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Ant Colony Optimization Based Orthogonal Directional Proactive–Reactive Routing Protocol for Wireless Sensor Networks

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Abstract Routing protocols for wireless sensor networks are important in addressing the various quality-of-service (QoS) issues pertaining to different applications. The most important QoS issues while designing routing protocols for WSN are energy awareness, scalability and network lifetime. However to deal with these issues the solutions provided in related literature have certain inherent disadvantages like high control overhead, low packet delivery ratio and requirement of global location information. In order to resolve these issues, we propose an orthogonal transmission based scalable, lightweight and energy aware routing protocol named as OD-PPRP which does not require global location information and has low control overhead. The proposed protocol OD-PRRP has the characteristics of both reactive and proactive routing protocols and utilizes fuzzy logic and Ant Colony Optimization to identify energy efficient and optimal paths. The simulation results show in both static and dynamic environment, OD-PRRP has better network lifetime, low end to end transmission delay, less overhead and high packet delivery ratio than other state of art QoS aware routing protocol viz. EARQ, EAODV and EEABR.

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1 Introduction

A wireless sensor network comprises of a distributed collection of wireless sensor nodes which have limited sensing, processing and communicating capabilities. The main task of sensor nodes is to sense, collect and process information and then relay the processed information to the base station. This communication is performed in a single or multi hop fashion depending on the location of the sensing nodes as well as of base station. Sensor nodes in WSN are battery powered and in most of cases, it is not possible to recharge or change batteries. Thus energy consumption is the most significant parameter, which needs special attention while designing communication protocols for WSNs. Moreover, in wireless sensor networks thousands of sensors are randomly deployed for a given application. With this high density of nodes, communicated data is likely to suffer communication failures due to contentions in shared communication medium. Besides these, changes in network topology due to node destruction or battery depletion require exchange of state information for maintaining and updating the links in network [1–3]. All these characteristics of wireless sensor networks make energy efficiency, scalability and optimal resource management as main research challenges while designing protocols for network layer.

To address the above mentioned challenges, existing routing protocols usually characterize the network with metrics such as residual energy, reliability, communication cost or delay [4]. For finding the routes that are energy efficient, reliable and short, a lot of control messages are broadcasted and exchanged between nodes. In most of the existing protocols it is assumed that the location information of the entire network is known to all the sensor nodes. This location information is assumed to be obtained either from the installed GPS receiver on nodes or from any other localization method. However, these existing solutions are costly in implementation and have accessibility and scalability related issues. Thus, there is a need for a routing methodology that provides an acceptable path which is energy efficient and does not require explicit positioning and high control overhead.

Considering the above, we have proposed a new routing method that avoids excessive overhead in maintaining complete link state information. The proposed method does not require global position information and ascertains efficient and balanced use of energy resources. The method named Orthogonal Directional Proactive Reactive Routing Protocol (OD-PRRP), optimally utilizes the characteristics of both the proactive and reactive routing model. In order to relax information requirements such as co-ordinate space embedding and node localization we have chosen the nodes to transmit packets in orthogonal directions. The orthogonal transmission leads to less congestion and contention losses, which in turn makes the system more scalable. Also, orthogonal transmissions achieve connectivity between source and destination with high probability even in sparse networks having voids and require only $O(N^{3/2})$ total state information to maintain an N-node network [5].

In OD-PRRP, routing information is proactively maintained by certain selected "*proactive*" nodes using Ant colony optimization. These proactive nodes are periodically selected by using random back-off scheme [6]. Subsequently, the balance nodes (with no route information) reactively identify the route with the help of routes already identified by these selected proactive nodes. The overhead are controlled as only few selected "proactive" nodes are utilized for proactive route maintenance. This responsibility of being *proactive* nodes is periodically shared among the nodes in the network to avoid non uniform energy consumptions. For the nodes other than the selected proactive nodes, the

delays associated with reactive methods are addressed at the time of route identification as any node having route information itself sends the route reply to the respective node on behalf of the sink node. Thus the nodes other than the proactive nodes utilize the methodology prescribed in AODV [7] method. However the delays associated with AODV method are addressed by proactive route maintenance by few selected proactive nodes as discussed above.

Further in OD-PRRP, Ant colony optimization [8], which is a widely accepted optimization method, has been applied to choose between different available routes. In wireless sensor networks multiple parameters i.e. energy efficiency, path length and hop length are to be considered while making routing decisions. The multiple parameters increase the complexity. To address this, we have modeled our network as directed fuzzy graph. In the proposed fuzzy graph the same is addressed by representing edge weight as a function of both residual energy as well as hop distance.

The performance of OD-PRRP has been analyzed by comparing the performance with state of art routing methods such as EARQ [9], AODV [10] and EEABR [11] by using MATLAB simulations. The simulation results indicate that the proposed method results in enhanced network lifetime, low end to end transmission delay, high delivery ratio, low overhead and balanced load distribution. Moreover, the performance of the proposed method is evaluated in dynamic environment i.e. after incorporating node mobility. The simulation done in dynamic environment indicate that the performance of the proposed protocol is reasonably well in terms of network lifetime, end to end transmission delay, control overhead and packet delivery ratio.

The main contributions of this paper are as follows:

1. Less memory requirement, low congestion and contention losses and no requirement of global location information have been ensured by using orthogonal transmission.
2. The advantages of both the proactive routing and reactive routing methodology i.e. fast response and low overhead respectively have been harnessed by combining the use of both these methodologies.
3. Ant colony optimization is used to find a path which is energy efficient and does not leads to excessive delay in terms of hops.
4. Modeling of network as Fuzzy Graph has led to efficient modeling and leads to less complexity.
5. The performance of OD-PRRP has been analyzed by comparing the performance with state of art routing methods EARQ and EAODV by using MATLAB simulations in both static and dynamic environment i.e. after incorporating node mobility.

This paper is organized as follows. Section 2 presents related work. Section 3 presents the system model. In Sect. 4, network modeling and detailed description of the proposed method OD-PRRP is given. In Sect. 5 simulation results are presented and effectiveness of our work is evaluated. Conclusions are given in Sect. 6.

2 Related work

Routing protocols are responsible for discovering and maintaining the routes in the network. Most of the routing protocols available in literature are either reactive or proactive in nature and use Omni directional communication mode. *Proactive routing* protocols are those protocols in which each node stores the routing information to every node in the network in its storage tables and keeps on refreshing these tables periodically. Some

examples of *proactive routing* protocols are Destination-Sequenced Distance Vector (DSDV) [12], Optimized Link State Routing (OLSR) [13] and Topology Broadcast Reverse Path Forwarding (TBRPF) [14]. *Reactive or on-demand routing* protocols are those protocols in which routing information is acquired by a node at the time, when it actually has some data to communicate. Some examples of *reactive routing* protocols are such as Dynamic Source Routing (DSR) [15], Adaptive On-Demand Distance Vector (AODV) [7], On-Demand Multicast Routing Protocol (ODMRP) [16] and Cluster Based Routing Protocol (CBRP) [17]. In addition to these basic routing protocols, in literature Hybrid routing protocols are also proposed. These Hybrid routing protocols divides the network into clusters, trees or zones and proactively or reactively maintain routes at different stages. GPSR (Greedy perimeter stateless routing) [18], ZRP (Zone Routing Protocol) [19] and Directed diffusion [20] are the examples of hybrid routing protocols.

In wireless sensor networks, due to limited available energy resources and inherent QoS requirements, researchers have developed various QoS and energy aware routing protocols. In most of these methods existing proactive and reactive routing methods are modified to make them energy efficient and QoS aware. EARQ [9] is a kind of proactive routing. It provides real-time, reliable delivery of a packet, while considering energy awareness. In EARQ, a node estimates the energy cost, delay and reliability of a path to the sink node, based only on information from neighboring nodes. Then, it calculates the probability of selecting a path, using the estimates. To achieve real-time delivery, only paths that may deliver a packet in time are selected. To achieve reliability, a source node may send a redundant packet via an alternate path. In [10] Li et al. has presented an enhanced AODV (EAODV) routing protocol for wireless sensor networks. In EAODV method the proper transmission energy required for communication between two nodes is calculated using dimidiate search arithmetic. Multiple routes between source and sink are found on demand using AODV protocol and finally a cost effective route is selected using accumulative summing method. The delay associated with finding the route is high as final path selection executes the iterative process dimidiate search arithmetic for selecting proper transmission power and then selects the route on the basis of accumulative power required for transmission. In [21] SAR algorithm is proposed to minimize the average weighted QoS metric throughout the lifetime of the network. It takes into consideration both energy resources, QoS metric on each path and priority level of each packet. However, the protocol suffers from the overhead of maintaining the tables and states at each sensor node and hence not suitable for densely deployed WSNs. Maximum lifetime energy routing proposed by Chang and Tassiulas [22] is a network flow base routing approach. The main objective of the approach is to maximize the network lifetime. To maximize network lifetime a new link cost as a function of node remaining energy and the required transmission energy is formulated. In [23] multiple-objective fuzzy decision making based routing protocol (MOFDMR) has been proposed for WSNs. In MOFDMR nodes periodically executing HEED [24] protocol for cluster heads selection and then multiple trees rooted from these cluster heads are established. Out of multiple paths, MOFDMRW chooses a path through complete comparisons of energy reserves, time latency and the reliability using multiple-objective fuzzy decision making and location information. However, due to periodic re-clustering, establishment of new routes for every new round may increase the overhead and can lead to inefficient utilization of energy. In [25], the author has proposed two online (reactive) fuzzy based routing algorithms. First algorithm FML attempts to maximize the WSN life time while the second algorithm FMO is for optimizing lifetime as well as energy conservation. Due to purely reactive nature of the protocol Delay and control overhead is very high and hence not suitable for delay sensitive applications. Jabbar et al.

