Energy and congestion aware routing based on hybrid gradient fields for wireless sensor networks

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Response Sheet

We address all the requested major and minor concerns in revised manuscript. The respected changes for each concern are summarized in following:

Concern 1 : Given the addressed topic, it is crucial to be very very convincing in presenting the technical originality of the proposal, i.e., to highlight well the exect elements of technical originality of the proposal if compared with the very rich literature in the field. IMHO there are sufficient ones, but the point is to be able to convince the reviewers, given that really many and many papers about WSN routing have already appeared and also the idea of field-based routing is not novel.

Answer : The required changes to address this concern are highlighted in introduction section. Moreover, the technical originality and the exact elements of all PBDR based algorithms are presented in Table 1.

Concern 2 : The related work should mention also the seminal work by Zambinellu about field-based coordination of distributed agents. Old but significant.

Answer : The important work of Zambinellu is mentioned Section 3.2

Concern 3 : The strongest and exact elements of technical originality have to be well presented before going into the detail of the ECAR algorithm, so at the beginning of Section 4. The intro will shortly and concisely mention them; here they have to be well explained.

Answer : We restructure the paper according to yours' suggestion, and all the strongest and exact elements of technical originality are shifted into Section 4, before the exact details of ECAR algorithm.

Concern 4 : Section 6 should describe more extensively and clearly why it is reasonable to include the performance comparison with IDDR and not others. Also, is it possible to write that IDDR, in this specific context, is already a good performer if compared with more general-purpose routing solutions, by referring some existing literature?

Answer : We consider the integrity sensitive IDDR for conceding the better half of proposed algorithm. However, the reason for considering only integrity sensitive IDDR because it perform better in most cases of data packet routing in sensor network [6].

Concern 5 : Is it possible to make the simulation code available to reviewers and readers? There is a strong push of the community towards the reproducibility of reported results and so this availability could have positive effects...

Answer : Few of the functions of proposed algorithm are available to disclose.

Concern 6 : Minor revisions:

- "Quality of Services" - "Quality of Service" in page 1.
- the content of footnotes 1 and 2 should be put in the paper body.
- "authors of [6], discuss" - "authors of [6] discuss" in page 1.
- the second occurrence of footnote 2 could be omitted in the paper text.
- "time varaint" - "time variant" in page 2
- the first sentence of Section 4 is badly written
- remove the first three lines of Section 5

Answer : All these minor revision are addressed in respective sections.

Hybrid Gradient Field Routing Model for Wireless Sensor Network

Abstract

The principles of physics and system sciences are increasingly used in the field of network engineering to design network protocols. This work proposes an energy and congestion aware routing algorithm inheriting the concepts of potential field. It uses depth and time variant network parameters for forwarding the data packets through low congestion and energy balanced path. We defines a novel forward aware energy density as decision metric along with residual energy and queue-length for forwarding data packets. This results in network wide balanced residual energy and enhanced network lifetime. The proposed mechanism is evaluated for the transmission rounds before the first dead node (FDN) is detected. It was found that in typical traffic conditions there was an average increment of 45% transmission rounds till the FDN appeared. Moreover, the simulated and theoretical findings are compared using statistical measures to justify the proposed mechanism energy and congestion awareness.

Keywords: Wireless Sensor Networks, Potential Field, Forward Aware Energy Density, Quality of Service.

1. Introduction

Wireless sensors for sensing the environmental parameters are gained the increasing attention in next generation network based applications including the scenario of Internet of Things (IoTs) [1] and Cyber Physical Systems (CPSs) [2]. The applications dependent on these sensor stimuli will have different Quality of Service (QoS) requirements including delay and integrity sensitiveness[3]. However, to attain delay sensitiveness, the bottleneck nodes (means nodes which are lying on shortest route or placed near the sink) are often subjected for data transmission. So the energy depletion rate of these nodes are very high and runs out of energy within short span of transmission rounds. Similarly, to attain the integrity sensitiveness, the packets are routed through less congested path that causes the higher delay and more energy consumption [4]. Conclusively, the decision of next hop selection is very challenging to meet the desired QoSs of each network application.

To make it more clear the challenges occurred in packet transmission we consider a scenario where an event occurred in Area 1 (see Figure 1) far away from sink. Most energy efficient routing mechanisms will route the packets from Area 1 through the nodes on shortest path (let it be Area 2). Since the nodes in Area 2 are subjected to relay traffic from other nearby areas, Area 2 becomes a potential point for network partition due to unbalanced energy. In addition to this the nodes near to sink or nodes on the shortest path are subjected to congestion and result in decreased packet reception rate (PRR) at sink.

In wireless sensor networks, network protocol bears the extreme pressure on utilizing the various crucial resources like node energy, computing power and storage capacity and the inappropriate use of node resources can be adverse for network long-term health. Authors of [5] highlight that, by the time when nearby nodes exhaust their energy, an approximate 90% of initial energy is left at nodes that are farther away from sink. Therefore, network wide energy balance becomes a compelling need to enhance the network long term health.

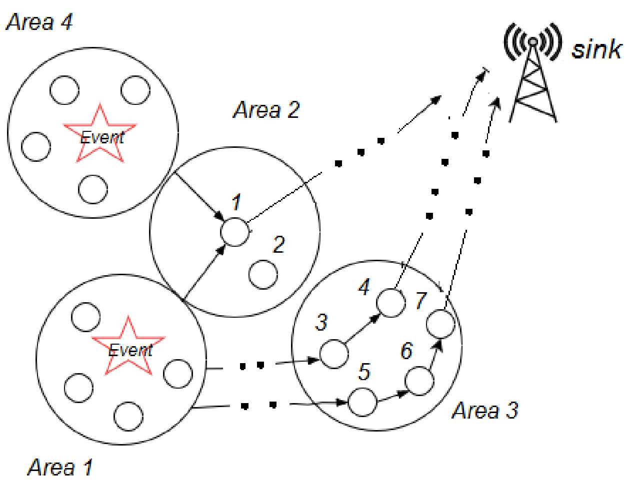

Figure 1: Typical scenario describing a node in Area 2 which subjected to increased traffic and leading to network partition

The information infrastructure applications require a good PRR at the cost of minimum delay. Thus routing protocol requires to route the packets pertaining to such application, through idle or less congestion areas. Based on this philosophy, authors of [6] discuss a gradient based routing protocol that calculates gradient fields according to the sensitivity of network traffic (transmission delay) and route the packets accordingly to preserve the information fidelity of realtime applications. Therefore, in essence, an energy aware communication mechanism along with the congestion awareness is equally important for increased network lifetime and PRR.

To do so, the optimal use of scarce resources such as node energy, buffer space etc., is required while designing the communication mechanism. Several existing communication mechanisms focus on routing, duty cycling, event based transmission for optimality. Thereafter, energy aware gradient based mechanism where the selection of next hop node for packet forwarding is done locally using residual energies of direct neighbors. But only energy awareness in routing causes the uneven delay for transmitting packets that further results in network wide uneven energy distribution. Thus, as a result, it is required to have an energy and congestion aware routing algorithm that balance the network wide energy consumption alongside with increased PRR.

The proposed energy and congestion aware routing (ECAR) mechanism inherit the concept of potential field for building the gradient, where this considers *residual energy* and *forward aware residual energy density* along with node depth and queue length to forward packets through the less congestion and energy balanced path. This prevents the early death of shortest route nodes via creating the bulges over gradient surface. These bulges keep away the transmitting packets from the routing path, where the nodes[2] are frequently engaged in transmission process.

The remainder of this paper is organized as follows: The next section describes the related work and Section 3 discusses the assumptions related to network model, energy consumption model followed by problem formulation and the novel energy aware potential field. The complete ECAR mechanism based on hybrid potential field model is presented along with loop detection and elimination strategy in Section 4. Analysis of theoretical findings for various parameters is discussed in Section 5. The evaluation of ECAR with extensive experiments is presented in Section 6. Finally section 7 concludes the paper.

2. Related work

Most of the QoS provisioning approaches discussed in [6, 7, 8] for Ad-hoc network have large overhead to discover end to end path and also require resource reservation to earn QoS at a significant cost of energy. Moreover, a number of energy-efficient routing algorithms in [9, 10, 11, 12] aims at minimizing network wide energy consumption by forwarding packets through shortest path. Nevertheless, some recent advancement in existing energy efficient algorithms recognized the imbalance in energy consumption. For example, several well known distributed clustering algorithms in [13, 14, 15, 16] provide localized solution for energy balance at intra cluster level. These approaches do not discuss load balance at inter-cluster level transmissions and can cause extra burden of high relay at inter cluster level.

In [17], authors consider the uneven energy balancing and proposed a protocol for single hop scenario but it is not appropriate for current application scenarios. Apart from this, the nature-inspired algorithm also used for optimum next hop decision in multi-hop scenario [18]. However, this way of routing requires several rounds of transmission for converged decision of next-hop. Moreover, it caused the uneven energy distribution if network is deployed with heavy traffic conditions. The energy aware algorithm like [5] tried to minimize the energy consumption but does not tried to balance energy consumption by forwarding the packets to through alternate paths. [17] maintains multiple paths and selects one for which network survivability increases. Frequent exchange of routing information makes the protocol computationally expensive. The integrated transmission mechanism to balance uneven energy consumption is investigated in [19] which switches the traffic between single hop and multi hop paths depending on their residual energy.

