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RESEARCH ARTICLE

A Power-Aware River Formation Dynamics Routing Algorithm for Enhanced Longevity in MANETs

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Abstract – Mobile Ad Hoc Networks (MANETs) are made up of battery-powered wireless devices that create an ad hoc network for communication. The power used by these devices can be very high since their batteries are limited and their topology fluctuates. This makes energy consumption and network longevity critical issues to be considered for routing algorithms in MANETs. This research aims to minimise energy consumption and extend the network's longevity among MANET nodes. This paper introduces the Power-aware River Formation Dynamics Routing Algorithm (PRFDRA); an algorithm that uses energy offerings in its path selection mechanism. The PRFDRA mechanism is based on river formation dynamics (RFD), a water metaheuristic. The algorithm finds the iteration's best solution, the shortest path between any origin and end point in MANETs, based on a cost function that incorporates factors which include energy, number of hops, and time delay, with energy having the highest weight factor. The mechanisms for determining the probability of choosing a node and the erosion of nodes that cater for a neighbour with positive, negative, and flat gradients also incorporate these factors. Also, the mechanisms for determining the gradient of a path, the computation of the sediment of a drop added to the altitude of a node, and the computation of the altitudes of nodes incorporate these same factors. PRFDRA outperformed EMBO, RFD, AODV, and DSDV in packet delivery ratio, end-to-end delay, energy consumption, and network lifetime in NS-3 simulations. Importantly, in terms of variation in node speeds, the energy consumption and network lifetime improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 7.54 joules and 62.74 seconds, 5.10 joules and 68.76 seconds, 15.70 joules and 315.90 seconds, and 21.43 joules and 351.35 seconds. In terms of variation in terrain dimension, the energy consumption and network lifetime improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 2.91 joules and 50.34 seconds, 6.32 joules and 128.44 seconds, 18.02 joules and 255.01 seconds, and 22.56 joules and 302.04 seconds. The results reveal that incorporating energy-proficient and RFD mechanisms in the path selection significantly minimises energy consumption while enhancing network

longevity. As future work, PRFDRA can be enhanced with fuzzy logic and cloud-assisted techniques.

Index Terms – River Formation Dynamics, Metaheuristics, Optimization, MANETs, Energy, Energy Consumption, Network Lifetime, Routing.

1. INTRODUCTION

Conventional wireless networks rely on a fixed backbone over which communication occurs. In situations where creating an infrastructure-based network is demanding or impossible, other alternatives must be established, which may include MANETs. A MANET organises and configures itself without external intervention and can transmit data over multiple hops. MANETs have interesting applications and features; however, the absence of a central framework, the constantly fluctuating layout, the restricted resources, and the dispersed structure of the network, among other characteristics, create a difficult environment for providing routing services, particularly at the network layer. The task of route selection between any origin and endpoint falls under the responsibility of routing algorithms. A routing algorithm that does not consider power consumption aims to enhance network performance even if it results in higher power usage [1]. Given the battery-powered nature of nodes in MANETs, optimizing power consumption by employing power-aware routing protocols instead of conventional routing algorithms becomes paramount to extending their operational longevity [2]. Network lifetime, or longevity, is defined as the time between when the network begins and its' closure. The route's lifespan improves when the network is stable, while the power of a given node decreases if it is used for an extended period due to traffic distribution [2].

1.1. Philosophy of MANETs

Mobile ad hoc networks (MANETs) are transitory networks where devices connect without a central boss or structure [3]. The nodes of MANETs can move freely at any time. As such, the network's topology can change quickly and suddenly. Moreover, the network nodes play dual roles as data gateways and sources, facilitating the exchange of information between devices that lack direct links [4]. This type of network can use a gateway node to promote communication between nodes and an external network. Nodes use antennas to facilitate signal transmission. The antennas radiate and receive signals based on their transmission range (R) influenced by the measure of transmission power. Neighbour nodes are the nodes situated in the R of a node. When a node sends transmissions to another node, neighbouring nodes within its R can also hear them. The region covering the R is referred to as the capture area. The network's interference surges as transmission power surges since there is a rise in the capture area and the number of neighbouring nodes. A MANET is created immediately after a node communicates the desire to perform some unicast or multicast communication. A node can communicate a packet to nodes outside of its R by using nodes that serve as relay points. MANETs are aptly called wireless multi-hop since they are widely recognised for using a method known as wireless multi-hop [5]. The movement of messages from an origin to a target node is shown in Figure 1.

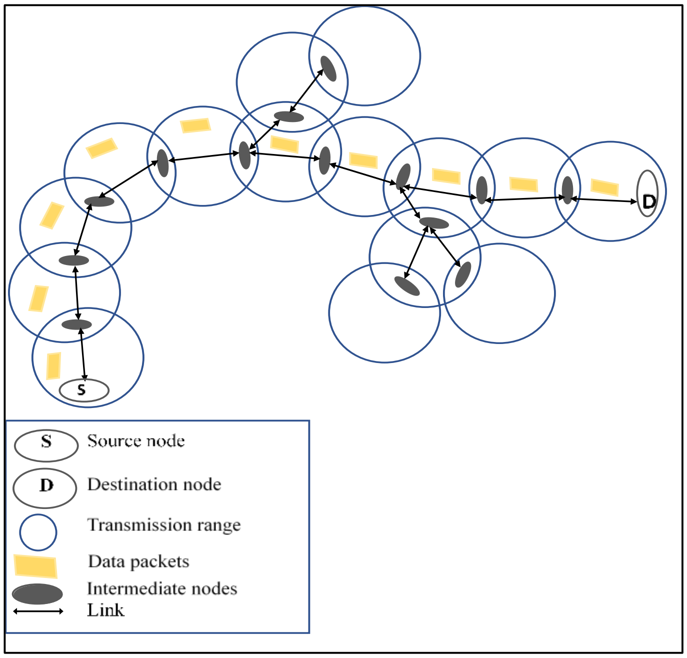

Figure 1 Transfer of Data Packets from a Source to a Destination Node in a MANET

1.2. Major Design Characteristics and Challenges of MANETs

Despite sharing generic features with wired and wireless infrastructure-based networks, MANETs exhibit unique properties due to node mobility, their media characteristics, and the planned path schemes used. These properties have intensified the complexities and limitations that render the design of such networks challenging. The subsequent discussion delves into these exceptional properties:

1.2.1. Energy Constraints

Various OSI reference model layers can be used to address the energy efficiency issue in MANETs. Currently, most researchers are focusing on optimising the energy consumption of nodes from various perspectives. The suggestions range from controlling wireless nodes' sleep states to modifying their transmission power. These ideas span from MAC layer proposals to combined MAC and routing function proposals.

1.2.2. Node Mobility Leads to Dynamic Network Topology

Since nodes can freely enter and exit their geographic coverage area, MANETs are distinguished by dynamic network topologies. Over time, this leads to sudden alterations in their network structure. Nodes must obtain information about network connectivity from other nodes. This implies that the overhead associated with obtaining topology information increases. Mobility is of great concern in the design and analysis of MANETs.

1.2.3. Hidden and Exposed Terminal Problem

A notable limitation of MANETs relates to issues concerning exposed and hidden terminals [6]. The former scenario, involving exposed terminals, leads to delays in delivering data to a sender node due to an accumulation of transmissions within its coverage area [7]. In contrast, the latter scenario, hidden terminals, occurs when two nodes attempt to send data simultaneously without sensing each other, often because they are out of each other's direct communication range.

