International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Ingénierie des Systèmes d'Information
Vol. 28, No. 5, October, 2023, pp. 1353-1359
Journal homepage: http://iieta.org/journals/isi

# Optimizing Cluster Head Selection in Mobile Ad Hoc Networks: A Connectivity Probability Approach Using Poisson Distribution and Residual Energy

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https://doi.org/10.18280/isi.280524

**Received:** 22 May 2023
**Revised:** 26 August 2023
**Accepted:** 9 October 2023
**Available online:** 31 October 2023

***Keywords:***
*cluster head, connectivity probability, mobile ah hoc network, network performance, network stability, poisson distribution, residual energy.*

**ABSTRACT**

The selection of an optimal cluster head (CH) node, acting as an intermediary between the base station and ancillary nodes, is a pivotal challenge in mobile Ad Hoc networks, significantly impacting network performance and efficiency. This study introduces a novel approach for CH node selection in Mobile Ad Hoc Networks (MANETs), aiming to bolster network efficiency. This approach selects the head of a nodes cluster based on the Connectivity Probability (CP), derived from the Poisson probability and each node's residual energy. The Poisson distribution, governed by a key parameter, lambda, serves to determine the likelihood of a specific outcome. In the context of this study, lambda signifies the average distance between any given node and the base station, measured relative to their communication range. Considering the direct influence of a node's residual energy on connection probability, the product of these two parameters is computed to ascertain CP. Nodes demonstrating the highest CP values are considered prime candidates for CH selection. The efficacy of the proposed algorithm was evaluated against established protocols, namely the LEACH and R-LEACH. Simulation results suggest that the proposed algorithm significantly improves network performance, extending the network lifetime by over 6 times and 3 times that of LEACH and R-LEACH, respectively. It also enhances network stability by approximately 7 times compared to LEACH and over 2 times that of R-LEACH. Furthermore, the algorithm notably improves throughput, exhibiting an increase by approximately 7 times relative to both protocols. In conclusion, the proposed algorithm offers a promising strategy for CH node selection in MANETs, potentially benefitting a wide gamut of applications.

## 1. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) are characterized as dynamically self-organizing networks typically composed of mobile devices that operate devoid of a fixed infrastructure. These networks are predominantly comprised of multiple nodes that function as both transmitters and receivers, communicating in a peer-to-peer manner. MANETs find their usage in scenarios where static networking is impractical, such as military operations, medical care tracking, environmental monitoring, disaster relief, and critical incidents, among others [1, 2].

A significant challenge within MANETs is the identification of an optimal cluster head node. This node is tasked with managing communication within a group of nodes, representing the cluster, in a manner that bolsters network performance and sustains energy longevity, thereby extending the network's lifespan [3, 4]. As the size of the MANET expands, the selection of the cluster head node becomes crucial to ensure efficient communication, optimal resource utilization, and secure communication routes [5, 6].

A wealth of research has been directed towards energy conservation in MANETs, with the objective to prolong their operational lifespan. A prominent approach from recent studies involves the hierarchical selection of cluster heads (CHs) to manage node groups and ensure equitable energy dispersion across the network [7-9]. These CHs are primarily responsible for data aggregation, managing node transmissions, reducing data redundancies, compressing information, and forwarding the compressed data to either a base station or another CH [10, 11]. The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol has emerged as a significant contribution, extensively utilized in mobile Ad Hoc networks [12-14]. The LEACH protocol employs a probabilistic methodology to determine CHs for each round, enabling each CH to assign Time Division Multiple Access (TDMA) schedules to its corresponding nodes for data forwarding within specific time frames.

Huang et al. [15] introduced a clustering algorithm integrated with a hierarchical routing protocol, designed specifically for large-scale mobile ad hoc networks. Each cluster encapsulates a cluster head, multiple gateway nodes, several guest nodes, and other cluster members. The proposed routing protocol employs proactive strategies within clusters and reactive methods for inter-cluster communications.

An optimized clustering algorithm aimed at enhancing network stability is presented in the study of Pathak and Jain [16], achieving this by limiting cluster head changes and reducing clustering overhead. This algorithm incorporates a backup node within each cluster, assuming the role of the cluster head in the event of the primary cluster head's unavailability or failure. The primary cluster head then selects a new backup node. The ranking for the cluster head and its backup is determined based on both the node degree and the residual battery life of mobile nodes.

