Arabian Journal for Science and Engineering (2022) 47:1321–1335
https://doi.org/10.1007/s13369-021-05841-y

RESEARCH ARTICLE-COMPUTER ENGINEERING AND COMPUTER SCIENCE

Cuckoo Energy-Efficient Load-Balancing On-Demand Multipath Routing Protocol

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Received: 4 August 2020 / Accepted: 9 June 2021 / Published online: 3 July 2021

Abstract

As mobile ad hoc networks spread increasingly worldwide, an energy-efficient load-balancing routing protocol has become an urgent necessity, particularly considering the nodes' limited battery resources. Most proposed energy-efficient load-balancing routing protocols have encountered increasing delay because they have mainly considered energy at the expense of time and routing overhead. Cuckoo energy-efficient load-balancing on-demand multipath routing protocol is an alternate model of addressing routing challenges using meta-heuristics rather than heuristic-based routing schemes. Thus, we are proposing here a cuckoo search-inspired meta-heuristic-based attempt for an optimized load-balancing energy-efficient routing protocol. The proposed protocol employs the cuckoo search technique to designate an optimum routing path based on individual nodes' residual energy to balance the routing overhead among the individual nodes participating in routing. The new protocol has been evaluated and compared with the benchmarks of efficiencies achieved by energy-aware adaptations of on-demand Multipath Distance vector, packet count based routing mechanism, load balancing ad hoc on-demand multipath distance vector protocol, enhanced metric based ad-hoc on demand distance vector protocol, and Ant HocNet routing protocol. Upon analyzing the simulation-based results, the proposed routing scheme showed significant enhancements in packet delivery ratios, better battery life, and minimal packet delay time.

Keywords MANET · Multipath routing · Cuckoo search · CEELBRP · Load balancing

1 Introduction

A mobile ad hoc network (MANET) is a dynamically self-configuring, infrastructure-less communication network paradigm of wireless mobile communicating nodes. In the last few decades, MANET's idea did receive sufficient attention for improved hardware to enhanced protocol design [1]. The major challenge that is inherent to any self-organizing communication setup is route identification and possible route assessment. Based on various approaches and performance tradeoffs in route identification, various routing protocols for ad hoc networks are available both in the literature and practice. Figure 1 shows a range of routing protocols that made a distinction in addressing efficient route identification. These protocols have been addressed in classes of traditional, static, on-demand, table-driven, performance-centered, and application-specific [2, 3].

On-demand/reactive routing protocols are the most popular among other variants of routing protocols that have been designed for wireless mobile networking. They provide path discovery and maintenance in a wide variety of network topologies and environments and attempt to minimize control overhead by eliminating periodic routing updates and using only on-demand messaging [4, 5]. As an advanced rioting scheme, On-demand routing involves source updating and route reconstituting per demand [6, 7]. Some more advancements in the genre of dynamic routing protocols, such as the temporally ordered routing algorithm (TORA), have been developed, which are mainly based on ad hoc route assessments [8, 9]. Lately, improvements in the direction of Multipath on-demand protocols like the ad hoc on-demand multipath distance vector (AOMDV) have received attention and widespread acceptance [10, 11]. This has made the AOMDV the basis of various recent on-demand multipath distance vector protocols, such as multipath dynamic source routing [12, 13]; node-disjoint multipath routing

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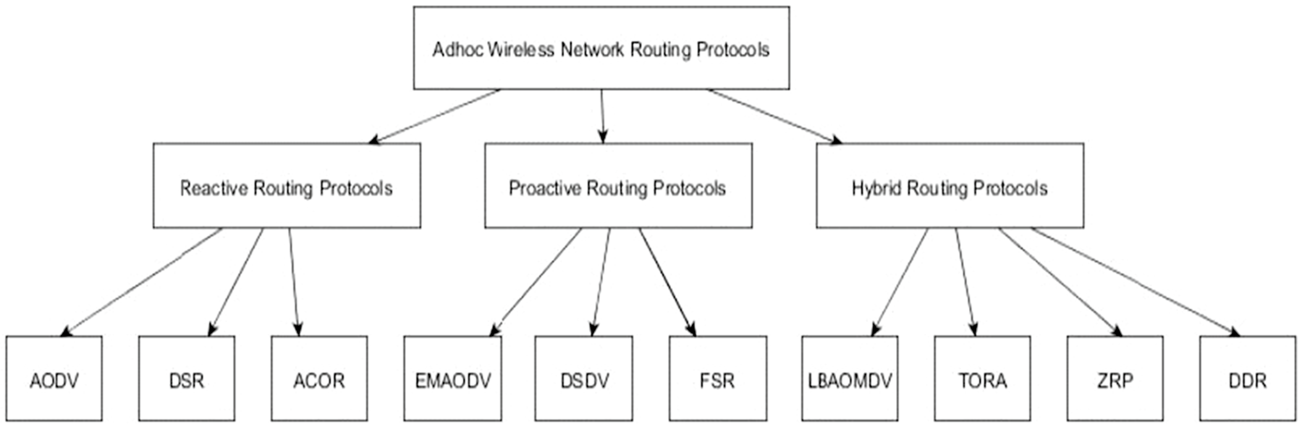

Fig. 1 Ad hoc wireless network routing protocol classification

(NDMR) [14, 15]; routing on-demand acyclic multipath [16, 17], which essentially is a multipath version of DUAL [18] that uses a concept called the feasible distance to maintain routes and loop freedom; load-balancing AOMDV [19]; and load-balancing maximal minimal nodal residual energy AOMDV [20].

Energy-aware on-demand multipath routing protocols include the grid-based energy-aware node-D disjoint multipath routing algorithm [21, 22], which considers energy awareness and node-disjoint multipath and uses the grid head election algorithm to select the grid head, which is responsible for forwarding routing information and transmitting data packets. Additionally, the maximal minimal nodal residual energy AOMDV (MMRE-AOMDV) [23, 24] essentially determines the minimal nodal residual energy of each generated link-disjoint route, sorts these generated routes in descending order according to their nodal residual energy, and finally, starts with the route with maximal residual energy to forward data packets. When a new route with greater nodal residual energy emerges, it is selected to forward the remaining data packets.

A blend of the advantages of proactive and advantages of reactive protocols have lead us to the theory of Hybrid routing protocols, as initial route identification is leveraged from the former approach and dynamically adjusts to a demand-based approach by leveraging from the latter approach, respectively [25, 26]. Hybrid routing protocols include zone routing protocols [27, 28], zone-based hierarchical link state [29, 30], virtual backbone routing [31, 32], hybrid ad hoc routing protocol [33, 34], and sharp hybrid adaptive routing protocol [35, 36].

