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Dynamic directional routing for mobile wireless sensor networks

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ABSTRACT

The interest in Mobile Wireless Sensor Networks (MWSN) has grown considerably due to its various applications in the fields of military, industrial infrastructure, automation, health, traffic, and many consumer areas. Hence, as the modern world shifting to the age of IoT with possibly new emerging technologies and applications, there will be a number of implications that influence the design and deployment of such networks. Precisely, residual energy utilization, mobility, topology, scalability, and data routing are key factors in the design of MWSN to meet application's specific demand. This article presents a novel routing protocol that adapt to the mobility of sensor nodes to achieve a reliable and energy-efficient routing. The proposed scheme is dynamic directional routing (DDR) to control the flow of data in network, which optimizes the routes toward the sink. The protocol has been evaluated and compared with state-of-art protocols, and the simulation results show that DDR protocol can improve network lifetime by around 13% compared to T-LEACH protocol. It also enhances the packet delivery rate, energy consumption, while maintain shorter routes toward the sink by around 33% compared to T-LEACH protocol.

1. Introduction

In today's world, smart grid, intelligent transportation, and many other applications, are infrastructure systems that connect the word by a common vision of internet of things (IoT), through the use of sensors coupled with information and communication technologies. In such systems, a large number of devices are interconnected to transmit specific measurements and control instructions via distributed wireless sensor networks (WSN). One of the major advancements in the WSN field is the introduction of the Mobile Wireless Sensor Network (MWSN) being much more versatile than static WSNs as the deployed sensor nodes have to adapt to the changes in the network's topologies. Examples of applications of MWSNs are military surveillance, habitat monitoring, agriculture applications, healthcare management, industrial monitoring, and environment monitoring [1–3]. However, MWSNs have major design challenges such as the hardware cost, system architecture, memory and battery size, processing speed, dynamic topology, sensor mobility, scalability, localization, coverage, protocol design, etc. [4,5].

MWSNs introduce mobility in two approaches, either by having static sensor nodes while the sink devices are moving, while in the second approach the sink devices are static, and the sensor nodes are mobile. Examples of the first approach include crops on a farm deploying sensors and sending measurements about the humidity and temperature to the farmer's smartphone as he/she walks in the field. The second approach is clarified by static sink that can be used to collect tracking information stored in sensor nodes when the animals are in its range. The two approaches can be combined to have all nodes mobile such as in assistant personnel systems.

Mobile sensor nodes consist of a microcontroller, various sensors (i.e., light, temperature, humidity, pressure, mobility, etc.), a radio transceiver powered by a battery [6–8]. Usually the sensor nodes are deployed on land, underground, under water environments, and can be classified into heterogeneous or homogenous [9,10]. The heterogeneous nodes in MWSNs consists of sensor nodes that have identical properties, but the homogenous MWSNs consist of identical sensor nodes according to the resources of the sensor nodes such as battery power, memory size, computing power, sensing range, transmission range, and mobility, etc. [11].

The unique characteristic of MWSNs imposes extra challenges on the design of an efficient routing protocol that considers the dynamicity of the network's topology, node's mobility, and other node's related constraints such as energy, computation complexity, resource availability,

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storage, and bandwidth. Therefore, this article discusses some of the challenges related to mobility and routing in MWSN, as well as proposes a mobility-based routing protocol that enhance the reliability of MWSN based on the geographical placement of sensor nodes.

The rest of the article is structures as follows: Section 2 presents a background theory in relation to WSN, mobility and topology and reviews the existing routing protocols in WSN. Section 3 explains the proposed DDR routing approach and the relevant algorithms, while Section 4 illustrates the system setup and presents the performance analysis of the proposed protocol as compared to state-of-art protocols. Finally, Section 5 concludes the article.

2. Background theory

2.1. Mobility and topology in MWSN

The effectiveness of large scale mobile wireless sensor networks depends on communication reliability, network connectivity, data collection, sensor mobility, and management of network topology [12]. Therefore, the accurate modelling of sensor mobility and topology management is a key element when designing an appropriate, and efficient routing protocols for WSNs. The topology provides a reliable network and better QoS in terms of traffic, and end-to-end connectivity, while mobility characterizes the behaviour of sensor nodes through their movement pattern [13,14].