The R-LEACH algorithm, an augmented version of the LEACH protocol, is presented in the study of Behera et al. [17]. R-LEACH employs a CH selection strategy that considers the residual energy of nodes across different rectangular zones. The group of CHs is designated based on the cluster head values. The results suggest that R-LEACH outperforms LEACH in enhancing the lifetime and residual energy of wireless ad hoc networks.

A focus of Sindhanaiselvan et al. [18] is the implementation of a clustering mechanism to minimize the energy utilized in communication from source to destination. Several parameters were analyzed to select the appropriate cluster head based on energy consumption, as this directly impacts the network's lifespan.

In the study of Ahmad et al. [19], a Memetic Algorithm (MA)-based clustering algorithm is introduced, devised explicitly for partitioning Mobile Ad Hoc Networks (MANETs) into clusters. The MA elucidates local exploration techniques to avert premature convergence and seeks the optimal local solution prior to employing other evolutionary algorithms. The network is modeled as a graph G (V, E), wherein V signifies Mobile Nodes (MNs), and E delineates communication connections between neighboring MNs. The goal of this study is to identify the cluster headset (CH) as expeditiously as possible.

Metaheuristic search algorithms are utilized for Cluster Head selection in the study of Kathiroli et al. [20-22] to circumvent the problem of local optima. These algorithms consider factors such as residual energy, and distances between node and base station for CH selection, resulting in an uneven distribution but with a degree of stability. The effectiveness of these algorithms is contingent upon their comprehensiveness and connectivity.

A novel algorithm termed the Node Quality-based Clustering Algorithm (NQCA), which employs Fuzzy-Genetic to select Cluster Head and Gateway in hybrid-MANET, is introduced in the study of Rahul et al. [23]. The Improved Weighted Clustering Algorithm is amalgamated with NQCA to create this algorithm. The NQCA algorithm segments the network into clusters, taking into account factors including node priority, transmission range, and neighbor reliability.

A dual-purpose routing mechanism—safety and energy efficiency—is presented [24]. It utilizes group key management. The initial step involves using Particle Swarm Optimization (PSO) for efficient cluster head selection and malicious node detection. The subsequent phase engages two distinct nodes—the Calculator Key (CK) and the Distribution Key (DK). These nodes are tasked with the creation, verification, and dissemination of secret keys among nodes utilizing Asymmetric key cryptography.

Despite the extensive use of MANETs and the various methodologies proposed for CH node selection, these methods do not account for the connectivity probability between nodes, a vital component in maintaining the connection.

This paper makes an original contribution to the literature by proposing a novel CH selection method that considers both connectivity probability (CP), derived from the Poisson distribution, and the nodes' residual energy. The Poisson distribution is employed to calculate the likelihood of having a single node within the communication range of the Base Station (BS). Conventionally, the Poisson distribution determines the probability of a specific outcome based on a key parameter, lambda. In this research, lambda represents the average distance between any node and the base station, in relation to their communication range. Since the residual energy of a node directly impacts the connection probability, multiplying these two values helps determine the CP value for every node within the cluster. Nodes with higher CP are given higher priority during the selection process.

The proposed method's efficacy is evaluated through simulations using MATLAB (R2019b). The results demonstrate that this approach is superior to existing algorithms concerning network stability, lifetime, throughput, and energy efficiency.

The remainder of this paper is organized as follows: The second section presents the proposed method, detailing the network and system model, Poisson distribution with its pertinent parameters, and calculations related to residual energy. The third section showcases simulation results related to network analysis and evaluation. This section considers the impact of the CP value on network stability, lifetime, the number of transmitted packets, and residual energy, contrasting these findings with results from other existing methods. Finally, the fourth section summarizes the most critical conclusions.