[26] has proposed REAR, to achieve the real-time routing with energy awareness. It follows the customized proactive routing with in-network processing and localized behavior. Actual node position is required in this method. Time, Hop Count and Energy are taken as selection parameters with priorities in the respective order. Due to proactive nature and concept of mobility, overhead in maintain a route is very high. In [27], in order to enhance network life time, the author has proposed a centralized reactive routing method that uses fuzzy logic and A-star algorithm. Optimal path is determined using residual energy of nodes, number of hops between source and destination and current traffic load on nodes The base station determine the routing schedule based on the information received from nodes. But, due to centralized approach, control overhead in this solution is very high.

In paper [28], Network rOle-based Routing Algorithm (NORA) and Network role-based Routing Intelligent Algorithm (NORIA) are developed to perform role assignment during route establishment and maintenance. NORA performs decision making by using a series of mathematical operations whereas NORIA, follows a fuzzy-rule-based paradigm. It is a kind of proactive routing protocol and different types of control messages are broadcasted during route finding process. FEAR [29] protocol is a fuzzy based energy as well delay sensitive reactive protocol. FEAR consumes much less bandwidth or have less control overhead as compare to proactive protocols, but the delay in determining a route is substantially large. Routing decisions in FEAR are based on the fuzzy distance to the Base station in terms of hops as well as remaining energy of nodes on the path towards the base station.

In literature, some ant colony optimization based routing methods have been proposed for WSNs. The main objective of these methods is to optimize energy and delay metric. In [11], an energy efficient Ant colony optimization based routing method (EEABR) has been proposed. The method is proactive in nature and periodically each node sends a colony of artificial ants through the WSN to look for paths between the sensor nodes and a sink node. The selection of path by ant is based upon path length and energy efficiency. The EEABR protocol builds a routing tree with optimized energy branches through various iterations. However, proactive nature and route maintenance by all nodes results in the very high overhead. In [30], a centralized chain-based routing protocol, (AntChain) has been proposed for WSNs. In this algorithm, the base station finds routes of all the sensor nodes by using ACO. After forming the routes, the information is broadcasted to respective sensor nodes. Being a centralized approach, the method is not suitable for large scale WSNs as it results in high overhead. Moreover, the routing paths are formed by using only the energy metric and without considering the length of the path which leads to high end-to-end delay. In [31], an ant colony optimization based method ("E&D ANTS") has been proposed with primary objective of minimizing the delay in delivering a fixed number of data packets. In order to optimize energy and delay, the reinforcement learning (RL) algorithm has been introduced to train the model. The key idea of E&D ANT's method is the consideration of both energy and delay in wireless communication network to update the nodes' pheromones. In [32], an ant routing algorithm based on deflection angle is proposed for WSNs. In this algorithm, the energy, distance, and deflection angle are considered for the selection of routing path. However, due to proactive route maintenance, the routing overhead is very high in [31, 32] algorithms.

Cheng et al. [5] have introduced an Orthogonal Rendezvous Routing Protocol (ORRP) for meshed wireless networks. ORRP is a lightweight-but-scalable routing protocol utilizing directional communications to relax information requirements such as coordinate space embedding and node localization. The ORRP source and ORRP destination send route discovery and route dissemination packets respectively in locally-chosen orthogonal

directions. Connectivity happens when these paths intersect (i.e. rendezvous). However, in ORRP energy awareness and various QoS provisions are not considered as protocol is developed for simple mesh networks. Our proposed protocol uses orthogonal directional communication to increase delivery ratio by reducing contention losses, increase system throughput by maximizing spatial reuse and decrease energy consumption. Moreover, our proposed method has characteristics of both proactive and reactive routing characteristics and route finding is by using ACO which lead to minimization of both delay and excessive control overhead and results into energy and delay efficient paths.

3 System Assumptions

We consider a WSN with a large number of sensor nodes randomly deployed over a 2-D planer area. All the sensor nodes are identical in computational capabilities and starts with equal initial energy σ, $\sigma > 0$. The sensor nodes can communicate with each other through short-range radios. After initialization of network, each node $u \in V$ discovers its respective one hop neighbor nodes N_u. Transmission between node u and neighboring node v is possible only if current energy of transmitting node $ce(u)$ is greater or equal to energy required for transmitting one unit of data. In this paper we use log-distance path loss model presented in [33], which is one of the most widely used models in network simulations and theoretical analysis. According to this model, power received by a remote node at distance d meters from the sender can be expressed as follows:

$$P_r(d) = P_o \times \left(\frac{d_o}{d}\right)^{\alpha} \tag{1}$$

where, P_o is the received signal power at the distance d_o from a transmitter and α is the path loss exponent which varies from 2 to 6.

In addition to above following assumptions have been made:

1. The received signal strength is measurable and hence nodes can adjust their transmission power.
2. Nodes transmit and receive packets in orthogonal directions with directional antenna.
3. All sensor nodes are location-unaware.
4. Every node in the network knows (1) its 1-hop neighbors and (2) direction/interface to send packets so that it reaches the respective neighbor.
5. Each node has its own local perception of direction with respect to a local North.

4 Proposed Method

In this section we discuss the network modeling and the proposed routing method OD-PRRP in detail.

4.1 Modeling of Network

We have modeled the WSN as directed Fuzzy vertex and edge graph [34] $\tilde{G}(V, E, \mu(E)$, where V represents the set of n nodes and $E \subseteq V \times V$ is the set of edges. The main characteristic of Fuzzy vertex and edge graph is that it considers both vertex set and edge

set as fuzzy sets and allows the attachment of fuzzy membership function (value) to both vertices and edges. The resulting degree of an edge of the said fuzzy graph is the function of its own primary edge degree and the degree of the two vertices connected by the incremented edge.

In this paper, we have considered directed fuzzy vertex and edge graph for which $\mu_{\tilde{G}}(E_{uv})$ represents the resulting degree of an edge between two nodes u and v. $\mu_{\tilde{G}}(E_{uv})$ is a function of its own primary edge degree $\mu_{\tilde{E}}(e_{uv})$ and the degree of the end node connected by the incremented edge; $\mu_{\tilde{V}}(v)$. We define $\mu_{\tilde{V}}(v)$ as the membership degree of a node v in a fuzzy set $\tilde{V}$ of nodes having *high* residual energy. Similarly $\mu_{\tilde{E}}(e)$ is the membership degree of an edge e in a fuzzy set $\tilde{E}$ of edges having *desirable* edge length (optimal transmission power required to transmit data). Here *high* and *desirable* represents the linguistic variables [35] for defining fuzzy node set $\tilde{V}$ and edge set $\tilde{E}$ respectively. In the next subsection we present the definition of fuzzy set and membership function and then one by one define the fuzzy membership values assigned to nodes i.e. $\mu_{\tilde{V}}(v)$, edges i.e. $\mu_{\tilde{E}}(e)$ and $\mu_{\tilde{G}}(E)$ respectively.
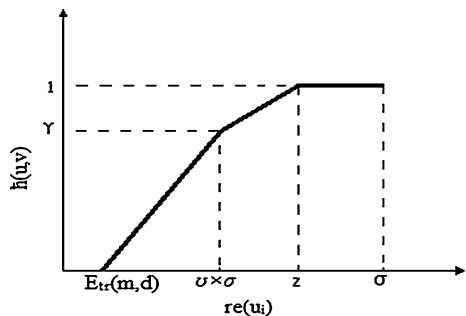
4.1.1 Fuzzy set and membership function

Fuzzy set theory provides mathematical tools for carrying out approximate reasoning processes, when available information is uncertain, incomplete or imprecise. These features of fuzzy set theory can add more flexibility and capability in modeling wireless sensor networks where most of the information regarding network is collected from a dynamic topology. The mathematical frame work to describe Fuzzy Logic was suggested by Zadeh [35] in his seminal paper entitled "Fuzzy Sets" (Zadeh 1965). According, if X is a collection of objects denoted by x, a fuzzy set $\tilde{A}$ in X can be defined as a set of ordered pairs:

$$\tilde{A} = \left\{ \left(x, \mu_{\tilde{A}}(x) \right) | x \in X \right\} \tag{2}$$

where $\mu_{\tilde{A}}(x)$ is called the membership function of x in $\tilde{A}$ that maps X to the membership space M. The range of the membership function is a subset of the non-negative real numbers whose supremum is finite. The said membership function is not limited to values between 0 and 1 but if $sup_x\left(\mu_{\tilde{A}}(x)\right) = 1$, the fuzzy set $\tilde{A}$ is called normal i.e. $\mu_{\tilde{A}} : X \rightarrow [0, 1]$ (including 0, 1). In comparison to crisp set, fuzzy set is a 'vague boundary set' [36].