1.2.4. Limited Bandwidth and Variable Link Capacity

Wireless networks are generally bandwidth-constrained, and the situation is worse in MANETs, which even operate on variable link capacity. Such networks often experience fast disruptions, low output, large reaction times, and compromised security, which further contribute to network traffic due to inadequate link capacity. Therefore, the optimum use of bandwidth is desirable to maintain the overhead associated with any protocol as low as possible.

1.2.5. Security

MANET nodes rely on individual security solutions outsourced from each mobile node since it is difficult to operate centralised security control. The major attacks experienced by MANETs include passive and active attacks. Therefore, security is of great concern in the design of routing algorithms [8].

1.2.6. Quality of service (QoS)

The network's QoS is significantly impacted because of its varied and dispersed structure [9]. MANETs offer enormous promise for boosting the exchange of information in high-stakes rescue and critical situations. Despite offering communication services, MANET's quality of service has decreased as a result of various issues that lower their worth [10]. Bandwidth, delay, throughput, packet delivery ratio, jitter, and so on are possible QoS parameters.

1.3. Power-Aware Routing in MANETs

The majority of non-power-aware routing schemes prioritise network efficacy above power. The shortest path is not necessarily the best option in terms of power efficacy, so power-aware protocols work to find paths that can reduce energy use. The main challenge lies in node mobility, as the duration of a node's movement is determined by its battery lifespan. Using a large amount of battery power increases the node's mobility time. Several routing protocols have been suggested to improve power efficiency, but none of them is ideal in every situation. Employing power-aware routing protocols reduces the amount of battery power used by each node [2].

1.4. Classifying Power-Aware Protocols in Routing

These protocols are classified into eight groups as shown in Figure 2, namely: Transmission Power Control-Based Approach, Location-Based Approach, Load Balancing-Based Approach, Multicast-Based Approach, Link State-Based Approach, Source-Initiated-Based Approach, Power Management-Based Approach, and Metaheuristic-Based Approach.

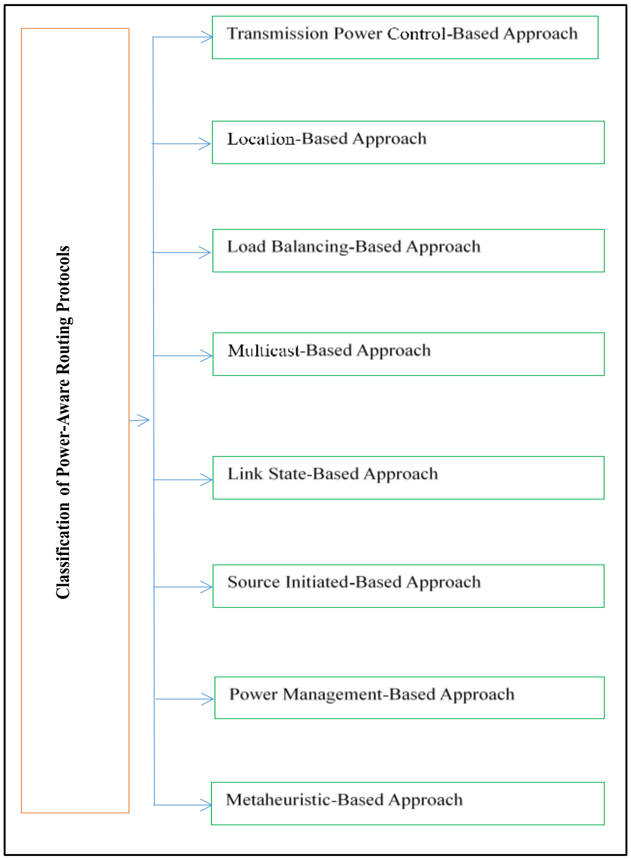

Figure 2 Power-Aware Routing Classification

1.4.1. Transmission Power Control-Based Approach

Power transmission can be controlled by regulating the structure of a MANET. Transmission strength determines the range across which the sent signal is completely acquired, and this is crucial for assessing network performance based on throughput, delay, and power consumption. These protocols find the most practical pathway that lowers overall transmission power between the origin and the target. A typical example of Transmission Power Control-Based Approaches is the Online Max-Min Routing Protocol (OMM).

1.4.2. Location-Based Approach

The energy minimisation mechanism employed is based on the location of the nodes. For instance, to increase path-finding speed, the Zone-Based Routing with Parallel Collision Guided Broadcasting Protocol (ZCG) uses a parallel-distributed technique for broadcasting. In this approach, the clustering algorithm employed is one-hop-based in which the network is partitioned into several zones known as static reliable leader-assisted zones.

1.4.3. Load Balancing-Based Approach

This approach underscores the significance of proactive involvement, aiming primarily to distribute energy usage equitably across network nodes, thus extending the network's longevity. It achieves this by steering clear of high-energy-consuming nodes while selecting routes. Only intermediate nodes that are rich in energy are allowed to transmit data packets. Such protocols also avoid overloading certain nodes. Typical examples of Load Balancing-Based Approaches include Conditional Max-Min Battery Capacity Routing (CMMBCR)，and Energy-Efficient and Load-Balanced Geographic Routing (ELGR).

1.4.4. Multicast-Based Approach

As data is sent simultaneously to several recipients, multicast routing aims to minimise the cost of transmission. Nevertheless, the main objective of multicast routing is to ensure energy efficiency, reduced delay, and stability of paths. An example is PEERMR (Predictive Energy Efficient and Reliable Multicast Routing).

1.4.5. Link State-Based Approach

Protocols classified under this group have their energy minimisation mechanisms based on the links established among the nodes. For example, in Energy-Aware OLSR (OLSR_EA), a reviewed path estimation algorithm is used for the election of paths. The energy utilised per link is predicted and computed using a technique known as auto-regressive integrated moving average series of time.

1.4.6. Source-Initiated-Based Approach

Protocols under this group have energy consumption mechanisms initiated by the source node. In DE-AODV, which is the Dynamic Energy Ad-hoc On-Demand Distance Vector Routing Protocol scheme, each node's transmit, active, and sleep modes are considered by the energy scheme. The protocol chooses the best and quickest route between origins and targets by evaluating the energy efficiency and trustworthiness of the nodes.

1.4.7. Power Management-Based Approach

The numerous performance needs introduced by the various programs in use, including throughput, must be taken into account by power management strategies. Historically, comprehensive research has delved into disc management, memory, and CPU [2]. A typical example of a Power Management protocol is the Power and Delay aware Temporally Ordered Routing Algorithm (PDTORA).

1.4.8. Metaheuristic-Based Approach

Most metaheuristic-based approach power-aware routing algorithms are nature-inspired. Typical examples include the Ant Colony Optimization_AODV (ACO_AODV)，and the Predictive Energy Efficient Bee Routing algorithm (PEEBR).