## 2. NETWORK AND SYSTEM MODEL

This work assumes that the system model utilizes a homogeneous battery-powered ad hoc network. This is predicated on the likelihood that the majority of devices may come from the same manufacturer or possess similar capabilities. However, real-world scenarios may have some devices with different power sources or those undergoing battery depletion. To accommodate such occasional discrepancies, a 10% variation in battery capacity is introduced to cater to such infrequent deviations. The nodes were propagated according to a Poisson distribution in the area of interest (AoI). The Poisson distribution is a common model for representing random events within a fixed area or time frame, making it suitable to model such situations. More over the geographic positions of the nodes are communicated via information sharing. This mirrors real-world device-to-device communication scenarios for traffic management. While the base station maintains its stationary position and controls the sensitization field, the nodes possess the ability to adapt their transmission power according to their distance from the destination to ensure efficient energy use. Each node transmits its data periodically during a specific time slot, which it is informed about through a schedule. This corresponds to time-division multiple access (TDMA) protocols to ensure that there's no data collision and the channel remains clear for each transmission. The network operates until the energy of all nodes is exhausted. As mentioned from Huo et al. [25], the time span leading up to the depletion of the first node's energy is termed network stability. Meanwhile, the duration from the onset of the network to the depletion of the final node's energy is defined as network lifetime. Eq. (1) and Eq. (2) define these two parameters, with $T_{NS}$ and $T_{Nl}$ symbolizing network stability and network lifetime, respectively. Tn denotes the lifetime of node n. In MANETs, packet routing is the main contributor to energy consumption. The communication model from Ahle [26] is used to determine and evaluate the energy usage in these networks.

$$T_{NS} = min_{n \in N}(T_n) \tag{1}$$

$$T_{Nl} = max_{n \in N}(T_n) \quad (2)$$

where, N represents the total number of nodes in the network. The energy used during transmission varies based on the distance between the transmitting and receiving nodes. If this distance exceeds a specific threshold, termed '$d_o$', the energy model for multi-path fading is applied. Conversely, for distances up to 'do', the free space energy model is employed. Eqs. (3) and (4) outline the energy consumption for sending an L-bit data packet to a node situated d meters distant [25].

$$E_{Tx}(L, d) = L(E_{elec} + \varepsilon_{fs}\, d^2), \qquad for\ d \leq d_o \quad (3)$$

$$E_{Tx}(L, d) = L(E_{elec} + \varepsilon_{mp}\, d^4), \qquad for\ d > d_o \quad (4)$$

$$d_o = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}} \quad (5)$$

where, the energy expended per bit by either the transmitter or receiver is labeled as $E_{elec}$. Meanwhile, the transmission parameters for multi-path and free space are designated as $\varepsilon_{mp}$ and $\varepsilon_{fs}$, respectively. To determine the energy used in receiving L-bit data, the following calculation can be employed:

$$E_{Rx}(L) = LE_{elec} \quad (6)$$

The choice of this specific energy consumption model is rooted in its ability to accurately represent real-world transmission scenarios. In practical wireless environments, the energy needed for transmitting data is largely influenced by the distance between the communicating nodes. However, while this model offers a close representation of many real-world scenarios, there are potential limitations, such as: a fixed threshold '$d_o$' might not always representative in dynamic environments, and the multi-path model can be vary based on some factors like obstacles and atmospheric conditions.

In Poisson distribution a random variable α is termed a Poisson random variable with the parameter λ, if:

$$\rho(\alpha = i) = \frac{e^{-\lambda}}{i!}(\lambda)^i, \qquad i = 0, 1, 2, \ldots \quad (7)$$

where, λ represents the mean count of events [27].

A graph of the probabilities of a Poisson random for different values of λ is presented in Figure 1.

In the system model, it is assumed that there are N mobile nodes propagating within the AoI, representing a certain cluster. The positional centering degree of any node j can be calculated relative to the surrounding nodes within the cluster as follows:

$$d_j = \frac{1}{N-1}\left(\sum_{i=1}^{N} ||P_i - P_j||^2\right)^{1/2} \quad (8)$$

where, $P_i$ and $P_j$ represent the coordinates of node i and node j respectively. The value within the summation signifies the cumulative Euclidean distances between node j and the other nodes within the cluster. To derive an average distance, indicative of the centrality (or centering degree) of this node amongst the cluster nodes, the summation was divided by the count of distances computed, which is (N-1). This excludes the distance where node 'i' equates to node 'j'. On the other hand, if the distance from node j to the base station is represented as $d_{BSj}$, then the average cumulative distance from each node i in the cluster to the base station, routing through node j, is denoted by:

$$\chi_j = d_j + d_{BSj} \quad (9)$$

If j is the candidate node to be selected as a CH, then the value of $\chi j$ will represent the average distance between any node i to the CH and then to the BS.