Fig. 1 Membership function for node set with high energy

4.1.2 Fuzzy membership function of node $\mu_{\tilde{V}}(v)$

In the proposed method a fuzzy set $(\tilde{V})$ (nodes with high residual energy) is defined on vertex set V and a fuzzy membership function $\mu_{\tilde{V}}(v)$ (Fig. 1) is assigned to nodes $v \in V$ corresponding to its current residual energy $re(v)$. A high membership value is assigned to a node having a large amount of residual energy. At the time of network initialization, the residual energy of all the nodes is high and is near to σ, hence the membership function value 1 is assigned to these nodes till their residual energy decreases to a level say z. After level z, the membership value is first made to fall at a low rate. Subsequently, when the residual energy level decreases below another threshold point $\mho \times \sigma$ (where $\mho \in [0, 1]$ is an algorithmic parameter) [25], the corresponding membership is decreased at a sharper rate. This behavior of the membership function is chosen to strongly discourage the selection of nodes for special responsibilities that have depleted their energy beyond a certain threshold value. The threshold point may be altered by adjusting the value of $\mho$. The characteristic Equations showing the membership degree assigned to a node v are depicted in Eq. 3.

$$\mu_{\tilde{V}}(v) = \begin{cases} 1 & : & if \ \ z < re(v) \leq \sigma \\ 1 - \left(\dfrac{1 - \gamma}{1 - \mho}\right) * \left(1 - \dfrac{re(v)}{\sigma}\right) & : & if \ \ \mho * \sigma < re(v) \leq z \\ \dfrac{\gamma}{\mho * \sigma - E_{tr}(m, d)} * (re(v) - E_{tr}(m, d)) & : & if \ \ E_{tr}(m, d) < re(v) \leq \mho * \sigma \\ 0 & : & if \ \ re(v) \leq E_{tr}(m, d) \end{cases}$$

(3)

Here,

$$re(v) = ce(v) - E_{tr}(m, d)$$

(4)

where $ce(v)$ denote current energy and $re(v)$ denotes predicted residual energy after one unit of data transmission by node v respectively, and $\theta \in [0, 1]$, $\gamma \in [0, 1]$ are algorithmic parameters. $E_{tr}(m,d)$ is the average energy consumed in one unit of data transmission.

4.1.3 Fuzzy Membership function of an edge $\mu_{\tilde{E}}(e)$

Wireless Sensor networks consist of nodes with limited energy resources. Sensor nodes dissipate energy while sensing, receiving, sending and processing data. The most energy-consuming component is radio module while the energy requirement for computation is substantially low. The energy consumption while transmitting 1 bit of data on the wireless channel is equivalent to energy required to execute thousands of cycles of CPU instructions [1, 2]. Thus the energy consumption for transmission is the determining factor for network life. With the advancement in VLSI technology, all modern radio transceivers have capability of adjusting the transmission power [37]. Thus data transmission towards destination can be done either with high transmission power (small number of larger hops) or low transmission power (large number of smaller hops). However, both high power transmission and low power transmission methods have their inherent advantages and disadvantages. Routing with short hops minimizes the transmission energy but overall energy consumption (transmission + reception) increases with the communication distance. On the other hand, transmitting packets using long hops reduces the reception cost (due to decrease in number of nodes involved in data routing), but it requires high transmission power and also leads to more contention losses, congestion losses and

attenuation losses. By optimization of hop lengths, energy can be saved which in turn extends the network lifetime [38]. For calculating optimal hop length we have used Eq. (1) i.e. log-distance path loss model to define the minimum power required to communicate over a given distance between two nodes. According to this model in order to guarantee the signal detection at the receiver node, the transmitted signal by node A must be at least equal to the value such that received power by node B is at least equal to sensitivity threshold P_t of the receiver or we can write:

$$P_t = P_x \times \left(\frac{d_o}{x}\right)^\alpha \tag{5}$$

Here, P_x denotes the minimum transmitted energy requited to transmit up to distance x between sender and receiver and is given by:

$$P_x = P_t \times \left(\frac{x}{d_o}\right)^\alpha \tag{6}$$

Though energy cost for receiving data is low as compared to transmission cost, but is not negligible. The energy cost for receiving data can be represented equivalent to transmitting over a distant r [39]. Thus reception energy cost P_R can be represented as:

$$P_R = P_t \times \left(\frac{r}{d_o}\right)^\alpha \tag{7}$$

Figure 2 represents two different topologies of multi-hop routing between two distant nodes, a source A and a destination B, with a distance d. The first topology uses *n short* hops of length x to transmit data from A to B; While the second uses *m long* hops of length y i.e. $n = \lambda m$ and $y = \lambda x$, so we can write:

$$P_t = P_x \times \left(\frac{d_o}{x}\right)^\alpha = P_y \times \left(\frac{d_o}{y}\right)^\alpha \quad for \;\; 2 \leq \alpha \leq 6 \tag{8}$$

Thus, transmission power required to communicate at distance x and y respectively is given by:

$$\left.\begin{array}{l} P_x = P_t \times \left(\dfrac{x}{d_o}\right)^\alpha \\[2mm] P_y = P_t \times \left(\dfrac{y}{d_o}\right)^\alpha \end{array}\right\} \tag{9}$$

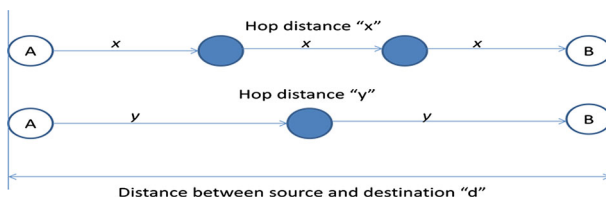Since $y = \lambda x$ using Eq. (9) we can write:

Fig. 2 Communication between node A and node B using long hop and short hop

$$P_y = P_x \times \lambda^\alpha \tag{10}$$

Using Eqs. (6) and (7), the energy required to communicate data from node A to node B using n short hops of length x is given by:

$$P_{short} = nP_x + nP_R \tag{11}$$

This can be written as

$$P_{short} = \lambda m \times P_x + \lambda m \times P_R \tag{12}$$

Using Eq. (10), this can be written as:

$$P_{short} = m \times P_y \left[\frac{1}{\lambda^{\alpha-1}} + \lambda \frac{P_R}{P_x} \right] \tag{13}$$

Similarly, power required to transmit data from A to B using m *long* hops is given by

$$P_{long} = mP_y + mP_R \tag{14}$$

This can be written as

$$P_{long} = m \times P_y \left[1 + \frac{P_R}{P_y} \right] \tag{15}$$

Now we have calculated the difference in power requirements using n small hops and m long hops

$$P_{short} - P_{long} = m \times P_y \left[\frac{1}{\lambda^{\alpha-1}} + \lambda \frac{P_R}{P_y} \right] - m \times P_y \left[1 + \frac{P_R}{P_y} \right] \tag{16}$$

This result into

$$P_{short} - P_{long} = m \times P_y \left[\frac{1}{\lambda^{\alpha-1}} - 1 + \frac{P_R}{P_y} \right] \tag{17}$$

Since $m \times P_y > 0$, therefore, $P_{short} - P_{long} > 0$, if and only if

$$\frac{1}{\lambda^{\alpha-1}} - 1 + \frac{P_R}{P_y} > 0 \tag{18}$$

Therefore, $\frac{P_R}{P_y} > 1 - \frac{1}{\lambda^{\alpha-1}}$
Using Eqs. (16), (17), (18) we get

$$y < \frac{r}{\sqrt[\alpha]{1 - \frac{1}{\lambda^{\alpha-1}}}} \tag{19}$$

Since $y = \lambda x$, Eq. (19) results into:

$$x < \frac{r}{\lambda \times \sqrt[\alpha]{1 - \frac{1}{\lambda^{\alpha-1}}}} \tag{20}$$

Since $y > x$, results obtained in Eqs. (19) and (20) propose that optimal energy consumption can be achieved when the hops lengths are included in the interval given by Eq. (21). Results indicate that optimal hop length is dependent on attenuation constant and energy consumed in receiving data.

$$\left] \frac{r}{\lambda \times \sqrt[\alpha]{1 - \frac{1}{\lambda^{\alpha-1}}}}, \frac{r}{\sqrt[\alpha]{1 - \frac{1}{\lambda^{\alpha-1}}}} \right[\qquad (21)$$

In randomly deployed wireless sensor networks, network may have voids or low density of nodes at some places and it may not be tenable to have fixed transmission range based upon the optimum hop distance value. In order to address this limitation resulting from random deployment and for energy efficiency (optimal and required hop length), in OD-PRRP transmission power has been divided into different levels i.e., from PTXMIN to PTXMAX. Thus, a node can transmit within this range of minimum and maximum transmission power, so as to maintain connectivity within a randomly deployed network. Additionally, by choosing the next hop node at optimal hop distance the system becomes more adjustable and energy efficient for randomly deployed network.

In the proposed method, fuzzy logistics has been used to formulate this situation. Assuming that it is required to have optimal transmission power equal to or near to P_{Tx}^{opt}, where P_{Tx}^{opt} lies in range

$$\left[\frac{r}{\lambda \times \sqrt[\alpha]{1 - \frac{1}{\lambda^{\alpha-1}}}}, \frac{r}{\sqrt[\alpha]{1 - \frac{1}{\lambda^{\alpha-1}}}} \right].$$

The function depicted in Eq. (22) below presents a possible value of fuzzy membership function $\mu_{\tilde{E}}(e)$ in fuzzy set of edges $\tilde{E}$ corresponding to optimal transmission power. It is shown that the highest membership function value of $\mu_{\tilde{E}}(e) = 1$ is for $P_{Tx} = P_{Tx}^{opt}$. Transmission range is allowed up to minimum P_{Tx}^{Min} and maximum P_{Tx}^{Max}, but with a dropping membership function.

$$\mu_{\tilde{E}}(e) = \begin{cases} 0 & P_{Tx} < P_{Tx}^{\min} \\ \dfrac{P_{Tx} - P_{Tx}^{\min}}{P_{Tx}^{opt} - P_{Tx}^{\min}} & P_{Tx}^{\min} \le P_{Tx} < P_{Tx}^{opt} \\ 1 & P_{Tx} = P_{Tx}^{opt} \\ \dfrac{P_{Tx}^{\max} - P_{Tx}}{P_{\max} - P_{opt}} & P_{Tx}^{opt} \le P_{Tx} \le P_{Tx}^{\max} \\ 0 & P_{Tx} > P_{Tx}^{\max} \end{cases} \qquad (22)$$

Here P_{Tx} is the calculated minimum required transmission power by a node v to reach the particular transmitter u.

