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Research Article

A Modified PRoPHET Protocol for Energy and Buffer Optimization in Delay Tolerant Networks: Performance Evaluation for an IoT Smart City Scenario

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Abstract

In smart cities, Delay Tolerant Networks (DTNs) support Internet of Things (IoT)-based services, where the density of interconnected devices is very high, making energy management even more critical. Considering energy-constrained scenarios, optimization of energy consumption will ensure the longevity of the individual nodes and sustainability of the whole infrastructure of the smart city. In such scenarios, energy-aware routing is a very important solution for efficient management of limited energy resources. In this work we present a modification of the Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) protocol that integrates both energy-aware message forwarding and Acknowledgment (ACK) based buffer management to enhance the efficiency of message delivery in DTNs, especially in smart city IoT scenarios with limited energy and buffer resources. To validate the effectiveness of this modification, simulations are conducted to compare the performance of the modified PRoPHET protocol with the original version. The key metrics for evaluation include delivery probability, routing overhead and average buffer time. The modifications improve performance under energy constraints while managing buffer utilization more effectively.

Keywords: IoT; Smart City; Buffer Optimization; Routing Protocol; Energy Aware; DTNs.

INTRODUCTION

Nowadays, Internet of Things (IoT)-enabled devices are integrated in different smart city applications such as traffic management, environmental monitoring, smart infrastructure.

Smart city sensors continuously monitor the environment to avoid critical situations and waste of resources and deliver new services to the end users. However, the traffic generated by these sensors may not be supported by existing networks without huge infrastructure investments.

Delay Tolerant Networks (DTNs) offer a robust solution to these challenges by enabling data delivery in networks, where continuous end-to-end connectivity cannot be guaranteed. DTNs use a store-and-forward approach, making them highly effective in scenarios with network disruptions, high mobility, or sparse infrastructure. Typical use cases include remote environmental sensing [1], internet connection in rural regions [2], rural health monitoring, wildlife tracking, and post-disaster communication, where traditional network architectures often fall short. In DTNs, data can be opportunistically stored and forwarded and are highly suitable for environments such as vehicular networks, where nodes are mobile and partitions are frequent. The potential of DTN to contribute to a variety of Internet applications is discussed in [3].

People, cars, and public transportation means, such as buses or trams, are continuously moving inside the city. Pedestrians move along sidewalks and city centres, following distinct movement patterns, while vehicles and public transportation means follow specific routes according to schedules.

Mobility is one of the key factors that can help in data dissemination within smart cities. In [4], opportunistic networks are introduced as a promising solution for smart cities, utilizing device mobility to enable data relaying in a distributed and efficient manner. In [5] a new routing protocol based on game theory that improves energy efficiency of DTNs in city environments is proposed. Adaptive solutions based in DTN can facilitate reliable smart city network [6].

In DTNs, routing is particularly challenging due to the intermittent connectivity between nodes, and protocols must be designed to handle this dynamic environment. Traditional DTN routing protocols, like the Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) [7], rely on encounter probabilities to make forwarding decisions, but they often overlook resource constraints like energy and buffer space.

In [8] authors propose a modified version of the PROPHET routing protocol that enhances the representation of both direct and transitive links between nodes.

In our previous work, [9-13] is evaluated the performance of different routing protocols in DTNs. DTNs rely on battery-powered nodes that have limited energy resources. By implementing energy-efficient protocols, we can optimize the use of energy and prolong the lifetime of nodes, resulting in longer network operation.

In this work, we propose a hybrid protocol for energy and buffer optimization in DTNs for an IoT Smart City scenario. The proposed protocol is a modification of the PRoPHET [7] and uses two mechanisms: an energy-aware message forwarding mechanism and a buffer management mechanism that uses Acknowledgement (ACK) messages.

In the energy-aware message forwarding mechanism, each node calculates the message forwarding probability based on the remaining energy. A threshold energy value is set and the nodes with higher energy will forward the messages. The low energy nodes are not overloaded, and the high-energy nodes contribute more to the process of data forwarding making forwarding load more efficient.