1.1 Research Motivation

The stochastic nature of application scenarios where a mobile ad hoc network (MANETs) may be operating requires an adaptive approach of underlying routing protocols to cater for potential constraints. On the one hand, this diverse nature of applications has lead to the categorization of routing techniques based on given scenarios. In contrast, on the other, some common requirements and bottlenecks have converged the efforts in achieving adept techniques and universal solutions. As mobile ad hoc networks come up with many challenges and most of these challenges are addressed at the network layer and data-link layer of the protocol stack. Among the challenges in mobile wireless scenarios, the route identification for data transmission gets complicated as individual nodes' mobility keeps an unrelenting process of route formation and deformation. The routing process is computationally sensitive to both network size and optimizations, thus require an ever efficient method for route identification while equally addressing other network constraints. Many previous attempts to improve the routing process as in advancing the capabilities of route identification have come forth which lead to better and efficient schemes of route identification. The limitations with such approaches have been due to the legacy approaches where route identification remained a procedural method (independent constraints imply the route searching criteria). The legacy route identification model must be challenged with an alternate model that redefines route identification by envisaging route identification and route selection on a behavioral and probabilistic approach. The current body of work takes leverage from a bio-inspired route searching methodology, which has been leveraged in many advanced fields for providing an alternate and efficient searching method where time and space constraints are both well addressed. The motivation is to examine the applicability of the Cuckoo search (CS) algorithm in the domain of wireless mobile network scenarios and analyze the subsequent impact of this approach on a given network's performance.

1.2 Research Contribution

The present work provides a unique approach to improving routing quality while ensuring the fairness of load and energy consumption across the nodes of a given wireless mobile ad hoc network. The logical derivation of efficiency achieved by cuckoo search-based route identification has been the main contribution of the work. The performance efficacy of the proposed cuckoo energy-efficient load-balancing on-demand multipath routing protocol routing protocol (CEELBRP) is expected to be an essential foundation for solving the dynamics of route finding associated with wireless mobile ad hoc networking.

1.3 Paper Outline

This paper is organized as follows: Sect. 2 provides a detailed survey and progress of multipath routing as a challenge and existing solutions available in the literature. Section 3 contains a brief understating of the research problem and the objectives of this work. Section 4 includes a detailed discussion of the proposed energy-efficient CEELBRP protocol. Section 5 contains a description of the simulation settings and a thorough analysis of the results. Section 6 provides an outline of the conclusions of this study.

2 Literature Survey

Given the importance and success of bio-inspired and load balancing techniques for solving most MANET routing problems, we introduce an energy-efficient load-balancing multipath routing protocol based on the MMRE-AOMDV routing protocol and inspired by the CS optimization algorithm called CEELBRP. The MMRE-AOMDV has the advantages of saving node energy and thus preserving the number of nodes, reducing network portioning, and increasing the packet delivery ratio. However, these functions cannot be accomplished unless the data load is efficiently balanced among suitable paths. This is the role of the CS, that is, it evaluates the generated paths and selects appropriate paths for transmitting packets based on each path's transmission speed, which is a formula of the path nodes' maximum available bandwidth. Bio-inspired techniques provide efficient approaches to solve complex problems in the real world. This encourages researchers to apply these techniques in various problem domains, such as the MANET routing problem. They have proven to be very adaptable and a good fit for the challenge. Their success for the MANET routing problem was motivated by their general characteristics, including their capability to self-organize, self-heal, and make local decisions.

Some bio-inspired routing protocols involve AntNet [37]; hybrid Ant Colony Optimization (ACO) AntHocNet [38, 39]; ACO-based routing algorithm [40]; improved ant colony optimization routing algorithm for MANETs [41]; ACO-based on-demand distance vector [42]; ACO-based dynamic source routing [43]; Emergent Ad hoc Routing Algorithm with QoS provision (EARA-QoS) [44, 45], which is a new version of the self-organized emergent ad hoc routing algorithm (EARA) [46] enhanced with QoS; BeeAdHoc [47, 48], which was designed to create an energy-efficient routing protocol where a packer agent represents a food-store bee that resides inside the network node; and energy-aware AOMDV (EA-AOMDV) [49], which is an extension of AOMDV in which active communication energy is reduced by adjusting a node's radio power sufficiently to reach a receiving node by considering the link and transmission overhead.

The success of these bio-inspired routing protocols has encouraged researchers to introduce other energy-aware multipath bio-inspired routing protocols, such as the ant-based energy-aware disjoint multipath routing algorithm [50], which is based on both swarm intelligence and ant colony-based meta-heuristic algorithms, and the binary particle swarm optimization TORA (BPSO-TORA) [51, 52] algorithm, in which BPSO adds the energy-awareness feature to the TORA routing protocol.

Most previous routing protocols concentrated on generating single or multiple paths that were link-disjoint or node-disjoint; however, with an increasing load of data that needs to be transmitted and considering problems with MANET energy consumption and limited bandwidth between nodes, load balancing has become necessary. Many modern routing protocols have considered data load balancing among multiple paths. On-demand load-balanced ad hoc routing protocols have been categorized considering load balancing from three perspectives: delay-based, traffic-based, and hybrid-based. Delay-based is where load balancing is achieved by attempting to avoid nodes with high link delay, such as load-aware on-demand routing [53]. Traffic-based is where load balancing is achieved by evenly distributing the traffic load among network nodes, such as associative-based routing [54], load-balanced ad hoc routing [55], and traffic-size aware [56]. Hybrid-based is where load balancing is achieved by combining the features of traffic and delay-based protocols, such as content-sensitive load-aware routing [57]; termite [58, 59], a biologically inspired algorithm, where the principles of swarm intelligence are used to define a probabilistic algorithm for which routing through paths of maximum throughput is an emergent property; load-aware routing in ad hoc [60]; and an energy-aware net-based routing scheme for MANETs (E-MANET Net) [61], for which the routing decisions are enabled based on the nodes' residual energy.

In 2011, Dhivya et al. [62] proposed an optimization of a network formulated using the cuckoo-based particle approach, in which nodes are deployed randomly and organized as static clusters. After the cluster heads are selected, information is collected, aggregated, and forwarded to the base station using a generalized particle model algorithm [63, 64], which transforms the network energy consumption problem into the dynamics and kinematics of numerous particles in a force field. In both studies, CS proved to significantly lengthen the network lifetime compared with traditional methods.

