\ P_{Tx} \\ a\eta^2\ P_{Tx} \end{cases} \quad \text{non-coherent coherent} \qquad (30)$$

$$E_{Tx}|_{VBS}(l,d) = \begin{cases} \dfrac{E_{Tx}(l,d)}{\eta} \\ \dfrac{E_{Tx}(l,d)}{\eta^2} \end{cases} \quad \text{non-coherent coherent} \qquad (31)$$

The selected VBS has a threshold residual energy level E_{BS} to avoid energy depletion in the middle of the PTB distribution process when the current VBS reaches E_{BS}, given in Eq. (32), it selects a new VBS

$$E_{BS} = \begin{cases} l_c\left[E_{elec} + \varepsilon_{mp}\ d^4_{to\ BS}\right] & d_{toBS} > d_o \\ l_c\left[E_{elec}\ + \varepsilon_{fs}\ d^2_{to\ BS}\right] & else \end{cases} \qquad (32)$$

Similarly, the residual energy of each DAE preferably exceeds the maximum value of energy consumed in one ROI-to-BS transmission E_{BS} to contribute in transmission process and avoid the occurrence of routing holes. Thus, whenever VBS receives the data from the network, it receives the nodes residual energy and location in the packet as well. Thus, it selects η DAEs within d_o and having highest residual energy. Thus, it identifies the DAE ids in the PTB is broadcast. On the other hand, as the energy of the VBS depletes gradually, it reaches the threshold level E_{BS}. When the VBS residual energy reaches E_{BS}, it determines the suitable new VBS based on the node locations and residual energy information it received from the nodes during data aggregation process. The priority of a node to become a new VBS, $s(i).p$, is calculated based on its residual energy and displacement from the current VBS, as shown in Eq. (33). To ensure load distribution and avoid the energy-hole problem, this priority is directly proportional to the ratio of residual energy $s(i).E\ /E_o$ and the ratio of displacement to the distributed antenna system radius $s(i).d/d_o$. According to this priority, the VBS selects the most suitable new VBS, which is the node with the highest priority.

$$s(i).p = \frac{s(i).d}{d_o} \times \frac{s(i).E}{E_o} \qquad (33)$$

The node probability to be a VBS will lead to selecting the node with the highest residual energy and the furthest node from the

Algorithm 1 Virtual Base Station.

VBS Algorithm

```
Inputs TM, S
Outputs distributed antenna network formation
1.  TM ← {OHCR, OHA}
2.  VBS.id = 1
3.  Broadcast $s(i).id$ = VBS.id as VBS
4.  Tree formation according to TF rooted at VBS
// As the energy of the selected VBS exceeds the threshold
5.  While $VBS.E > E_{BS}$
      // The role of each node in the network
6.    For each $i \in S$ do
        // In case of node loss, use the configured topology maintenance algorithm
7.      If $s(i).E == 0$
8.        Use the selected TM
9.        End if
10. End for
11. Data collection phase
12. Select DAE
13. Broadcast PTB to its DAE with the required synchronization information
14. DAEs and VBS transmit the aggregated data to the BS as a distributed antenna system
15. End while
// Select the new VBS
16. For each $j \neq i$ & $s(j).E > E_{VBS}$ & $j \in N$ do
17.   $[M] \leftarrow s(j).id$
18.   Calculate $s(j).p$
19.   $[P] \leftarrow s(j).p$
20. End for
21. Find $s(j).id$ with $\max(P) \rightarrow$ VBS.id
22. Got to step 4
```

old VBS. Thus, the new DAE will be less probably one of the previous DAE group. Thus, ROI to BS data transmission duty will not be attached to a single group of sensor nodes and the aggregation duty as well. Thus, energy fairness will be achieved properly, leading to network lifetime maximization. Assuming uniform node distribution in the ROI, the ratio of nodes within the circle of radius d_o denoted as η_{unif} and the area of the ROI equals the ratio of nodes within this circle and the total number of nodes in the ROI. Accordingly, the ratio of selected DAE element to the total number of nodes is the ratio of the PTB broadcast area to the total area of ROI is given in Eq. (34).

$$\frac{\eta_{unif}}{N} = \frac{\pi d_o^2}{M^2} \qquad d_o > \frac{M}{2} \tag{34}$$