Table 1: Comparison of potential field based Routing mechanisms in terms of their objectivity

Mechanism	*Objective*	*Approach*	*Remark*
IDDR [6]	Reduce end to end delay	PBDR	Uneven residual energy distribution
Energy aware routing [5]	Minimize the energy consumption	PBDR	Congestion aspect not taken
Proposed mechanism (ECAR)	Balancing uneven energy, Improving end to end delay and PRR	PBDR	*Benefits:* (i) Increase the network lifetime (ii) Increase the PRR

A virtual hybrid potential field model is discussed in [6] to meet the application QoS requirements. The delay sensitivity of application packets is captured through the scalar value in the packet header assigned by the application according to its sensitivity requirement to end-to-end delay. Intermediate nodes forward the packets to corresponding gradient field based on the weight of the decision parameters. This protocol do not discuss about the residual energy of neighbor node(s) while deciding the route which can result in network wide uneven residual energy distribution. Energy aware potential field model proposed in [20] discusses virtual potential field based routing that consider energy for routing the packets. However, the issue of congestion is not taken in to account. Thus it becomes imperative to consider less PRR in typical load conditions and balance the network wide residual energy distribution without incurring much overhead while designing routing protocol for WSN. TABLE 1 depicts the PBDRs mechanisms.

The proposed ECAR algorithm builds the virtual hybrid potential field by considering depth and time variant metrics like queue length, residual energy and forward aware residual energy density to forward data packets through relatively less congested and balanced energy path. This way of forwarding preserves the balanced energy distribution and also mitigate the problem of early packet drop at congested node in typical load conditions.

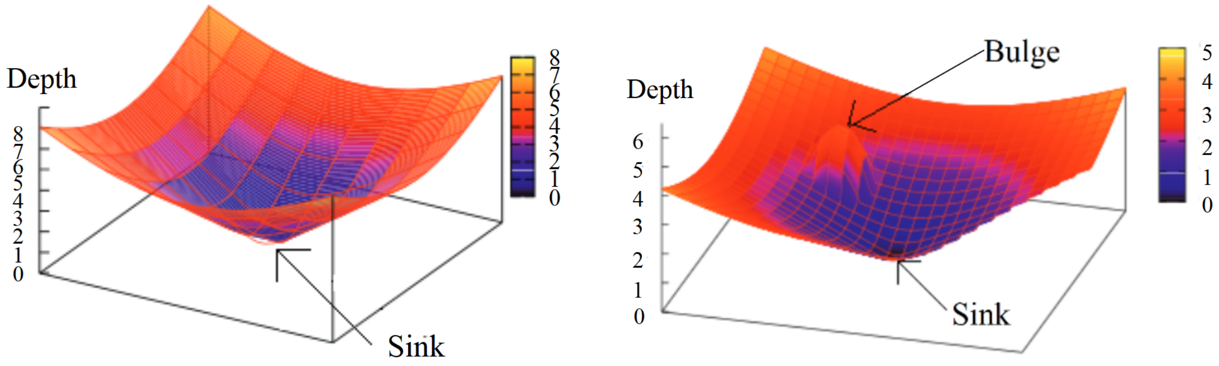

Figure 2: (a) Bowl surface in light load condition (b) Bowl surface in heavy load condition

3. Network model and Problem formulation

This section discusses related assumptions, network configuration details and problems of existing potential field models.

3.1. Network model

The network consists of N homogeneous sensor nodes having fixed transmission range R deployed randomly in a square grid structure with side length L and a single sink. The network is dense near the sink to prolong the network lifetime (as nodes near the sink have large relaying pressure). The nodes are stationary and a multi-hop communication paradigm is considered and radio model adopted in [21] is considered for the estimation of energy consumption in packet delivery.

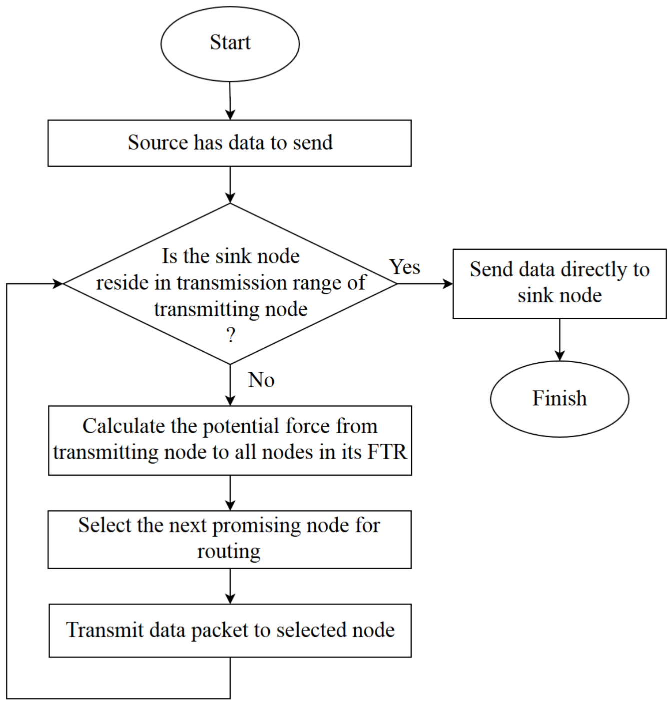

Figure 3: Flow diagram of potential field based dynamic routing

3.2. Potential field based routing algorithm (PBDR)

PBDR algorithm is a prerequisite of proposed mechanism. The sequential flow of operations for data transfer in PBDR is shown in Figure 3. Further, to explain the working of PBDR we consider the bowl model where complete network is assumed potential field surface that can be viewed as a bowl with sink node at the bottom (see Figure 2). Packets are assumed to be the drops of water that are moving under the actuation of artificial steepest gradient force to reach the bottom of bowl surface (means sink) [22].

The calculation of steepest gradient force (route estimation) requires the knowledge of scalar potential field at each node. Authors of [6] proposes the scalar hybrid potential field value by considering depth and queue-length potential field for the routing decision.

The depth potential field at each node a is defined as $V^d_a(t) = d^{sink}_a(t)$, which represents the distance from node a to sink at time t. Similarly, the queue length potential field of node a at time t is defined as as $V^q_a(t) = q_a(t)$, which denote the normalized queue length to the buffer size at time t. The resultant force $F^{res}_{a!\ b}(t)$ is estimated in [6] with accounting the force of both fields, from node a to node b at time t, and expressed as:

$$F^{res}_{a!\ b}(t) = \quad F^d_{a!\ b}(t) + F^q_{a!\ b}(t) \qquad (1)$$

where $F^d_{a!\ b}(t)$ and $F^q_{a!\ b}(t)$ are the force exerted because of depth and queue length potential fields respectively and   is the queue length field regulating parameter to explore more underutilized path and its range is (0,1]. Thus, $F^{res}_{a!\ b}(t)$ 2 [1; 1].

Note that with fixed value of , the lesser backlog packets at node b, larger the potential force in the direction of b due to queue length potential field. This results in the selection of a node from $nbr(a)$. The problem formation is discussed in following section.

3.3. Problem formation

Consider the bowl model of PBDR where the surface of bowl is smooth in light load conditions of network (means in initial stage of transmissions, see Figure 2a) and algorithm of [6] directs the packets through shortest path to sink. Moreover, with increase in transmission rounds the residual energy of the network nodes are different from each other, especially the nodes near the sink (bottom part of the bowl surface) where energy drain faster than others due to heavy relaying. In this scenario, bulges are observed at the bowl surface (see Figure 2b), which hinder the packet flow towards the sink along shortest path and algorithm of [6] bypass the relay traffic through alternative low queue length paths. However it results in increased path length and more energy consumption compared to its shortest path counterpart which causing network wide uneven energy distribution, which eventually leading to network partition. Thus, this paper consist the following three objectives for tackling the problem of uneven energy distribution in data transmission:

1. Design ECAR mechanism where the force due to proposed hybrid field helps to find an obstacle (bulges of uneven energy and congestion) free path in the region of nodes with higher energy density and less congestion.

2. Minimize the network wide imbalance (Δ) in transmission delay and energy consumption in each transmission round i which is calculated as follows:

$$\Delta = \sqrt{\frac{1}{NTR} \sum_{i \in NTR} (X(i) - \mu)^2} \quad (2)$$

   where $X(i)$ is the mean value of considered measure e.g., delay bound or energy consumption, for all packet in transmission round i and μ is corresponding theoretical value. NTR is number of transmission rounds.

3 Validate the ECAR mechanism with extensive simulation and compare its results with other peer mechanisms to identify percentage improvement in network lifetime and packet reception rate.