In 2014, Nancharaiah and Mohan [65] proposed a hybrid MANET routing optimization technique using ACO and CS to enhance the on-demand distance vector (AODV) protocol's performance. In 2015, Sekhar and Prasad [66] used the CS algorithm to secure adversaries by misdirecting multihop routing in a MANET generated by the trust-predicated routing framework with optimized cluster head selection, where the CS solved the re-clustering problem by selecting the secondary cluster head within the initially formed cluster group and eliminating the re-clustering process. Nancharaiah and Mohan's proposed framework enabled a node to select a reliable and secure route for a MANET [66].

In 2016, Adnan et al. [67] presented a centralized energy-aware clustering algorithm for wireless sensor networks using the novel bio-inspired CS algorithm. The cost function was defined to maximize the network lifetime and minimize the intra-cluster distance. The performance of Adnan et al.'s proposed algorithm was evaluated using well-known centralized and decentralized clustering protocols. In 2017, Kaur and Singh [68] introduced the improvement of AODV using CS and bee colony bio-inspired techniques, where the mutual nodes between the optimal path selected by AODV, and the optimal path selected by CS and the bee colony were set as the nodes of the best path for packet routing. The simulation results indicated that using CS and a bee colony improved the performance of AODV in terms of throughput, delay, and packet loss.

In 2018, Kout et al. [69] introduced a routing protocol inspired by the CS method based on the waypoint model as the mobility model. The protocol was called AODV with Cuckoo Search Algorithm (AODVCS), and was simulated and tested using Network Simulator 2 (NS2). The results were compared with three routing protocols, AODV, destination sequenced distance vector (DSDV), and AntHocNet, regarding packet delivery ratio and end-to-end delay. Kasthuribai et al. [70] proposed a secured energy-aware multipath routing hybrid model based on a PSO-gravitational search algorithm for energy-efficient multipath selection then the CS algorithm for the optimal path selection. The simulation results indicated that the proposed model outperformed state-of-the-art algorithms in terms of energy efficiency and network lifetime.

More recently, in 2019 and early 2020, some advancements in the direction of leveraging cuckoo-inspired optimization techniques have been proposed, which are furthering the concept of cuckoo-inspired searching and form a basis for future multipath routing[71, 72]. Multipath routing is a prime optimization objective to enhance any generic multipath routing algorithm has also been recently added to the literature to achieve better heuristics about wireless networking in general [73, 74]. Multicasting is a challenge in isolation in the context of contemporary wireless communication environments has also received some attention as an optimization objective for a CS-based solution optimization [75–77].

Multiple routing approaches, either unique to ad hoc wireless environments or inherited from the existing general wired or wireless computer network scenarios, came to the fore. Many of these approaches are based on distance-vector, dynamic source routing, and link-state routing among both academic research and the wireless technology industry. Previous attempts starting from early efficient routing schemes in ad hoc wireless networks like AODV and its variants resulted in accurate and better performance. Still, they lagged in addressing bandwidth fairness usage and thus resulted in poor average battery and utilization and conservation [6]. Schemes based on dynamic source routing like DSR provided dynamic routing but performed poorly in essential performance factors like throughput, packet delivery ratios, and jitter. Of late, the schemes based on link-state routing, like optimized link-state routing (OSLR), performed better for scenarios where node battery power and bandwidth consumption were a prominent design issue. The link-state variations were further enhanced and clubbed with the basis of distance vector routing resulting in hybrid routing schemes for wireless mobile ad hoc networks while addressing most of the routing performance factors. The latest in the direction of routing in wireless ad hoc networks have been based on an on-demand distance vector with variations of multipath routing. Our previous attempts in this direction were proposing routing protocol improvements based on load balancing of scarce parameters like energy and bandwidth. A link residual energy assessment-based protocol LBMMRE-AOMDV where path generation is based on the maximal nodal residual energy and the actual number of packets that could be transmitted over that path [19]. Further Load Balancing Ad hoc On-demand Multipath Distance Vector (LBAOMDV) protocol, an advanced version of the on-demand routing protocol for mobile wireless networks, was proposed [20]. As evident, all the previous approaches to solving the route identification problem in wireless mobile ad hoc network scenarios had been well adapted but inherently carried the limitation of addressing the routing problem procedurally with scenarios specific constraints given unfair weight over others.

The current work is part of the contribution in the direction of deriving a novel and better routing paradigm, which is equally sensitive to factors like energy, time, bandwidth, and fairness, among other parameters of concern. This approach, based on meta-heuristics of the cuckoo-based search technique, has a robust statistical record and thus provides enough motivation and encouragement to leverage and to be adapted in wireless ad hoc routing.

3 Problem Statement & Research Objective

3.1 Problem Statement

The limitations of previous attempts and approaches in developing a suitable, efficient routing paradigm where each of the significant constraints of transmission like bandwidth, battery usage, routing overhead, and load balancing were addressed either in complete isolation or have been partially consistent. One of the most significant reasons for these lackadaisical approaches has been the bottleneck associated with route identification overhead, mainly due to the lack of an optimal route searching algorithm.

The adaptation of the CS based search algorithm for a multipath data transfer scenario eradicates the above-discussed limitation. It ensures a complete paradigm shift in dealing with the route identification process. The proposed CEELBRP algorithm is an attempt to redo the route identification processes with the following key constructs.

Const 1 Criterion based efficient route identification.
Const 2 Incurring the least routing overhead.
Const 3 Reliable data transfer across a given wireless mobile ad hoc network.

These three constructs form the basis of meta-heuristic based CS-inspired CEELBRP technique, which adheres to the concept of fair bandwidth and energy usage across the participating nodes of a given wireless mobile ad hoc network.

3.2 Research Objectives

The primary objective of this work is to designate an optimum data routing path based on the residual energy of individual nodes while keeping a balance in the routing overhead among the individual nodes participating in routing. The selection of a route is to be determined by the fitness of a path which includes the energy level of the participating nodes. The prime objectives of the CEELBRP protocol are as following;

1. To perform route identification in a given multipath transmission environment.
2. To minimize routing overhead cost for standard data transmission.
3. To provide balanced usage of battery power across the nodes of a given network.
4. To minimize energy consumption due to the route identification process.

The conclusive objective of CEELBRP is to demonstrate the performance efficacy achieved from leveraging the adaptation of cuckoo-search (CS) in identifying the most efficient route based on a given set of criteria function. The standard problem structure of the current work is summarized in Table1.