However, the uniform distribution is not feasible in random deployment; it can be used as a reference for estimating the feasible values of η. If $d_o > \mathrm{M}/2$ and the VBS is in the middle of the ROI, all the nodes in the ROI will probably be selected for the distributed antenna system, which is not the case in random distribution scenario. On the other hand, CDA introduces the need for multicasting the aggregated data packet to the set of DAE, which adds significant increase in network overhead despite the distance limitation of the DAE selection process. Thus, the total energy cost of the CDA Algorithm within r_N due to the selection of the total number of VBS, n_{VBS}, assuming that $(\eta - 1)$ DAE are selected every round is formulated as given in Eq. (35)

$$E_{CDA} = \begin{cases} n_{VBS} l_c \left(E_{elec} + \varepsilon_{mp} M^4\right) + r_N l_s \left(\eta E_{elec} + \epsilon_{fs} d_o\right) & M > d_o \\ n_{VBS} l_c \left(E_{elec} + \varepsilon_{fs} M^2\right) + r_N l_s \left(\eta E_{elec} + \epsilon_{fs} d_o\right) & else \end{cases} \tag{35}$$

5.2.1. Load distribution

To ensure energy fairness of CDA we measured the difference in load distribution between the node with maximum load distribution and the one with minimum load. In this work, we used energy consumption in data transmission process as the load of the node. Thus, the difference in load distribution will be measured in terms of total energy consumption of the node in data transmission process. Eq. (36) describes the maximum average energy consumed in data transmission E_i in one round, where the node is the VBS with $(\eta - 1)$ DAE. Thus, it transmits PTB to the DAE nodes within distance $d_o$and cooperates with $(\eta - 1)$ DAE in PTB data packet transmission to the BS, where the size of PTB is l_s

$$E_i = \begin{cases} l_c\left(E_{elec} + \varepsilon_{mp} M^4\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{mp} d_{to\ BS}^4\right) & \\ \quad + l_s\left(E_{elec} + \varepsilon_{fs} d_o^2\right) + \eta E_{DA} & M, d_{toBS} > d_o \\ l_c\left(E_{elec} + \varepsilon_{fs} M^2\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{mp} d_{to\ BS}^4\right) & \\ \quad + l_s\left(E_{elec} + \varepsilon_{fs} d_o^2\right) + \eta E_{DA} & d_{toBS} > d_o > M \\ l_c\left(E_{elec} + \varepsilon_{fs} M^2\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{fs} d_{to\ BS}^2\right) & \\ \quad + l_s\left(E_{elec} + \varepsilon_{fs} d_o^2\right) + \eta E_{DA} & M, d_{toBS} < d_o \\ l_c\left(E_{elec} + \varepsilon_{fs} M^4\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{fs} d_{to\ BS}^2\right) & \\ \quad + l_s\left(E_{elec} + \varepsilon_{fs} d_o^2\right) + \eta E_{DA} & M > d_o > d_{toBS} \end{cases} \tag{36}$$

DAE node consumes in data transmission the amount of energy that is given in Eq. (37) every round

$$E_i = \begin{cases} \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{mp} d_{to\ BS}^4\right) & d_{toBS} > d_o \\ \dfrac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{fs} d_{to\ BS}^2\right) & else \end{cases} \tag{37}$$

Whereas, if the node is not a DAE, it consumes the amount of energy given in Eq. (38). The distance between every two nodes in the ROI, d_{nn}, which doesn't exceed d_o

$$E_i = l_s\left(E_{elec} + \epsilon_{fs} d_{nn}^2\right) \tag{38}$$

For simplification, assume $d_{nn} = d_o$. Thus, the maximum load difference in terms of the energy consumption between nodes in ROI in one round is calculated from Eq. (39) in case of coherent data transmission, and Eq. (40) in case of non-coherent data

Table 2
System parameters.

Type	Parameter	Symbol	Value
Homogeneous network	The number of nodes in the ROI	N	100
	The initial energy of sensor node	E_o	0.5 J
	Node distribution	–	Random
	BS location	–	(50, 200)
Application	Minimum distance from ROI to BS	$d_{to\,BS}$	100 m
	The diameter of the maximum dimension of the *ROI*	M	100 m
	Data packet size in bits	l_s	800 Bytes
	Control packet size in bits	l_c	50 Bytes
	Transmitter/Receiver Electronics	E_{elec}	50 nJ/bit
	Energy consumed in data aggregation	E_{DA}	$\frac{5\text{nJ}}{\text{bit}}$ /signal
Radio model	Multi-path propagation loss	ε_{mp}	$0.0013\,\frac{\text{pj}}{\text{bit}}/\text{m}^4$
	Free space propagation loss	ε_{fs}	$10\,\frac{\text{pj}}{\text{bit}}/\text{m}^2$
	The threshold distance of wireless propagation energy model	d_o	$\sqrt{\frac{\varepsilon_{fs}}{\epsilon_{mp}}}$
	Antenna model	–	Omni-directional