1.5. Metaheuristics

The Glover [11] phrase "metaheuristic" can be defined as a higher-level heuristic devised to locate a heuristic that can give a rough solution to an optimization problem. Metaheuristics have been the norm for some years now. This section outlines the reasons for its popularity [12]:

- Flexibility: They can easily be applied to several problems without changing their structure. Issues or problems are taken as black boxes, meaning that input and output are the most vital aspects of a metaheuristic system.
- Simplicity: A high percentage of metaheuristics are inspired by simple concepts such as the behaviour of animals, evolutionary principles, or physical phenomena. The simple nature of metaheuristic algorithms permits researchers to simulate varieties of natural ideas, improve on current metaheuristic ideas, propose new techniques, or hybridise two or more metaheuristics.
- Local Optima Avoidance: Metaheuristics is a great technique for escaping local optima. The whole search space is searched due to the stochastic nature of metaheuristics, and therefore stagnation in local search is prevented. Thus, metaheuristics is a great technique for optimising problems with large local optima.
- Gradient-free or Derivation-free method: There is no need to compute the derivate of search spaces for finding the optimum since the optimization starts with random solutions.

1.6. River Formation Dynamics (RFD)

In 2007, the concept of RFD was introduced, involving water droplets landing on flat, erodible ground [13]. Upon dispersal, certain droplets reach exits or sinks, eventually forming a sea-like area where they vanish (referred to as the "sea"). These droplets carry soil from nearby sites as they journey towards the sea, leading to land loss and decreased altitude in proximity to the sea. This creates gradients, causing subsequent drops to follow gravity and accelerate erosion, which progressively extends to more distant areas. This erosion process naturally carves paths downslope, originating from rainy drop-spawning regions and culminating in sea pathways. Figure 3 illustrates the resultant river basin, a manifestation of nature's design to channel raindrops from wet zones to the sea, complete with possible tributaries and meandering features.

Figure 3 Water Dynamics with the Waterfall at Boti in Ghana

1.7. Algorithm for River Formation Dynamics (RFD)

The basic algorithm is given as follows [13], [14]:

```
drops are initialized
nodes are initialized
do again
drops are moved
paths are eroded
sediments are deposited
paths are analyzed
until the terminating condition is achieved
```

Commencing the algorithm, nodes are initialized to predetermined positive values, indicating a level surface. Emerging at the starting point, droplets disperse over this plane. Their descent towards the sea triggers erosion at differing altitudes, resulting in a downward slope. This process leads the slope to propagate back towards the origin across multiple training cycles. The movement of drops is based on random selection probability $P_k(i, j)$ [15], as provided in equation (1).

$$P_k(i,\ j) = \begin{cases} \dfrac{\text{decreasingGradient}\ (i, j)}{\sum_{l \in v_k}(i)\text{decreasingGradient}(i,\ l)} & \text{if } j \in\ V_k(i) \\ \mathrm{O} & \text{if } j \notin\ V_k(i) \end{cases} \qquad (1)$$

In which $P_k(i,\ j)$ is set as the probability assigned to drop k to choose node j at node i, while V_k encompasses the group of neighbouring nodes that the drop can traverse from node k. The term $\text{decreasingGradient}\ (i,\ j)$ signifies the gradient with a negative value between nodes i and j, formulated as outlined in equation (2) [16]:

$$\text{decreasingGradient}(i, j) = \frac{\text{altitude}(i) - \text{altitude}(j)}{\text{distance}(i,j)} \qquad (2)$$

In this context, $\text{distance}(i, j)$ symbolises the edge's length connecting nodes i and j. $\text{altitude}(x)$ is the node x's altitude. As the process initiates, the entirety of the decreasing gradient is initialized at zero, while all nodes share an equivalent altitude. Droplets gain the freedom to disperse by attributing a non-zero probability for a drop to traverse an edge exhibiting a gradient of zero. As a drop descends from one node to a lower altitude, erosion takes place at the starting node. It is crucial to emphasise that the sea's altitude is set at zero and remains immune to erosion. Notably, the altitudes of nodes directly correspond to the extent of erosion, as outlined in equation (3) [17].

$$\text{erosion}(j) = \alpha(\text{altitude}\ (i) - \text{altitude}(j)) \qquad (3)$$

Following erosion, sedimentation emerges as another process within the algorithm. This phenomenon comprises two distinct types. Firstly, the algorithm periodically deposits sediments onto all nodes, uniformly and marginally elevating their altitudes. Keeping altitudes above zero is the goal. This measure arises after numerous iterations, addressing diminishing gradients that could potentially jeopardise established pathways. Secondly, as droplets traverse the network, they gather and transport sediments, a byproduct of erosion. The interplay between erosion quantity at each node and sediment deposition impacts the gradual accumulation of a droplet's sediment load. This process influences continuous shifts in sediment levels at individual nodes. The quantity of sediment carried by a droplet at a specific juncture dictates sediment deposition, as shown in equation (4) [17]:

$$\text{sediment} = \beta * \text{carried\_sediment} \qquad (4)$$

A positive number that is a constant denotes β. In the final phase, the route connecting the initial and terminal points is scrutinised to identify the condition that dictates termination. Should the quality prove impractical, the drop-sending procedure is repeated until a viable outcome is achieved or the peak iteration limit is attained.

1.8. Problem Statement and Contributions

Routing in MANETs is a constantly evolving optimization problem because its' options change over time. The policy for routing is determined by rules that determine the next steps at each decision point to arrive at the end node. The MANET nodes used in routing include smartphones, laptops, sensors, personal digital assistants, cell phones, and others. These nodes have energy constraints because they use small, hand-held battery-powered transmitters [18]. Packets are transmitted on more than one path, which results in the exhaustion of the batteries of the various nodes at the same rate. Also, mechanisms of signal transmission, retransmission, beaconing, and reception consume a lot of energy. During critical settings like disaster areas or battlefield operations, it is more challenging to replace their batteries. Developing energy-efficient algorithms is crucial to extending the operational lifespan of nodes within the system [19]. This study seeks to propose a routing algorithm for optimising path selection with minimum energy usage for enhanced network longevity.

Of late, metaheuristics have gained popularity as a solution to complex optimization problems, finding feasible solutions efficiently [20]. In response to the no-free-lunch theorem, a surge of water metaheuristics has emerged in recent years. These techniques draw inspiration from the behaviour of water in nature. In addressing the optimization problem, the river formation dynamics (RFD) is used. Metaheuristics have to maintain a balance between exploring and exploiting solutions in the optimization problem's search space. Failure to maintain this balance causes the algorithm to produce suboptimal solutions for any complex optimization problem [21]. This challenge introduces an open field of research to propose modifications to the RFD algorithm that can improve performance in producing optimal solutions. The contributions of the proposed approach include

- The algorithm's optimum path selection is based on RFD.
- The iteration's best solution is based on a minimization cost function which incorporates minimum energy, number of hops, and time delay. Minimum energy has the highest weight factor.
- The algorithm has energy, number of hops, and time delay saved in individual nodes, which promotes efficient load balancing.
- The mechanisms for determining the probability of choosing a node and eroding nodes that cater to a neighbour with positive, negative and flat gradients also incorporate, time delay, minimum energy and the number of hops. Also, the mechanisms for determining a path's gradient and the altitudes of nodes incorporate these same factors.

1.9. Motivation

The motivation for developing an energy-proficient routing algorithm for mobile ad hoc networks (MANETs) stems from the aim to optimise energy consumption and extend network longevity. Such algorithms target the efficient utilisation of energy resources, thereby ensuring sustained communication among nodes in dynamic and resource-constrained environments. By conserving energy, these algorithms enhance the overall network lifetime and reliability, contributing to environmental sustainability by reducing carbon emissions and energy usage. Energy-proficient routing algorithms prioritise resource management, balancing communication needs with energy constraints to improve scalability and adaptability.