The newly defined potential fields that are incorporated with existing ones of the decision metric of IDDR algorithm [6] are presented in coming section.

4. The ECAR Algorithm

In this section first we discuss the newly discuss the newly introduced energy and congestion aware potential fields. And then the related preliminaries like neighbors discovery procedure, routing table attributes, signaling, detection and elimination of possible loops etc. are discussed. All these are essential for better understanding proposed algorithm. After that the working steps of newly defined ECAR algorithm is presented.

4.1. Energy and congestion aware potential fields

The proposed work inherits the potential field model of [6] and extends its hybrid capability by considering the residual energy and forward aware residual energy density as additional decision parameter to model the hybrid potential field. The detailed description of each field is explained in upcoming subsections.

4.1.1. Residual energy potential field

Residual-energy potential field aims to ensure that packet will always choose the node having energy above a given threshold. Residual energy potential field of node a at time t is defined as $V_a^{re}(t) = \frac{1}{RE_a(t)}$ and the force from node $b \in nbr(a)$ to node a is expressed as

$$F^{re}_{a \to b}(t) = \begin{cases} \dfrac{V_a^{re}(t) - V_b^{re}(t)}{V_a^{re}(t)}; & \text{if } RE_b(t) \geq RE_a(t) \\[2ex] \dfrac{V_a^{re}(t) - V_b^{re}(t)}{V_b^{re}(t)}; & \text{otherwise} \end{cases} \quad (3)$$

The range of $F^{re}_{a \to b}(t)$ is $[-1, 1]$. Note that more residual energy at node b implies more potential force in the direction of b and thus packets are forwarded towards b.

4.1.2. Forward aware residual energy density potential field

To restrict the excessive exploration of idle paths, packet should be forwarded through the same or lower depth nodes. Packet forwarding via higher depth nodes cause an unwanted delay to packet transmission. The introduction of forward aware residual energy density in an existing hybrid field ensure that packets are routed through a dense energy spread area. The estimation of residual energy density $RED_a(t)$ of node a at time t requires the set of nodes ($fnbr(a)$) in forward transmission region ($FTR(a)$) and is computed by Algorithm 2.

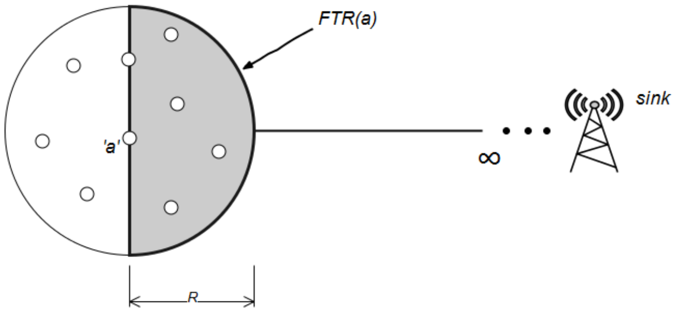

Figure 4: Depiction of forward transmission region of node 'a' (FTR(a))

The $RED_a(t)$ is defined as the ratio of the sum of residual energy of the nodes in $fnbr(a)$ to the area of $FTR(a)$.

$$RED_a(t) = \frac{\sum_{i \in fnbr(a)} RE_i(t)}{\text{area}(FTR(a))} \quad (4)$$

Next the forward aware residual Energy density potential field of node a at time t is expressed as $V_a^{fred}(t) = \frac{1}{RED_a(t)}$ and the corresponding force is given by Eq. (5).

$$F^{fred}_{a \to b}(t) = \begin{cases} \dfrac{V_a^{fred}(t) - V_b^{fred}(t)}{V_a^{fred}(t)}; & \text{if } V_a^{fred}(t) \geq V_b^{fred}(t) \\[2ex] \dfrac{V_a^{fred}(t) - V_b^{fred}(t)}{V_b^{fred}(t)}; & \text{otherwise} \end{cases} \quad (5)$$

The range of $F^{fred}_{a \to b}(t)$ is [-1,1].

4.1.3. Virtual hybrid potential field

We construct virtual hybrid potential field $V^m_a(t)$ by linearly combining all the potential fields discussed earlier.

$$V^m_a(t) = \; \cdot V^d_a(t) + \;_1 \cdot V^q_a(t) + \;_2 \cdot V^{re}_a(t) + \;_3 \cdot V^{fred}_a(t) \quad (6)$$

So the force exerted by node b to node a by such hybrid potential field is defined as:

$$F^{Res}_{a \to b}(t) = \; \cdot F^d_{a \to b}(t) + \;_1 \cdot F^q_{a \to b} t + \;_2 \cdot F^{re}_{a \to b}(t) + \;_3 \cdot F^{fred}_{a \to b}(t) \quad (7)$$

where $\in (0, 1]$ and $_1, \; _2, \; _3 \in [0, 1]$ are regulating parameters of the respective potential fields and $+ \; _1 + \; _2 + \; _3 = 1$.

With Eq. (7), it can be easily seen that the regulating parameters determine the proportion of each potential field in hybrid potential field which shows the dynamic behavior of proposed mechanism. For example, with $= 1$, the route constructed by the hybrid potential field becomes the shortest path mechanism. similarly, with $, \; _1 > 0, \; _2 = 0$ and $_3 = 0$, hybrid potential field based route finding mechanism becomes congestion efficient shortest path tree.

Optimization of these parameters are usually subjected to theoretical or experimental experience of sensor application. For theoretical formulation of the problem, we assume that the sample set of the potential field at each node is $\{p_{ij} \mid i = 1, 2, \ldots, n; \; j = 1, 2, \ldots, m\}$ and the regulating weight of j^{th} potential field is to be a_j; $\forall j$. $\forall i$ the hybrid potential field and $z(i)$ is obtained by weighted combination of regulating weight and potential field sequence p_{ij}.

$$z(i) = \sum_{j=1}^{n} a_j p_{ij} \quad (8)$$

With different reasonable weight distribution of each potential field $a = (a_1, a_2, \ldots, a_m)$, forces from each alternative node is calculated. Hence the minimum $z(i)$ is the next-hop node because it exerts the maximum force towards the transmitting node. Here, regulating weight vector $a = (a_1, a_2, \ldots, a_m)$ is a unit vector and has the following constraints:

$$\begin{cases} 0 \quad a_j \quad 1 \\ \sum_{j=1}^{n} a_j = 1 \end{cases} \quad (9)$$

Thus the selection of potential weight is converted to a constraint optimization problem which could be solved using various optimization algorithm like Lagrange multiplier methods, linear programing and nature inspired algorithms etc. The complete ECAR mechanism with related description is discussed in following section.

Algorithm 1 Next_Fittest_node (a, $fnbr(a)$)

Output: Fittest next hop node

Calculate Hybrid potential field $V^m_b(t)$ by combining the $V^d_b(t)$,$V^q_b(t)$,$V^{re}_b(t)$ and $V^{red}_b(t)$ for each node $b \in fnbr(a)$ at time t using Eq. 6.
if $sink \in fnbr(a)$ **then**
  $nbest(a) = sink$
end
else
  Calculate best node $b \in fnbr(a)$ for which gradient force $F^{Res}_{a \to b}(t)$ is maximum (using Eq. 7).
  $nbest(a) = b$
end
return *nbest(a)* /* fittest node of node a */

4.2. Neighbors' discovery

Initially each sensor node is require to aware about its neighbors set. Thus in setup phase, each sensor node finds the neighboring nodes at same or lower depth and maintains the neighbor's attributes in routing table, which is illustrated in the Algorithm 2.

Algorithm 2 Neighbor discovery ($fnbr(a)$)

/* Advertising Packet format of node a at time t FNBR_DET(a): $\langle$NID$_a$, $d^{sink}_a(t)$, $q_a(t)$, $RE_a(t)$, t(time stamp)$\rangle$ */
$fnbr(a) =$
FNBR_DET_$Sent_a$ = **false**
if FNBR_DET(b) ⊳ node a && $d^{sink}_b(t)$ $d^{sink}_a(t)$ **then**
  /* (packet x ⊳ node a) means packet x received by node a */
  if $b \in fnbr(a)$ **then**
    $fnbr(a) = fnbr(a) \cup \{b\}$
    Update Routing Table of node a with FNBR_DET(b)
    if FNBR_DET_$Sent_a$ == ***false*** **then**
      FNBR_DET_$Sent_a$ = **true**
      Node a broadcast the FNBR_DET(a)
    end
    else
      Drop the Packet
    end
  end
  else
    Drop the Packet
  end
end

As the network subjected to traffic, the initiator node (which chosen randomly in the network, because initially all node's residual energy is the same) broadcasts a control packet FNBR_DET, which contains the node ID, depth from sink, normalized queue length and residual energy of the node. The neighbor node that receives the FNBR_DET packet will update the routing table. If the advertising node ID is already in the routing table, then the packet is dropped by the recipient node. The recipient node broadcasts the FNBR_DET control packet if it does not broadcasts before. After the neighbor discovery phase, each node has a list of its candidate neighbor nodes of forward region.