transmission

$$\Delta E = \begin{cases} l_c\left(E_{elec} + \varepsilon_{mp}M^4\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{mp}d_{to\ BS}^4\right) & \\ \quad + \eta E_{DA} & M,\ d_{toBS} > d_o \\ l_c\left(E_{elec} + \varepsilon_{fs}M^2\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{mp}d_{to\ BS}^4\right) & \\ \quad + \eta E_{DA} & d_{toBS} > d_o > M \\ l_c\left(E_{elec} + \varepsilon_{fs}M^2\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{fs}d_{to\ BS}^2\right) & \\ \quad + \eta E_{DA} & M,\ d_{toBS} < d_o \\ l_c\left(E_{elec} + \varepsilon_{fs}M^4\right) + \frac{l_s}{\eta^2}\left(E_{elec} + \epsilon_{fs}d_{to\ BS}^2\right) & \\ \quad + \eta E_{DA} & M > d_o > d_{toBS} \end{cases} \tag{39}$$

$$\Delta E = \begin{cases} l_c\left(E_{elec} + \varepsilon_{mp}M^4\right) + \frac{l_s}{\eta}\left(E_{elec} + \epsilon_{mp}d_{to\ BS}^4\right) & \\ \quad + \eta E_{DA} & M, d_{toBS} > d_o \\ l_c\left(E_{elec} + \varepsilon_{fs}M^2\right) + \frac{l_s}{\eta}\left(E_{elec} + \epsilon_{mp}d_{to\ BS}^4\right) & \\ \quad + \eta E_{DA} & d_{toBS} > d_o > M \\ l_c\left(E_{elec} + \varepsilon_{fs}M^2\right) + \frac{l_s}{\eta}\left(E_{elec} + \epsilon_{fs}d_{to\ BS}^2\right) & \\ \quad + \eta E_{DA} & M,\ d_{toBS} < d_o \\ l_c\left(E_{elec} + \varepsilon_{fs}M^4\right) + \frac{l_s}{\eta}\left(E_{elec} + \epsilon_{fs}d_{to\ BS}^2\right) & \\ \quad + \eta E_{DA} & M > d_o > d_{toBS} \end{cases} \tag{40}$$

If the control packet is very small with respect to the data packet, the effect of the size of ROI ($M \times M$) on the CDA energy cost can be neglected. Moreover, as the number of DAEs increase, the load fairness is more ensured in case of either coherence or non-coherence, since $E_{DA} \ll E_{Tx}(l, d)$. The main weakness of CDA is that energy efficiency is not completely accomplished due to the need of multicasting data packet PTB and control information. However, the energy fairness achieved provides a relatively high stability region and a very low rate of node loss. On the other hand, the CDA protocol algorithm complexity for each VBS node is $\Omega(N^2)$ due to DAE selection at the beginning of the CDA task and the priority calculation at the end of its task to select the new VBS.

6. Experimental results

Since random deployment is common in WSN, we perform our simulation experiments using MATLAB2017a on randomly deployed WSN. The experimental results in this section proved the availability of generalizing our analytical study in Section 4, our analytical optimal node degree, and the energy efficiency on CDA. The system parameters and performance metrics used throughout this work are shown in Section 6.1.

6.1. System parameters and performance metrics

The proposed scenario is based on the transmission model and system parameters illustrated in Section 3 and Table 2, respectively. Throughout this paper, the minimum distance between the ROI and the BS is used to represent the best case scenario where routing hole occurrence is least probable.

CDA protocol is applied on DCT and compared to OHA and OHCR algorithms that are based on DCT. We choose DCT with $\Delta = 3$ which is the optimal node degree for minimum energy consumption. Furthermore, CDA is compared to the recent energy efficient routing protocols NEECP [16] and UCCGRA [35], and the parent of energy efficient clustering protocols, LEACH [36,32]. The parameters of UCCGRA are chosen according to the simulation results in [35]. Since the authors in [35] didn't provide the optimal protocol parameters for minimizing energy consumption, we choose $R_{max} = d_o$ and *protocol constant* $(c) = 0.3$ which provide the highest stability period according to their system assumptions. For NEECP, we compared CDA to NEECPWA that provides the data aggregation capability to minimize energy consumption. For LEACH, the probability of CH selection used in our simulation environment is the optimal probability for energy efficiency p_{opt}, and k_{opt}, the optimal number of CHs that minimizes the average energy consumption of the network, as proven in [32], can be calculated based on system parameters from the Eqs. (41) and (42)

$$k_{opt} = \sqrt{\frac{N}{2\pi}}\,\frac{M}{d_{to\ BS}^2}\sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \tag{41}$$

$$p_{opt} = \frac{k_{opt}}{N} \tag{42}$$

To show the feasibility of the optimal node degree for energy efficient DCT, the number of levels $\mathcal{J}$ that corresponds to each node degree is obtained. The network lifetime within which the ROI is connected to BS and the breakdown energy E_b at which this connection is lost is measured for both DCT and SPT. These results are linked to node level-degree relationship. Additionally, the gradient of energy decay E_{grad}, which is the average rate of energy decay throughout network lifetime is calculated from Eq. (43) and obtained from measuring the average network residual energy E_{avg}

$$E_{grad} = \frac{E_o - E_b}{r_N} \tag{43}$$

On the other hand, the network efficiency represented in terms of the ratio of the instability period to the whole network lifetime r_{is}%. The instability ratio shows the amount of ROI perfect coverage