1.10. Objective

To design a routing algorithm using a modified RFD metaheuristic for optimising path selection with minimum energy for enhanced network longevity and to implement the suggested routing algorithm in a network simulator, assess its performance, and contrast it with some existing routing algorithms.

1.11. Organization of the Paper

The rest of the paper is organised as follows: Section 2 explains related work. Section 3 presents the proposed power-aware river formation dynamics routing algorithm (PRFDRA). Section 4 discusses the results. The paper ends in Section 5 with the conclusion.

2. LITERATURE REVIEW

This section elaborates on the various RFD routing models presenting a comprehensive summary of these models in Table 1.

Mehrjoo and Khunjush [22] present an enhanced rendition of the RFD algorithm termed IRFD, applied for the construction of an improved aggregation tree. This algorithm factors in variables such as network neighbours, residual energy, and proximity to the sink node. Moreover, two energy-related parameters are incorporated into the gradient equation. The original RFD's erosion operation is adapted in the IRFD algorithm, involving the inclusion of hop count and costSolution.

Guravaiah and Velusamy [23] present three energy-efficient clustering methods that analyse energy consumption in WSNs through RFD-based multi-hop communication. These algorithms prioritize energy efficiency while extending the RFDMRP algorithm to manage clustering operations. The three algorithmic variants, named Hybrid Clustering Communication using RFDMRP (HCCRFD), Intra (within) Cluster Communication using RFDMRP (IaCCRFD), and Inter (between) Cluster Communication using RFDMRP (IrCCRFD), utilize RFDMRP and focus on forming clusters by grouping sensors and assigning each cluster to a nearby base station. RFDMRP is leveraged within clusters to disseminate local base station information to a global base station, enabling a move operation.

Sharma and Gupta [24] employ the RFD algorithm to compute optimal paths within a designated time limit in a

WMN. The initial phase involves establishing a mesh network, where each node is associated with a specific radio range. Routing metrics which are generated for nodes within the radio range are continually renewed and maintained. Once the network is identified, all nodes compute the Integrated Link Cost (ILC) for neighbouring nodes. The ILC determines the desired route length for the specific origin and target pairs, guiding the determination of optimal paths based on the ILC-derived data from adjacent nodes.

Guravaiah and Velusamy [25], [26] introduce and assess RFDMRP, a data collection routing protocol, forged upon the principles of RFD to enhance energy efficiency and prolong the lifespan of WSNs. RFDMRP is formulated based on the RFD concept, with a hop count and residual energy of nodes serving as crucial parameters in data forwarding decisions.

Amin et al. [27] introduce a power and congestion-aware swarm-based routing protocol called "SMART" for MANETs. Data packets can route themselves through routes that are less congested and throughout nodes with higher battery capacity to load balance the network.

"RFDManet" [27] is proposed, with a primary focus on enhancing routing reliability within MANETs through the utilisation of RFD. A central objective of the protocol is to achieve network-wide equilibrium. RFDManet introduces the novel concept of informed packets, actively involved in knowledge acquisition and autonomously navigating the network to select the best routes.

The authors in [17] introduce a hybrid Ant Colony Optimization (ACO) and River Formation Dynamics (RFD) swarm intelligence routing protocol, "SMART", in MANET. In the initial stage of the route set-up, ACO is used to build multipath routes to the destination. The routing protocol uses RFD as its base algorithm. Instead of increasing the control agents, the protocol uses data packets to act like control agents or drop packets. The data packets can adapt altitude tables, and their environments are learned by the network.

Table 1 Comparison of Discussed Approaches

Existing work	Methodology	Advantages	Disadvantages
IRFD [22]	Construct a data aggregation tree to optimize communication energy consumption in WSN	Two energy-based parameters are introduced in the gradient	costSolution in altitude update is not defined
HCCRFD, IrCCRFD, IaCCRFD [23]	Creates three different variants of clustering algorithms based on RFDMRP in WSN	RFDMRP is enhanced with clustering and energy is considered	Few RFD operations are used
RFD [24]	Routing protocol with path selection based on integrated link cost (ILC) in WMN	Energy is considered part of ILC	1. Energy is not considered in RFD operations 2. Some RFD operations and parameter values are not defined
RFDMRP [25], [26]	Data collection routing protocol in WSN	Energy is considered as part of node selection probability	The probability function in the move drops is not based on climbing drops
SMART [27]	Power and congestion-aware data packet routing protocol which is based on RFD in MANET	Energy is considered in RFD operations	The probability function in the move drops is not based on climbing drops
RFDManet [27]	RFD based Routing protocol which uses intelligent data packets for learning in MANETs	The learning process guides data packets to select the best routes	Energy is not considered in RFD operations
SMART [17]	Based on the hybridization of RFD and ACO in MANET	Uses both normal and intelligent data packets	1. Energy is not considered in RFD operations 2. The probability function in the move drops operation is not based on climbing drops.

3. POWER-AWARE RIVER FORMATION DYNAMICS ROUTING ALGORITHM (PRFDRA)

3.1. General Description

In the PRFDRA protocol, a routing table is established by utilising hello and drop messages. Also, along with a separate table to track the node's altitude towards other nodes, each node in the network keeps an altitude table that collects the altitude values of nearby nodes. The data structures (refer to Section 3.2), the pseudocode (refer to Section 3.3, and link failure management (refer to Section 3.4) are provided subsequently.

3.2. Data Structures

Each network node keeps two data structures: the routing table named node_altitude table (refer to Table 2), which contains routing information, and the neighbour table named neighbour_altitude table (refer to Table 3), which maintains the list of active neighbours.

Table 2 Node_Altitude Table

Next Hop (N)	Destination (D)	Altitude (AL)	NHops (H)	Time Delay (TD)	Energy (E)
N_1	D_1	AL_1	H_1	TD_1	E_1
N_2	D_2	AL_2	H_2	TD_2	E_2
----	----	----	----	----	----
N_k	D_k	AL_k	H_k	TD_k	E_k
----	----	----	----	----	----
N_n	D_n	AL_n	H_n	TD_n	E_n

Table 3 Neighbour_Altitude Table

Neighbour (N)	Altitude (AL)	Expire time (T)
N_1	AL_1	T_1
N_2	AL_2	T_2
---	---	---
N_{j-1}	AL_{j-1}	T_{j-1}
N_j	AL_j	T_j

3.3. PRFDRA Algorithm Steps

Input: Graph $G = (V, E)$ and Drops

Output: Iteration best solution

Step 1: Initialize the graph, source, destination, and intermediate nodes.

Step 2: Set the number of nodes and paths.

Step 3: Launch Drops at the source node.

These first three steps form the initialization stage of the algorithm. At the start, the graph and nodes are initialized. This is followed by the initialization of the number of nodes. The definitions include three distinct places or positions: the drop-producing location or source (S), the intermediate location (I), and the destination location (D) or sea. The altitude ranges of these places vary. Drops are consistently created at the source site. Droplets are collected at the source and transported to the sea by intermediary sites. We associate altitude values with nodes. In the initialised node phase, the altitude of both the source and intermediate nodes is the same and of a positive value which is 10000 while that of the sea is set to 0.

Following that, the Drops are initialized by placing them at the source location. At the outset, all Drops have equal values, resulting in their dispersal across the level terrain. Moreover, the cumulative gradient is initialized to zero.