The ratio of the average distance $\chi j$ to the communication range R is a suitable indicator for determining the probability of a successful communication between the cluster nodes and the base station through their respective CH. A smaller distance indicates a higher chance of achieving a strong connection, while a greater distance implies a lower chance of success. Then according to Poisson distribution of Eq. (7), the probability of having one node within the communication range to the base station is:

$$\rho(\alpha = 1) = \frac{e^{-\frac{\chi_j}{R}}}{\alpha!}\left(\frac{\chi_j}{R}\right)^{\alpha} = e^{-\frac{\chi_j}{R}}\left(\frac{\chi_j}{R}\right) \quad (10)$$

As the residual energy of the suggested CH is of paramount importance in ensuring uninterrupted communication coverage, this value can be viewed as a scaling factor impacting the probability derived from the Poisson distribution. As the residual energy value rises, the communication probability correspondingly increases. Conversely, as the energy diminishes, the probability of communication decreases. Thus, the connectivity probability (CP) is calculated by multiplying this energy with the Poisson distribution.

$$CP_j = E_j\rho(\alpha = 1) = E_j\frac{e^{-\frac{\chi_j}{R}}}{\alpha!}\left(\frac{\chi_j}{R}\right)^{\alpha} = E_j e^{-\frac{\chi_j}{R}}\left(\frac{\chi_j}{R}\right) \quad (11)$$

Among the connectivity_probability of all cluster nodes, the nodes with the highest probability are selected to function as CHs. Adopting nodes with high CP values means ensuring continuity of communication and, as a result, ensuring network stability. Also, not relying on a single node to act as a cluster head achieves a state of balance in the network loads, which increases its performance efficiency.

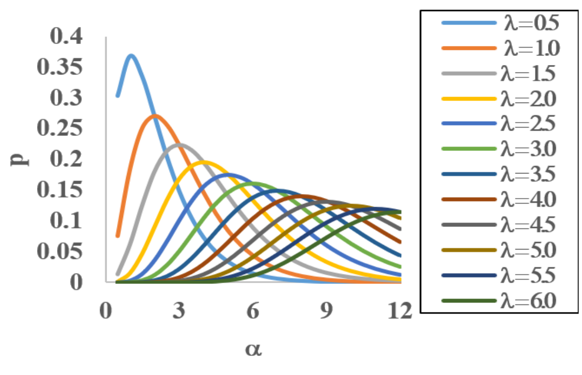


**Figure 1.** Poisson distribution for different values of λ

## 3. SIMULATION RESULTS

The simulation assumes that a MANET comprising of 100 mobile nodes follows the Poisson distribution while propagating in an area of 500m*500m. The area is facilitated by a stationary BS. This BS is positioned at a central location, ensuring uniform signal strength and coverage in every direction, there by optimizing accessibility for all devices or nodes. The BS is strategically situated at a central location to ensure uniform signal strength and coverage from all directions, thus optimizing accessibility for all nodes or devices. Within the network, the BS plays several key roles. It primarily acts as the main communication hub. Furthermore, the BS manages resource allocations, such as bandwidth, and sets the communication timelines for nodes, particularly in time division multiple access (TDMA) systems. Additionally, it handles various network management responsibilities. About 90% of the nodes possess identical initial energy levels, while the remaining nodes have more energy. The network model aligns with the parameter values outlined in Table 1.

**Table 1.** Parameter values of the network

| Parameter | Value |
|---|---|
| Initial energy of 90% of the total Nodes | 0.5*J* |
| Initial energy of 10% of the total Nodes | 0.75*J* |
| Communication range R | 100*m* |
| Free space transmission parameter ($\varepsilon_{fs}$) | $0.1*10^{-12} J/bit/m^2$ |
| Multi-path transmission parameter ($\varepsilon_{mp}$) | $1.3*10^{-15} J/bit/m^4$ |
| Consumed energy per bit ($E_{elec}$) | $50*10^{-9} J/bit$ |
| Energy of Data aggregation per bit ($E_{DA}$) | $5*10^{-9} J/bit$ |
| Number of bits per packet (*L*) | 4000 *bit* |

### 3.1 Network analysis

The study examined the impact of varying CP values on network stability, lifespan, the number of packets transmitted from nodes to CHs and from CHs to BS, and the remaining energy levels. Figure 2 shows the effect of CP values on the network stability and lifetime. This figure displays three curves, indicating: the round when the first node died, when half of the nodes were no longer active, and when the final node ceased functioning in the network.