The buffer management mechanism is used to optimize the buffer space and bandwidth. ACK messages are used when a packet arrives at the destination to clear the same packet copies that are still in the buffers of other nodes. Low-energy nodes, which are less likely to forward messages, will benefit from this mechanism. Even though these nodes receive messages but do not forward them, the dissemination of ACK messages ensures that their buffers do not clog up with packets that have already been delivered. This minimizes wasted buffer space and ensures low-energy nodes are not overwhelmed with unnecessary packet storage.

The proposed modified PRoPHET is an adaptation of the PRoPHET protocol to operate in environments where energy management is critical. Unlike [14] and [15], our approach scales predictability inversely with energy depletion to prevent overload, while adding ACKs for multi-protocol compatibility. This adaptation allows for more efficient operation in energy-constrained situations, ensuring that nodes can manage their energy levels effectively while still attempting to deliver messages based on delivery predictability.

To evaluate the effectiveness of communication protocols, the Working Day Mobility Model (WDMM) [16] is incorporated into mobility models for more appropriate simulation of realistic movement by pedestrians, vehicles, and public transport within smart city applications. The following are the main contributions of this work:

1) Design a modified PRoPHET routing protocol with an efficient forwarding strategy that balances energy consumption and buffer management, ensuring optimal message delivery in energy-constrained DTNs.

2) Enhance network lifetime by integrating energy-aware and buffer optimization, reducing message drops due to node depletion or buffer overflow.

3) Improve message delivery efficiency through adaptive forwarding decisions based on node energy levels and buffer status.

The remainder of this paper is structured as follows. First, we review relevant literature to provide context for our work. Next, we present the problem statement along with the details of our proposed protocol. We then describe the simulation tools, parameter settings, and the results obtained from our experiments. This is followed by a discussion analyzing the findings. Finally, we conclude the paper and outline directions for future work.

LITERATURE REVIEW

Routing in Delay-Tolerant Networks (DTNs) has been extensively studied since the early development of multi-hop communication protocols, with foundational works such as [17] laying the groundwork for evaluating routing performance in static wireless networks. In smart cities, network resources are constrained, and energy efficiency and buffer management are critical for reliable data delivery. Many approaches have been proposed, but significant gaps remain in integrating energy and buffer awareness under realistic urban mobility conditions.

Energy-Aware Routing in Smart Cities

Several studies propose energy-aware routing protocols. In [18], a data forwarding scheme considers both buffer space and residual energy levels of nodes, improving delivery rates and reducing dead nodes. While [18] uses multi-attributes, it overlooks transitive predictability, our work bridges this. Kang et al. [14] proposed an energy aware protocol that relate forwarding to battery level, node type, and delivery predictability, achieving better performance than PRoPHET. In [19], a genetic algorithm selects the best relay node to improve residual energy and reduce dead nodes, while Mottaghinia et al. [20] use fuzzy inference to minimize message replications by considering distance and energy. Khalid et al. [15] adapt HBPR to purge packets after delivery and select relay nodes based on energy, and [21] explicitly exploits available energy to optimize transmission and sensing.

Epidemic-based protocols have also been adapted. Bista et al. [22] propose an energy-aware Epidemic variant considering energy and buffer availability, improving network lifetime and delivery rates. In [23], energy-efficient variants of Epidemic and MaxProp employ thresholds and one-hop acknowledgments to reduce energy consumption. Triadi et al. [4] use game-theoretic decision-making to reduce redundant scanning, improving energy efficiency in urban DTNs. GEER [24] integrates geographic awareness, dynamic TTL, node density, and energy levels to improve delivery accuracy and energy efficiency. [25] provides insights into energy consumption under trace-based mobility, but without proposing new mechanisms.

Despite these advances, most protocols either focus solely on energy or provide limited integration with buffer management under realistic urban conditions. Few evaluate performance under fully described smart city scenarios, considering urban mobility, node density, and traffic patterns, leaving a gap in real-world applicability.