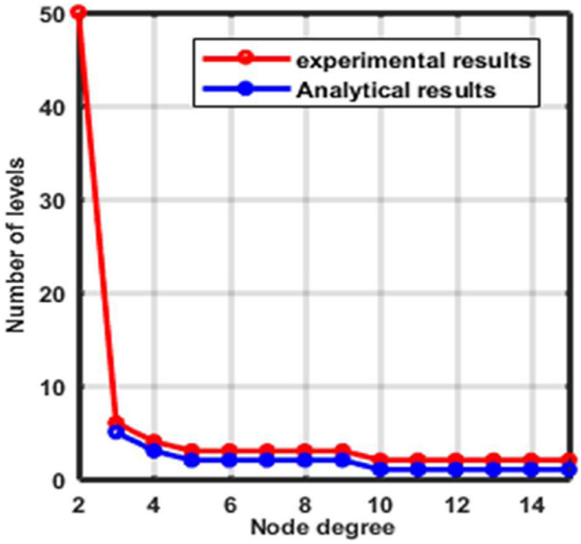

Fig. 4. The degree-level relationship.

to the non-perfect one for dynamic routing protocols like CDA and is calculated from Eq. (44)

$$r_{is}\% = \frac{r_N - r_s}{r_N} \tag{44}$$

The percentage of introduced energy overhead $\%\mathcal{O}E$ due to network change, defined in [3], can be calculated from Eq. (45)

$$OE(r) = \sum_{r=1}^{r_{\mathcal{N}}} \frac{E\mathcal{N}(r)}{E\mathcal{G}(r)} \tag{45}$$

6.2. Node degree vs. number of levels

Using the uniformly distributed node deployment and the symmetric tree shown in Fig. 4, the relation between the number of levels and the node degree in the DCT were derived in Eq. (10). However, the derivations were based on ideal conditions, which are a predetermined deployment with the complete tree, equidistance between the levels of the tree, and perfectly symmetric tree. The comparison between the analytical results obtained from Eq. (10) and the experimental results of randomly distributed nodes are shown in Fig. 4. If every parent $\mathcal{P}$ has only one child as in chain topology $\Delta = 2$ then $\mathcal{J} = 48 = \frac{N}{\Delta} - \Delta$, as shown in the experimental results curve in Fig. 4. In that case, beamforming is not effectively used. Thus, we started our experimental results at $\Delta = 3$. As depicted from Fig. 4, the number of levels estimated by analytical results on setting node degree $\Delta = 3$ to 9 is nearly identical to the actual ones that were obtained from experimental results on randomly distributed nodes. The results obtained from Fig. 4 show the availability of applying the derived optimal node degree analysis on all randomly deployed WSNs with medium node density and a BS outside the ROI to obtain the number of levels in the tree.

6.3. Network lifetime

Since network lifetime maximization is the most significant evidence of energy efficiency of WSN routing protocol. The effect of node degree Δ and consequently, the number of levels $\mathcal{J}$ on network lifetime $r_{\mathcal{N}}$ is studied in this subsection.

6.3.1. Degree Constrained Tree

The problem of the premature end of network lifetime of single setup phase networks can be represented in terms of breakdown energy, as discussed in [37]. Accordingly, the optimum node degree must lead to the lowest breakdown energy. In other words, as network breakdown energy decreases, the network energy efficiency increases. Fig. 5 shows the relationship between node degree and breakdown energy. The simulation results proved that the lowest breakdown energy is obtained when node degree is 3 and increases as node degree increases. This result proved that the optimal node degree of DCT to maximize energy efficiency is 3 as proved analytically in Section 4.