Network topology management is the task responsible for managing the membership of sensor nodes group by managing the new and withdrawn members. Depending on the nature of the MWSN, in order to achieve the best performance and to ensure reliable data gathering, different types of network topologies are deployed. The available topologies are flat or unstructured, chain, mesh, tree, clustered, and hybrid [6,15]. Network topologies can also be classified as:

- Distributed topology: In this topology there is no management by central node, hence the network consists of nodes having equal roles and not prior infrastructure is imposed before the network start running.
- Hierarchical topology: The organization of senor nodes in this topology can be in several levels, making a hierarchical topology. WSNs are more manageable and scalable in this hierarchical topology.
- Centralized topology: All the sensor nodes in this topology have the task of sensing new information and sending it to central node for processing. However, a single point of failure the main problem of this topology.

On the other hand, the modelling of node's mobility predicts the future positioning of the sensor nodes. Thus, it brings the opportunity of reducing the number of hopes to the sink nodes, which results in a reduction of the latency. However high mobility scenarios can reduce the successful transmission of data to the sink nodes, therefore, increasing the complexity of the routing protocols [16–18]. Here, different mobility models can be applied to the sensor nodes or sinks depending on the application of the MWSN, by characterizing the mobile sensor movement patterns either in an independent or dependant way. Mobility models can define the movement of the sensor nodes using both analytical or simulation based models [19]. The analytical models usually provide simple mathematical models for the change in node's movement. In contrast, the simulation-based models provide more realistic mobility scenarios by introducing more complicated solutions. The mobility can further be classified into (a) trace models: a deterministic mobility pattern of real-life systems; (b) syntactic models: represents the movements towards/ away mobile sensor nodes realistically. Another classification based on mobility patterns and histories such as directional, random, and habitual mobility models. Generally, the various models available in the literature can be classified into four major categories including: random, temporal dependency, spatial, and geographic-restricted models.

2.2. Routing in MWSN

Data routing plays an important role in WSN as it performs a substantial task in establishing routing paths between sensor nodes and forwarding the data packets between the sensor nodes and the sink. Therefore, the main objective of the routing protocols is the establishment of effective paths between the sensor nodes in the network. In MWSN, the routing protocols should consider mobility, data redundancy, energy efficiency, and the dynamic nature of network topology. For this, routing in MWSNs should be carefully managed and employed due to the nature of sensor networks that attract many challenges and limitations [20,21]. Generally, routing protocols are classified based on several properties such as network structure and application, which implies that no single routing mechanism can be efficient and practical for all types of WSN applications [22,23]. Therefore, the routing protocols can be classified as: network structure-based protocols, path establishment-based protocols, initiator of communications protocols, and operation-based protocols [24]. Routing protocols based on network structure are broken down into flat-based, hierarchical-based, and location-based. On the other hand, the operation-based category splits up into multipath-based [25], query-based, negotiation-based, QoS based, and coherent/non-coherent-based. Whereas proactive, reactive, and hybrid protocols fall under path establishment-based category [26] .

First, in network structure-based approach, the flat-based routing is suitable for large networks with huge number of deployed sensor nodes, where it is infeasible to assign global identifiers (IDs) to each and every node in the network [27]. This lack leads to data-centric routing approach, where all nodes in the network are equal and perform the same functionality. Examples of the major Flat based routing Protocols are: Flooding [22], Gossping [28], Directed Diffusion [29], rumor Routing [30], Minimum Cost Forwarding Algorithm [31], Active Query forwarding in sensor networks [32],etc., In addition, the hierarchical or cluster-based routing is another well-known routing approach that aims to optimize energy consumption by dividing the network into clusters, each controlled by a cluster head, so the routing is performed in two layers. Cluster heads are responsible for collecting data from cluster members, processing them, then forwarding it to the sink through other cluster heads. Clustering-based routing has proven to optimize power consumption and prolong network lifetime. Examples of such routing techniques are: Low-Energy Adaptive Clustering Hierarchy (LEACH) [33], Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [22], Threshold-sensitive Energy Efficient Protocols (TEEN) [31], Adaptive Periodic Threshold-sensitive Energy Efficient protocol (APTEEN), etc. Finally, in location-based routing, the routing decision is based on nodes locations, which implies that nodes are aware of their location information, using either the Global Positioning System (GPS) or other technologies. The location information can be used by nodes to optimize the routing path by considering energy consumption [34]. Examples of such protocols are Geographical Adaptive Fidelity (GAF), Geographical and Energy Aware Routing (GEAR), and Minimum Energy Communication Network (MECN) [35,6].

The second approach of routing protocols is based on the protocol operation and functionality. Some of the routing protocols in this approach fall under the categories: multipath routing protocols, query-based routing protocols, and negotiation-based routing protocols. In multipath routing protocols, the routing protocols use multiple paths to transmit data packets to the base station. Due to the usage of alternative paths, such protocols can offer lower end-to-end delay. Examples of this category include DD and SPIN [36]. In addition, the query-based routing is another class of protocols that permit the base station to send a query messages to nodes to request particular information. COUGAR, DD, and RR are examples of query-based routing protocols [37]. To minimize the level of data redundancy, negotiation-based routing protocols are used to achieve this by performing negotiation between neighbour nodes and selecting the optimized route. SPIN is a good examples of negotiation-based routing protocols [38].