Step 4: Determine the nodes accessible from the current node and compute the gradient along the edges using equation (5).

$$gradient(i,j) = \frac{(altitude(i) - altitude(j)).TD_j}{\mathrm{E}_j.N_{Hops}(i,j)} \tag{5}$$

Here, altitude(i) denotes the node i altitude and altitude(j) is node j altitude. The number of hops from node i to node j is represented by $NHops$. $E(j)$ stands for the energy left in node j. To identify crowded nodes, $TD(j)$ specifies the time delay for node j to send a packet. The benefit of using a node as a forward node decline as congestion rises.

In PRFDRA, the gradient expression considers the number of hops, energy and time delay parameters, addressing the limitations of relying solely on number of hops for node selection. Hence, PRFDRA incorporates the remaining energy of neighbouring nodes and time delay in addition to the number of hops when choosing the next node.

Step 5: Calculate the probabilities of selecting the accessible nodes using equation (6).

$$P_k(i,j) = \begin{cases} \dfrac{gradient(i,j).TD_j}{sum.\mathrm{E}_j.N_{Hops(i,j)}}, & for\ j \in V_k(i) \\ \dfrac{(\omega/|gradient(i,j)|).TD_j}{sum.\mathrm{E}_j.N_{Hops(i,j)}}, & for\ j \in U_k(i) \\ \dfrac{\delta.TD_j}{sum.\mathrm{E}_j.N_{Hops(i,j)}}, & for\ j \in F_k(i) \end{cases} \tag{6}$$

$$sum = \left(\sum_{l \in V_{k(i)}} gradient(i,l).TD_j\right) + \sum_{l \in U_k}\left(\frac{\varpi.TD_j}{|gradient(i,l)|}\right) + \sum_{l \in F_{k(i)}}\left(\delta.TD_j\right) \qquad (7)$$

Where $V_k(i)$ denotes the set of neighbours with a positive gradient meaning that node i possesses a higher altitude than node j. $U_k(i)$ represents the set of neighbours with a negative gradient meaning that node j possesses a higher altitude than node i. $F_k(i)$ denotes the set of neighbours with a flat gradient meaning that node i possesses the same altitude as node j. The coefficients ϖ and δ are specific fixed small values; 0.01 for both coefficients. The sum denotes the sum of the weights of all the neighbours from various collections mainly the numerators and is computed using equation (7).

Step 6: Choose the next node based on the highest probability value and proceed with movement.

Step 7: If convergence is not reached go to step 8.

Step 8: Repeat steps 8.1 to 8.5 then go to step 4. If convergence is reached go to step 9.

Step 8.1: Erode node along the best paths using equation (8).

$$erosion(i,j) = \begin{cases} \frac{\varepsilon_V.gradient(i,j).TD_j}{(N-1).M.\mathrm{E}_j.N_{Hops}(i,j)}, & for\ j \in V_k(i) \\ \frac{\varepsilon_U.TD_j}{|gradient(i,j)|.(N-1).\mathrm{E}_j.N_{Hops(i,j)}}, & for\ j \in U_k(i) \\ \frac{\varepsilon_F.TD_j}{(N-1).M.\mathrm{E}_j.N_{Hops(i,j)}} & for\ j \in F_k(i) \end{cases} \qquad (8)$$

Where ε_V, ε_U, and ε_F represent parameters associated with respective collections of neighbours that possess positive, negative, and flat gradients. N and M denote the number of nodes and Drops respectively. E_j and TD_j respectively represent the remaining energy of node j and the time delay for node j to send a packet.

Step 8.2: Compute the altitude of the eroded node using equation (9). The altitude of the eroded node decreases.

$$altitude(i) = altitude(i) - \frac{erosion(i,j)}{N} \qquad (9)$$

Step 8.3: Compute sediment of the Drop added to the altitude of node j using equation (10).

$$sediment(i,j) = \frac{\beta.\big(altitude(i) - altitude(j)\big).carriedSediment(i,j).TD_j}{\mathrm{E}_j.N_{Hops}(i,j)} \qquad (10)$$

Also, β is a constant introduced to control the number of sediments deposited and it is set to 0.1. Paths that have higher slopes will have move-carrying sediments as such tuning β will cause sediments to deposit faster. Further, $carriedSediment(i,j)$ is the previously carried sediments.

Step 8.4: Calculate the present amount of sediment transported by the Drop to the subsequent node by utilizing equation (11).

$$carriedSediment(i,j) = carriedSediment(i,j) + erosion(i,j) - sediment(i,j) \qquad (11)$$

Where $carriedSediment(i,j)$ represents the sediment transported by the Drop from node i to j.

Step 8.5: With equation (12) we increase slightly altitude of every node to carry sediment from erosion over all nodes. However, if a Drop becomes blocked, its node's altitude increases following the expression given in the equation (13).

$$altitude(l) = altitude(l) + \frac{erosion(i,j)}{N} \qquad (12)$$

$$altitude(l) = altitude(l) + paramBlockedDrop.carriedsediment \qquad (13)$$

Where $paramBlockedDrop$ is a parameter, whose value is set to 1.

Step 9: Analyze paths. This step involves finding the optimum solution. The analysis of iteration solutions involves comparing their solution costs to select the one with the minimum cost. The best solution for the iteration is determined using equation (14).

$$T^{IB} = arg\ min\ \forall T^{Drop} cost(i,j) \qquad (14)$$

Where each solution is denoted as T^{Drop}. $cost(i,j)$ is computed using equation (15).

$$\mathrm{cost(i,j)} = \sigma \times \mathrm{TD} + \mu \times \frac{1}{\mathrm{Min(E)}} + \tau \times \frac{1}{N_{Hops}} \qquad (15)$$

Where $\sigma = 0.02$, $\mu = 0.06$, and $\tau = 0.02$.

Time delay (TD), minimum energy ($\mathrm{Min(E)}$), and the number of hops ($\mathrm{N_{Hops}}$) are derived from the path's nodes. Concerning $\mathrm{Min(E)}$, the routing algorithm should select a path that has the maximum value of the minimum energy that a node has in a path across all the possible paths.

Step 10: If $iter_{count} \leq iter_{max}$ then go to step 3 or else produce the optimum route found and end the algorithm. Steps 4 to 10 form the second stage of the algorithm.

Algorithm 1 gives the pseudocode of the PRFDRA.

```
Input: $Graph\ G = (V, E)$ and Drops
Output: Iteration best solution
1: Initialize the graph, Drops, source node, destination node
2: Define location of nodes, number of nodes, number of paths
3: Generate Pop
4: while ($\mathrm{iter_{count}} \leq \mathrm{iter_{max}}$) do
```

```
    Compute gradient$(i,j)$ using eq (5)
    for (each Node in G)
        Compute probability using eq (6) and eq (7)
        Select Node with max ($P_k(i,j)$) and move
        if (Convergence is not reached)
            Perform erosion (i, j) using eq (8)
            Compute altitude using eq (9)
            Compute sediment (i, j) using eq (10)
            Compute and deposit carriedSediment using eq (11)
            Compute altitude using eq (12)
            Use eq (13) for blocked nodes
        end if
    end for
    Analyze paths
    Update $T^{IB}$ using eq (14) and eq (15)
    $iter_{count}++$
end while
Project $T^{IB}$
```

Algorithm Listing 1 PRFDRA Pseudocode

3.4. Link Failure Management

Routing algorithms in line with the described approach detect route failures by monitoring the absence of hello messages from neighbouring nodes for a duration surpassing twice the hello interval, signalled by the absence of acknowledgements after data transmission or packet drops. In case of a malfunction, nodes update their altitude tables and deactivate the affected routes. Nodes attempt to forward packets to the most suitable neighbour while adjusting their altitudes when a transmission fails.