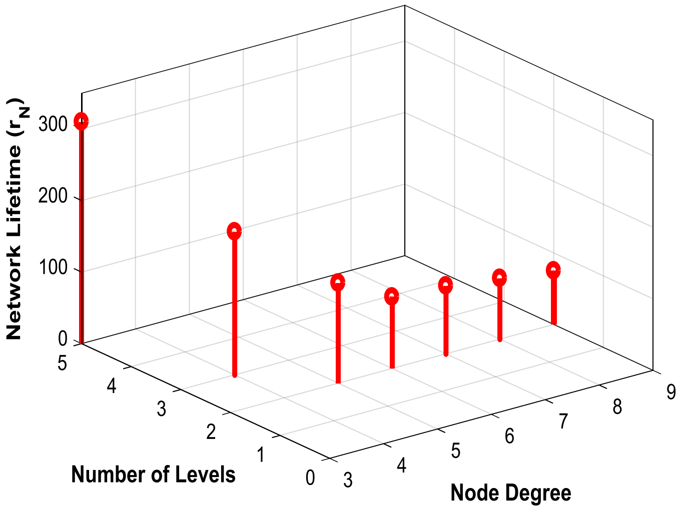

Fig. 5. The node degree Δ and the number of levels $\mathcal{J}$ vs. the network lifetime $\boldsymbol{r_N}$.

Table 3
The relationship among node degree Δ, the number of levels in the tree $\mathcal{J}$ and network lifetime $\boldsymbol{r_N}$ for 100 nodes.

Δ	$\mathcal{J}$	r_N
3	5	310
4	3	192
5	2	140
6	2	100
7	2	95
8	2	83
9	2	75

According to Fig. 5, the effect of increasing Δ on decreasing $r_{\mathcal{N}}$ is due to the effect of increasing Δ on decreasing $\mathcal{J}$ which increases the internode distances and directly affects $r_{\mathcal{N}}$, as proven in [3]. However, the distance between nodes is minimized, which increases the network lifetime to about 310 rounds in minimum degree tree at $\Delta = 3,$ *and* $\mathcal{J} = 5$. However, as node degree increased by one, the distances between nodes increase leading to the decrease in $r_{\mathcal{N}}$ to be about 200. In short, the increase in c decreases $\mathcal{J}$ tremendously according to Eq. (10) which increases the distance between the nodes. Thus, it minimizes the network lifetime, and this explains the reason of preferring multi-hop routing approaches for prolonging the network lifetime in spite of its complexity. The relationship among the number of nodes, their corresponding number of levels, and network lifetime for the 100 nodes that are randomly deployed in 100 × 100 ROI that is 100 m away from the BS is summarized in Table 3.

6.3.2. Collaborative Distributed Antenna

The rate of node loss gives a clear picture about the length of network lifetime and the ratio of coverage throughout this lifetime. High ratio of network coverage is achieved through the energy fairness provided by the routing protocol design. This ratio is indicated by measuring the rate of node loss throughout the network lifetime.

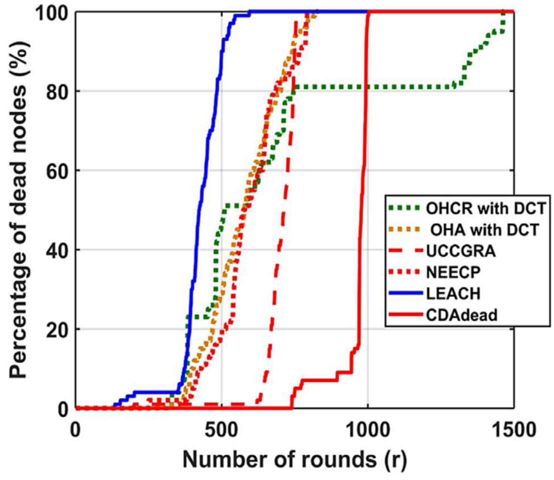

Fig. 6. The percentage of node loss throughout network lifetime.

Fig. 6 shows that CDA offers the lowest rate of node loss. Although OHCR offers the maximum network lifetime among all the competitors, the length of time that only 20% of the nodes are alive is relatively large with respect to the whole network lifetime. Accordingly, there is at most 800 rounds where there are more than 20% of the nodes working for all CDA competitors. Whereas, LEACH shows the highest rate of node loss followed by OHA and NEECP that show slightly similar patterns. On the other hand, UCCGRA shows a noticeable sustainability by showing a very low rate of node loss for about 700 rounds. CDA keeps about 50% of the nodes working until few rounds before the end of network lifetime. Thus, it proved to be an energy fairness aware routing protocol. Additionally, it overcomes the problem of OHCR and OHA, which is the loss of the nodes that are closer to the BS too early. Consequently, CDA proved to provide better network coverage throughout its lifetime like other dynamic clustering protocols.

6.4. Energy decay and overhead

The overall rate of network energy decay and the breakdown energy reflect the sustainability of the network in terms of energy efficiency and lifetime maximization. In this subsection, the rate of energy gradient and energy overhead of CDA compared with its competitors is discussed.