4 Cuckoo Energy-Efficient Load-Balancing On-Demand Multipath Routing Protocol (CEELBRP)

Among the many optimization algorithmic techniques available, brooding parasitism motivated optimization, and optimal search technique has received the attention of the research community of late. The first noteworthy work in this direction was Yang and Deb in 2009 [65]. Yang and Deb formulated a meta-heuristic based optimal search solution technique and named it CS after the famous brood parasitic bird species cuckoo. The CS algorithm is a two-phase iterative algorithmic solution to any optimization process where iterations involve the phase of new solution formation and

Table 1 CEELBRP Problem Structure

Objective function	Determining the best energy-efficient path
Solution feasibility criteria	Available residual node energy
Solution space	All available paths from source to destination Node
Solution selection	Governed by the Levy Flight Equation
Solution space refining	Probability-based removal

the phase involving the removal of deficient solutions. The initial phase is about the formation of new nests for cuckoos where each cuckoo's displacement is governed by Levy flight to ensure efficient discovery of new nests [65, 66]. Lévy flights are performed using the equation given in (1).

$$X_i^{t+1} = x_i^t + \alpha \oplus L\dot{-}vy(\lambda) \ , \tag{1}$$

where represents the current generation, the symbol '$\oplus$' is used to indicate the entry-wise multiplication, α and 'λ' indicate the step size and transaction probability, respectively. The next phase of removing deficient solutions is governed by the probability-based random selection of nests for further removal before the next iteration [79]. The main aim of this algorithm is to use new and better solutions to replace a less efficient solution. The best nests with high-quality eggs (solutions) carry over to the next generation, where the quality or fitness of a solution can simply be proportional to the value of the objective function. The number of available host nests is fixed, and in case the host bird discovers an alien egg, it either throws away the cuckoo egg or abandons the nest to build a new nest in a new location. A host can discover an alien egg with some probability given by $\mathbf{P_a}$where $\mathbf{P_a \in [0, 1]}$. The pseudo-code for the basic form of a CS technique is given in Algorithm 1.

```
Begin
  Objective function f(x), x = (x1, ..., xd)^T
  Generate initial population of
      n host nests xi (i = 1, 2, ..., n)
While (t <MaxGeneration) or (stop criterion)
      Get a cuckoo randomly using Lévy flights
      Evaluate its quality/fitness Fi
  Choose a nest among n (say, j) randomly
  If (Fi > Fj),
      Replace j by the new solution
  End
  Fraction (pa) of worse nests are abandoned and new nests are built
  Keep the best solutions (or nests with quality solutions)
  Rank the solutions and find the current best
```

Algorithm 1 Cuckoo search pseudo-code [65]

The objective is to designate an optimum data routing path based on the residual energy of individual nodes while keeping a balance in the routing overhead among the individual nodes participating in routing. The selection of a route is to be determined by the fitness of a path which includes the energy level of the participating nodes. Each path is a candidate solution possibility to the problem resembling the idea of a nest in a CS technique. In contrast, a single path is chosen at a particular instant, thus representing the best solution at hand. The abandoning of the rest of the paths for any future transmission resembles the fractional removal of not-so-fit problem solutions. The ability of CS toward achieving optimization lies in refining the solution space for the next iteration and thus inching toward a better solution. In this paper, we propose an energy-efficient routing protocol called the CEELBRP, which balances the nodal energy consumption through selecting and routing packets over multiple paths based on path minimum nodal residual energy that must exceed the energy required to forward a certain number of data packets. The CEELBRP essentially follows the CS algorithm in optimizing energy awareness by balancing the data load on the energy-efficient paths with maximal speed. The path's speed is calculated as a function of the path's available bandwidth. The host nests represent the paths, and cuckoo eggs represent the data packets that need to be forwarded. To place the data *(eggs)* on the paths (*nests*), paths need to be evaluated and the best-fitting paths selected to forward data (*place eggs in the nests with quality solutions*) in less time and without exhausting the nodes energy.

Multipath routing scheme has been a significant breakthrough in the routing paradigm, especially in the area of mobile wireless ad-hoc networks. The extensions in multipath routing, which included energy-efficient load-balanced protocols, have been noteworthy work that led to the development of some popular advanced routing schemes like AOMDV, packet count based routing mechanism (PCRM), LBAOMDV, enhanced metric based ad-hoc on demand distance vector protocol (EM-AODV), and AntHocNet [38, 56]. These all attempts in the direction of efficient multipath routing schemes have to lead to remarkable improvements but always invited additional routing overhead. The main reason behind the increased routing overhead has been due to subsequent route selections. In this paper, we have employed the meta-heuristic CS technique to improve upon the time constraints of initial and subsequent route selections which in turn influences the overall routing overhead. The initiation of the route finding process takes only after route request packets (RREQ) are flooded across the whole network and subsequent route reply packet (RREP) is received. Among these multiple discovered routes or paths, the criterion for route selection is based on the amount of energy to be consumed over a path for a single data transfer. The effectiveness of the proposed CEELBRP is in balancing the nodal energy consumption through selecting and routing packets over multiple paths based on minimum nodal residual energy that must exceed the energy required to forward a data packet. The CEELBRP essentially follows the CS algorithm in optimizing the route selection while balancing the data load on the energy-efficient paths. Here the routes represent the paths and data packets represent the cuckoo eggs. To transmit a data packet *(eggs)* over a path (*nests*), multiple paths are evaluated and the best available route is selected to forward data (*place eggs in the nests with quality solutions*) with minimal overhead ensured by the CS technique. The CEELBRP protocol has three main phases:

Disjoint path discovery;
Load-balancing; and
Path maintenance.

4.1 Disjoint Path Discovery

In this phase, the CEELBRP follows almost the same methodology as the MMRE-AOMDV by discovering the available *n* multi-link disjoint paths. Source node *S* propagates RREQ messages to destination node *D* to establish multiple reverse paths both at intermediate nodes and the destination. However, in the case of redundant RREQs with the same < Source Address, Request Id > pair, the RREQs with the maximal nodal residual energy and minimal hop count are saved in the intermediate node cache and forwarded, whereas the others are discarded.

As shown in Fig. 2, source node *S* propagates an RREQ to destination *D*, where the green arrows represent a valid path from *S* to *D*, the red arrow represents a discarded path because the RREQ cannot reach the destination *D. T*he blue arrows represent the duplicated RREQs, which are evaluated based on maximal nodal residual energy and number of hop counts. The duplicated RREQ that holds the route with the maximal nodal residual energy and minimum hop count is saved in the intermediate node cache, and its RREQ message is forwarded to the destination.