As the value of CP decreases, more nodes become eligible to be elected as CHs, increasing the number of participating CHs and thereby extending the network lifetime. Conversely, increasing the value of CP reduces the number of CHs, leading to a slight decrease in network stability, as reflected in Figure 2. It is worth noting that having a low connectivity probability among CHs can make communication unstable and transition from one cluster head to another.

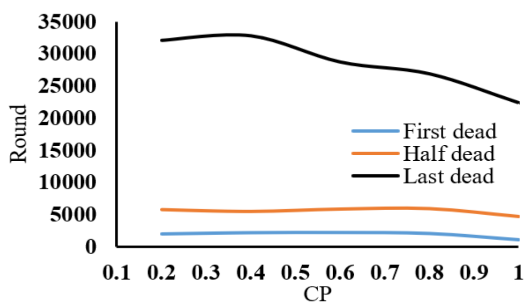


**Figure 2**. Effect of CP values on both network stability and lifetime

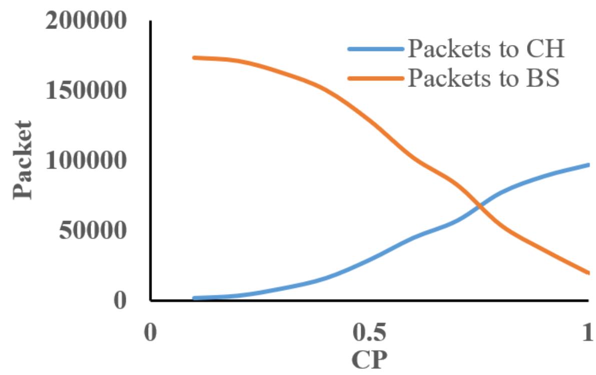


**Figure 3.** Impact of CP values on packet transmission count from nodes to CHs and from CHs to BS

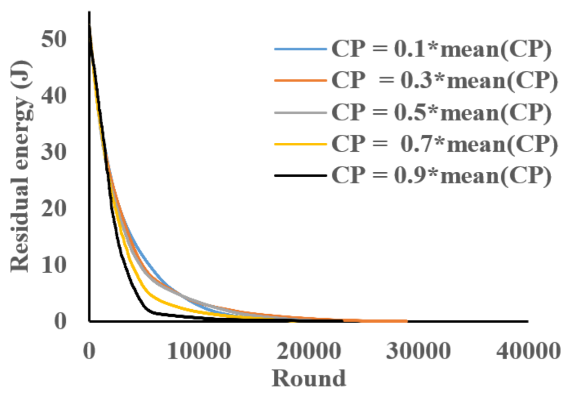


**Figure 4.** Residual energy for different values of CP

Figure 3 shows how changing the CP values affects the throughput, measured in terms of the packet count transmitted from regular nodes to CHs and from CHs to the BS. With a rise in the CP value, there's an uptick in regular nodes dispatching packets to CHs. Yet, a higher CP value corresponds to a reduced number of CHs, consequently diminishing the packet transfers from CHs to the BS.

Figure 4 illustrates the network's residual energy for various CP values. The figure indicates that a decrease in CP value is associated with extended node energy durations. This can be attributed to a lower CP value enabling more nodes to assume the CH role. As a result, nodes rotate tasks and roles based on their mobility and remaining energy. However, it's essential to recognize that a low connectivity probability among CHs can lead to unstable communication and frequent transitions between cluster heads. Therefore, when selecting the CP value, caution is necessary; it should ideally be moderate. Such a choice ensures balanced workloads and uniform energy consumption, allowing nodes to conserve their energy over extended periods.

### 3.2 Comparative results

To assess the efficacy of the CP algorithm, it's imperative to select fitting protocols. As previously mentioned, LEACH is a hierarchical routing protocol primarily aiming to extend a network's lifespan through equitable energy consumption among sensor nodes. This is achieved by segmenting the network into clusters and periodically changing the cluster head. The protocol's adaptable clustering and data consolidation features have established it as a preferred choice for energy-efficient networks. R-LEACH builds upon the original LEACH, enhancing energy efficiency by refining the cluster head selection process. This iteration modifies the pace at which cluster head rotation occurs, thereby equalizing energy consumption among nodes.