6.4.1. The rate of energy consumption

Fig. 7(a) shows a comparison between how the overall network energy is drained for the addressed energy efficient routing protocols throughout its lifetime. This figure shows that LEACH is the first to drain all the network energy and OHCR is the last. However, the rate of energy decay in CDA is the lowest, leading to a very high level of coverage throughout the network lifetime. Although the main source of most of the network energy draining is the energy consumed in PTB multicasting, this energy overhead helps the network to avoid node loss and useless network reconstructions. On the other hand, OHA, UCCGRA, and NEECP show an approximately similar rate of energy drainage that is higher than that of CDA and OHCR, as well. However, OHCR and OHA solve the same problem of minimizing network overhead. The advantage of CDA over OHCR is the load distribution of data transmission, which minimizes the rate of node loss and the need for network maintenance leading to the avoidance of many OHCR multicasts.

6.4.2. Energy overhead

Energy overhead is one of the most important factors that affects the rate of network energy drainage. Fig. 7(b) shows the percentage of energy consumed on network setup to the energy consumed in data transmission. The higher this percentage is the lower the network efficiency of the routing protocol is. Although PTB is considered a high energy overhead due to periodic multicasting, limiting the multicast radius to d_o adds less overhead than the periodic broadcasts performed in LEACH, NEECP and UCCGRA. Additionally, the threshold energy of VBS limits the useless network reconstruction performed in those dynamic protocols. Moreover, using distributed data transmission task limits the need for network maintenance, unlike, the case of applying OHCR to single

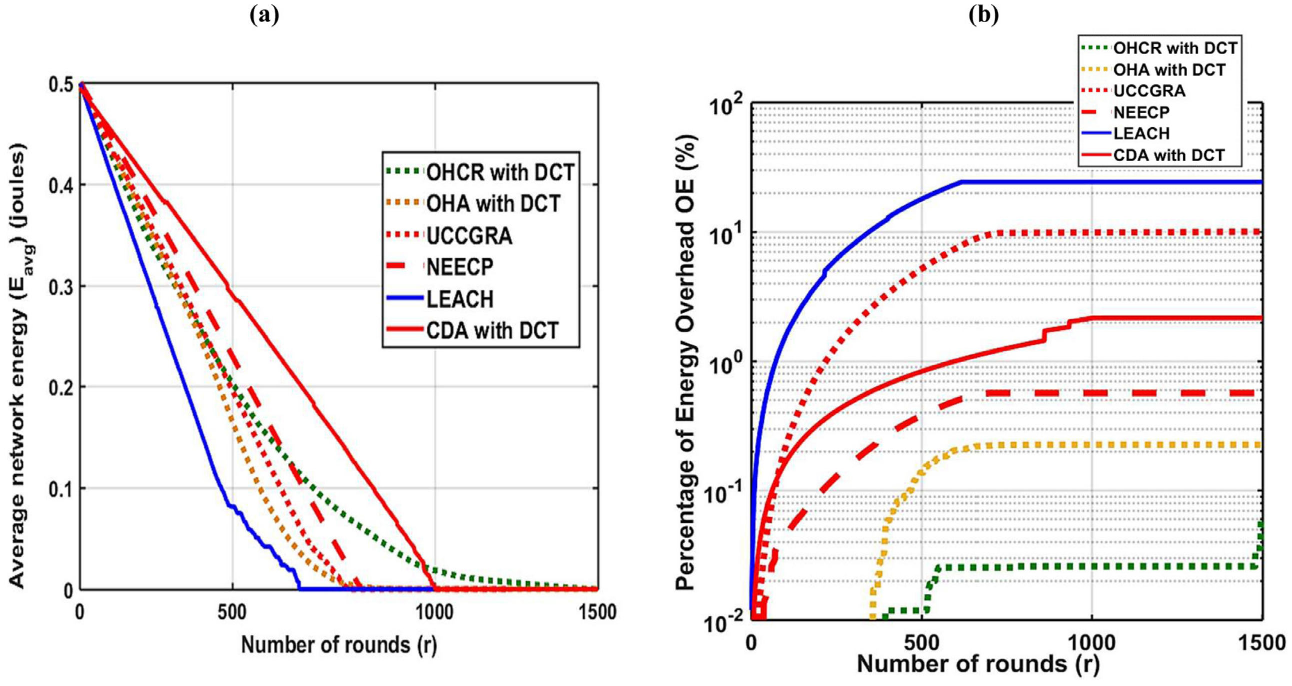

Fig. 7. The variations of (a) average network energy and (b) percentage of energy overhead throughout network lifetime r_N.