4.3. *Routing table*

The routing table of node comprises the routing information of all related nodes which are in its transmission vicinity. Initially routing table of each node contain null entries but during neighbor's discovery, each node saves the sender information in its routing table. The routing information of table consist the following attributes,

i. *Node ID (NID)* : Identification number of advertising neighbor.

ii. *Depth* (d_a^{sink})*:* Minimum number of hop required to reach the sink from advertising node *a*.

iii. *Normalized Queue length* ($q_a(t)$)*:* It is the fraction of packets by buffer size which reside at advertising node *a* at time *t*.

iv. *Residual Energy* ($RE_a(t)$)*:* Residual energy of advertising neighbor *a* at time *t*.

v. *Time of Update (ToU):* Time stamp value when the corresponding entry gets update.

The storage and maintenance cost of routing table is less compared to cumulative path approaches.

4.4. *Signaling*

Before starting the original procedure of ECAR, signaling is essential, through which each node transmit the query packet in own forward transmission range for accounting the hybrid potential field of each node. Hence, the time interval that how often this update is made with neighbors is quite important since too less period leads to much overhead while too large period leads to imprecise information. We adopt the concept of LUI (Least update interval) and MUI (Maximum update interval) of [23] for refreshing gradient fields at periodic interval.

4.5. *Loop detection and elimination*

It is obvious that packet might be stuck in *local 'valleys'* if next-hop decision uses the time variant metrics. There are two prominent situations of ECAR, where the data packet suffer with routing loop.

a. Nodes at bottom of local valley are very likely to choose each other as next hop node.

b. A packet could return to bottom of valley when it try climb along the surface.

So the assessment of possible valleys/loops is equally important to escape and diverge the packet through alternative path. Next we define types of possible loops and the way of identifying locally in multi-hop scenario.

4.5.1. *Loop detection*

To detect already formed loop locally, path tracing of packet is required and it is done with adding a field for node ID in *IEEE 802.15.4* packet header to carry node ID of nodes through which it pass during transmission. The ECAR mechanism is also tested for the case where one-hop loop, queue loop and origin loop are occurred during data transmission [24]. These loops are illustrated in Figure 5.

1. *One-hop loop:* It occurs between a local node and its parent(next hop). In Figure 5, two nodes in Area 3 select each other as their parents, which is a typical one-hop-loop. It can be easily detected by checking the source address in packet header. If source address is the *ID* of former node which sending this packet.

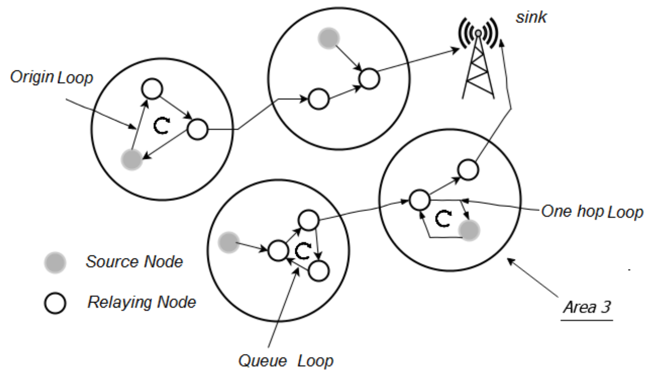

Figure 5: Example scenario of possible loops in a multi-hop transmission scenario

2. *Origin loop:* Origin loop occurs when loop consists of one or more relay node and packet came again to source of node. It can be easily detected at local node by checking the origin address[1] of packet and loop is confirmed if it matched with *ID* of parent of local node.
3. *Queue loop:* Queue-loop is a special type of multi-hop loop which does not involve origin node, formed only by relaying node of packet as shown in Figure 5. This type of loop is detected at local node by examining the path vector[2]( ) of packet header.

Algorithm 3 simultaneously does the task of loop detection and elimination along side with packet transmission. So, whenever the loop is detected in transmission path, the data packet is routed through alternative path to maintain integrity of running application.

4.6. *Working steps of ECAR*

This section summarize work of ECAR in two phases and the working of these phases are given in following:

1. *Setup phase:* This consists the following two steps,
   a. Queuing threshold: Broadcast the queuing threshold (qt) for each node by sink.

[1] Origin address of packet is the node which generates that packet.
[2] Path vector ( ) of packet is set of nodes through which packet visited in earlier transmission route.

Algorithm 3 ECAR Algorithm

Input : Queue threshold qt

Output: Next hop node of forwarding node a

Calculate the Forward neighbor's set (**$fnbr(a)$**) of node a. /* (using **Algorithm 2**) */

Calculate $nbest(a)$ = **Next_Fittest_node(a;$fnbr(a)$)**. /* (using **Algorithm 1**) */

Extract Source ID from packet header and copied in to S_ID at node a.

Extract Origin ID from packet header and copied in to O_ID at node a.

if S_ID ! = O_ID **then**
- **if** $S\_ID == nbest(a)$ **then**
  - $nbr(a) = nbr(a) - \{S\_ID\}$
  - Recalculate $nbest(a)$ = **Next_Fittest_node(a;$fnbr(a)$)**. /* (using **Algorithm 1**) */
  - Forward packet towards $nbest(a)$:
  - Increment in queue length of packet at node a.
  - $exit()$
- **end**
- **else**
  - **if** $O\_ID == nbest(a)$ **then**
    - $nbr(a) = nbr(a) - \{O\_ID\}$
    - Recalculate $nbest(a)$ = **Next_Fittest_node(a;$fnbr(a)$)**. /* (using **Algorithm 1**) */
    - Forward packet towards $nbest(a)$:
    - Increment in queue length of packet at node a.
    - $exit()$
  - **end**
  - **else**
    - Put queue length value of packet header into ql variable.
    - **if** $ql \geq qt$ **then**
      - Extract path vector of packet header and copied into $\pi(a)$ at node a.
      - Find node k_0 with $dist(k_0; sink) = \min_{k \in \pi(a)\ \&\ nbr(a)} \{dist(k; sink)\}$ with index k_0 in $\pi(a)$.
      - $nbr(k_0) = nbr(k_0) - k_0$
      - Recalculate $nbest(k_0)$ = **Next_Fittest_node(a;$fnbr(a)$)**. /* (using **Algorithm 1**) */
      - Forward packet towards $nbest(k_0)$:
      - Increment in queue length of packet at node k_0.
    - **end**
  - **end**
- **end**

end

else
- Forwards packet towards $nbest(a)$.
- Increment in queue length of packet header at node a.

end

b. *Depth calculation:* It is an iterative procedure where sink node initiates the depth calculation procedure by flooding the depth calculating packet (DCP) with depth value 0. Afterwards, each node calculate depth own depth by unit increment in depth value received in DCP packet (see Figure 6). Thus, at the end this procedure all nodes having the depth value with reference to sink node.

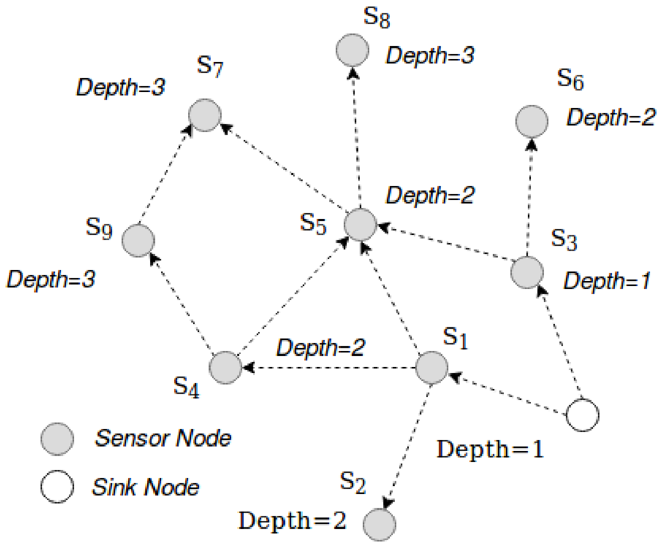

Figure 6: Iterative procedure of depth calculation

2. *Operational phase:* This phase consists the proposed ECAR mechanism where the loop maintenance (detection and elimination) along side the packet forwarding is discussed (see Algorithm 3).

In following we present some analytical approach to describe the correctness of ECAR mechanism. The related propositions which are needed to describe how a node chooses next hop on same depth to increase PRR and balance the network wide energy consumption. Consider scenario with two different cases:

Scenario 1: Let $S = \{x \mid d_x(t) = d; x \in nbr(a)\}$ be the neighborhood set of node a and all of these nodes are of the same depth d. L denote the neighborhood set $L = \{x \mid d_x(t) = d - 1; x \in nbr(a)\}$ of node a with depth $d - 1$.