Buffer Management and Message Prioritization

Buffer management is crucial for optimizing delivery under storage constraints. Statistical learning-based policies [26] approximate optimal global-knowledge performance, outperforming traditional approaches. SS-Drop [27] deletes messages of appropriate size during overflow, avoiding bias, while MaxDelivery [28] targets disaster and rural networks by removing delivered messages, prioritizing low-hop messages, and forwarding to nodes with less than 90% buffer occupancy. Weighted message prioritization [29] uses two queues for high and low-weight messages, selecting transmission based on priority, size, hop count, and TTL, which is effective in transportation applications. EBR [30] integrates energy and buffer awareness, selecting relays with higher resources, and [25] shows the effects of buffer size variation on delivery, highlighting limitations in previous studies.

Most existing buffer management strategies are either isolated from routing protocols or tested under simplified mobility, limiting their applicability in dense urban smart cities with heterogeneous node types and dynamic traffic conditions.

Smart City Applications: Comparative Insights

In smart city scenarios, routing strategies vary in effectiveness. In [31], Direct Delivery is buffer-efficient but has low delivery probability; First Contact achieves balanced performance; Epidemic provides high delivery at high overhead; and multi-copy protocols balance delivery rate and latency. EMR [32] improves delivery probability and latency by regulating replication based on buffer, energy, TTL, and encounter history. Weighted buffer management [29] prioritizes safety-critical messages, while MaxDelivery [28] works well in constrained disaster networks but has not been evaluated in dense urban contexts.

Comparing all State-of-the-Art approaches, it is evident that while energy and buffer awareness improve delivery and resource utilization, few protocols integrate both under fully described smart city conditions. Most assume static or simplified mobility, uniform node types, or idealized buffer availability, making it difficult to predict real-world performance.

Gap Analysis and Motivation for the Proposed PRoPHET Modification

The reviewed approaches highlight three main gaps in smart city DTNs. First, most protocols consider energy or buffer strategies in isolation rather than jointly, limiting holistic optimization. Second, few studies simulate realistic urban mobility, node density, or traffic patterns, so results cannot be reliably generalized to operational smart city scenarios. Third, evaluation metrics are inconsistent, making direct comparisons of delivery rate, latency, and energy consumption challenging.

Our proposed modification of the PRoPHET protocol addresses these gaps. No prior work combines energy-scaled PRoPHET with epidemic ACKs in WDMM-simulated cities Unlike other PRoPHET variants and State of the Art protocols, our approach integrates energy-aware relay selection, buffer prioritization, and urban mobility modelling under fully described smart city conditions. By considering both residual energy and buffer availability when selecting relay nodes, our protocol reduces dead nodes and unnecessary transmissions. Furthermore, by incorporating realistic node mobility, heterogeneity, and urban traffic patterns, it provides a comprehensive evaluation framework not covered by existing studies such as [14, 15, 18, 24].

This combination of energy-aware routing, buffer management, and realistic urban modelling ensures that our modification is particularly suited for smart cities where node density, heterogeneous devices, and traffic patterns create dynamic challenges that existing protocols fail to address simultaneously.

PROPOSED PROTOCOL

Problem statement

In DTNs, the available energy resources are often finite, while effective energy management acts as one of the crucial factors to ensure network longevity. The conventional PRoPHET routing protocol [7] uses encounter history with transitive properties for approximating the probability that a node can successfully deliver a message to its destination.

However, PRoPHET does not take the energy constraints into consideration, and this may lead to an imbalance in the energy use across nodes, resulting in node failure and a short lifetime of the network. PRoPHET, as a multi-copy routing protocol, keeps storing and transmitting the delivered messages, and once a message is delivered, its copies may remain in the buffers of other nodes. These nodes continue to transmit the message even though it has already reached its destination, utilizing buffer inefficiently with unnecessary consumption of network bandwidth.

In energy-constrained scenarios, such as in smart cities and IoT-based applications, the optimization of energy use along with buffer management becomes mandatory. The PRoPHET shall be equipped with an energy-aware forwarding mechanism to maintain a balanced use of energy across nodes for effective resource utilization. Furthermore, it must be equipped with efficient buffer management to discard the packets that are already delivered and avoid redundant transmission of packets. This will ensure an improvement in message delivery rates and network lifetime.