The reasons behinds selecting these two protocols is grounded in several reasons. Firstly, LEACH is one of the pioneering hierarchical routing protocols in WSN, making it a benchmark for comparison in many research studies. R-LEACH, as a revised version, further enhances the original protocol's capabilities. Both LEACH and R-LEACH focus on energy efficiency, a critical factor in MANETs, where devices often run on battery power. Moreover, the dynamic nature of cluster formation and head rotation in LEACH and R-LEACH can be particularly relevant to MANETs, which often have changing topologies due to node mobility. By comparing with these protocols, it provides a perspective on how a the proposed method stands concerning network stability, lifetime, residual energy, and throughput.

Therefore, the proposed method was compared to the LEACH and R-LEACH protocols using consistent initial data and mobile node placement coordinates across various sessions. The displayed results represent the average values derived from multiple iterations.

Figure 5 illustrates the network lifetime. Initial node failures are observed around round 300 for LEACH, round 900 for R-LEACH, and round 2200 for CP. On the other hand, the average rounds at which the last node fails are 3000 for LEACH, 5500 for R-LEACH, and 19000 for CP. This difference arises because LEACH's CH selection depends on a threshold from a random value, making the selection less effective. On the other hand, R-LEACH adds the residual energy as an extra factor to the LEACH threshold selection equation, adjusting the threshold. Meanwhile, CP chooses CHs by iteratively merging the vectors of residual energy with those based on location, utilizing the Poisson distribution to pinpoint nodes with optimal connectivity probabilities.

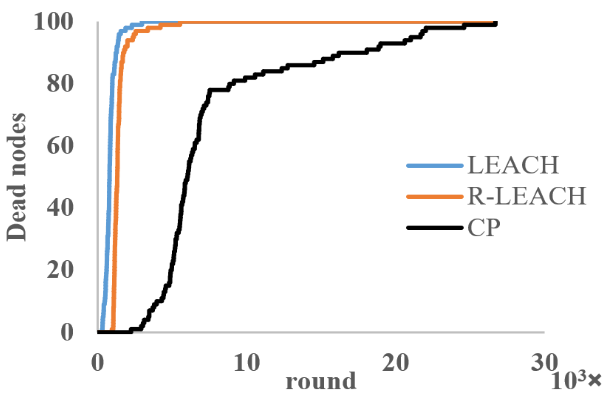


**Figure 5.** Network stability and lifetime

Figure 6 displays the residual energy results, which show that the energy values of LEACH and R-LEACH protocols are quite similar, both depleting around round 3000. In contrast, the CP algorithm effectively prolongs energy conservation over an extended period, continuing up to round 21000. This translates to a remarkable 700% increase in the lifetime of the network compared to LEACH and R-LEACH. The superior energy conservation of the CP algorithm can be attributed to its excellent load balancing capabilities and uniform energy consumption.