4. RESULTS AND DISCUSSIONS

4.1. Simulation Setting

In recent times, simulation has become very useful in scientific research [28]. For research where experimentation or analytical methods are not realistic, simulation is used as an alternative [29]. This research employs network simulation as the primary tool to model the MANET wireless system, perform performance evaluation, and validate the proposed algorithms. NS-3 was introduced in 2008 as the third iteration of the NS series [30]. It is a substitution for NS-2 and not an extension [31]. It is a discrete-event, open-source simulator [32]. It employs both C++ and Python [33]. For this study, NS-3 was chosen due to its high academic citations in IEEE and ACM Digital Libraries, with 7320 publications for NS-3 LTE and 19000 for NS-3 wireless in September 2020.

This research adopts the two-way ground reflection propagation model for a simulation involving mobile nodes and omnidirectional wireless links in the network model. 802.11 protocol is used for MAC services. The MAC interface queue accommodates a maximum of 50 packets using a drop-tail queue configuration, while the contrasting routing methods involve employing CBR over TCP at the transport layer. CBR traffic generation was employed to create data traffic with packet sizes of 512 bytes. Each node's battery has 100 joules set at the application layer before any simulation begins. Moreover, data in the form of FTP is produced at the application layer and transmitted over TCP. The experiment is performed in two scenarios. The first scenario involves variation in node speed, while the second involves variation in terrain dimension. Table 4 provides an overview of the experimental settings.

Table 4 Simulation Settings

Simulation Parameters	Value(s)
NS-3 Version	3.37
Mobility Model	Random waypoint
Radio Propagation Model	Two-ray ground reflection model
MAC Protocol	IEEE 802.11
Antenna Model	Omni direction
Network Interface Type	Wireless physical
Application Agent	FTP
Traffic	CBR
CBR Traffic Model	32Kbps
Transport Agent	TCP
Network Layer Protocols	AODV, DSDV, RFD, EMBO, and PRFDRA
Initial Node Energy	100J
Bandwidth	11Mbps
Data Packet Generation Rate	2 to 8 packets per second
Transmission Power	3W (34.77 dBm)

Receiving Power	1.5W (31.76 dBm)
Sleep Power	0.6W
Idle Power	0.05W
Default Transmission Range	250M
Antenna Power	1.5W
Packet Size	Control packet: 8 Bytes, The data packet: 512 Bytes
Queue Length	Maximum of 50 data packets
Queue Type	Drop tail primary queue
Simulation Time	1500 Seconds
Terrain Dimension	$1000 \times 1000\ m^2$, $1125 \times 1125\ m^2$, $1250 \times 1250\ m^2$, $1375 \times 1375\ m^2$, $1500 \times 1500\ m^2$
Node Speed	10, 20, 30, 40, 50 m/s
Number of Nodes	250

4.2. Packet Delivery Ratio (PDR)

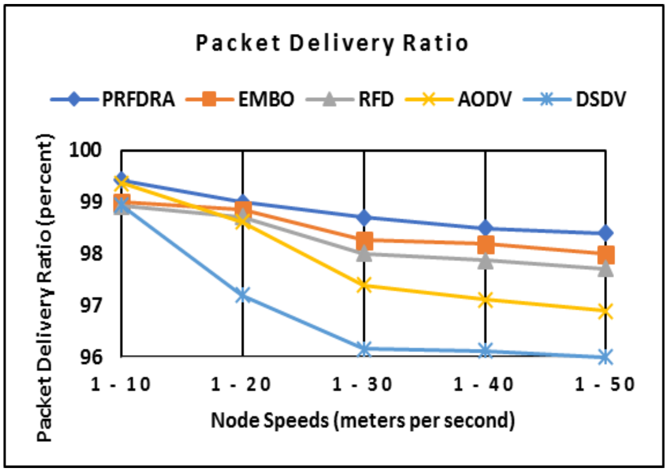

Figure 4 Packet Delivery Ratio Under Various Node Speeds

PDR is calculated by dividing the total data packet counts at the destination by the counts passed on [34]. Achieving a high score for this metric is crucial, even though measurements only account for data packets and not control packets. Figure 4 and Table 5 show the link between PDR and different node speeds. The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 0.35 per cent, 0.5 per cent, 0.93 per cent, and 1.92 per cent. The highest PDR of 99.42 per cent occurred with PRFDRA at a maximum speed of 10 meters per second, while the lowest PDR of 96.01 per cent occurred with DSDV at a peak speed of 50 meters per second. The graph shows that as node speed increases, the PDRs of all four routing algorithms decline, but PRFDRA experiences a less sharp decline when compared to all others.

Table 5 Packet Delivery Ratio Under Various Node Speeds

	Packet Delivery Ratio (PDR)				
	Node Speeds (meters per second)				
Methods	1 - 10	1 - 20	1 - 30	1 - 40	1 - 50
PRFDRA	99.42	99	98.71	98.5	98.4
EMBO	99	98.85	98.26	98.19	98
RFD	98.92	98.72	98.01	97.88	97.71
AODV	99.36	98.62	97.4	97.12	96.9
DSDV	98.94	97.2	96.16	96.13	96.01

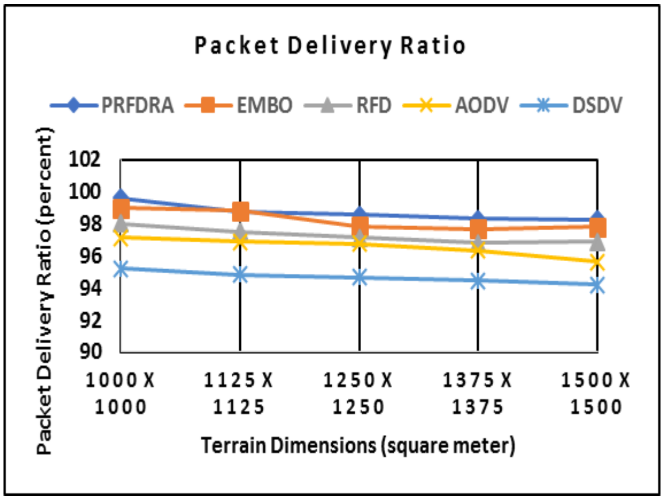

Figure 5 Packet Delivery Ratio Under Various Terrain Dimensions

Figure 5 and Table 6 showcase the correlation between PDR and different terrain dimensions. The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 0.46 per cent, 1.41 per cent, 2.15 per cent, and 4.02 per cent. The optimum PDR of 99.62 per cent occurred with PRFDRA at 1000 × 1000 square meter terrain size, while the lowest performance of 94.21 per cent occurred with DSDV at 1500 × 1500 square meter terrain size. The proposed method takes a better PDR for variation in terrain dimension.