4.2 Load-Balancing

Effective load-balancing is a challenging task in MANETs because of their dynamic behavior and unpredictable topology

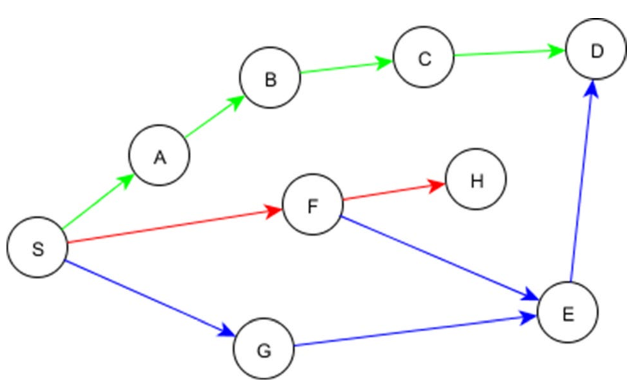

Fig. 2 CEELBRP RREQ propagation

changes. The load should be efficiently distributed throughout the network. Otherwise, heavily loaded nodes may cause a bottleneck, resulting in congestion, longer delays, and worse network performance.

In the CEELBRP load-balancing phase, the refining process of the discovered paths is conducted based on Eqs. (2) and (4), where the path x_i with maximal nodal residual energy μ_{x_i} greater than or equal to the energy needed to transmit the minimum number of packets that path can process ($\mu_{x_i} \geq P_{x_i}$) is added to the source cache; otherwise, it is abandoned:

$$\mu_{x_i} = \min_{j \in k} E_{jx_i}, \tag{2}$$

where μ_{x_i} is the maximal nodal residual energy of the path x_i. and E_{jx_i} is the residual energy of node j on path x_i. The energy consumed for one packet is given by Eqs. (3) [80]:

$$E_P = \sum_{j=1}^{R-1} E\left(n_j, n_{j+1}\right), \tag{3}$$

$$P_{x_i} = \frac{T_p \ * \ E_P}{n}, \tag{4}$$

where *E* denotes the energy consumed in transmitting and receiving a packet over one hop, $n_j, \ldots, n_{R\text{-}1}$ are the nodes along a path, T_P is the total number of packets to be transmitted, and P_{x_i} is the energy required to transmit the minimum number of packets path x_i can process.

After refining, the paths stored in the source cache are sorted in descending order based on path speed $S\ x_i$, where data packets are forwarded on each path based on the path speed ratio to the total speed of all paths, as in Eqs. (5) and (6):

$$Sx_i = \min_j m\left(C_j \sum_{kN_j} F_{jk}\left(\sum_{vN_k} F_{kv}\right)\right), \tag{5}$$

where *m* is the number of nodes on a path x_i, C_j is the capacity of node *j*, F_{jk} is the traffic flow from node *j* to its neighbor node *k* in bits/second, where traffic is generated at node *j* and transmitted through a link to node *k*, and F_{kv} denotes the traffic flow from node *k* to its neighbor node *v* in bits/second, where traffic is generated at node *k* and transmitted through a link to node *v*. To summarize, F_{jk} and F_{kv} donate the traffic flow from node *j* to the neighbors of its neighbors to accurately measure the maximum available bandwidth (MAB) at node *j*.*S* x_i is the path x_i speed, that is, the minimum MAB among all nodes along x_i. The number of packets to be transmitted over path x_i is given by

$$PLx_i = TP * \frac{Sx_i}{\sum_i^T Sx_i}, \tag{6}$$

where *TP* is the total number of data packets that need to be transmitted from *S* to *D,* and *T* is the number of paths stored in the source cache.

4.3 Path Maintenance

Most wireless mobile ad-hoc network routing protocols start the new path discovery process when one or more of the paths fail through flooding the RREQ from the source node to the destination, which represents a significant overload on the network; however, this is necessary for forwarding data packets to the destination. Path maintenance is one of our main priorities because it is one of the primary factors that guarantee increasing the packet delivery ratio. In the path maintenance phase in the CEELBRP, the role of CS arises where the failed path is replaced by the abandoned path with the maximal nodal residual energy, and the new path discovery process only starts when the number of abandoned paths equal zero. The pseudo-code for the CEELBRP is given in Algorithm 4.

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1. **Function and variables**
   E_{ij}: Residual energy of node j on path i
   μ_{x_i}: Maximal nodal residual energy of path x_i
   T_P: Total number of packets to be transmitted
   P_{x_i}: Energy needed to transmit the minimum number of packets path x_i can process
   C_j : Capacity of node j
   F_{jk} , F_{kv}: traffic flow from a node to its neighbors
   Sx_i: Path x_i speed
   Input: Nodes, *S, D,* and n_j
   Output: Data transmitted on the fittest paths
2. **Generating the *n* link-disjoint paths**
3. **Initialize a population of *n* paths where x_i (*i* = 1, 2, . . . , *n*)**
4. **For all x_i, calculate**
   Maximal nodal residual energy
   $$\mu_{x_i} = \min_{j \in k} E_{ji}$$
   Energy required to transmit the minimum number of packets over x_i
   $$P_{x_i} = \frac{T_p * \sum_{j=1}^{R-1} E(n_j, n_{j+1})}{n}$$
5. **While $\mu_{x_i} \geq P_{x_i}$, add x_i to the source cache else abandon x_i**
6. **Forward data on each path stored in the source cache based on the path speed ratio to the total speed of all paths**
   $$Sx_i = \min_j m\,(C_j - \textstyle\sum_{k \in N_j} F_{jk}\,(\sum_{v \in N_k} F_{kv})$$
   $$PLx_i = T_P * \frac{Sx_i}{\sum Sx_i}$$
7. **If (# of failed paths = 0)**
   Then repeat steps 4–6 until the end of transmission

   Else if (# abandoned paths ≠ zero)
   Then replace the failed path with the maximal nodal residual energy abandoned path
   Else goto step 1
   End if
   End if
8. **End**

Algorithm 4 CEELBRP pseudo-code

Table 2 Simulation parameters

Simulator	NS-2.34
Routing protocols	CEELBRP, AOMDV, PCRM, LBAOMDV, EM-AODV, AntHocNet
Simulation time (s)	50, 100, 150, 200
Simulation area	1000 m × 1000 m
Number of nodes	50, 100,150, 200
Transmission range (m)	500
Mobility model	Random waypoint
Maximum speed	5 m/s
Data packet size	512, 1024 bytes
Traffic source CBR	Traffic source CBR
Initial node energy (J)	50

5 Performance Evaluation of CEELBRP

5.1 Performance Metrics

The performance of any wireless setup/network is a multi-factor function where several indicators are available for assessing the performance of a network. While the functional requirement of any network communication system is to ensure reliable transmission of data across the network from a sender to receiver, some other non-functional requirements provide some vital information regarding the network performance as a whole. The parameters such as packet delivery ratio, End-to-end delay, efficient routing, data redundancy, node energy consumption, fairness in bandwidth consumption are standard indicators of network performance. Albeit few, not all of the parameters are evenly relevant and informative in all applications or network type scenarios, like node energy consumption is highly relevant in a wireless scenario. In contrast, this parameter is less likely of any importance in a wired node setup. In general terms, these evaluation parameters are reasonable indicators of a network performance that are fine-tuned and regulated as per requirement. The introduction of a novel protocol in a network system impacts the majority of these parameters and thus, the induced effects have been studied and compared with the existing & alternate protocol standards.