Case 1: Let node $l \in L$ has minimal queue length defined as $l = \{x \mid \exists x \in L; \forall y \in L - \{x\}$ *such that* $q_x(t) <= q_y(t)\}$ Similarly, $s \in S$ has the smallest queue length and is defined as $s = \{x \mid \exists x \in S; \forall y \in S - \{x\}$ *such that* $q_x(t) <= q_y(t)\}$

Case 2: Let node $l \in L$ have maximum residual energy and defined as $l = \{x \mid \exists x \in L; \forall y \in L - \{x\}$ *such that* $RE_x(t) >= RE_y(t)\}$ Similarly,$s \in S$ have maximum residual energy defined as $s = \{x \mid \exists x \in S; \forall y \in S - \{x\}$ *such that* $RE_x(t) >= RE_y(t)\}$

Proposition 1. *In Case 1 of scenario 1, if* $V_l^{fred}(t) = V_s^{freq}(t)$, $q_l(t) = q_s(t)$ *and satisfies that* $RE_s(t) > RE_l(t)\left(1 + \frac{\cdot RE_s(t))}{2 \cdot RE_a(t)}\right)$, *then node a will choose node s rather than node l as the next hop at time t to protect a node l which suffer with less energy.*

Proof. In the proposition it is given that $V_l^{fred}(t) = V_s^{freq}(t)$ which means the spread of energy in transmission region of node l and s is balanced and so this parameter does not take part in the process of choosing next hop. Given that node a does not choose node l as next forwarding node it will not choose any other node in L since the queue-length of node l is the smallest among all other nodes in set L and equal to node s which has smaller queue length in its own set S. Thus, decision would be based on residual energy of node s and node l.

The potential field values at node a,l and s are,

$$V_a^m(t) = \cdot d + {}_1\cdot q_a(t) + {}_2\cdot\frac{1}{RE_a(t)} + {}_3\cdot V_a^{fred}(t) \quad (10)$$

$$V_l^m(t) = \cdot(d \quad 1) + {}_1\cdot q_l(t) + {}_2\cdot\frac{1}{RE_l(t)} + {}_3\cdot V_l^{fred}(t) \quad (11)$$

$$V_s^m(t) = \cdot d + {}_1\cdot q_s(t) + {}_2\cdot\frac{1}{RE_s(t)} + {}_3\cdot V_s^{fred}(t) \quad (12)$$

Assuming that the source node has not enough energy to transmit the packet to sink. To choose the next hop node calculate the force from source node a to its neighbors node at same and lower depth by using Eqs. (10, 11, 12)

$$F_{a\rightarrow l}^{Res}(t) = \quad + \; {}_1\cdot\{q_a(t) \quad q_l(t)\} + {}_2\cdot\left(1 \quad \frac{RE_a(t)}{RE_l(t)}\right) + {}_3\cdot\left\{V_a^{fred}(t) \quad V_l^{fred}(t)\right\} \quad (13)$$

$$F_{a\rightarrow s}^{Res}(t) = \; {}_1\cdot\{q_a(t) \quad q_s(t)\} + {}_2\cdot\left(1 \quad \frac{RE_a(t)}{RE_s(t)}\right) + {}_3\cdot\left\{V_a^{fred}(t) \quad V_s^{fred}(t)\right\} \quad (14)$$

Node a chooses node s as a next hop when Eq. (15) is satisfied.

$$F_{a\rightarrow s}^{Res}(t) > F_{a\rightarrow l}^{Res}(t) \quad (15)$$

Thus, it can be written as:

$$RE_s(t) > RE_l(t)\left[1 + \frac{\cdot RE_s(t))}{{}_2\cdot RE_a(t)}\right] \quad (16)$$

Eq. (16) proves that the packet of any node a will get forwarded to a node at same depth when node on same depth has more energy to queue the packets. □

Proposition 2. *For Case 2 of scenario 1, if* $V_l^{fred}(t) = V_s^{fred}(t)$; $RE_l(t) = RE_s(t)$ *and satisfies that* $q_l(t) > q_s(t) + \frac{\ }{{}_1}$ *,then node a will choose node s at same depth rather than node l as the next hop at time t.*

Proof. The decision of the next hop is now based only on queue length of node l and node s while considering their residual energies (see Eqs. (13, 14)) same. Thus the relation between their forces is represented by Eq. (15).

$$q_l(t) > q_s(t) + \frac{\ }{{}_1} \quad (17)$$

Eq. (17) indicates that the queue length of node l is greater than the queue length of node s by a factor of $\frac{\ }{{}_1}$. This confirms that the packet is forwarded to the node at same depth when the queue length of the node at the same depth is lesser than the node at lower depth. This proves proposition 2. □

Propositions 1 and 2 confirm that ECAR allows a node to choose next hop at same depth. Further it confirms that in the presence of a high queue length node at a lower depth or less residual energy the ECAR algorithm chooses a node at the same level to extend the lifetime of network.

5. Theoretical evaluation of ECAR

In this section we establish the theoretical relationship of considered performance metrics like expected delay (calculated in terms of hop-counts), energy consumption with network parameters like grid size (L), transmission range (R), number of nodes in forward transmission range (n_f) etc.

5.1. Expected hop-counts from source to sink

The theoretical formulation of expected hop-counts requires the computation of,

- Expected one hop distance $E(D_{oh})$ between source node to forwarder node.
- Expected distance $E(D_{sd})$ between source node to sink node.

In [25], the expected one hop distance $E(D_{oh})$ is calculated as:

$$E(D_{oh}) = \frac{n_f R}{n_f + 1} \quad (18)$$

where n_f represent the number of nodes in forward transmission range and R represent the transmission range of a node. Moreover, the expected source to sink distance $E(D_{sd})$ is defined as:

$$E(D_{sd}) = \frac{1}{2\sqrt{2L}}\left[2L^2 \quad {}^2\right] \quad (19)$$

where represent the minimum possible distance between source and sink node. For simplicity authors of [25] takes = 1. So it becomes as:

$$E(D_{sd}) = \frac{1}{2\sqrt{2L}}\left[2L^2 \quad 1\right] \quad (20)$$

Thus, the expected hop-counts $E(HC)$ is calculated as,

$$E(HC) = \frac{E(D_{sd})}{E(D_{oh})} = \frac{(n_f + 1)\ 2L^2 \quad 1}{2\sqrt{2}n_f LR} \quad (21)$$

Eq. (21) states that if we increase the grid size with keeping the number of nodes constant, the required number of hops from source to sink increases. Similarly, the large grid size with large transmission range also requires significantly more hops to reach the sink (see Figure 7a).

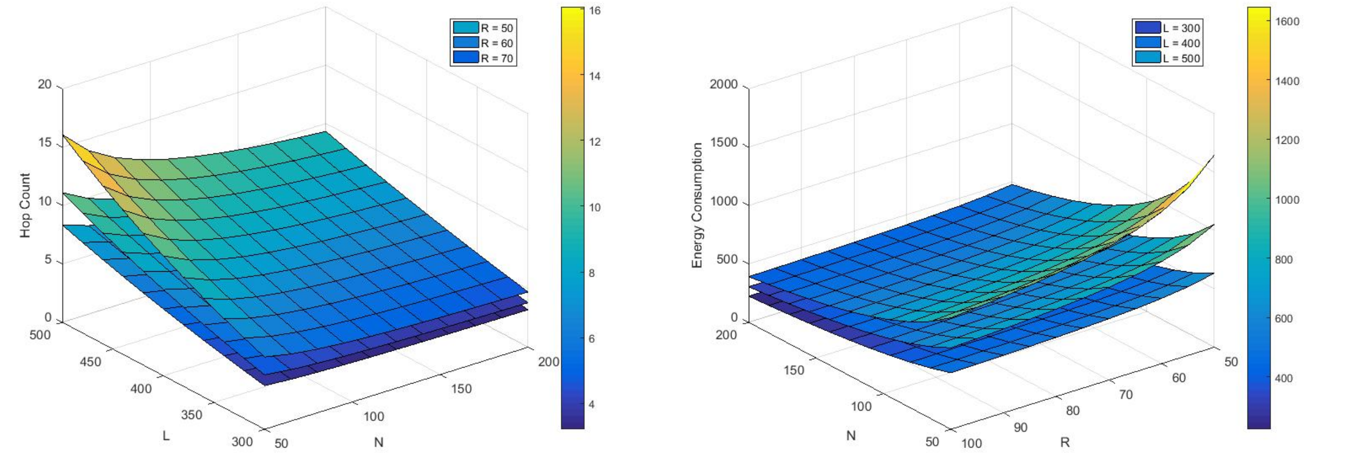

Figure 7: (a) Hop count with varying grid size (L) and number of nodes (N) (b) Energy consumption with varying transmission range (R) and number of nodes (N)