Table 6 Packet Delivery Ratio Under Various Terrain Dimensions

	Packet Delivery Ratio (PDR)				
	Terrain Dimension (square meter)				
Methods	1000 x 1000	1125 x 1125	1250 x 1250	1375 x 1375	1500 x 1500
PRFDRA	99.62	98.71	98.55	98.31	98.26
EMBO	98.98	98.82	97.84	97.69	97.8
RFD	98.01	97.53	97.14	96.81	96.9
AODV	97.12	96.9	96.74	96.32	95.64
DSDV	95.21	94.83	94.65	94.44	94.21

4.3. Average End-to-End Delay (AE2ED)

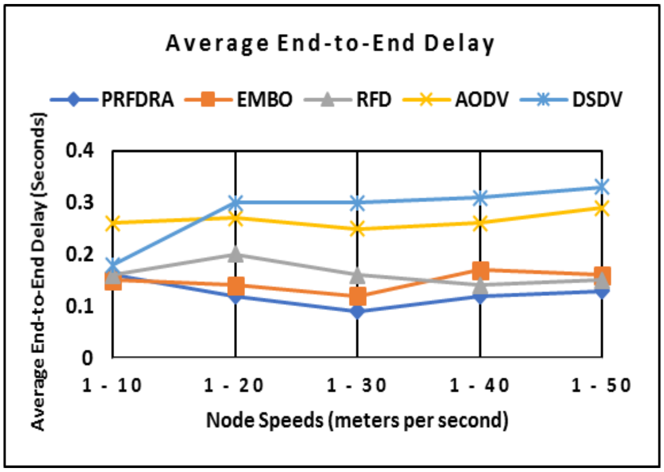

Figure 6 Average End-to-End Delay as a Function of Varying Node Speeds

The interval between when a packet is sent and received, respectively, at the sender and recipient nodes [35]. A lower AE2ED implies faster data transmission. Figure 6 and Table 7 provide the correlation between AE2ED and the different speeds of nodes. The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 0.02 seconds, 0.04 seconds, 0.14 seconds, and 0.16 seconds. PRFDRA exhibited the lowest delay of 0.09 seconds at a top speed of 30 meters per second. At the 10-meter-per-second speed limit, DSDV had a delay of 0.18 seconds, which sharply increased to 0.30 seconds at 20 meters per second. This delay gradually peaked at 0.28 seconds as speed continued to rise; thus, DSDV had the worst performance. The results indicate that the proposed method had the best performance in AE2ED in terms of variation in node speeds.

Table 7 Average End-to-End Delay Under Various Node Speeds

	Average End-to-End Delay (AE2ED)				
	Node Speeds (meters per second)				
Methods	1 - 10	1 - 20	1 - 30	1 - 40	1 - 50
PRFDRA	0.16	0.12	0.09	0.12	0.13
EMBO	0.15	0.14	0.12	0.17	0.16
RFD	0.16	0.2	0.16	0.14	0.15
AODV	0.26	0.27	0.25	0.26	0.29
DSDV	0.18	0.3	0.3	0.31	0.33

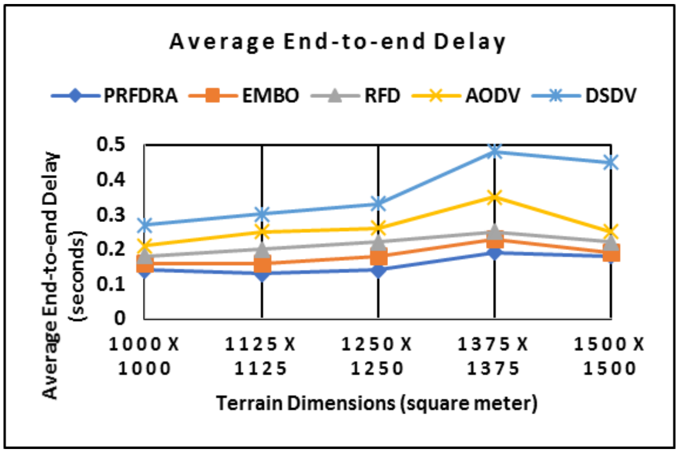

Figure 7 Average End-to-End Delay Under Various Terrain Dimensions

Table 8 Average End-to-End Delay Under Various Terrain Dimensions

	Average End-to-End Delay (AE2ED)				
	Terrain Dimension (square meter)				
Methods	1000 x 1000	1125 x 1125	1250 x 1250	1375 x 1375	1500 x 1500
PRFDRA	0.14	0.13	0.14	0.19	0.18
EMBO	0.16	0.16	0.18	0.23	0.19
RFD	0.18	0.2	0.22	0.25	0.22
AODV	0.21	0.25	0.26	0.35	0.25
DSDV	0.27	0.3	0.33	0.48	0.45

Figure 7 and Table 8 show the connection between average end-to-end delay and various changes in terrain dimensions. The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 0.03 seconds, 0.06 seconds, 0.11 seconds, and 0.21 seconds. The optimum delay performance of 0.13 seconds occurred with PRFDRA when the terrain size was 1125 × 1125 square meters, while the lowest performance of 0.48 seconds occurred with DSDV when the terrain size was 1375 × 1375 square meters. PRFDRA outperformed all other methods in terms of variation in node speeds.

4.4. Energy Consumption (EC)

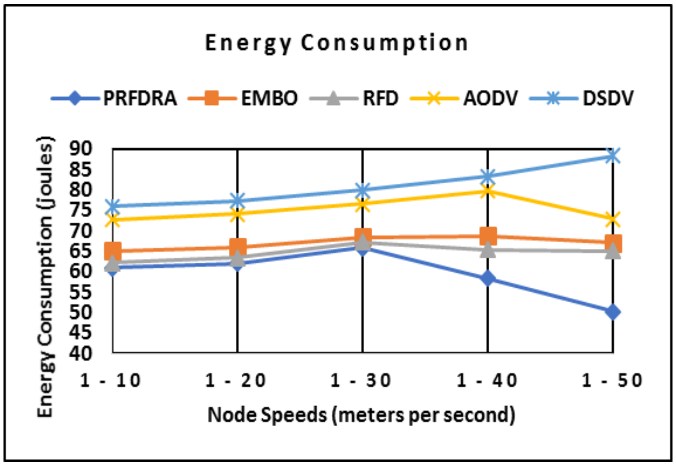

Figure 8 Energy Consumption Under Various Node Speeds

Table 9 Energy Consumption Under Various Node Speeds

	Energy Consumption (joules)				
	Node Speeds (meters per second)				
Methods	1 - 10	1 - 20	1 - 30	1 - 40	1 - 50
PRFDRA	61	62.03	65.87	58.41	50.3
EMBO	65	66.01	68.5	68.79	67
RFD	62.22	63.42	67.19	65.3	65
AODV	72.77	74.05	76.55	79.81	72.94
DSDV	76	77.24	79.93	83.22	88.37

Represents the overall energy utilised by network entities during the period of the experiment [36]. A graph showcasing the relationship between energy consumption and varying node speeds is shown in Figure 8. Table 9 shows the EC values for the proposed model and other models. The improvement rates of PRFDRA The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 7.54 joules, 5.10 joules, 15.70 joules, and 21.43 joules. PRFDRA had the best average performance of 59.52 joules, while DSDV had the lowest average performance of 80.95 joules. The lowest EC of 50.3 joules occurred with PRFDRA at the peak speed limit of 50 meters per second, while the highest EC of 88.37 joules occurred with DSDV, also at the same peak speed limit of 50 meters per second. The proposed algorithm exhibited a consistent rise in EC as the node speed limit increased to 30, followed by a steep decrease as the speed limit increased from 30 to 50 (when the network became highly dynamic). The results indicate that the proposed method had the best performance.