4.2 Resulting degree of edge $\mu_{\tilde{G}}(E)$

In the proposed method, fuzzy relationship *min* T-norm is used to calculate the final resulting edge degree i.e. $\mu_{\tilde{G}}(E)$ of directed fuzzy graph. Fuzzy relationship Triangular

norms (T-norms) are monotone, commutative and associative functions [0, 1] × [0, 1] → [0, 1] which are eligible for fuzzy set intersection [36].

Min T-norm has been used as during preliminary rounds of communication each node has sufficient and equal energy and the edge distance will be the sole determining factor for connection strength/weight of edge between nodes. However, in later rounds, the nodes will have non-uniform energy levels due to unequal energy consumption in each round and the residual energy shall also be another key determining factor so as to ensure to balanced energy consumption between nodes. Thus, the proposed methodology takes into consideration the dynamic nature of the network. Mathematically, for the given fuzzy graph $\tilde{G}$, the final resulting degree of edge i.e. $\mu_{\tilde{G}}(E)$ is represented as:

$$\mu_{\tilde{G}}(E_{uv}) = \mathop{\forall}_{uv \in E} \min(\mu(v), \mu(e_{uv})) \tag{23}$$
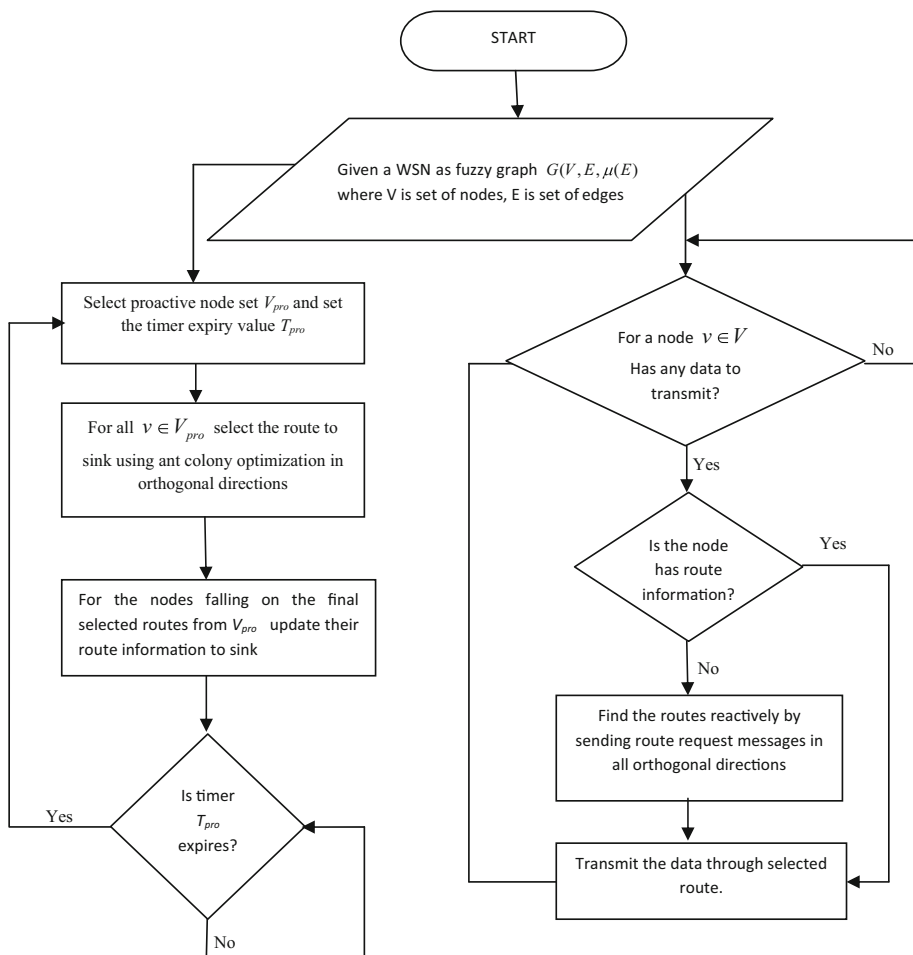
Fig. 3 Flow chart showing overview of OD-PRRP

4.3 Proposed Method "OD-PRRP"

Orthogonal Directional Proactive Reactive Routing Protocol (OD-PRRP), optimally utilizes the characteristics of both the proactive and reactive routing model. Figure 3 shows the Flow chart representing overview of the proposed method and the details associated with each element of OD-PRRP are discussed in the following sub-sections.

4.3.1 Selection of Proactive nodes

The selection of proactive nodes adopts a random back-off scheme to select certain nodes to initiate route request towards sink node. Each sensor node v sets its random back-off time b_v using a random number generator, random $(0,1)$. At the expiry of timer, nodes select themselves as proactive nodes and send route request message in all orthogonal directions by using directional antennas. The neighboring nodes receiving this route request immediately stop their timer and thus opt out from being selected as proactive nodes. The nodes having both higher value of back-off time and which do not receive any route request till the expiry of their respective timers select themselves as proactive nodes. Thus, if any sensor node v does not receive any route request messages during its back-off time, at the expiry of its timer it considers itself as a proactive node and sends route request message in all orthogonal directions. This in turn ensures that all the nodes have accessibility to a proactive node. In other words, there is no portion of network which is left without any proactive node.

This random selection of proactive nodes using this random back-off scheme does not require any information from neighboring nodes and exchange of control messages and thus it is a simple and cost effective scheme which does not require high computations at the respective nodes. The selection of proactive nodes using back-off scheme works irrespective of size of network, deployment type and number of sensor nodes. The pseudo code for selection of *proactive* nodes is illustrated in Algorithm 1.

Algorithm.1: The pseudo-code for Proactive Nodes Selection

Procedure *PR_Selection (V_{pro})*

Initialization
1. Each ordinary Sensor node v sets its back-off time b_v using a random number generator, random$(0,1)$,
   Where b_v is a positive real number between 0 and 1.   // random back-off timer

Proactive node selection

2. **If** $b_v == 0$ Then
3.   **If** sensor v does not receive any ant then   //ant is route finding agent in Ant Colony Optimization
4.   Select itself as proactive node
5.   **end** *if*
6.   **end** *if*
7. **end** Procedure

4.3.2 Proactive Route Discovery

The main goal of a routing protocol in wireless sensor networks is to establish an efficient route between a source and the sink. The route should be discovered and maintained with a

minimum of overhead and bandwidth consumption. In OD-PRRP, selection and utilization of some proactive nodes resolves both the issues pertaining to increased delays in reactive routing protocols and congestion losses in proactive routing protocols. The selected proactive nodes send forward ants in all the orthogonal directions. The communication in orthogonal direction resolves the necessity of global position information [5]. However, dense deployment of sensor nodes may lead to having multiple nodes in a particular orthogonal direction. In such situation, each ant chooses its next node through probabilistic method as per Eq. (24) para 4.2.3.a. Though the proactive nodes send the ants in all the orthogonal directions, each neighbor node after receiving the ant releases the ant at an angle of 180° i.e. ant continues to move in its original linear direction. In OD-PRRP each node maintains source and sender's ID along with hop count as against complete route information and is thus more scalable due to lower memory and updation requirements of state information. Also, forwarding of ants in orthogonal directions provides enhanced medium reuse. Once ants reach the sink node no more forwarding is required and de-pending upon the value of hop count sink updates the phenomenon value $\tau(u,v)$ using Eq. (25) and sends backward ant through the same route. This final route information shall be available with all the intermediate nodes en-route the sink reply path as well as with respective proactive nodes.

4.3.3 Ant colony optimization

Ant Colony Optimization (ACO) [8] is a meta-heuristic which works on cooperative behavior of ants with each other and is popular among researchers for solving combinational optimization problems. The basic idea behind ACO is to model the given problem as finding of best path in a graph which is representing different states of problem. These artificial ants communicate with each other by laying pheromone trails on the edges of the graph. The amount of pheromone deposition is dependent upon the quality of the solution found. The selection of the path by any ant is with respect to the probabilistic value which in turn is dependent upon the pheromone value layered by earlier ants.