CEELBRP is a routing protocol with its primary essence of improving the routing performance (minimizing routing overhead) of a wireless mobile ad hoc network while ensuring better energy efficiency, fairness in bandwidth consumption (Load-Balancing).

5.2 Simulation Environment

A simulation environment or running up the selected routing protocols for drawing the vital data for each parameter metric was set up. Network simulator NS is a discrete event simulator targeted at computer network scenarios that provide substantial support for the simulation of TCP, routing, and multicast protocols over wired and wireless networks. NSv2.34 version of NS network simulator was used for the simulation which provides custom-based liberty to add protocols at any level of a network protocol suite. Each of the said routing protocols (CEELBRP, AOMDV, PCRM, LBAOMDV, EM-AODV, and AntHocNet) was embedded for varying node numbers and against mentioned performance metrics. The standard simulation environment setup was used as summarized in Table 2.

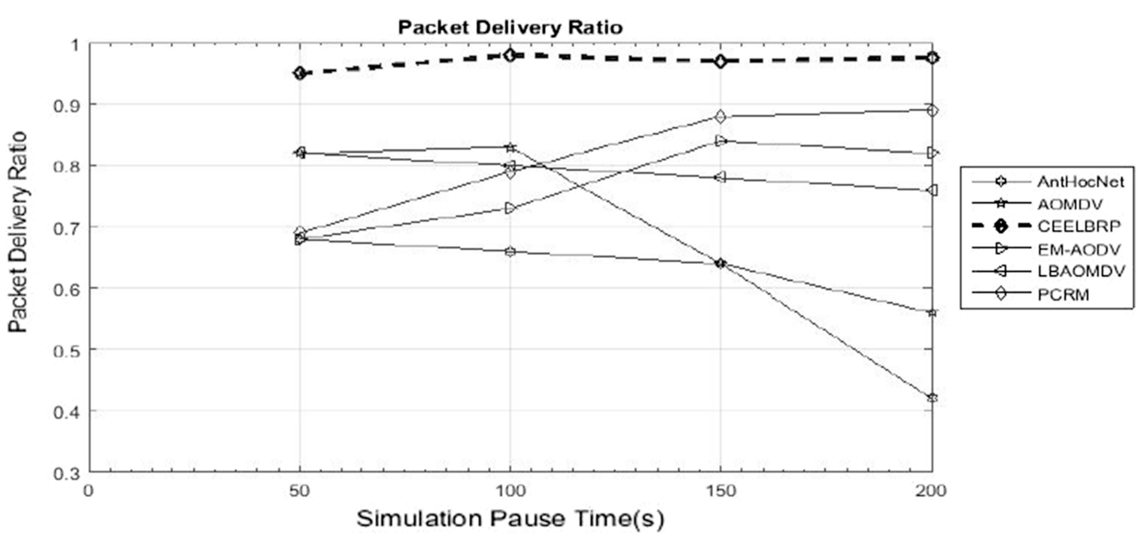

Fig. 3 Packet delivery ratio with respect to pause time, packet size 1024 bytes

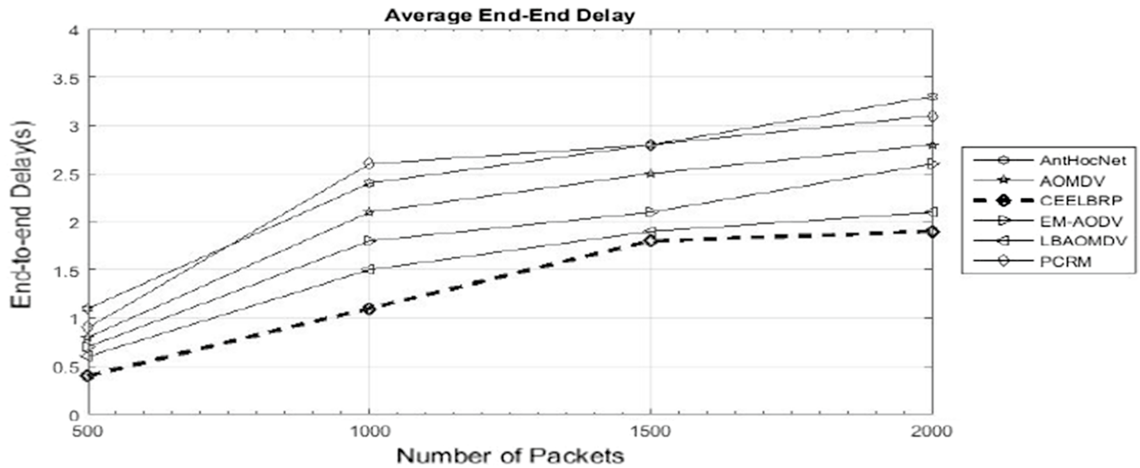

Fig. 4 Average end-to-end delay with respect to the number of packets

Here, performance evaluation of CEELBRP is compared with existing routing protocols like AOMDV, PCRM, LBAOMDV, EM-AODV, AntHocNet belonging to the same family of energy-efficient load-balanced routing protocols. The parameters of evaluation, in addition to routing overhead, bandwidth fairness, and node average energy consumption, also include standard parameters of *Packet delivery ratio*, *End-to-end delay*, and *Number of dead nodes*.

The following evaluation metrics were considered:

- *Average energy consumption*: the average energy consumed by all nodes in the network.
- *Routing overhead*: the number of control packets transmitted through the network.
- *Packet delivery ratio*: the ratio of the number of data packets delivered to the destination. The packet delivery ratio is obtained by dividing the number of data packets correctly received at the destination by the number of data packets sent by the source.
- *End-to-end delay*: average delay of data packets from the source to the destination.
- *Number of dead nodes:* number of nodes that drop out of the network at various simulation times.