The last category of protocols to discuss in this article is the path establishment-based routing protocols. In these protocols, the routing paths can be established in different way such proactive, reactive, and hybrid. The proactive protocols compute all routing paths and store them in a routing table in each node, and then maintained even if there is no data flow. In reactive routing, routing paths are computed only on demand. The hybrid routing protocols are combination of both proactive and reactive routing protocols [32].

2.3. Related work

In this article, the proposed routing protocol relies on the geographic information of the network sensor nodes to establish routing paths between the source nodes and sink devices. Many relevant protocols have been proposed in the literature that uses location information for routing decisions. It is assumed in this type of protocols, sensor nodes have access to location information by using low power GPS module, or it use distributed localization schemes based on the received signal power (RSSI), signals time of arrival, etc. Therefore, in position-based protocols [39,40], sensor nodes usually identifies the position of their neighbour nodes through periodic "Hello" messages, hence, reducing the communication overhead resulting from flooding. However, obtaining the location information of nodes is a costly process due to message transfer overhead and energy consumption especially in case of mobile nodes. Examples of position-based routing protocols are:

- Geographical Energy Aware Routing (GEAR) [41]: it is an energy aware geographic protocol that uses energy-aware metric to select neighbours and balance the energy consumption and increasing the network lifetime. The protocol implements a cost function that calculate the cost for reaching a neighbour based on its location and residual level.
- Geographical Adaptive Fidelity (GAF) [42]: it builds a geographical grid that consists of cells, each contains multiple cells, but in every cell, one node is active at a time. GAF aims at extending the network lifetime and lower energy consumption.
- Adaptive Face Routing (AFR) [43]: This an ad hoc routing protocol that is based on the Euclidean planar graphs, such that nodes and edges of a plane are divided into regions called faces. AFR used face routing to traverse the faces in a restricted way. If the face routing fails to deliver the data to the destination, the protocol repeats the same process using eclipse of double size.
- Mobility Aware Routing (MAR) [44]: It is a hierarchal position-based routing protocol, such that the network is divided into geographic grid and cluster heads based on the mobility metric. Hence, the node having the minimum mobility metric is selected as cluster head. The main weakness in this protocol is that it does not consider node energy in the cluster head selection process.
- Geographic Robust Clustering (GRC) [45]: This protocol uses cluster-based routing and select the cluster heads based on energy levels, and nodes position. It also implements inter-cluster communication phase to recover packet loss.
- Minimum Energy Communication Network (MECN) [35]: MECN is an energy-efficient routing protocol that aims to minimize the power consumption of the entire network by using low power GPS. The idea of this protocol is to transmit the data packets through intermediate nodes rather than sending it directly to the base station since direct communication consumes more energy than transmitting data by several relay nodes.

3. Proposed dynamic directional routing approach

In this section, a new routing geographic-based routing protocol named Dynamic Directional Routing is proposed. The DDR protocol provides directional-based routing approach that dynamically adapts the routes to the sink based on the change in the network topology due to sensor nodes mobility. Generally, the data packets are forwarded in a limited zone, and only neighbour nodes that resides within the allowed routing zone defined by a given search angle are allowed to participate in the routing process as clarified in Fig. 1.

In order to explain the routing mechanism, we assume a sensor network that consists of N mobile nodes, all have a same mobility speed of (Vm/s), and moving at random directions. One sink is deployed in this study (*the terms sink and base-station are used alternatively in this article*), which is placed at fixed location (x_s,y_s). We assume the mobile nodes can determine their location using GPS or relevant technologies. The sensor nodes are communicating through the IEEE 802.15.4 and the quality of the communication signals is based on the received signal power as discussed later. A communication with the base-station is established by creating a sector pie-shaped region defined by angle (α) with respect to base-station location. However, in reality it is not necessary that the geographic region which has the potential next hope nodes forms perfect pie shape, as this depends on the topology, node's placement, number of sensor nodes and the search angle assumed. The selection of the next hope is based on two phases as presented below.