5.2. Expected energy consumption from source to sink

The energy consumption in data transmission through the provided route from S to D, is the sum of energy consumption in data transmission and reception separately [21]. In multi-hop transmission scenario, one-hop distance is varying in own radio range, correspondingly, the energy consumption is also varied. Thus, the expected energy consumption in transmission of k bit packet through the random path length r is represented by $Energy_{(tr)}$ and expressed by,

$$Energy_{(tr)} = \underbrace{kEnergy_{(elec)} + k\epsilon_{fs} r^2}_{\text{Transmission energy}} + \underbrace{kEnergy_{(elec)}}_{\text{Reception energy}} \quad (22)$$

$$Energy_{(tr)} = 2kEnergy_{(elec)} + k\epsilon_{fs} r^2 \quad (23)$$

So probability distribution function (PDF) of $Energy_{(tr)}$ is:

$$\begin{aligned} f(Energy_{(tr)}) &= CEnergy_{(tr)} \\ &= C(2kEnergy_{(elec)} + k\epsilon_{fs} r^2) \end{aligned} \quad (24)$$

where we take constants $C_1 = 2kEnergy_{(elec)}$ and $C_2 = k\epsilon_{fs}$ so it becomes as:

$$f(Energy_{(tr)}) = C(C_1 + C_2 r^2) \quad (25)$$

By the definition of PDF we calculate the cumulative sum energy consumption in transmission grid as follows:

$$\int_0^R f(Energy_{(tr)})dr = 1 \Rightarrow C \int_0^R (C_1 + C_2 r^2)dr = 1$$
$$\Rightarrow C = \frac{1}{C_1 R + C_2 \frac{R^3}{3}} \quad (26)$$

therefore the PDF of $Energy_{(tr)}$ becomes as:

$$f(Energy_{(tr)}) = \frac{1}{C_1 R + C_2 \frac{R^3}{3}} \left[C_1 + C_2 r^2 \right] \quad (27)$$

Expected value of $Energy_{(tr)}$ is,

$$\begin{aligned} E(Energy_{(tr)}) &= \int_0^R \left(C_1 + C_2 r^2 \right) f(Energy_{(tr)}) dr \\ &= \frac{1}{C_1 R + C_2 \frac{R^3}{3}} \int_0^R \left(C_1 + C_2 r^2 \right)^2 dr \end{aligned} \quad (28)$$

$$E(Energy_{(tr)}) = \frac{1}{C_1 R + C_2 \frac{R^3}{3}} \left(C_1^2 R + C_2^2 \frac{R^5}{5} + 2C_1 C_2 \frac{R^3}{3} \right) \quad (29)$$

where $C_1 = 2kEnergy_{(elec)}$ and $C_2 = k\epsilon_{fs}$.

Eq. (29) express the theoretical expected energy consumption in one hop distance so overall energy consumption in transmission of k bit data packet through a routing path from S to D is given by,

$$E(Energy_{(total)}) = E(Energy_{(tr)}) \times E(HC) \quad (30)$$

$$E(Energy_{total}) = \frac{1}{C_1 R + C_2 \frac{R^3}{3}} \left(C_1^2 R + C_2^2 \frac{R^5}{5} + 2C_1 C_2 \frac{R^3}{3} \right) \times E(HC) \quad (31)$$

Figure 7b shows that the expected energy consumption of network decreases if transmission range of sensors increased with constant grid size. This is also obvious that if we increase the transmission range of a node than data packets take fewer hop to reach the sink. Moreover, with constant grid size and transmission range if we increase the node density the energy consumption further increase. The reason for this is the more nodes are spent their energy in redundant sensing and redundant transmission. Further, in next section we analyze the simulation results and also correlate them with theoretical ones.

6. Results and Analysis

The ECAR mechanism is evaluated for its performance in a simulated environment of randomly deployed network. The proposed method incurs the same cost for virtual field setup as the other potential based routing protocol [6, 26]. The potential field information is also updated in same way as does in [6, 23]. Similarly, a node awaiting for forwarding decision inquires its neighbors for their hybrid potential field and calculate best neighbor on a loop free path using the proposed mechanism for forwarding a packet. This local gradient formation strategy reduces the number of field request messages as compared to other loop free path findings algorithm [24]. Consequently, this surplus network overhead is reduced because of local decision making for next-hop. and the underlying applications experience the less end-to-end delay in packet transmission. Moreover, the balanced energy consumption also directly related to number of dead nodes. Therefore, for flawless performance measurement, it is required to take effective metrics. Therefore, we take the appropriate and precise metrics for simulation experiments and discuss in coming section.

6.1. Performance metrics

To assess the quality of proposed mechanism, we evaluated it in NS2 [27] under the following performances metrics,

1. *Variation in expected energy consumption (VEC(t))*: We introduce this metric to assess the network wide energy variation while packet delivery is done under heavy load condition. It formally defined as the standard variance of energy consumption of all nodes with specific number of transmission.

$$VEC(t) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(EC_i(t) - EC_{avg}(t)\right)^2} \quad (32)$$

   where N is number of nodes in network, $EC_i(t)$ represents the energy consumption of node i in transmission round t and $EC_{avg}(t)$ represents the average energy consumption of all sensor nodes in transmission round t. The $EC_i(t)$ is calculated as:

$$EC_i(t) = RE_i(t-1) - RE_i(t) \quad (33)$$

   where $RE_i(t)$ and $RE_i(t-1)$ is residual energies of node i after t^{th} and $(t-1)^{th}$ transmission round, respectively.
2. *Expected hop-count*: It is defined as the average number of hop required to transmit packet in multi-hop scenario.
3. *Dead nodes count* [6]: It is the number of nodes which run out of energy after the specified number of transmission rounds. This metric is used to measure the variation in dead nodes with varying transmission rounds.
4. *Network lifetime* [4]: It is defined as the number transmission rounds till the first dead node appeared. Moreover, this metric is closely related to network partition and also affected the network coverage because the instance after that nodes of network runs out of energy is become a potential point for network hole. Consequently it causes low network coverage.

Now before discussing the simulations outcomes, it is necessary to discuss the relevant assumption and different parameter configurations that we take in experiments.

6.2. Network Setup

Figure 8, shows a network of 200 nodes that are deployed at random coordinates in a yard of 300 $\times$ 300. The sink node is deployed at center of the yard, however it can be placed anywhere in the yard. The transmission range of all nodes except sink is 50m. The detailed configuration is summarized in TABLE 2.

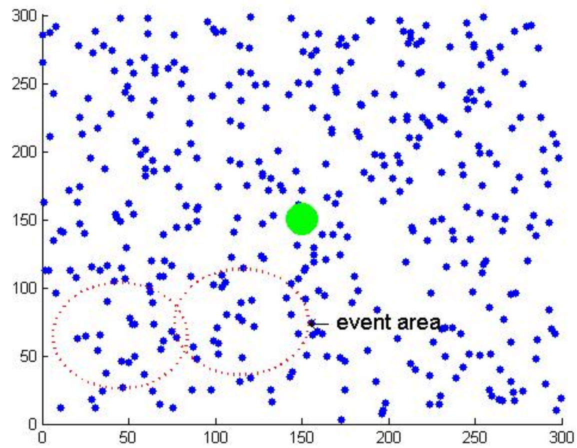

Figure 8: Spatial distribution of nodes with sole sink placed at center

The nodes which are in the vicinity of event area will start transmitting the data packets that contain the event information. This transmission process is continued till 500 rounds of transmission, and we scrutinized the complete network for dead node count and remaining battery power of each node in all transmission rounds. Moreover, to concede the better half of proposed algorithm the same is computed for its competitive IDDR algorithm. The comparison of proposed algorithm is done only with integrity sensitive IDDR because it perform better in most cases of data packet routing in sensor network [6]. The comparison of these results are presented in next section.

6.3. Performance evaluation of ECAR

Performance evaluation of proposed mechanism is required to answer the question that how far the proposed mechanism

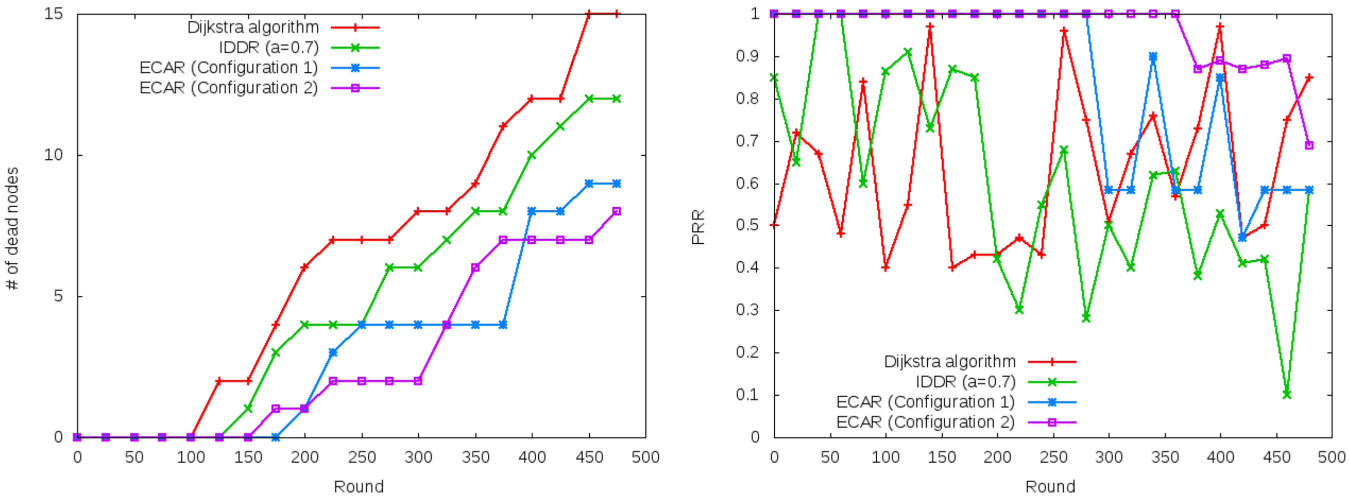

Figure 9: (a) Comparison of dead nodes in each transmission round for ECAR algorithm with Dijkstra's and IDDR for different regulating parameters (b) Comparison of PRR for ECAR with Dijkstra's and IDDR for different regulating parameters