In the proposed method, artificial ants find solution by moving on the given directed fuzzy graph $\tilde{G}(V, E, \mu(E))$ representing the wireless sensor network. For finding path, at each iteration the number of artificial forward ants n_a, started from a proactive node u and moving through neighbor nodes v, until ants reach at the final destination i.e. sink node. The identification of every visited node is saved onto a memory M_k, carried by ant. At each node u, selection of the next relay node v by a forward ant is based upon probabilistic decision rule which is given by:

$$P_k(u, v) = \begin{cases} \dfrac{\left[[\tau(u, v)]^\alpha [\lambda(u, v)]^\beta \right]}{\sum_{v \in N_v} \left[[\tau(u, v)]^\alpha [\lambda(u, v)]^\beta \right]} & \text{if } v \notin M_k \\ 0 & \text{otherwise} \end{cases} \tag{24}$$

Here, $P_k(u, v)$ the probability with which an ant k chooses to move from node u to v. Here $\tau(u,v)$ represents the pheromone value which depends upon the length of the path. When a forward ant reaches the destination (sink node), it is transformed into backward ant. The responsibility of backward ants is to update the pheromone trail of the path according to the desired quality of the path. Ants use reinforcement learning to discover the best paths. In reinforcement learning, the intelligent system is just given a goal to reach. The system then adopts the goal by a trial and error interaction with the environment. For

the interaction that takes the system close to the target, a positive reward is received and while going away from the target, a negative reward is assigned. All this is done by an artificial system by introducing the concept called pheromone update. The pheromone update policy depicted as follows in Eqs. (25) and (26).

$$\tau_t(u, v) \leftarrow \Delta\tau(u, v) + \rho * \tau_{t-1}(u, v) \tag{25}$$

$$\Delta\tau_s(u, v) = \begin{cases} \dfrac{1}{L_s} & if \ route\_found \\ 0 & otherwise \end{cases} \tag{26}$$

where, L_s is the length of tour, which is covered by ant s at any iteration t. ρ is the pheromone decay parameter (lies between 0 to 1) which shows the evaporation rate since the last time $\tau(u, v)$ was updated. This decay parameter ensures the balanced use of resources.

$\lambda(u,v)$ is the attractiveness of the move, which can be computed by some heuristic indicating the a priori desirability of the move [40] i.e. $\lambda(u,v)$ value of the heuristic related to the performance metric under consideration. In our proposed method $\lambda(u,v)$ is made equal to fuzzy membership value $\mu_{\tilde{G}}(E)$ assigned to edges which addresses both residual energy and communication distance of the next hop node and communication is done in orthogonal directions only. α and β are the control parameters related to control the weight/importance of pheromone and heuristic value. The pseudo code for the proposed ant colony method is given by Algorithm 2.

Algorithm.2 : ANT_ORTHO

Input: A set consisting of sensor nodes V

     {Initialization phase}
     Initialize
     $\tau_t(u,v), \ \lambda(u,v) = \mu_G(E_{uv}), \quad \rho \quad \forall \ (u,v) \in E$
     {Construction phase}
1. $\forall$ source u
2.   best-path = ∞
3.   while (n_a = no. of ants)
4.   set forward ant (start in all orthogonal directions);
5.   while (sink not reached y)
6.   apply probability rule ( );
7.   move to choose vertex in orthogonally opposite direction ,
            Append the chosen move to the ant k's memory list M_k

8.   end while
9.   if length (ants journey)< length (best path)
10.   best path = ants journey ;
11.   end if
12. Generate backward ant
13.   update pheromone;
14.   End while
15. end
16. return best possible path;

4.3.4 Reactive element

In the wireless sensor networks, an event sensed by a sensor node has to be routed towards sink for further processing of the information. In case the source node is not aware of route to sink, it finds the same by sending out route request message in all locally chosen orthogonal directions. In case the neighboring node receiving the route request message also does not know the route towards sink node, it forwards it again while maintaining the similar direction i.e. to neighboring nodes at 180°. Since the source node sends the route request message (RQM) in all locally chosen orthogonal directions, it has high probability to encounter a node that has a path to the sink [5]. When the route request reaches a node with knowledge about the route to sink, no more forwarding is done and it itself sends route reply on behalf of the sink node. When the source receives the route reply message (RRM), it generates a "destination-next hop" routing entry and forwards the packets accordingly.

In case of any link failure between sink and source; the nodes reactively found other energy efficient path to the sink as discussed above. Though nodes are assumed to be densely deployed in the given region but in case if there is no neighbor in the sector covered by the required antenna, the protocol searches for neighbor in the adjacent sectors and if found it forwards the packet to such a neighbor. The allowed deviation is ±90° from the desired direction. The proposed method uses multiplier angle method (MAM) for deviation correction [5]. The pseudo code for the proposed method OD-PRRP is given by Algorithm 3.

Algorithm.3: OD-PRRP

Input: A set consisting of sensor nodes *SNSet*

1. Schedule each node wait time with T_{pro} delay counter
                                                                    // time to start proactive node selection after every T_{pro} time delay
2. if ($T_{pro} = 0$)
3. call Procedure PR_Selection (V_{pro})   //select proactive nodes
4. end if
5. for $\forall\ v \in V_{pro}$
6. call Procedure ANT_ORTHO   // route selection using Ant Colony Optimization in orthogonal directions
7. update route information of nodes falling on
        selected path from V_{pro} to sink node v_s
8. *end for*

9. For each $v \in V$
                If *data_trx(v)* ==1   //node has data to transmit
10. if v has route information
11.   Transmit data using optimal path.
12. Else
            Send *RQM* in all orthogonal directions   // route request
13. Neighbor on receiving route request
14. If neighbor know the path
            Send *RRM* through the way route request received   //route reply
15.   Else forward the *RQM* through orthogonally opposite interface
16.   End if
17. Transmit data using the discovered path
18. End if
19. End for

---

5 Performance Evaluation

In this section, we have evaluated the performance of proposed routing method through MATLAB simulations. For the simulation analysis, wireless sensor network is modeled into fuzzy graph. The simulation metrics and implementation are described in Sect. 5.1. On the basis of metrics discussed in 5.1, performance of the proposed method is compared with EARQ, EAODV and EEABR in Sect. 5.2. In Sect. 5.3, the performance of the proposed method is evaluated in dynamic environment by introducing node mobility. The dynamic performance has been compared with EARQ, EAODV and EEABR in terms of network lifetime, end to end delay, routing overhead and packet delivery ratio.

5.1 Simulation Environment and Metrics

We consider a wireless sensor network consisting of sensor nodes and one base station. The sensor nodes are deployed randomly in a 1000×1000 m^2 sensing field and base station is located at the center. All the nodes have an equal level of initial energy σ i.e. 2 J. Nodes in the network randomly generate multiple messages per communication period. The control and data packet sizes are fixed and kept equal to 64 bytes. To simulate, we used the log distance path loss energy model as presented in [33]. In the simulations, maximum and minimum available powers i.e. P_{max} and P_{min} are defined in terms of communication range of 200 and 80 m respectively.

For each simulated scenario, we generated ten different random topologies and for each topology we performed a simulation run consisting of 800 communication periods. For all final simulation results, each simulation is repeated ten times and a 95 % CI is obtained. Proactive node selection procedure is repeated after every ten communication periods. The anti-pheromone rate ρ is kept fixed at 0.1. In addition to this, the following system parameters as summarized in Table 1 are considered during simulations.

Performance of OD-PRRP is done in terms of: (1) Network life time: Network lifetime is defined as the distribution of alive sensor nodes with respect to number of rounds. For calculating network lifetime, we have considered the number of rounds until the first node, 25, 50 and 75 % nodes die. For each case the number of sensor nodes is varied from 100 to 500. (2) End to end transmission delay is the average of both route discovery latency and data transmission delay experienced by the source nodes while transmitting data packets. (3) Overhead in terms number of packets, which is the ratio of total number of transmitted control packets to the transmitted actual data packets. (4) Packets delivery ratio, which is the ratio of total number of packets sent to the total number of packets received. (5) Load distribution, which presents the average variance and standard deviation in resulted residual energy of nodes after every 100 communication rounds.

The simulation experimental analysis also includes the comparison of the OD-PRRP protocol against routing protocols EARQ, EAODV and EEABR. EARQ, EAODV and

Table 1 Simulation parameters		
E_{elec}		100 nJ/bit
E_{amp}		50 pJ/bit/m^4
M_k		4
N		[100–500]
Route timeout		5 s
Minimum required energy(E_{min})		50 nJ

EEABR address the proactive, reactive and ant colony optimization based category of routing methods respectively. Also, compared protocols represent the energy aware approach of routing in wireless sensor networks. In EARQ, based upon the delay, reliability and energy consumption from a node to sink, probabilities are assigned to nodes proactively. Whenever actual data is to be communicated, a node selects the next forwarding neighbouring node based upon the proactively maintained probability values. EAODV is an extension of one of the basic reactive routing protocol AODV and comes out to be more competant than AODV for wireless sensor networks due to its ability to consider suitable transmission power required for transmission and total power consumption while selecting a route. EEABR is a ACO based method, which proactively forms routes from source to sink nodes. In EEABR, pheromone updation is based on the length of the route in terms of hops, average residual energy and minimum residual energy of the route. For the simulation of EARQ, EAODV and EEABR protocols, we use the same values as suggested in [9–11] for its parameters. For comparison same random seed has been used to generate the identical WSN topology.