5.3 Packet Delivery Ratio

Each protocol delivered successfully for various pause time values, where the pause time represents the time for which the nodes freeze and the effect of their mobility disappears. As depicted in Fig. 3 CEELBRP exhibited a higher packet delivery ratio than the *AOMDV, PCRM, LBAOMDV, EM-AODV, AntHocNet* for all pause time values. For example, at

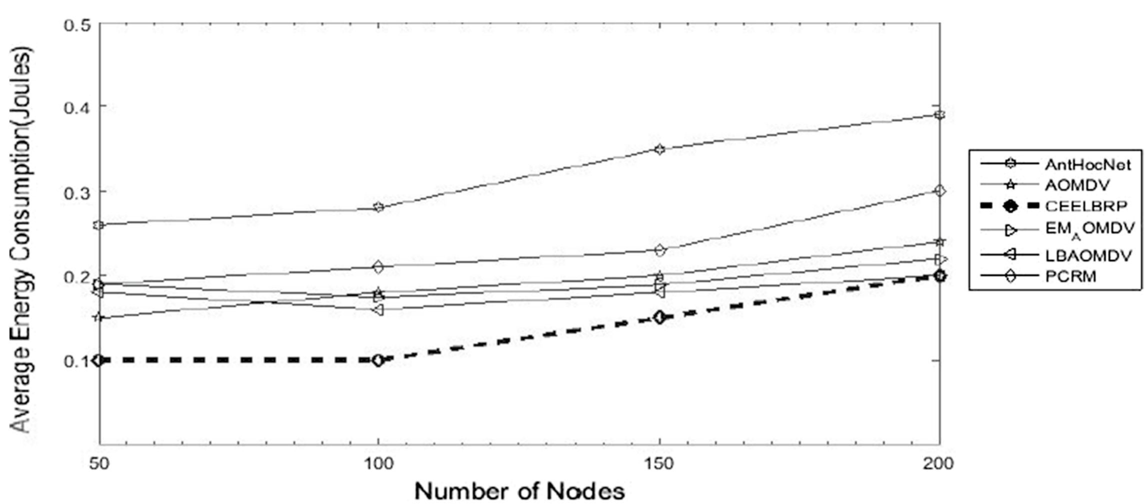

Fig. 5 Average energy consumption with respect to the number of nodes

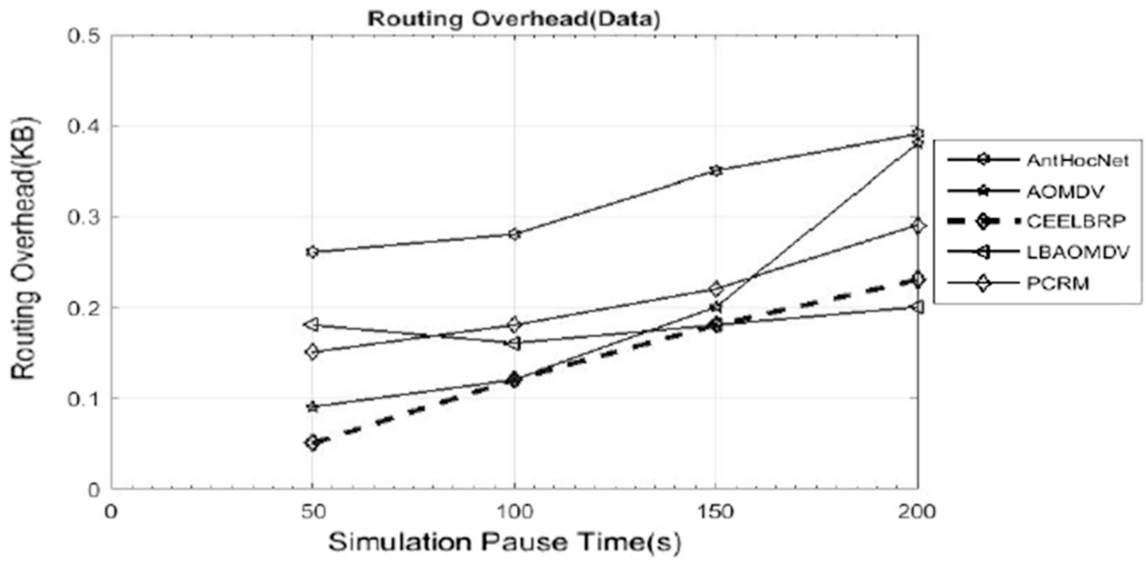

Fig. 6 Routing overhead with respect to pause time

the 200-s pause time, the proposed protocol packet delivery ratio was 98% compared with *PCRM*, which only achieved 88%, and *EM-AODV* with 82%, *LBAOMDV* achieving 76%. As in most non-energy-efficient routing protocols, the *AMODV* has a comparatively lower percentage of 56%. The smallest packet delivery ratio at 42% is for *AntHocNet*, because the longer the time, the higher the consumed energy and dead nodes, which certainly affected the packet delivery ratio. A significantly higher packet delivery ratio ensures better transmission reliability across a given network and thus encourages a proportional effect on any secondary or non-functional system requirements.

5.4 End-to-End Delay

Most energy-efficient protocols suffer from higher end-to-end delay because they only consider energy consumption, which we attempted to resolve by balancing the data load on the energy-efficient paths' speed. Figure 4 shows the average end-to-end delay with various numbers of data packets. Most of the simulated protocols nearly had an equal end-to-end delay during the transmission of 500 data packets, starting from the CEELBRP with 1.8 s to the *LBAOMDV* with 2.2 s. However, with an increasing number of transmitted data packets, the end-to-end delay of the AOMDV, EM-AODV, AntHocNet, PCRM continued to move up. For example, the AOMDV at 2,000