Proposed Solution

We propose a modified PRoPHET routing protocol that integrates both the energy-aware message forwarding and ACK based buffer management to enhance the efficiency of message delivery in DTNs, especially in scenarios with limited energy and buffer resources. Our proposed solution is different from [22] because another method is used to include the energy level. Unlike [14] and [15], our approach scales predictability inversely with energy depletion to prevent overload, while adding ACKs for multi-protocol compatibility. Our protocol is based on the PRoPHET protocol but introduces two key modifications to improve performance under energy constraints while managing buffer utilization more effectively.

Energy-aware Message Forwarding

We introduce an energy-aware forwarding probability that dynamically adjusts based on a node's remaining energy. In our modified protocol, the delivery predictability (used to decide whether to forward a message) is adjusted based on the node's remaining energy. The forwarding probability $P_{adjusted}$ is calculated by multiplying the original delivery predictability $P_{original}$ by the ratio of residual energy $E_{residual}$ to a predefined energy limit E_{limit} as shown in equation (1):

$$P_{adjusted} = P_{original} * (E_{limit}/E_{residual}) \tag{1}$$

where:

- $P_{original}$: The original delivery predictability between two nodes, as calculated by the PRoPHET protocol based on historical contact information.
- $E_{residual}$: The current remaining energy of the forwarding node.
- E_{limit}: A predefined energy threshold used to normalize the energy ratio.
- $P_{adjusted}$: The modified forwarding probability that incorporates both delivery predictability and the node's residual energy.

The adjustment is to give more priority to nodes with more energy for message forwarding, while nodes with less energy reduce their participation to conserve resources. The node dynamically reduces energy levels based on scanning intervals and transmission requirements, while the original PRoPHET protocol focuses on delivery predictability based on historical contact information without considering energy depletion.

The original PRoPHET protocol does not specify an initial energy setup for nodes, whereas our implementation allows for configuring initial energy levels and how energy is consumed during operations. Initial energy refers to the total amount of energy available to a node at the start of the simulation. Problematic energy defines the energy range [0–1500 J] within which nodes are considered at risk of depleting their battery. When a node's remaining energy falls within this range, it may alter its behavior, such as reducing message forwarding or entering an energy-saving mode.

Our approach introduces flexibility by allowing message forwarding based on a node's residual energy. This strategy results in a balanced distribution of energy consumption throughout the network. A node is said to be in a problematic state when its current energy level drops below this problematic energy threshold. A problematic energy threshold establishes when a node's energy level drops very low, affecting message delivery predictability. By reducing the likelihood that nodes with low energy will be selected for message forwarding, this approach helps nodes save energy and improves the likelihood that messages will be delivered successfully throughout the network. Nodes that have energy levels below the threshold are therefore less likely to be selected for message forwarding, which preserves the energy that remains in them. Algorithm 1 presents the process for forwarding messages based on the node's residual energy, the message is not forwarded. When a message is received (Line 3), the node checks if its current energy level meets the minimum threshold required to participate in forwarding (Line 5). In this algorithm, the minimum_energy_required is the lowest residual energy a node must maintain to remain active in forwarding. Nodes below this threshold either drop packets or enter a low-energy state. If the condition is satisfied, the node calculates a forwarding probability based on its residual energy (Line 8). The threshold_probability parameter defines the minimum forwarding probability a message must reach in order to be transmitted to another node. If the adjusted forwarding probability of a message is lower than this threshold, the message will not be forwarded. In practice, this prevents unreliable transmissions through weak candidates and reduces unnecessary energy consumption, since only nodes with sufficiently high forwarding likelihoods participate in message delivery. This probability is then evaluated (Line 11) to determine whether the message should be forwarded (Line 14) or dropped. If the node's energy is below the required threshold, it either discards the message or enters a low-energy state (Line 16). This ensures that energy-constrained nodes reduce their communication burden, thereby extending their operational lifetime.