5.2 Results

In this section, we analyze the simulation results. The comparison of the results is in terms of five parameters i.e. network life time, route discovery latency, overhead, packets delivery ratio and load distribution is discussed as under:
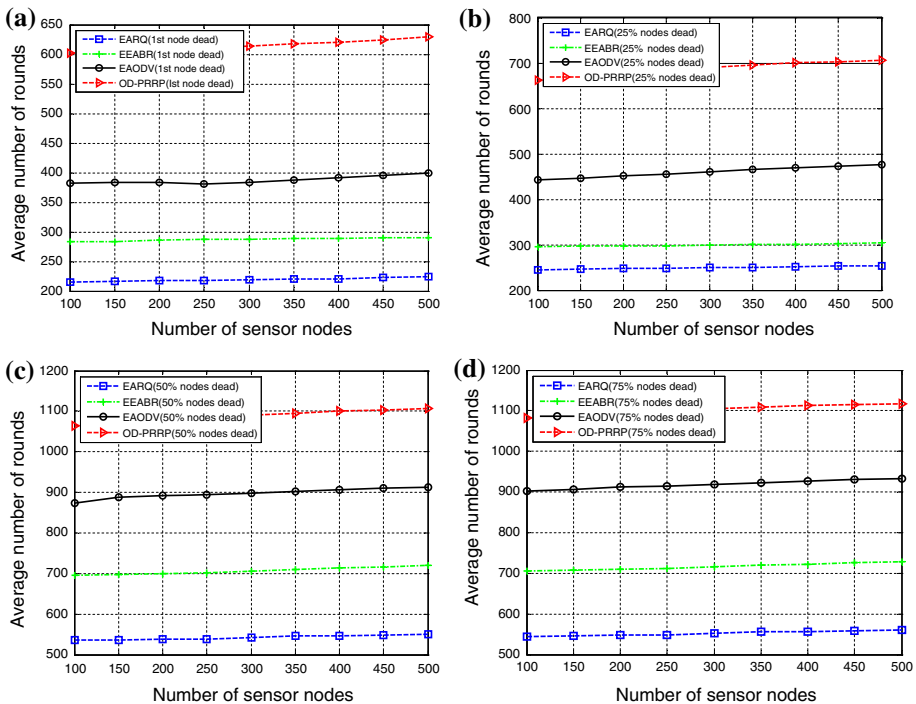
Fig. 4 Lifetime comparison between EARQ, EAODV, EEABR and proposed OD-PRRP with varying number of sensor nodes

5.2.1 Network lifetime

This metric examines the energy efficiency by calculating the number of alive nodes. The simulation results for network lifetime are shown in Fig. 4a–d. Figure 4a shows the number of communication rounds when 1st node drain off the energy. Figure 4b–d shows the number of rounds before 25, 50 and 75 % nodes of the network are dead. The network is considered operationally dead when 50 % of the nodes drain off their energy and when 75 % of the nodes drain off their energy the network is considered fully dead. For observing network lifetime, the number of sensor nodes is varied from 100 to 500. The results indicate that the better performance of our proposed method results in deferment of death of the nodes indicating thereby highest operational network life. The reasons for better performance can be attributed to the following factors:

1. Performance of EARQ and EEABR in terms of network lifetime is lowest, because it uses a pure proactive method and energy dissipated during proactive route discovery is quite high.
2. OD-PRRP has outperformed with respect to EARQ and EAODV as OD-PRRP has used orthogonal direction transmission, has characteristics of both reactive and proactive routing protocol.
3. OD-PRRP has considered expected residual energy, hop distance and required transmission power as decision parameter to select next suitable forwarder node. The ability of OD-PRRP to maintain even load distribution results in more number of functional rounds and results in improved network lifetime.

5.2.2 End to End Transmission Delay

This metric examines the average of both route discovery latency and data transmission delay experienced by the source nodes while transmitting data packets. The average end-to-end delay is measured in seconds. The route discovery latency is the time lag between the transmission of route request and receipt of route reply. Transmission delay of a data
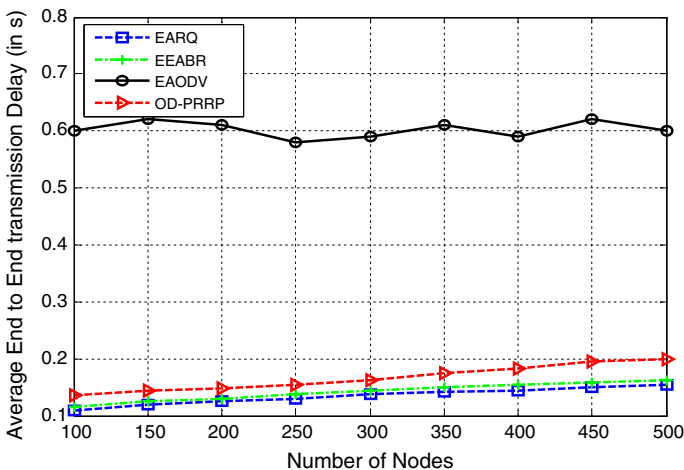
Fig. 5 Comparison of end to end delay in terms of seconds with varying number of sensor nodes

packet is the time period between transmission of data packet by source node and receipt of same at sink node.

The results for average end-to-end delay are shown in Fig. 5. From the results it has been observed that average end to end delay for EARQ, EEABR and OD-PRRP increases with increase in number of nodes. Moreover, results indicate that EARQ performs best in terms of low packet delivery delay. The resulted end to end delay in case of OD-PRRP is slightly higher than EARQ and EEABR, but the same is lower than EAODV.

5.2.3 Overhead in terms number of packets

Figure 6 shows the overhead i.e. control packets transmitted by nodes for finding routes for OD-PRRP, EARQ, EAODV and EEABR. This observation is obtained at different network densities. The Fig. 6 shows the overhead increases with increase in network density. However, for all the node densities resulted overhead in OD-PRRP is lower than EARQ, EAODV and EEABR. The observed overhead is lower due to route finding both proactively and reactively in orthogonal directions.

5.2.4 Packets delivery ratio

In Fig. 7 the performance of OD-PRRP, EARQ, EAODV and EEABR is observed in terms of packet delivery ratio by varying the number of nodes and number of flows. As shown in Fig. 7, as the number of sensor node increases, there is an increase in packet delivery ratio in the network. This increase in delivery ratio is due to increased connectivity of nodes. For simulations of packet delivery ratio, Data generation is done on the basis of probability P, *only if P is greater than a certain value* then node transmits a data packet to base station. Thus it is not necessary that in each round every node will generate data and there may be some nodes which are not generating data. It has been observed that packet delivery ratio in OD-PRRP is better as compared to EAODV and is comparable to EARQ and EEABR. Also number of packets successfully transmitted has improved. Improvement in delivery
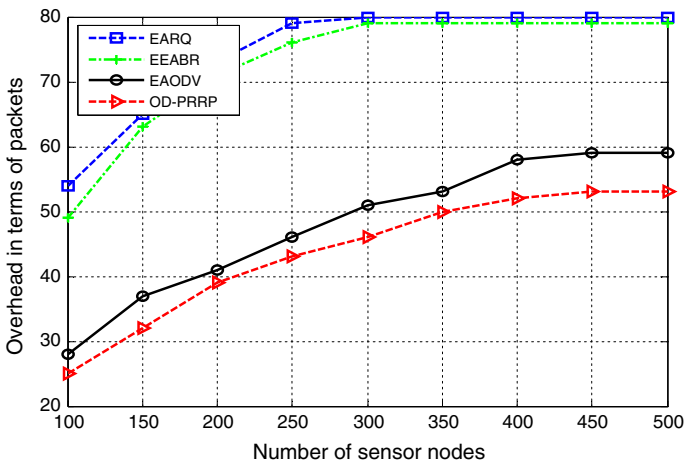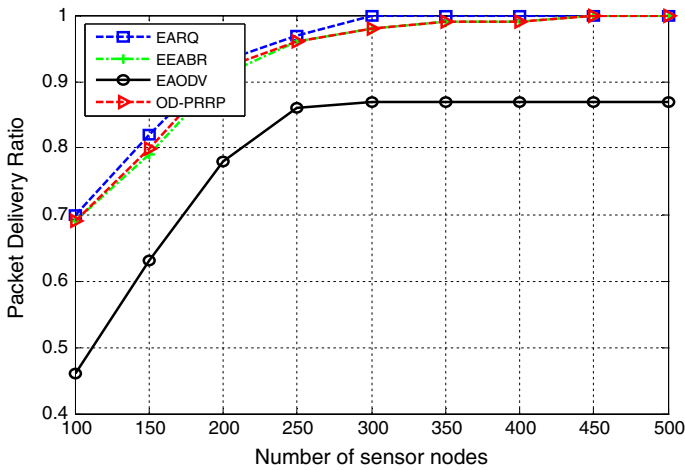

Fig. 6 Comparison of overhead in terms of packets with varying number of sensor nodes

Fig. 7 Comparison of packet delivery ratio with varying Number of sensor nodes

ratio as well successful transmission of packets can be attributed to directional communication.

5.2.5 Load distribution

Load distribution calculations are done on the basis of average and standard deviation in residual energy of nodes after every 100 communication rounds. Figure 8 shows the average remaining energy of the nodes with respect to communication rounds. From the Fig. 8 is has been observed that as the number of rounds increase, OD-PRRP obtains high average remaining energy after communicating as the number of rounds increases. This is because of directional communication and low overhead. Further, it has been observed that energy consumption in OD-PRRP is more linear than other approaches, which is due to
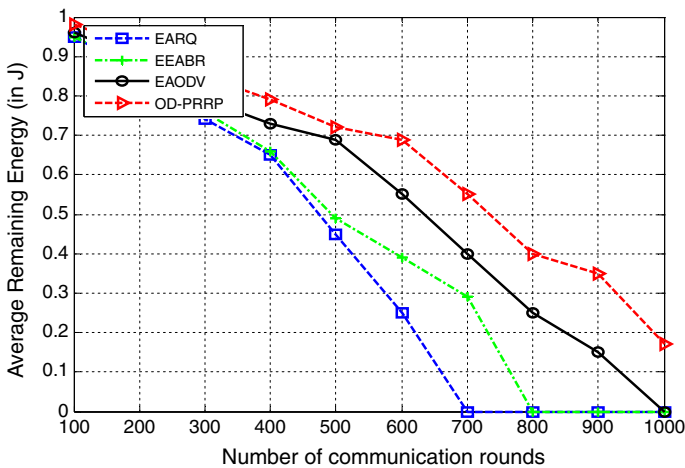
Fig. 8 Comparison of average remaining energy after every 100 communication rounds for 200 deployed sensor nodes
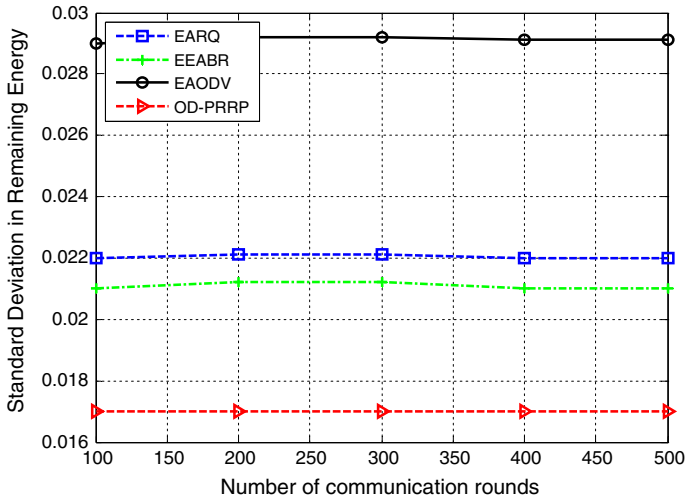
Fig. 9 Comparison of standard deviation of remaining energy after every 100 communication rounds for 200 deployed sensor nodes

orthogonal directional communication. Hence it can be inferred that energy utilization is more balanced in OD-ODRP.