3.1. Area discovery phase

When a node has data to transmit, it starts by discovering the area of communication which has the potential next hope candidates. The objective of this phase is the formation of an active region between the source node and the base-station, where all sensor nodes located within this region are considered as potential candidates. Therefore, during this phase the communication between source and the base-station create a virtual pie-shaped region calculated in Eq. (1) and illustrated in Fig. 1.

$$A = \frac{R^2}{2}\left(\frac{\pi}{180}\alpha - \sin\alpha\right) \tag{1}$$

Where α is the central angle in degrees that is fixed for all nodes in the network,R is the distance from the source node to the edge of the network area. Neighbour nodes are classified into competing and non-competing based on their position and direction with respect to the source node. The nodes that are in the active region of source node $x \in A$, while the non-competing nodes are the ones that reside outside the active area of the source node $x \notin A$. It is worth mentioning that the direct path between the source and the base-station is considered the centre of the active region-see Fig. 2. Therefore, in the area discovery

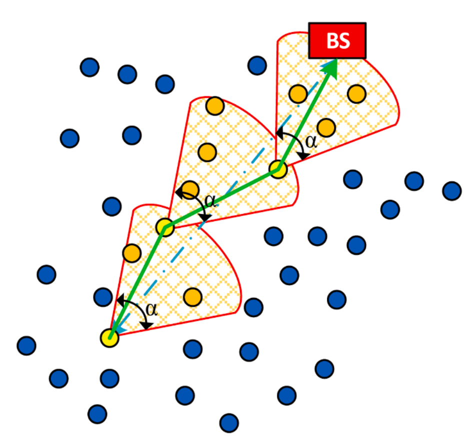

Fig. 1. Illustration of dynamic directional routing within specific routing sector.

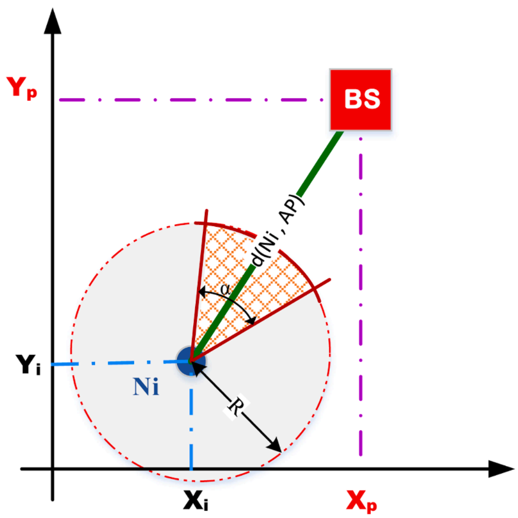

Fig. 2. Source node active region with respect to AP.

phase, the source node initiates the communication process by broadcasting a “discovery” message that contains its location (e.g. X and Y coordinates), and its preferred search angle. Neighbour nodes that receive the message, will check their position relative to the active area of the source node, and will respond to the source node in case they are considered competing nodes. Non-competing nodes ignore the discovery message without replying to the source. The phase-discovery process is clarified in Algorithm 1. It is worth mentioning that the discovery phase is triggered at each transmission attempt for the source node in order to account for the change in the network topology.

3.2. Node selection and data forwarding phase

The competing nodes respond to the source node’s “discovery” message with “available” message, which declares the existence of the competing node within source active area and provide the source node with competing node position (e.g. X and Y coordinates), availability status, and residual energy & received power levels at the competing node side. Having received all “available” messages, the node selection phase starts by creating a temporary database of competing nodes related information, and calculating the distance from the source node to each of completing nodes by solving the Euclidean distance given in Eq. (2):

$$d(N_i,\ AP) = \sqrt{(Xp - X_i)^2 + (Yp - Y_i)^2} \tag{2}$$

The source node uses the above-mentioned information to select the optimal next hope based on the Algorithm 2. For simplicity, we consider the network topology is static during phase 1 and 2 by assuming the time needed to accomplish the two phases ($t_{p1,p1}$) smaller than the change in competing node’s positions due to mobility $t_{mobility}$as clarified in Eq. (3):

$$t_{p1,p1} < t_{mobility} \tag{3}$$

According to Algorithm 2, the source node prioritize and select the forwarder list based on the list of competing nodes $\{N\}$responding to the source node, such that the forwarding candidate with residual energy RE_j and received power level Pr_jsatisfying Eqs. (4, 6) are chosen in the filtering process. Then the forwarding candidate satisfying the shortest distance to the sink is selected for data forwarding-Eq. (7). In Eq. (5), the source node calculates the average residual energy $\overline{RE}_{avrg}$ based on the shared information from the competing nodes.