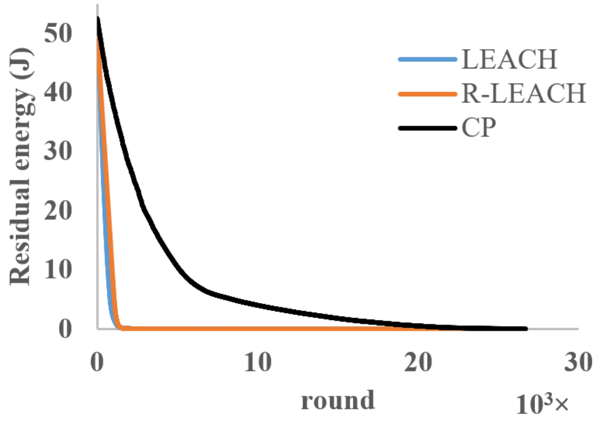


**Figure 6.** Residual energy

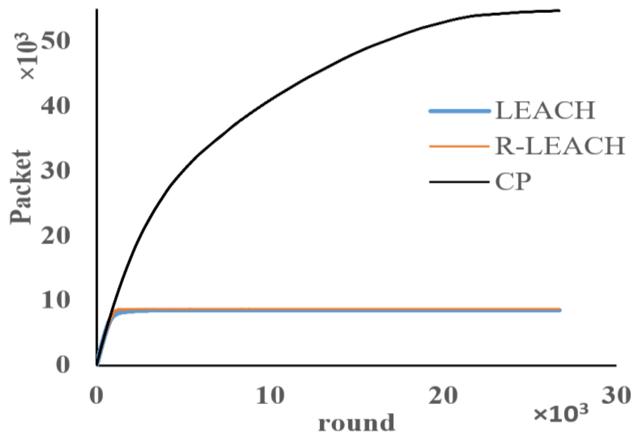


**Figure 7.** Network throughput

For real-world MANET deployments, these results point to a network that is more reliable, cost-effective, and efficient. It means longer operational times, and fewer interruptions. For the research community, these results offer a robust model that paving the way for continued innovation in the domain.

The ratio of received packets to send packets, also known as throughput, is a crucial measure. The CP algorithm enables the network to operate for an extended period by preserving residual energy. Additionally, the algorithm enables nodes to switch roles and responsibilities based on their mobility and residual energy, allowing them to function as either a CH or non-CH, resulting in higher throughput than both LEACH and R-LEACH, as shown in Figure 7.

## 4. CONCLUSIONS

In conclusion, this study proposed a reliable method for selecting Cluster Heads (CHs) in Mobile Ad-Hoc Networks (MANETs) by utilizing connectivity probability (CP) based on Poisson distribution and residual energy. Nodes with higher CP were chosen as CHs, resulting in a more stable network with a longer lifespan and increased throughput. The algorithm's ability to evenly distribute the load made it superior to other protocols like LEACH and R-LEACH, especially when considering network stability and longevity. This superiority stems from the algorithm's consideration of dynamic behavior continuity in MANETs, and the subsequent fluctuation in CP values. In contrast, LEACH's CH selection depends on a threshold derived from a randomized value, which can occasionally make its selection process less optimal.

R-LEACH, on the other hand, integrates residual energy as an added factor in the LEACH threshold formula, altering the threshold. However, a static threshold might not always be ideal in ever-changing environments. In scenarios where such a threshold remains consistent over extended durations, both LEACH and R-LEACH can operate efficiently.

The simulation outcomes highlight the enhancement in network performance achieved by the proposed algorithm. It prolongs the network's lifespan to over 6 times and 3 times that of LEACH and R-LEACH, respectively. Furthermore, the algorithm bolsters network stability, outperforming LEACH by approximately 7 times and R-LEACH by over 2 times. Additionally, the throughput sees a significant boost, amplifying nearly 7-times when compared to both protocols.

The proposed algorithm calculates nodes' CP iteratively based on their residual energy and the probability of being within communication range using Poisson random variables. This feature allows it to be easily adapted for use with mobile sinks. When utilizing the algorithm with mobile sinks, several benefits emerge. First, as mobile sinks move and potentially change their communication range with various nodes, the algorithm can adjust CP values in real time to ensure optimal data routing. This results in efficient data collection and reduced energy consumption. However, challenges could include the increased computational overhead due to continuous CP recalculations and potential delays in data routing during these recalculations. Nonetheless, the benefits of adaptability and improved network performance make the algorithm a promising choice for MANETs with mobile sinks.

Overall, the proposed CP algorithm shows promise for improving MANET performance.

## ACKNOWLEDGMENT

The author would like to extend heartfelt thanks to Mustansiriyah University (www.uomustansiriyah.edu.iq) in Baghdad, Iraq for their invaluable support.

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## NOMENCLATURE

| | |
|---|---|
| T | lifetime |
| E | energy |
| $E_{elec}$ | consumed energy per bit |
| N | total number of nodes |
| P | coordinate of node |
| R | communication range |
| CP | connectivity probability |
| d | distance |
| L | L-bit data packet |

### Greek symbols

| | |
|---|---|
| $\alpha$ | Poisson variable |
| $\chi$ | average distance between any node to the CH and then to the BS |
| $\varepsilon$ | transmission parameter |
| $\lambda$ | Poisson parameter |
| $\rho$ | Poisson probability |

### Subscripts

| | |
|---|---|
| n | node index |
| Nl | network lifetime |
| NS | Network stability |
| o | threshold level |
| fs | free space |
| mp | multi-path |
| Rx | receiving mode |
| Tx | transmitting mode |
| BS | base station |