Table 2: Configuration of parameter : Random deployment

Parameter	*Value*
Number of nodes	50-200 nodes
Control packet length	200 bits
Data packet length	1024 bits
Initial energy of node	$25J$
Transmitter energy consumption	$50mJ$
Receiver energy consumption	$50mJ$
Free-space energy	$10pJ{=}bit{=}m^2$
Buffer size	31 pkts

Table 3: Considered parameter configuration for ECAR

Field parameter	*Values*	
	Configuration 1	Configuration 2
(Depth)	0:2	0:2
$_1$ (Queue length)	0:1	0:2
$_2$ (Residual energy)	0:3	0:3
$_3$ (Energy density)	0:4	0:3

is superior than its competitive ones under the defined objectives. The extent of performance screening at the end of each transmission round consists of the following two steps:

- Compare the simulated behavior of ECAR mechanism with its competitive algorithm in terms of considered performance metrics.
- And then, compare the simulated and theoretical results statistically for identifying that how far the real-time transmission behavior in ECAR matches the outcomes of theoretical analysis.

However, the performance of ECAR mechanism is directly influenced by the proportion of each potential field in hybrid decision metric. Thus, it required to know the proportional weight of each field beforehand while simulating the realtime applications with ECAR algorithm. To obtain the optimum value of such potential fields weights, it is required to solve the constrained optimization problem as discussed in Section 3.3.3 under the desired objectives of meeting the QoS of running application. The procedure of solving the constrained optimization problem is out of scope of this paper but the relevant details of solving this problem is founded in [28]. Here we consider the two different configurations with optimum weights for performance measurement; first one is precisely biased towards the balanced energy consumption where the proportion of residual energy and energy density potential fields are slightly higher than others while other configuration is deal with congestion awareness situation where the proportion of queue-length potential field is more. The values of fields weights for both configuration are mentioned in TABLE 3. After setting the potential fields weight for both configuration, several simulation are performed for measuring the potential of proposed mechanism over others in terms of defined objectives. The theoretical and experimental details of all simulation experiments are presented in coming sections.

6.4. Comparison of ECAR with its peer mechanism in terms of residual Energy, PRR and network lifetime

The primary objective of this experiment is to assess energy and congestion awareness of proposed ECAR mechanism. Hence, we inspect the network for residual energy, dead node count and PRR in simulation of ECAR mechanism because increased network lifetime, PRR and more residual energy after packet transmission, express the high level of energy and congestion awareness in ECAR mechanism. This experiment consists of two phase:

a. Simulate the ECAR mechanism for residual energy, PRR and dead node count with varying network size for both configuration defined in TABLE 3.

b. Compare the simulated values of residual energy, PRR and dead node count of ECAR with its peer mechanisms i.e., Dijkstra's algorithm and IDDR [6], to concede the ECAR over its peer mechanisms.

The experiments are performed with following assumptions: (i) Each node starts its transmission process in the current transmission round, when it receives event information and (ii) Sink node maintain the accounting log for dead node count and for the number of packet received by itself. First, with these assumption the ECAR algorithm is evaluated for 500 transmission rounds in MATLAB R2012a where we compute the residual energy consumption, PRR and dead node count for Dijkstra's algorithm, Integrity sensitive IDDR (= 0:7), and ECAR algorithm with considered configuration (refer TABLE 3) for each round of transmission. The critical discussion of simulation results are presented in following subsection.

6.4.1. Results and discussion

This section consists the positive and adverse outcomes of proposed algorithm in above defined experiments. From the curve of dead node and PRR in Figures 9a and 9b, we observe that the ECAR protocol enhance the network performance, concerning the longterm health and high PRR. It is noted that ECAR with both configuration suffer from a sudden increases in dead node count, nearly at round 200; 150 in Configuration 1 and 2 respectively.

The reason for the sudden increase in dead node count is that every node in the event area was engaged in the transmission process, when it gets sensory information and its energy will be exhausted within a short period of the transmission rounds. But on the contrary, long-term figure of dead node count in ECAR is minimum compare to Dijkstra's and IDDR with = 0:7 algorithm.

Apart from this, sudden drop also means that the balanced energy consumption between the involved nodes is advisable because the packet needs to route through balanced energy and low-congestion area and try to avoid the area which is suffering from high congestions.

In Figure 9b, shows that PRR in ECAR mechanism with both configuration is significantly higher to IDDR whereas IDDR has too much variation in PRR in range of [0:46; 1]. The ECAR mechanism with both energy and congestion aware configurations, i.e., Configuration 1 and 2, respectively, give the long-run high PRR (1 till 278 and 323 transmission rounds in Configuration 1 and 2, respectively), is the primal evidence for less packet drop in ECAR mechanism.

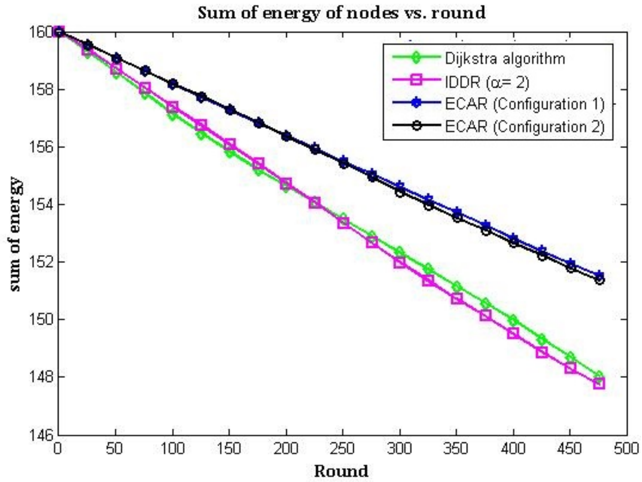

Figure 10: Comparison of network wide energy among ECAR, Dijkstra's and IDDR for different regulating parameters.

Moreover, the transmission round till PRR is 1, is less in ECAR with Configuration 1 as compared to Configuration 2. The reason for this includes more weightage of hybrid decision metric of ECAR with Configuration 2 towards the congestion control field and make the exploration of more underutilized path for packet transmission for alleviating large packet drop.

From Figure 10 it is clear that the total energy consumption in ECAR mechanism is 8:5J in packet transmission till 480 transmission rounds that is significantly lesser than its peer mechanisms like IDDR mechanism, where it is 12:4J. Thus, it shows that the ECAR mechanism has more rounds of transmission than its their peer ECAR mechanisms.

The above comparison justifies that the proposed ECAR algorithm enhance the performance in terms of balanced energy consumption, increased PRR and more functional lifetime.

Now the question that arises in our mind that how far the ECAR mechanism meets the theoretical results of delay (or hop-count) and balanced energy consumption? Thus for estimating this, we compared simulation results of delay and energy consumption with their respective theoretical results and analyzed them critically for concluding their outcomes. The critical analysis of these outcomes are presented in Section 6.5.

6.5. *Comparison of expected hop-count and energy consumption with their theoretical results*

In this section we compare the expectations of hop-count and energy consumption of energy aware configuration of ECAR with their theoretical results. For this, we simulate the energy referenced ECAR algorithm with Configuration 2, (as defined in TABLE 3) for different network sizes in NS2 [27] and noted the expected hop count and energy consumption. These results are plotted in GNUPlot [29].