$$RE_j > \overline{RE}_{avrg} \tag{4}$$

Where,

$$\overline{RE}_{avrg} = \sum_{i=1}^{N} RE_i \quad i \in N \tag{5}$$

$$Pr_j > \ Pr_{threshold} \tag{6}$$

$$Min(d\{N(j); Sink\}) \tag{7}$$

The $Pr_{threshold}$is assumed −88 dBm according to study performed in [46] which concluded that a received signal strength of approximately −88 dBm can achieve reliable data delivery in IEEE 802.15.4. The received signal power is calculated based on Eqs. (8, 9) considering the log-normal path-loss model [47]:

$$P_r(dBm) = \ P_t\ (dBm) - -\ PL\ (dB) \tag{8}$$

$$PL\ (dB) = \ PL(d_0) + \ 10nlog\left(\frac{d}{d0}\right) + \ X_0 \tag{9}$$

Where d_0 is the reference distance assigned to 1 m in this study, $PL(d_0)$ is given by $20{*}\log_{10}(4\pi d_0/\lambda)$, the path loss exponent $n = 2$, and χ_0 is the shadowing effect. According to our algorithm and due to mobility in sensor nodes, the same source node may chose different next hope each time it attempt to transmit data since it need to activate the area discovery process in each transmission attempt. This results in adaptive routing based on the change in network topology and nodes positions. As the data is forwarded to the next hope node, the latter will go through the same process again by activating phase 1 and 2 of the DDR protocol in order to choose the next potential node the route toward the base-station.

4. Performance analysis

4.1. Simulation setup

In order to verify and analyse the behaviour of the proposed DDR protocol, a Monte-Carlo simulation is done using Matlab tool, and the simulation performance is averaged over 5000 network realizations in order to achieve adequate simulation accuracy. The simulation environment consists of 500 sensor nodes deployed in two-dimensional geographic space forming a network in an area of 100 m X 100 m, assuming single source - destination pair. Random-waypoint mobility model is used to determine node positions, and packet sizes of 1000 and 100 bits for data and control packets consequently. To transmit β bit data from node(i) to node(j), the energy consumption is given by Eq. (10). However, the energy consumption for receiving β bit data by node (j) is presented by Eq. (11) [48]:

$$\left(\varepsilon_{fs} + \varepsilon_{mp}\ D^2_{(i \leftrightarrow j)}\right)\beta \tag{10}$$

$$E_r(j) = \varepsilon_{fs}\beta \tag{11}$$

Where ε_{fs} is the energy dissipated in transmitting and receiving one bit, while $\varepsilon_{mp}$is the free space amplification factor as clarified in Table 1.

Table 1
Simulation parameters.

Parameter definition	Symbol	Value
Sensor deployment area (Network size)	–	100 m × 100 m
Number of nodes	M	500
Sink position	$Sink$	(1, 1)
Nodes velocity	V	5 m/s
Transmission power	Pt	0 dBm
Initial energy	E_i	2 Joules
Tx or Rx Transceiver energy	ε_{fs}	50 nJ/bit
Free space amplifier energy	ε_{mp}	10 pJ/bit/m^2
Data packet size	β	1000 bits
Control message size	C	100 bits

Algorithm 1
Pseudocode of area discovery phase in DDR protocol.

Input: *nodeID*, $node_{(x,y)}$, $BS_{(x,y)}$, *noderangetransmission*α
Output: find the connected nodes in the rangeα associated with,$node_{(x,y)}$, *ResidualEnergy*, *Pr*, *Avalability* .
For $i \leftarrow 1$ **To** M //M is the total number of nodes in the WSN
$N\_Cur \leftarrow N(i)$ //N(i) is the current node ID
$Tr \leftarrow \left[\widehat{N(i)}_{(x,y)}\ \frac{\alpha}{2},\ \frac{\alpha}{2}\ \widehat{BS}_{(x,y)}\right]$//the Transmission range is the area from Ni to BS with angel α
For$j \leftarrow 1$ **To** $Z \subseteq M$ //Z is the total number of nodes within the transmission range Tr
$N\_Can \leftarrow N(j)$ //N(j) is the candidate node ID
If $N\_Cur \leftrightarrow N\_Can$ **Then** //the connection established
  $NodeID \leftarrow N(j)$
  $node_{(x,y)} \leftarrow N(j)_{(x,y)}$
  $RE \leftarrow RE(j)$
  $\mathrm{Pr} \leftarrow Pr(j)$
  $AV \leftarrow AV(j)$
End If
End For
End For

Algorithm 2
Pseudocode of node selection phase in DDR protocol.