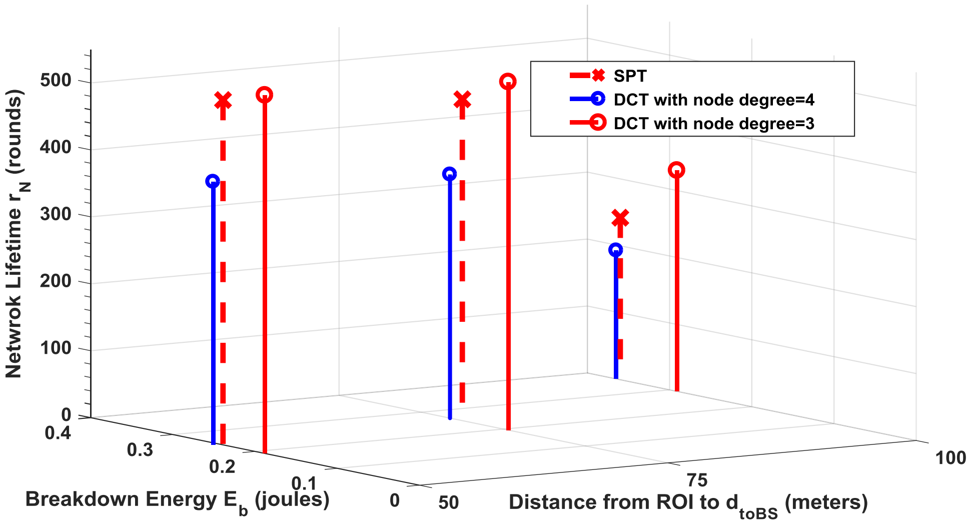

Fig. 8. Network breakdown energy E_b and network lifetime r_N vs. distance to BS d_{toBS}.

Table 4
Comparison between the addressed trees in terms of network lifetime and breakdown energy.

Tree	$d_{toBS} = 50$			$d_{toBS} = 75$			$d_{toBS} = 100$		
	$\mathbf{r}_\mathcal{N}$	E_b	E_{grad} (μj)	$\mathbf{r}_\mathcal{N}$	E_b	E_{grad} (μj)	$\mathbf{r}_\mathcal{N}$	E_b	E_{grad} (μj)
DCT $\Delta = 3$	535	0.188	583	520	0.194	588	330	0.291	633
DCT $\Delta = 4$	390	0.251	638	364	0.265	646	192	0.365	703
SPT	515	0.239	507	480	0.250	520	242	0..360	579

setup tree. Accordingly, Fig. 7(b) shows that LEACH and UCCGRA have the highest percentage overhead among the addressed ones. They are followed by CDA that is ranked the third, which is followed by NEECP. IN CDA, due to the periodic network overhead in PTB broadcast, it wastes about 2% of the network total energy on network setup. While NEECP, OHA and OHCR consume less percentage of energy. Therefore, OHCR adds the lowest network overhead followed by OHA.

6.5. The effect of ROI to base station displacement on network lifetime

Since the network breakdown occurs due to the loss of level-1 parents, the relay nodes, then, in case of medium network density, the number of nodes in the ROI will not affect the network lifetime. To generalize our derivations and results, we performed our simulation using different distances between BS and ROI, which are 50, 75, and 100. This subsection shows the effect of the distance between the ROI and BS on network lifetime and the breakdown energy for single-setup phase trees. Moreover, the effect of ROI to BS displacement on network lifetime for dynamic clustering protocols is studied in this subsection.

6.5.1. Degree Constrained Tree

Fig. 8 shows a comparison in terms of the overall network lifetime r_N, and break down energy E_b among DCT with an optimal number of children $\Delta = 3$, DCT with larger node-degree $\Delta = 4$, and Shortest Path Tree (SPT) [38], which has the same static and single setup phase nature as DCT. Since the threshold distance $d_o = 87$ m, the difference in network lifetime, as well as the breakdown energy between the two displacements 50 and 75 compared to the other displacements is significant. This is due to multipath propagation effect. Accordingly, the relay nodes that are responsible for ROI to BS connection suffer the most when the distance between BS and ROI exceeds 87 m. As a result, the network lifetime in all the trees decreases and the breakdown energy increases as the displacement between BS and the ROI increase.

The results also show that SPT has the lowest gradient of average energy loss per round at all the tested BS to ROI displacements. However, the network breakdown energy of SPT is approximately equal to that of DCT with $\Delta = 4$, which is higher than that of DCT with optimal node degree. Consequently, it is proven that the whole network breakdown energy of a tree is mainly dependent on the relay node lifetime that is maximized using optimal node degree in DCT network. Thus, DCT with $\Delta = 3$ extends network lifetime by at least 5% with respect to its competitors at all ROI to BS displacement. Thus, DCT with optimal node degree proved to be the most sustainable type of single-setup phase trees. The results obtained from our simulation results are summarized in Table 4 to show the network lifetime, network breakdown energy, and energy gradient of DCT with $\Delta = 3$, DCT with $\Delta = 4$, and SPT at different ROI to BS displacement.