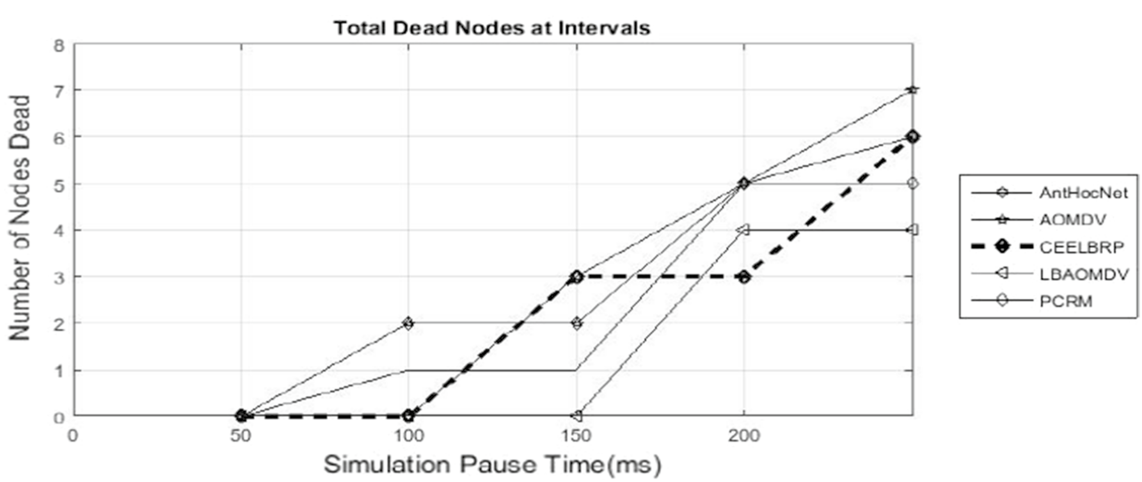

Fig. 7 Number of dead nodes (out of 50) at various simulation times

Table 3 Simulation result summary

Routing scheme	Packet delivery ratio	Average end to end delay(sec)	Routing overhead (Kb)	Dead node count	Energy consumption (J)
CEELBRP	0.98	1.8	0.21	6	0.15
LBAOMDV	0.76	2.2	0.19	4	0.15
EM-AODV / AOMDV	0.82/0.56	2.6	0.38	7/7	0.16 /0.18
AntHocNet	0.42	3.3	0.39	6	0.34
PCRM	0.88	3.1	0.29	5	0.23

data packets had a 2.7 s delay, and the EM-AODV had a 2.6 s delay. In contrast, the highest delay was 3. 3 s for the AntHocNet, while PCRM incurs 3.1 s of delay. It is ensuing from Fig. 4 that the CEELBRP performed better for the end-to-end delay, similar to most of the energy-efficient routing protocols.

5.5 Average Energy Consumption

Reduced energy consumption is one of the main aspects that MANET routing protocols try to achieve. Figure 5 shows that the average amount of energy consumed by the CEELBRP was much less than that of the other simulated protocols. For example, at 200 nodes, the average amount of energy consumed by the CEELBRP and LBAOMDV was 0.15 J, which was 0.19 J less than its worst performer, AntHocNet. Energy consumption for EM-AODV, PCRM, and AOMDV were 0.16, 0.23, and 0.18, respectively. The increasing rate of energy consumed was also less for the CEELBRP than the other simulated protocols. This indicates that CEELBRP achieves the desired node energy consumption and in turn, resorts to better load balancing.

5.6 Routing Overhead

Figure 6 shows that attrition in the routing overhead with respect to pause time was higher for the CEELBRP than the other protocols, which reaffirms that the CEELBRP achieved a notable decrease in routing overhead compared with the other protocols, which we consider is because of the robust path maintenance phase. At the 100-s pause time, the CEELBRP incurred an overhead of 0.11 Kb, which was 0.04 Kb less than its nearest competitor AOMDV, whereas, at 200 s, the CEELBRP overhead was 0.21 Kb compared with 0.39 Kb for the AntHocNet, 0.19 Kb for the LBAOMDV, 0.16 Kb for the EA-AOMDV, and 0.29 Kb for PCRM.

5.7 Number of Dead Nodes

Figure 7 plots the number of dead nodes counted at various simulation times while sending 1,000 512-byte sized data packets across a network of 100 nodes. At the 50-s simulation time, in a network of 100 nodes, all the simulated protocols attained zero dead nodes. In contrast, at 200 s, AntHocNet and CEELBRP equally attained 6 dead nodes, which was the second-highest number of dead nodes, and the LBAOMDV attained only 4 nodes. In a network of 100 nodes, as in Fig. 9, the number of dead nodes attained beyond a 200-s simulation time CEELBRP showed a uniform increase in dead node count in comparison to other evaluated routing protocols. This provides an insight into the expected behavior of CEELBRP as in the family of protocols it belongs to.

The simulation results indicate that the proposed protocol successfully integrated less energy consumption, average dead nodes, less routing overhead, less end-to-end delay, and a higher packet delivery ratio inspired by the positive effect of the CS optimization algorithm. Although the LBAOMDV outperformed the CEELBRP in the routing overhead metric, which we consider is because of the advanced path searching but gets compensated in terms of packet delivery ratio, End-to-end delay performance metrics. CEELBRP still outperformed the other simulated protocols, particularly because it is mainly designed to preserve the nodes' energy while reducing delay time. Many protocols had been proposed to preserve the nodes' energy and reduce the number of dead nodes, but they mainly consider energy at the expense of time and routing overhead, which was well addressed in CEELBRP. The summary of simulation results is provided in Table 3, which presents insight into the performance comparison of the proposed CEELBRP scheme with other standard protocols.

6 Conclusions

Various routing protocols have been proposed recently to partially solve the MANET dilemma, in which limited battery life and energy adversely affect the node's ability to forward packets on behalf of its neighbors, which directly causes network lifetime reduction and partitioning. Most of these protocols have successfully preserved nodes, but at the expense of time and routing overhead, which we substantially attempted and effectively managed.

In the current work, a new energy-efficient load-balancing multipath routing protocol called the CEELBRP was proposed based on the EM-AODV routing protocol optimized by the bio-inspired CS optimization algorithm. The proposed protocol attempted to balance the aspects of preserving the nodes' energy and reducing end-to-end delay to maximize the packet delivery ratio in less time by evaluating the generated paths based on maximal nodal residual energy and speed, which is a function of the path's available bandwidth, to select the fittest paths to transmit data packets without depleting the nodes' energy or increasing delay. The CEELBRP and four other routing protocols, the *AOMDV, PCRM, LBAOMDV, EM-AODV, AntHocNet,* were simulated using NS v2.34, studied under a wide range of scenarios, and evaluated based on five main QoS metrics: *packet delivery ratio, end-to-end delay, average energy consumption*, *routing overhead,* and the *number of dead nodes.* The evaluation results indicate that the proposed protocol outperformed the other three energy-efficient simulated protocols in all vital metrics.

The future scope of the current work is to adapt the cuckoo optimization search algorithm in the existing standard routing schemes which would ratify the inherent time efficiency of cuckoo-based route search. The possible scope of leveraging from the benefits of clustering with a blend of cuckoo search is expected to be a significant breakthrough in the routing design paradigm.

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