Input: *nodeID*, $node_{(x,y)}$, *ResidualEnergy*(*RE*), *Pr*, *Avalability*(*AV*)
Output: find the connectivity between the nodes.
For $i \leftarrow 1$ **To** M //M is the total number of nodes in the WSN
$N\_Cur \leftarrow N(i)$ //N(i) is the current node ID
For$j \leftarrow 1$ **To** Z //Z is the total number of nodes within the transmission range
$\boldsymbol{RE_{avrg}} = \sum_1^z \boldsymbol{RE_i}/z$ // the average of the residual energy for all Z nodes
Then Do While $i \neq j$
For $k \leftarrow 1$ **To** Z
  $AV \leftarrow Max(AV(k))$
  If $RE(K) > RE_{avrg}$
  If $Pr(K) > Pr_{threshold}$ **Then** // node SNR still in the high level
    // node energy still in the high level
      $N\_Can(l) \leftarrow N(K)$
      $1 \leftarrow l + +$
      Else
        $AV(k) \leftarrow 0$
      End If
  Else
    $AV(k) \leftarrow 0$
  End If
  End For
For $l \leftarrow 1$ **To** M//M is the total number of nodes fit with the previous requirements
  $dis \leftarrow Min(d\{N(l); Sink\})$
  If $dis = d\{N(l); Sink\}$ **Then**
    $N\_Can \leftarrow N(1)$
  End If
End While
End For
End For

4.2. Simulation results

The performance of the proposed DDR protocol is evaluated in terms of terms of network lifetime, energy consumption, packet delivery rate, and length of routing paths. The protocol is benchmarked against relevant state-of-art protocols: T-LEACH [49] and the area-based routing protocol proposed in [50]. T-LEACH is an enhanced version of the well-known LEACH protocol which considers mobility especially in large-scale area with dynamic and uneven distributed mobile sensor nodes. The protocol uses tree routing mechanism with enhanced power control techniques and multi-hop transmit scheme to improve packet delivery rate and power consumption. On the other hand, the area-based routing uses the relative position of the source and sink nodes to form an active region for routing and deploys an enhanced sleep-wakeup pattern to preserve energy. The protocol uses mobility vector information such as nodes location, mobility direction and speed, along with node residual energy to select a neighbour that provides the optimum connection retention time. Note that, in the implementation of DDR protocol, we assumed the search angel α=60°

4.2.1. Network lifetime

Fig. 3 depicts the number of active nodes over the number of rounds for the proposed DDR protocol, mobile T-LEACH and the area-based routing. We can notice that our DDR protocol provides longer network lifetime as compared to other protocols. The network lifetime for DDR protocol start decreasing after 4500 rounds, compared to 4000 and rounds for T-LEACH and area-based protocols consequently. It is worth mentioning that in the implementation of our DDR protocol. The figure also shows that in case of DDR protocol, all nodes are dead after 9000 rounds, compared to 8000 and 6000 for T-LEACH and area-based routing protocols, which implies 13% and 50% increase in network lifetime as compared to T-LEACH and area-based routing protocols. This could be justified by the fact that our proposed DDR protocol engages the sensors nodes that are within the source active area only (within 60 Degrees from source node perspective) in the process of establishing the route toward the sink. Therefore, there is no need for other neighbour nodes that are close to the source node but outside the active area (non-competing) to participate in the route establishment process and therefore saving their energy and extending the nodes lifetime.

4.2.2. Energy consumption

The second performance criterion that we consider in this study is the transmission energy consumption, which is a crucial factor in MWSN especially in battery constrained networks. The metric is defined as the average percentage of total residual energy for all mobile nodes in the network at each round interval. Fig. 4 shows that DDR protocol outperform the others, such that in the first 1000 rounds, all protocols consumes almost similar level of energy, however, as the number of rounds increase DDR and T-LEACH show better performance compared to the area-based protocol. For instance, after 3000 rounds, the DDR protocol show enhancement of 2% and 5% over T-LEACH and area-based routing protocols consequently. As the number of rounds exceeds 5000, more mobile nodes die which leads to larger differences in average energy consumption between DDR and other protocols.

4.2.3. Packet delivery ratio

The third performance criterion that we assess is the end-to-end packets delivery ratio, defined as the ratio of the number of data packets injected in the network to the number of packets successfully received at the intended addressee. In our simulation we assume one

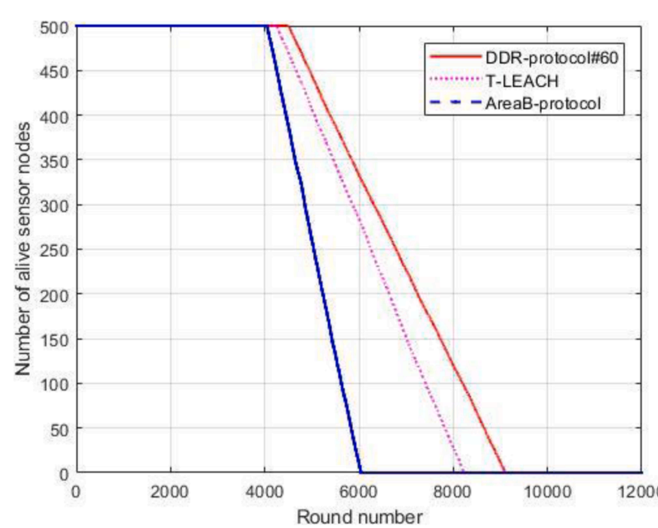

Fig. 3. Comparison of network lifetime.