The forwarding decision itself is computationally lightweight, requiring constant time, O(1). However, selecting the next node from the list of encountered nodes requires examining all potential candidates, resulting in O(n) complexity, where n is the number of nodes currently encountered. This ensures that nodes with low energy are conserved while maintaining efficient message propagation.

Algorithm 1: *Energy-Aware Message Forwarding Process*

```
1 START
2 // Step 1: Node receives a message
3 RECEIVE message
4 // Step 2: Check energy level
5 IF (energy_level >= minimum_energy_required) THEN
6 // Step 3: Calculate forwarding probability
7 forwarding_probability =
8 calculate_forwarding_probability(remaining_energy)
9 // Step 4: Check if forwarding probability is high
10 enough
11 IF (forwarding_probability >=
12 threshold_probability) THEN
13 // Step 5: Forward the message
14 FORWARD message to next_node
15 ENDIF
16 ENDIF
17 END
```

ACK-based Buffer Management

Even if a message reaches its destination, copies of that message may still reside in the buffers of other nodes. This can lead to inefficient use of buffer space and unnecessary retransmissions, consuming bandwidth, and energy. To address this issue, we introduce an ACK-based buffer management system. An ACK class which is not explicitly part of the original PRoPHET protocol is created to handle ACK messages. When a message reaches its destination, an ACK message is generated. This ACK is disseminated in an epidemic manner, meaning it spreads across the network as nodes encounter each other.

When a node receives an ACK message, it checks its buffer for any copies of the delivered message. If found, these copies are immediately dropped, freeing up buffer space and reducing network overhead. This mechanism ensures that buffer space is utilized efficiently, preventing the storage of already delivered messages and allowing nodes to focus on forwarding new, undelivered packets. By reducing buffer congestion, the likelihood of buffer overflow is minimized, and the probability of successfully forwarding packets increases.

Algorithm 2 outlines the steps for managing acknowledgments and optimizing buffer usage after successful message delivery. Once a message reaches its destination (Line 3), an acknowledgment (ACK) is generated (Line 5) and propagated through the network (Line 7). Upon receiving this ACK (Line 11), the node deletes the corresponding message from its buffer (Line 13), thus freeing up memory for future messages. This mechanism ensures efficient buffer utilization and prevents unnecessary storage of already delivered data.

Algorithm 2 handles ACK-based buffer management to efficiently remove delivered messages. Generating and marking an ACK for a delivered message is performed in constant time, O(1). Propagating the ACK to encountered nodes depends on the number of neighbors, resulting in O(n) complexity per node, while removing a message from the buffer requires scanning through the stored messages, giving O(b) complexity, where b is the buffer size. The algorithm is lightweight for individual nodes, with the main computational cost arising from buffer scanning and ACK propagation.

Algorithm 2: *ACK and Buffer Management*

```
1 START
2 // Step 6: Message delivered to destination
3 MESSAGE_DELIVERED()
4 // Step 7: Generate ACK
5 ACK = GENERATE_ACK(message)
6 // Step 8: Propagate ACK
7 PROPAGATE_ACK(ACK)
8 // Step 9: Check if ACK is received
9 IF (ACK_RECEIVED()) THEN
10 // Step 10: Remove delivered message from buffer
11 REMOVE_FROM_BUFFER(message)
12 ENDIF
13 END
```

Table 1 depict the simulation parameters

Table 1. Simulation parameters

Parameters	Values
Initial Energy	1000-7000J
Simulation Area	4500m×3400m
Nodes in the network	306~1806
Interface	WiFi
Interface Data Rate	2Mbps
Radio Range	100m
Pedestrian speed	0.5~1.5m/s
Cars speed	2.7~13.9m/s
Trams speed	7~10m/s
Buffer Size	50MB
Message Size Message	500KB~1MB
Generation Interval	25s ~ 35s
Message TTL	300minutes (5hours)
Simulation Time	43200s (12 hours)