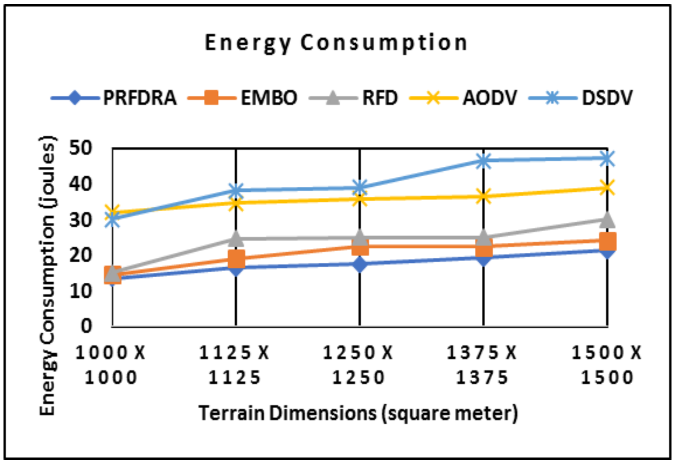

Figure 9 Energy Consumption Under Various Terrain Dimensions

Table 10 Energy Consumption Under Various Terrain Dimensions

	Energy Consumption (joules)				
	Terrain Dimension (square meter)				
Methods	1000 x 1000	1125 x 1125	1250 x 1250	1375 x 1375	1500 x 1500
PRFDRA	13.5	16.44	17.56	19.2	21.3
EMBO	14.5	19.02	22.5	22.38	24.17
RFD	15	24.6	25	25	30
AODV	32	34.7	35.9	36.51	39
DSDV	30	38.08	39	46.48	47.25

Figure 9 and Table 10 show the relationship between energy consumption and varying terrain dimensions. The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 2.91 joules, 6.32 joules, 18.02 joules, and 22.56 jouless. PRFDRA had the highest average performance of 17.6 joules, while DSDV had the lowest average performance of 40.16 joules. The lowest EC of 13.5

joules occurred with PRFDRA with 1000 × 1000 square meter terrain size, while DSDV performed worse with the highest EC of 40.16 joules with 1500 × 1500 square meter terrain size. From the graph, it is clear that the EC of DSDV increases steeply compared to the others. PRFDRA had significantly better performances than all the other four.

4.5. Network Lifetime (NL)

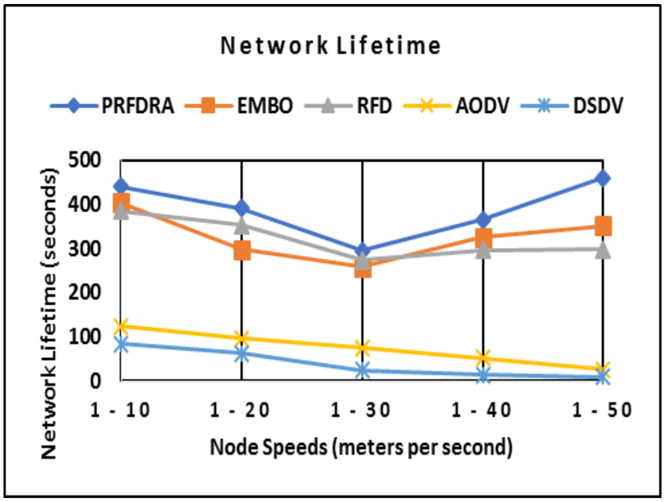

Figure 10 Network Lifetime Under Various Node Speeds

Table 11 Network Lifetime Under Various Node Speeds

	Network Lifetime (seconds)				
	Node Speeds (meters per second)				
Methods	1 - 10	1 - 20	1 - 30	1 - 40	1 - 50
PRFDRA	440	390.8	294.7	365.09	460.8
EMBO	403.05	298.7	258.53	325.09	352.34
RFD	385.4	353.8	273.2	297.17	298
AODV	123.37	96.33	75.07	51.1	26.04
DSDV	84.5	61.8	24.76	13.88	9.7

The time between when the network is launched and its closure is referred to as the network lifetime. For this study, it ends when the first node dies due to battery exhaustion [37]. A high NL is desirable at the end of the simulation. Figure 10 depicts the correlation between network lifetime and varying node speeds. Table 11 provides the numerical values of the energy consumption. The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 62.74 seconds, 68.76 seconds, 315.90 seconds, and 351.35 seconds. The maximum performance of 460.8 seconds occurred with PRFDRA at a speed limit of 50 meters per second. The minimum performance of 9.7 seconds occurred with DSDV at a maximum speed of 50 meters per second. PRFDRA exhibited a superior network lifetime compared to all others.

Figure 11 and Table 12 show a comparison of the proposed method with existing practices in terms of network lifetime and variations in terrain dimensions. The improvement rates of PRFDRA over EMBO, RFD, AODV, and DSDV, respectively, are 50.34 seconds, 128.44 seconds, 255.01 seconds, and 302.04 seconds. The highest performance of 563.21 seconds occurred with PRFDRA with the least terrain size (1000 × 1000) square meter, while the least performance of 63.55 seconds occurred with DSDV with the maximum terrain size (1500 × 1500) square meter. The proposed method has a better network lifetime under variations in terrain dimensions. are meter. The proposed method has a better network lifetime under variations in terrain dimensions.

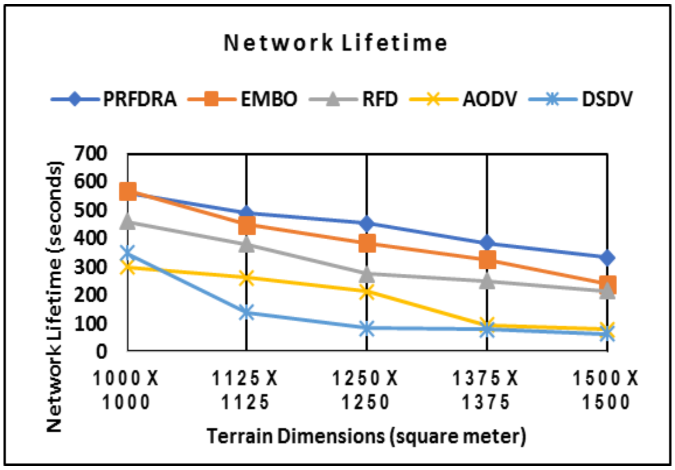

Figure 11 Network Lifetime Under Various Terrain Dimensions

Table 12 Network Lifetime Under Various Terrain Dimensions

	Network Lifetime (seconds)				
	Terrain Dimension (square meter)				
Methods	1000 x 1000	1125 x 1125	1250 x 1250	1375 x 1375	1500 x 1500
PRFDRA	563.21	490.2	454.01	383.62	332.22
EMBO	570.2	450	385	326.3	240.05
RFD	460.11	380	275.14	250.06	215.73
AODV	300.2	262.34	213.4	94.19	78.09
DSDV	347.91	139.34	83.24	79	63.55

5. CONCLUSION

In this paper, the Power-aware River Formation Dynamics Routing Algorithm (PRFDRA) is proposed. The algorithm's optimum path selection is based on the water mechanism, namely, river formation dynamics (RFD), and also incorporates factors such as the number of hops, energy, and time delay. PRFDRA is compared with EMBO, RFD, AODV, and DSDV protocols under variations in node speeds and terrain dimensions. The comparison results indicate that, in addition to having the best performance in packet delivery ratio and average end-to-end delay, PRFDRA has the greatest performance in energy consumption and network longevity. In future work, PRFDRA can be enhanced with fuzzy logic and cloud-assisted techniques.

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