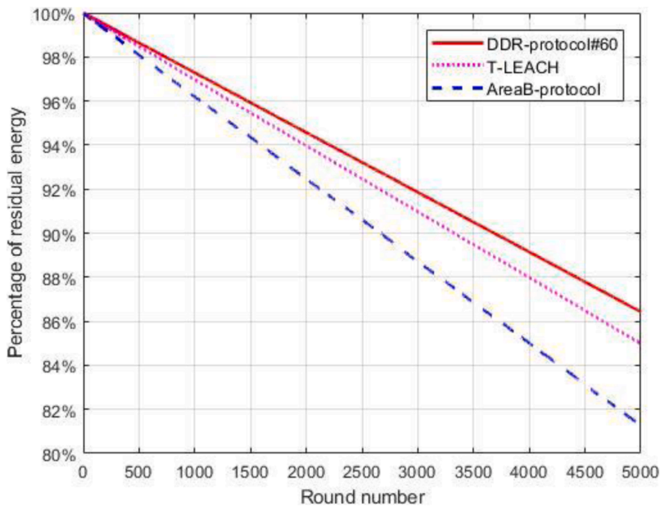

Fig. 4. Comparison of energy consumption.

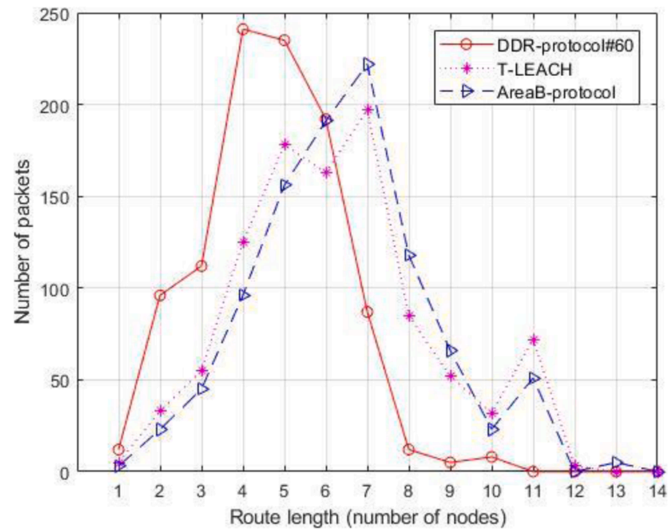

Fig. 6. Comparison of route length.

packet injected by each node in the network in every round, then we measure the percentage of packets delivered successfully to the sink based on the total sent in each round. Fig. 5 depicts the packet delivery rate for the three protocols, as it is clearly shown that DDR protocol offers higher packet delivery rates compared to the other state-of-art protocols. The figure shows a 100% delivery rate for all protocols for the first 3000 rounds, due to the high percentage of alive nodes in the first 3000 rounds as discussed before. As the number of dead nodes increase in the network, the three protocols start to show deviation in their performance, with DDR offering around 98% delivering rate at round number 6000, while T-LEACH and area-based protocol offering delivering rate of 90% and 10% consequently. Due to the higher number of alive nodes in the network in case of DDR protocol, a better delivery rate is achieved

4.2.4. *Average route length*

We have also analysed the average path length for the sensor nodes in our proposed protocol as one of the robust measures in MWSN, with a shorter average path length being more desirable. Path length is calculated by the number of hopes between the source and sink nodes. In order to clarify the impact of the proposed routing mechanism in this context, Fig. 6 presents the total number of packets that followed specific number of path lengths. It is worth mentioning that a total of 1000 packets are injected in the network in this case, where our proposed DDR protocol results in shorter routes length as compared to T-LEACH and the area-based protocols. For instance, 50% of the total packets are delivered to the sink over an average path length of 4 hops in the DDR protocol, while T-LEACH needed an average path length of 6 hops, and the area-based protocol used an average of 7 hops. The shorter path lengths experienced by the DDR protocol resulting from the routing approach that DDR follows, since it uses directional forwarding of data toward the sink, which limits the unnecessary long routs that a packet may follow since only the nodes within a specific directional range with respect to the source will participate in delivering the data, which yields shorter routes. Fig. 6 shows also that the DDR protocol needs an average of 8 routes to deliver all packets, while an average route length of 12 is needed in both T-LEACH and the area-based protocols.