SIMULATION RESULTS

For the simulations, we used the WDMM implemented in the Opportunistic Network Environment simulator (ONE) [7]. The WDMM has a close relationship with smart city applications because it models realistic mobility of people and vehicles within an urban environment. This model would simulate day-to-day activities of humans, like going to work or using public transportation, which are essential elements of city life. The model enables the simulation of how vehicles and pedestrians can interact in a smart city, especially when there is intermittent connectivity, within the context of Vehicular Networks and DTNs. This is useful for evaluating how data such as traffic updates or environmental monitoring information, is effectively disseminated within a city by means of smart routing protocols. Therefore, the WDMM is a useful tool to test the applications for a smart city, enabling them to perform efficiently in real scenarios.

The energy-related parameters are provided in Table 2. The simulations involved 1 group of cars, 2 groups of pedestrians, and 3 groups of trams, which had higher speeds, larger transmission ranges, and buffer space compared to the pedestrian and car groups. Pedestrians and cars moved along the shortest path using map-based movement, and trams followed predefined map-based routes.

Table 2. Energy parameters

Parameter	Value (units)
Problematic Energy	0 ~ 1500 J
Initial Energy	1500 J
Scan Energy	0.7 J
Transmit Energy	0.1 J

In our simulations, the mobility patterns of nodes are kept deterministic by setting the MovementModel.rngSeed to 1. This ensures that node trajectories remain consistent across simulation runs, allowing for a fair comparison of routing protocols without variability introduced by random movement. To model realistic traffic conditions, message generation is randomized with intervals ranging from 25 to 35 seconds and message sizes varying between 500 kB and 1 MB, reflecting natural variations in message creation while preserving controlled mobility. This approach provides sufficient variability in network load to evaluate protocol performance, while deterministic mobility simplifies the analysis and interpretation of results.

Three metrics are used to evaluate the proposed modified PRoPHET protocol: Delivery ratio: is calculated as the ratio of successfully delivered messages to the total number of generated messages. This is a key metric for evaluating the core functionality of the protocol. Since in the proposed protocol nodes with more energy are prioritized for message forwarding, the delivery ratio will show how well the energy-aware mechanism balances the energy consumption with message delivery.

Overhead: is calculated as the ratio of the total number of transmissions to the number of successfully delivered messages. Overhead shows how well the buffer management system is reducing unnecessary retransmissions and optimizing the use of available buffer space that is particularly important in DTNs with limited resources. A lower overhead means fewer redundant transmissions and more efficient use of network bandwidth and energy.

Average buffer time: the average duration that messages remain in the buffer nodes during transit. Managing the average buffer time in DTNs is important because it directly impacts message delivery success, buffer management, energy efficiency, overhead, and overall protocol performance. By minimizing average buffer time, DTNs can operate more efficiently, even in situations with constrained resources as in IoT applications.

In this work, we conducted simulations by varying the number of nodes from 306 to 1806 and applying or not the ACK mechanism to the original PRoPHET protocol and to the modified protocol with the energy-aware mechanism. The simulations were done for initial energy 1500 J and varying the problematic energy threshold. In our simulation model, we selected an initial energy of 1500 J as the problematic energy threshold. This value is grounded in empirical studies of LoRaWAN monitoring nodes, which report average daily energy consumptions up to 85 J under frequent sensing intervals [33]. Given that typical industrial IoT nodes operate with daily energy consumptions in this range, a 1500 J threshold provides a realistic baseline for evaluating energy-aware routing protocols. Initial node energy is chosen from different simulations conducted because the number of dead nodes is very high (to relate with the energy constrained network).

Figure 1 shows the results of delivery probability of both the original and modified PRoPHET with different values of problematic energy across varying numbers of nodes, when the energy-aware message forwarding mechanism is used, and the ACK mechanism is not applied.