6.5.2. Collaborative Distributed Antenna protocol

According to Fig. 9, OHCR achieves the highest network lifetime. However, the network coverage is not considered leading to the loss of a large percentage of nodes in the area that is closer to the BS so much earlier than the other nodes. Similarly, OHA does not guarantee network coverage; however, CDA provides 30% more lifetime than OHA. Accordingly, although CDA leads to the second highest network lifetime, it guarantees network coverage for the hole network lifetime like other dynamic routing protocols. Thus, CDA provides at least about 1.5 times longer network lifetime than other dynamic routing NECP, UCCGRA, and LEACH at all the ROI to BS displacements. Table 4 shows a comparison between the addressed dynamic routing protocols at different displacements between the ROI and BS. The percentage of node loss and energy gradient are measured for all the routing protocols at $d_{toBS} = 100$,

Table 5
Network efficiency at different ROI to BS displacements.

Protocol	Topology	Relay node	$d_{toBS} = 100$				$d_{toBS} = 75$	$d_{toBS} = 50$
			$\boldsymbol{r}_{\&}$	$\boldsymbol{r}_{\mathcal{N}}$	$\%r_{is}$	E_{grad} (μj)	$\boldsymbol{r}_{\mathcal{N}}$	$\boldsymbol{r}_{\mathcal{N}}$
CDA- DCT$\Delta = 3$	Tree	VBS and DAE	720	1004	28	498	1108	1120
OHCR- DCT $\Delta = 3$	Tree	Level-one nodes	330	1470	77	340	1496	1510
OHA- DCT $\Delta = 3$	Tree	Level-one nodes	330	850	60	588	876	890
UCCGRA	Vote-based clusters	Level-one CHs	200	760	74	658	781	789
NEECP	Chain-based clusters	Leader of the CHs chain	250	800	69	625	842	854
LEACH- $p = 0.03$	Cluster-based	Cluster heads	146	600	76	833	663	685

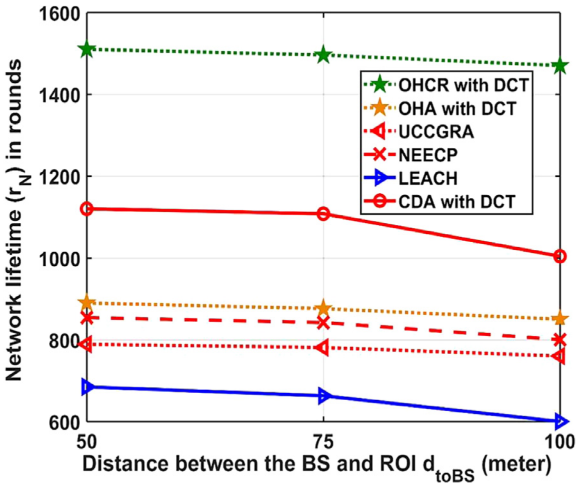

Fig. 9. Network lifetime $\boldsymbol{r_N}$ V.s. the distance between the ROI and the BS $\boldsymbol{d_{toBS}}$.

which is greater than d_o to show the network efficiency of CDA in the worst case. Table 5 summarizes the effect of the change in ROI to BS displacement on the network efficiency of CDA compared to its peers.

7. Conclusion and future work

In this paper, we analyzed in details the Degree Constrained Tree (DCT) routing protocol in terms of energy consumption during packet transmission. Our analysis derived the node degree that maximizes network lifetime analytically. Thus, we generalized this analytical derivation using experimental results. The results of our work proved that our analytical results are correct when applied to randomly distributed DCT of homogeneous sensor nodes. The optimal node degree that leads to lifetime maximization and breakdown energy minimization was proved to be 3. Accordingly, the number of levels in the tree was derived in terms of node degree. Therefore, CDA routing protocol that is based on DCT with optimal node degree is designed to provide high network performance in terms of network lifetime while doubling the stability period and minimizing the average rate of energy depletion compared to its peers.

Our future work will cover the scheduling algorithms that are most suitable for DCT and the optimal node degree for scheduling and energy consumption minimization. Additionally, network coverage problem will be studied in depth. The formed beam due to distributed beamforming in CDA will be analyzed showing the ability of directivity using antenna array system. We also aim to apply our model on the heterogeneous WSNs, and dynamic environments for both data monitoring and tracking purposes by adding a suitable distributed localization algorithm. Moreover, additional experiments will be conducted in a complex and wide range area.

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