In Fig. 9 we have calculated the standard deviation of the remaining energy at the end of every 100 communication rounds. Our proposed method has resulted in steady energy consumption by the sensor nodes. In OD-PRRP directional orthogonal communication with both reactive and proactive protocols, the energy consumption by sensor nodes is more uniform. This in turn makes more uniform energy consumption by sensor nodes during simulation time and in turn results in least standard deviation.

Thus the overall simulation results indicate that OD-PRRP performs better than other state of art methods i.e. EARQ, EAODV and EEABR. The same can be attributed to the orthogonal directional transmission and harnessing the benefits of both proactive and reactive methodologies.

5.3 Performance of the OD-PRRP in Dynamic Environment

In this section, we have analyzed the performance of the OD-PRRP, EARQ, EEABR and EAODV in dynamic environment i.e. after incorporating node mobility. For mobile environment, the performance has been evaluated in terms of its effect on network lifetime, packet overhead, end-to-end transmission delay and packet delivery ratio. In order to evaluate the performance of the methods for dynamic WSNs, we have used random waypoint mobility model which gives a true random node movement as expected in many mobile WSN applications. The Random Waypoint Mobility Model (RWMM) includes pauses between changes in direction and/or speed [41]. A mobile node begins by staying in one location for a certain period of time (i.e. pause). Once this time expires, the mobile node chooses a random destination in the simulation area and with a speed that is uniformly distributed between [min-speed, max-speed]. The mobile node then travels toward the newly chosen destination at this speed. Upon reaching the destination, mobile node pauses for a specified period of time before it again repeats this process.
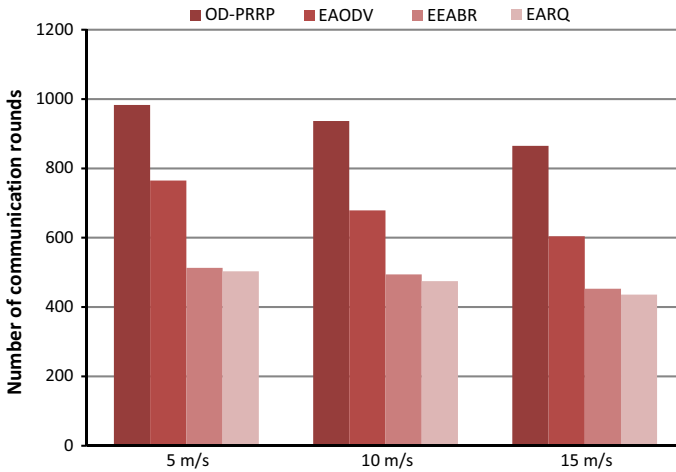
**Fig. 10** Lifetime comparison between EARQ, EAODV, EEABR and proposed OD-PRRP at different node speeds
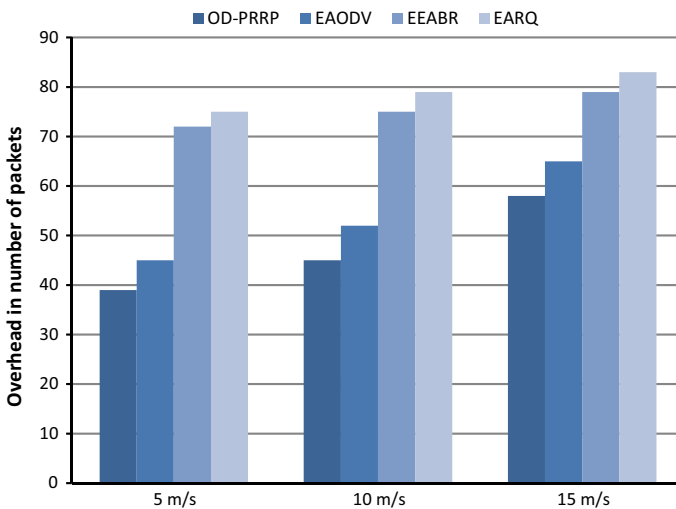
Fig. 11 Comparison of overhead in terms of packets at different node speeds, node density 200

For the simulations, route timeout parameter has been introduced and its value is set as 5 s [5, 9]. The simulation is done for a time period of 200 s, while keeping the other simulation parameters as considered in previous section. The performance of the protocols is evaluated at node density 200 and speeds viz. 5, 10 and 15 m/s are considered for node movement. These speeds have been chosen on the basis of some practical mobile WSN applications such as water quality monitoring in closed environment (low speed), health care monitoring (medium speed) or border security surveillance monitoring (higher speeds). The results calculated are based on the average of 50 trials of simulation.

Simulation results in Fig. 10 show the network lifetime of all the considered methods at different node speeds. From the analysis it has been observed that the network lifetime of
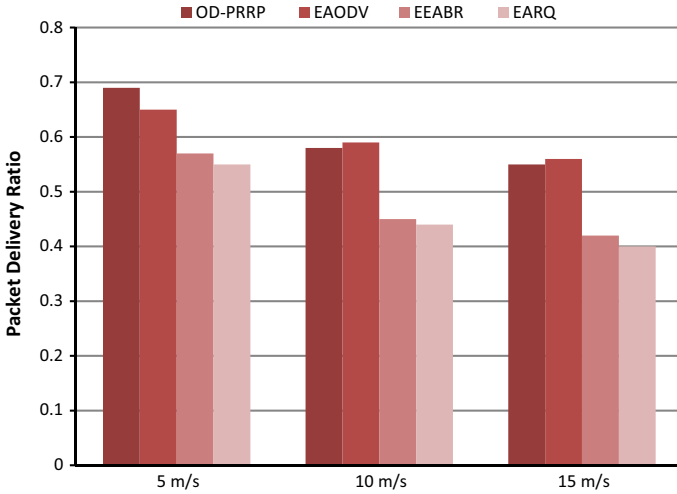
Fig. 12 Comparison of packet delivery ratio at different node speeds, node density 200
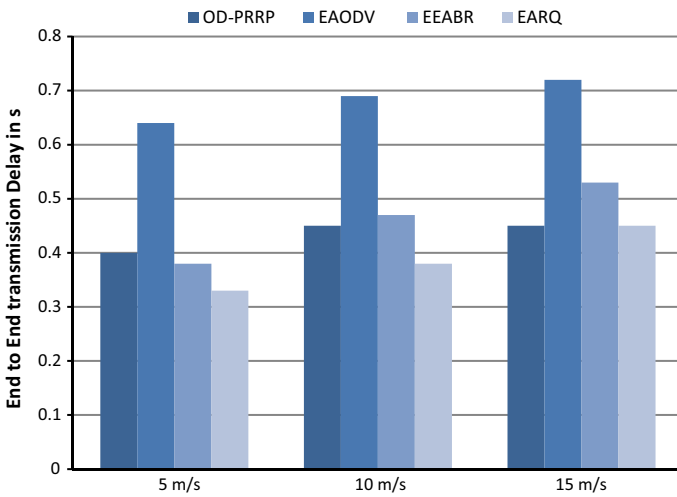
Fig. 13 Comparison of end to end delay in terms of seconds at different node speeds, node density 200

the all the methods decreased with the increase in node speed. However, the performance of OD-PRRP is better than other methods.

In respect to simulation results pertaining to overhead as shown in Fig. 11, it has been observed that in case of all the considered methods there is increase in overhead with increase in node speed. However at all the node speeds, our proposed method results low overhead as compared to other methods.

Figure 12 shows the comparison of packet delivery ratio at different node speeds. From the results it has been observed at low speeds, the packet delivery ratio of OD-PRRP,

EAODV is comparable. However at higher speeds, EARQ performs marginally better than OD-PRRP. The packet delivery ratio of EEABR and EARQ is lower at all the speeds.

Figure 13 shows that the end-to-end delay of OD-PRRP is lower than EAODV at all node speeds and is comparable to EARQ and EEABR at lower movement speeds viz. 5 and 10 m/s. From the results, it has been observed the proposed method OD-PRRP performs reasonably well in dynamic environments and can also be applied to mobile WSNs.