The experiments used energy aware ECAR with constant bit rate (CBR) application traffic (with 100 packets/second over the UDP connection and the simulation is performed for 500 transmission rounds) in Network simulator (NS2) tool. Trace files are processed to disintegrate results for expected hop-count and

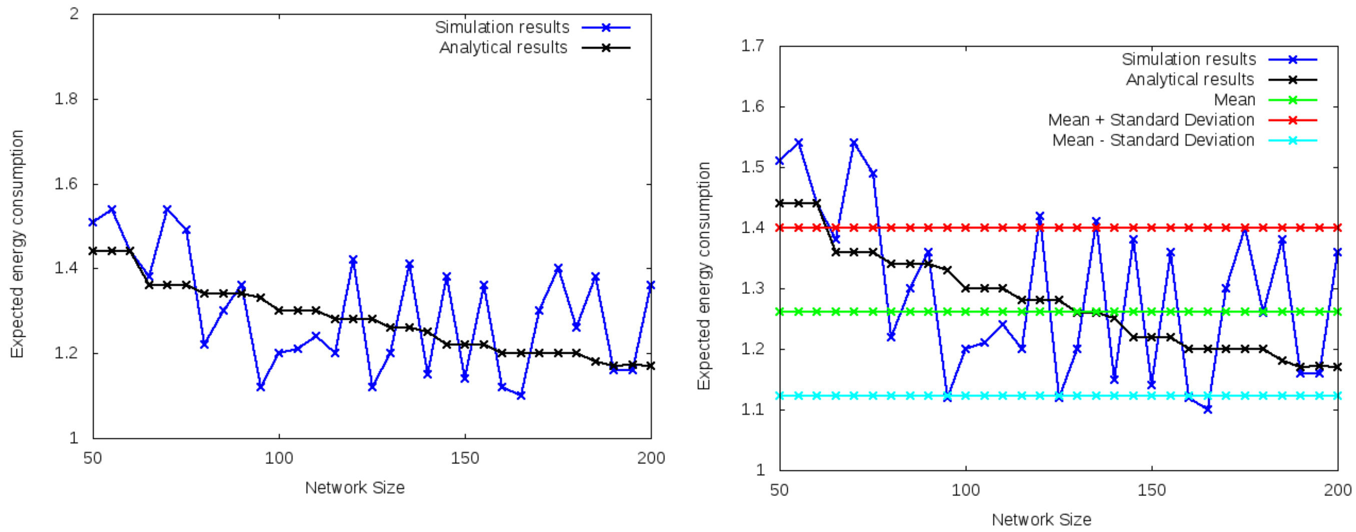

Figure 11: (a) Expected energy consumption vs Network size and its (b) Variation from mean

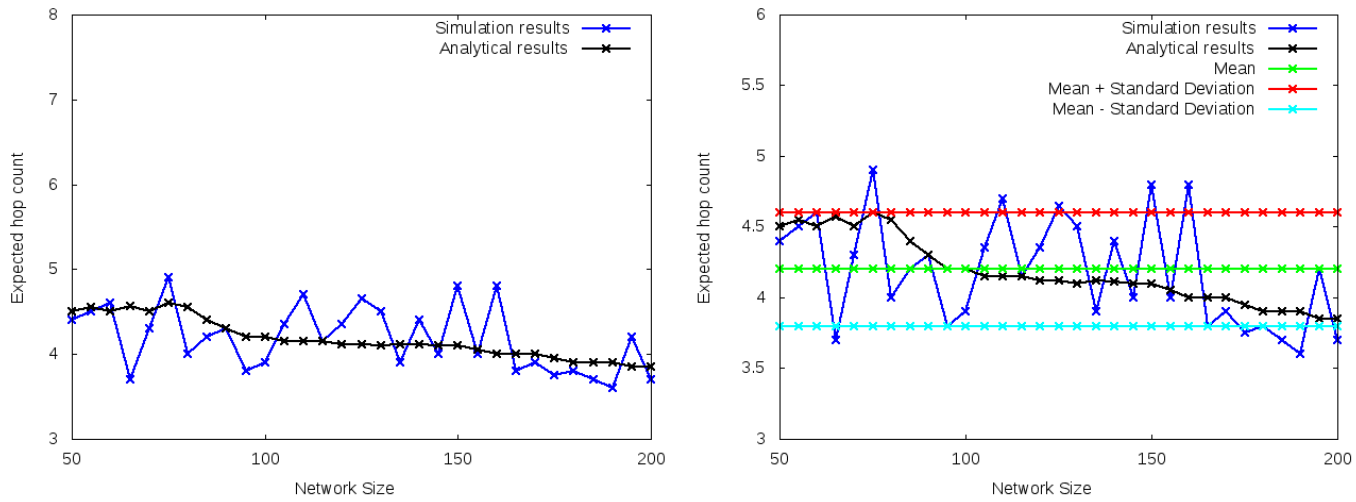

Figure 12: (a) Expected hop count vs Network size and its (b) Variation from mean

energy consumption on a per transmission round basis. Successively, the numerical results are compared with theoretical one and the deviation from its mean value is estimated *VEC(t)* metric defined in Section 6.1.

6.5.1. Results and discussion

The simulation starts with randomly selected source nodes in each transmission round. The simulation is monitored for hop-count and energy consumption required for transmission of a number of packets from selected source to sink. Moreover the variation of these results with its theoretical one for different network sizes, it is required to compute the expectation by averaging the results for any random source to common sink in each transmission round.

The statistical correlation of simulation and theoretical results for expected energy consumption and hop-count are shown in Figures 11a and 12a. From Figure 11a, it is observed that with the size of the small network the energy consumption is slightly higher but progressive increase in the deployed network size reduces the energy consumption in the packet transmission.

From Figures 11b and 12b, it has been observed that variation in simulated expected energy consumption and hop-count with varying network sizes, are within its adjoining lines (like Mean Standard-deviation (S.D.)), indicating that it surpasses the uneven energy and hop count gap in packet transmission.

Moreover measurement of how far proposed mechanism meet the desired goal, it is required to calculate the concrete value of mean square error ( ) for both energy consumption and expected hop-count because less value of pertains to the optimum result. The results of TABLE 4 shows the value of is significantly less which justify that the variation in expected hop count and energy consumption of proposed ECAR is within the theoretical limits in long-run of simulation. Finally the com-

Table 4: Statistical Measures of Energy Consumption and Hop Count

Statistical measures	*Energy consumption*		*Hop count*	
	Simulated value	*Analytical value*	*Simulated value*	*Analytical value*
Mean ( )	1:261	1:256	4:20	4:18
Standard deviation ( )	0:1387	0:083	0:401	0:383
Mean square error ( )	**0:00058**		**0:0053**	

parison of overall network lifetime with its peer mechanisms is shown in coming section. The network lifetime is calculated as similar to the one that discussed in Section 6:1.

6.6. Comparison of network lifetime of ECAR with its peer mechanisms

Figure 13 shows the variation in network lifetime (calculated in terms of transmission rounds) for all considered algorithm with different initial energy level of sensor nodes. From Figure 13 it is observed that the progressive increment in initial energy of the sensor nodes results in the increment of transmission rounds till the first energy exhausted node detected. Moreover, the network lifetime in proposed mechanism is comparatively higher for all initial energy configuration. When the initial energy of all nodes are 25J, the network lifetime for ECAR with Configuration 1 and 2, IDDR and Dijkstra's algorithm are about 175; 150; 125 and 100 transmission rounds, respectively (see Figure 13). The reason for this sudden drop in network lifetime of IDDR includes the more engagement of transmission nodes that are reside on overloaded paths whereas in same frame the nodes of underutilized paths keep idle. For the same case, ECAR mechanism take the residual energy of nodes in making the decision of routing and keep the nodes aside which are frequently engage in earlier transmission process. Thus, with this way the sensor network is survive for more number of transmission round in ECAR mechanism as compared to its peer mechanisms.

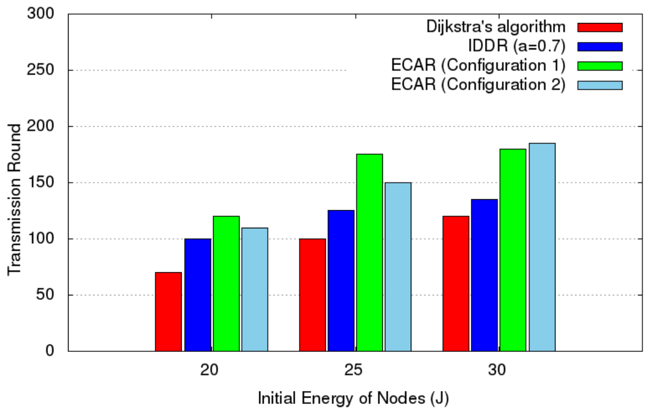

Figure 13: Network Lifetime comparision with various energy level

7. Conclusion

The paper proposes a situation aware routing protocol named ECAR that is build upon gradient field theory. The protocol considers $_{1}$, $_{2}$, and $_{3}$ as regulating parameters for queue length, residual energy and forward aware residual energy density respectively to model the virtual hybrid potential field that serves as the decision parameters for forwarding packets. The introduction of regulating parameters into the model resulted in extending the transmission rounds till the FDN is detected and improved PRR. This indicates for a given network setup the ECAR mechanism would help the network survive better from the view point of energy holes and extend network lifetime. It was observed that in heavy traffic conditions there was an average increment of 45% transmission rounds till the FDN appeared. At the same time it has been observed that squared deviation of expected energy consumption ($_{1}$) is 0.00058. Similarly, squared deviation of expected hop count ($_{2}$) is 0.0053. These results signify that ECAR algorithm minimize the expected hop-count, number of dead nodes and equally balance the network wide energy consumption which justifies the ECAR mechanism is energy and congestion aware.

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