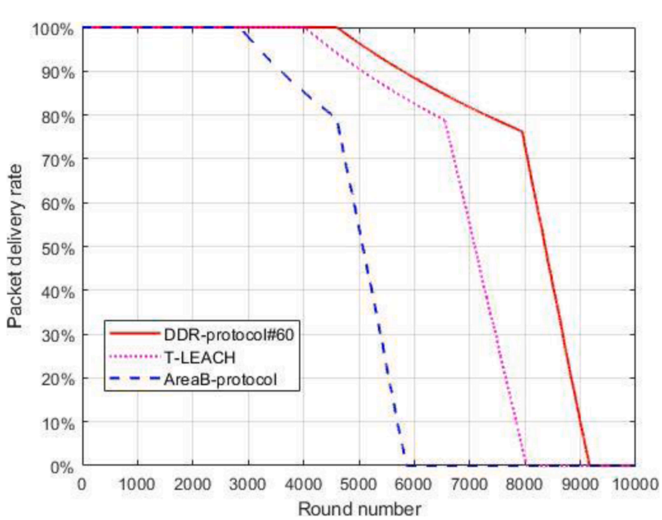

Fig. 5. Comparison of packet delivery ratio.

4.2.5. *Impact of α on DDR*

The results discussed above assumes a search angel of $\alpha = 60^\circ$ to establish the active region for the source node, however, the performance of the DDR protocol is mainly affected by α value. When decreasing α, this yields a smaller number of competing nodes that are engaged in path discovery process, which minimizes the chance of finding a good candidate for data delivery. The source node may need in this case to compromise metrics such as residual energy level, connection quality in order to deliver its data. However, this may also result in very directional transmission of data and shorter paths toward the sink. On the other hand, increasing α allows more nodes to complete in data delivery process by advertising themselves to the source nodes, and this yields better selection process for the optimum next hop node, but increasing the search angle for the source node may results in longer routes that packets may follow due to the wider range of completing nodes positions. In order to select a suitable α, we have carried out the simulation for $\alpha=30^\circ,60^\circ,120^\circ$ Fig. 7 shows the packet delivery rate for DDR protocols assuming different α values, with $\alpha=60^\circ$ & 120° achieving better performance compared to $\alpha=30^\circ$

5. Conclusions

In this article we presented a novel protocol for efficient and reliable routing in MWSN. Mobile nodes select the next hope in their data routing toward the sink based on specific configured search angle that determine the possible candidates of next hop node. The protocol is implemented in two phases: the discovery and data forwarding phases. The proposed routing approach focus on the implementation of one sink in the network and assume mobile nodes can determine their geographic location. The capability of our proposed scheme to achieve dynamic

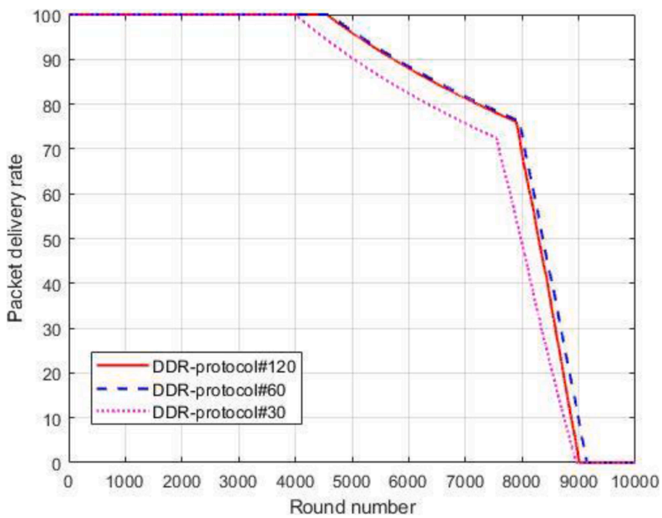

Fig. 7. Impact of α on packet delivery ratio.

directional routing leads to considerable gains over other relevant routing schemes such as T-LEACH and area-based routing in terms of network lifetime by 13% and 50% compared to T-LEACH and area-based routing protocols. It also provides enhancement in terms of packet delivery ratio by around 10% compared to T-LEACH and provides shorter route lengths by around 33% compared to T-LEACH and area-based routing protocols. The protocol can be dynamically configured based on network conditions by changing the search angle (α) in the discovery phase.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors declare that they have no competing interest.

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