6 Conclusion

In this paper, we presented an ant colony optimization based proactive reactive routing protocol (OD-PRRP), which has used fuzzy graph and orthogonal directional transmission. The simulation results of our proposed protocol OD-PRRP shows reduction in control overhead without compromising at cost and energy efficiency and without requirement of global position information. In OD-PRRP, both the proactive routing and reactive routing methodology has been used to achieve fast response along with lower overhead. In the proposed method we have modeled the wireless sensor network as fuzzy edge and vertex graph. The proposed modeling by fuzzy graph has addressed the significant issue arising from the dynamic nature of the WSNs i.e. non uniform energy consumption while ensuring optimization of transmission power. The performance of OD-PRRP has been evaluated by comparing with existing available methods viz. EARQ, EAODV & EEABR and the results indicated that it performs better at all significant parameters viz. Network lifetime, packet delivery ratio, delay and load distribution. The method can be applied for design of several types of sensor networks that require energy efficiency, scalability, prolonged network lifetime, and low control overhead without requiring location information e.g. in secured battlefield surveillance, habitat monitoring, underwater monitoring, and underground coal mine monitoring. The performance of the purposed method has also been evaluated in dynamic environment. From the results, it has been observed the proposed method OD-PRRP performs reasonably well in both static and dynamic environment. In future the proposed work can be extended for optimized routing in wireless mesh and adhoc networks.

References

1. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: A survey. *Computer Networks, 38*(4), 393–422.
2. Elson, J., & Römer, K. (2003). Wireless sensor networks: A new regime for time synchronization. *ACM SIGCOMM Computer Communication Review, 33*(1), 149–154.
3. Yick, J., Mukherjee, B., & Ghosal, D. (2008). Wireless sensor network survey. *Computer Networks, 52*(12), 2292–2330.
4. Akkaya, K., & Younis, M. (2005). A survey on routing protocols for wireless sensor networks. *Ad Hoc Networks, 3*(3), 325–349.
5. Cheng, B. N., Yuksel, M., & Kalyanaraman, S. (2009). Orthogonal rendezvous routing protocol for wireless mesh networks. *IEEE/ACM Transactions on Networking (ToN), 17*(2), 542–555.
6. Lee, S., Choe, H., Park, B., Song, Y., & Kim, C. K. (2011). LUCA: An energy-efficient unequal clustering algorithm using location information for wireless sensor networks. *Wireless Personal Communications, 56*(4), 715–731.
7. Perkins, C. E., & Royer, E. M. (1999, February). Ad hoc on-demand distance vector routing. In *Second IEEE workshop on mobile computing systems and applications, 1999. Proceedings. WMCSA'99*. IEEE, pp. 90–100.

8. Dorigo, M. (Ed.) (2006). *Ant colony optimization and swarm intelligence: 5th international workshop, ANTS 2006, Brussels, Belgium, September 4–7, 2006, Proceedings* (vol. 4150). Springer.

9. Heo, J., Hong, J., & Cho, Y. (2009). EARQ: Energy aware routing for real-time and reliable communication in wireless industrial sensor networks. *IEEE Transactions on Industrial Informatics, 5*(1), 3–11.

10. Li, W., Chen, M., & Li, M. M. (2009). An enhanced AODV route protocol applying in the wireless sensor networks. In *Fuzzy information and engineering volume 2*. Berlin Heidelberg: Springer, pp. 1591–1600.

11. Camilo, T., Carreto, C., Silva, J. S., & Boavida, F. (2006). An energy-efficient ant-based routing algorithm for wireless sensor networks. In *Ant colony optimization and swarm intelligence*. Berlin Heidelberg: Springer, pp. 49–59.

12. Perkins, C. E., & Bhagwat, P. (1994, October). Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *ACM SIGCOMM computer communication review*, vol. 24(4). ACM, pp. 234–244.

13. Clausen, T., Jacquet, P., Adjih, C., Laouiti, A., Minet, P., Muhlethaler, P., & Viennot, L. (2001). Optimized link state routing protocol (OLSR). In *IEEE INMIC'01*, pp. 151–162.

14. Ogier, R., Templin, F., & Lewis, M. (2003). *Topology dissemination based on reverse-path forwarding (TBRPF): Correctness and simulation evaluation*. Technical report, SRI International, Menlo Park, California.

15. Johnson, D. B., & Maltz, D. A. (1996). Dynamic source routing in ad hoc wireless networks. In *Mobile computing*. US: Springer, pp. 153–181.

16. Lee, S.-J., Gerla, M., & Chiang, C.-C. (1999, September). On-demand multicast routing protocol. In *Proceedings of IEEE WCNC*.

17. Yu, J. Y., Chong, P. H. J., & Zhang, M. (2008, September). Performance of efficient CBRP in mobile ad hoc networks (MANETS). In *Vehicular technology conference, 2008. VTC 2008-Fall. IEEE 68th*. IEEE, pp. 1–7.

18. Karp, B., & Kung, H. T. (2000, August). GPSR: Greedy perimeter stateless routing for wireless networks. In *Proceedings of the 6th annual international conference on mobile computing and networking*. ACM, pp. 243–254.

19. Beijar, N. (2002). *Zone routing protocol (ZRP)*. Finland: Networking Laboratory, Helsinki University of Technology.

20. Intanagonwiwat, C., Govindan, R., Estrin, D., Heidemann, J., & Silva, F. (2003). Directed diffusion for wireless sensor networking. *IEEE/ACM Transactions on Networking, 11*(1), 2–16.

21. Sohrabi, K., Gao, J., Ailawadhi, V., & Pottie, G. J. (2000). Protocols for self-organization of a wireless sensor network. *IEEE Personal Communications, 7*(5), 16–27.

22. Chang, J. H., & Tassiulas, L. (2004). Maximum lifetime routing in wireless sensor networks. *IEEE/ACM Transactions on Networking (TON), 12*(4), 609–619.

23. Li, G., Wang, L., & Li, H. (2008, April). Multiple-objective fuzzy decision making based routing protocol for wireless sensor networks. In *IEEE international conference on networking, sensing and control, 2008. ICNSC 2008*. IEEE, pp. 1273–1278.

24. Younis, O., & Fahmy, S. (2004). HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing, 3*(4), 366–379.

25. Minhas, M. R., Gopalakrishnan, S., & Leung, V. C. (2009, April). An online multipath routing algorithm for maximizing lifetime in wireless sensor networks. In *Sixth international conference on information technology: New generations, 2009. ITNG'09*. IEEE, pp. 581–586.

26. Jabbar, S., Minhas, A. A., Akhtar, R. A., & Aziz, M. Z. (2009, December). REAR: Real-time energy aware routing for wireless adhoc micro sensors network. In *Eighth IEEE international conference on dependable, autonomic and secure computing, 2009 (DASC'09)*. IEEE, pp. 825–830.

27. AlShawi, I. S., Yan, L., Pan, W., & Luo, B. (2012). Lifetime enhancement in wireless sensor networks using fuzzy approach and A-star algorithm. *IEEE Sensors Journal, 12*(10), 3010–3018.

28. Ortiz, A. M., Olivares, T., Castillo, J. C., Orozco-Barbosa, L., Marrón, P. J., & Royo, F. (2010, October). Intelligent role-based routing for dense wireless sensor networks. In *2010 third joint IFIP wireless and mobile networking conference (WMNC)*. IEEE, pp. 1–6.

29. Ahvar, E., Pourmoslemi, A., & Piran, M. J. (2011). Fear: A fuzzy-based energy-aware routing protocol for wireless sensor networks. arXiv preprint arXiv:1108.2777.

30. Ding, N., & Liu, P. X. (2005). A centralized approach to energy-efficient protocols for wireless sensor networks. In *2005 IEEE international conference on mechatronics and automation* vol. 3. IEEE, pp. 1636–1641.

31. Wen, Y. F., Chen, Y. Q., & Pan, M. (2008). Adaptive ant-based routing in wireless sensor networks using Energy* Delay metrics. *Journal of Zhejiang University SCIENCE A, 9*(4), 531–538.

32. Liu, Y., Zhu, H., Xu, K., & Jia, Y. (2007, August). A routing strategy based on ant algorithm for WSN. In *Third international conference on natural computation, 2007. ICNC 2007, v*ol. 5. IEEE, pp. 685–689.
33. Rappaport, T. S. (1996). *Wireless communications: Principles and practice* (Vol. 2). New Jersey: Prentice Hall PTR.
34. Koczy, L. T. (1992). Fuzzy graphs in the evaluation and optimization of networks. *Fuzzy sets and systems, 46*, 307–319.
35. Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*(3), 338–353.
36. Ross, T. (2004). *Fuzzy logic with engineering applications* (2nd ed.). Chichester: Wiley.
37. Heinzelman, W. B., Chandrakasan, A. P., & Balakrishnan, H. (2002). An Application-specific protocol architecture for wireless microsensor networks. *IEEE Transactions on Wireless Communications, 1*(4), 660–670.
38. Kheireddine, M., & Abdellatif, R. (2014). Analysis of hops length in wireless sensor networks. *Wireless Sensor Network, 6*(6), 109–117.
39. Correia, L. H., Macedo, D. F., Silva, D. A., dos Santos, A. L., Loureiro, A. A., & Nogueira, J. M. S. (2005, October). Transmission power control in MAC protocols for wireless sensor networks. In *Proceedings of the 8th ACM international symposium on modeling, analysis and simulation of wireless and mobile systems.* ACM, pp. 282–289.
40. Maniezzo, V., & Carbonaro, A. (2002). Ant colony optimization: An overview. In *Essays and surveys in meta heuristics.* Springer US, pp. 469–492.
41. Camp, T., Boleng, J., & Davies, V. (2002). A survey of mobility models for ad hoc network research. *Wireless Communications and Mobile Computing, 2*(5), 483–502.

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