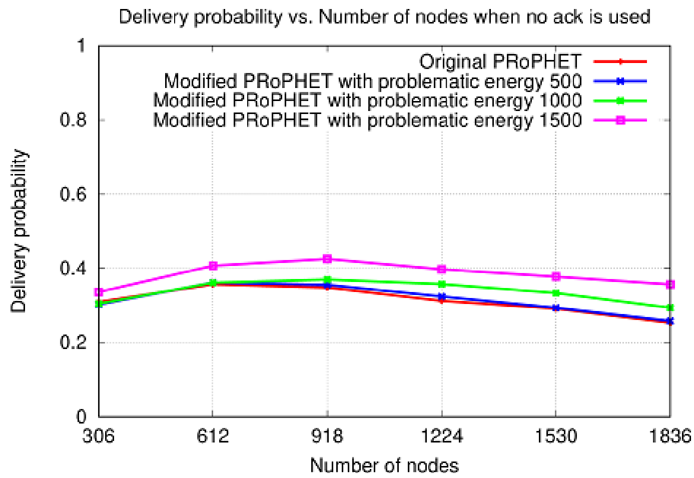

Figure 1. Delivery probability vs. No. of nodes when no ACK is used.

As shown in Figure 1, the delivery probability decreases slightly as the number of nodes increases. This behaviour can be attributed to increased network contention, buffer overflows, and message collisions due to higher message generation rates and more frequent encounters. In larger networks, nodes have more frequent contact opportunities but also face increased competition for buffer space and transmission resources, leading to potential message drops and reduced successful deliveries.

The results indicate that the delivery probability improves when the proposed energy-aware mechanism is used. In the modified protocol, the number of unnecessary transmissions is reduced, and nodes with critically low energy do not receive packets. This targeted transmission strategy helps preserve node energy and contributes to a higher overall delivery probability.

Figure 2 presents the results for delivery probability when both mechanisms are applied. The modified PRoPHET protocol with problematic energy performs better than the original PRoPHET.

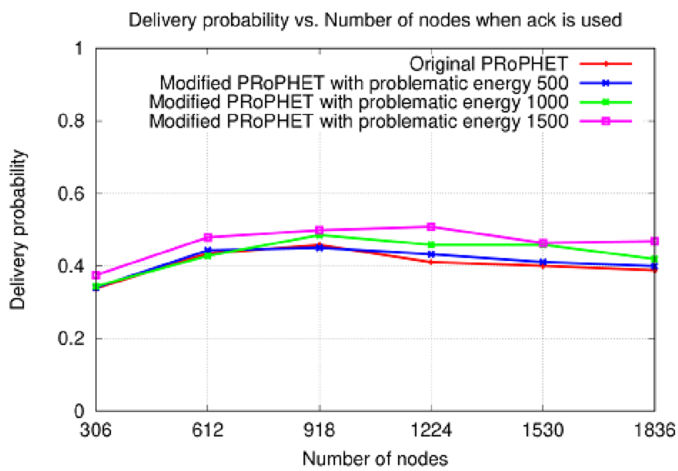

Figure 2. Delivery probability vs. No. of nodes when ACK is used.

The best results are achieved when the number of nodes in the network is large. This is because a higher number of nodes increases the probability of successful encounters between nodes, which improves message forwarding opportunities. In dense networks, the likelihood of contact between message carriers and destination nodes (or intermediate forwarders) is significantly higher, leading to improved delivery probability. Additionally, more nodes can help distribute the forwarding load, reducing individual energy consumption and improving network robustness.

A comparison of Figure 1 and Figure 2 reveals that the delivery probability results in Figure 2 are consistently better than those in Figure 1 for the same number of nodes. This improvement is due to the combined effect of the energy-aware forwarding mechanism and the ACK-based buffer management, both of which are applied in Figure 2, whereas Figure 1 considers only the energy-aware forwarding mechanism without ACK support.

Figure 2 benefits from the integration of an ACK-based buffer management scheme, which ensures that once a message is successfully delivered to its destination, it is promptly removed from the buffers of all intermediate nodes. This frees up memory, reduces transmission overhead, and prevents redundant forwarding. As the network becomes denser, these benefits become more pronounced.

Figure 3 and Figure 4. depict the effect of varying number of nodes on the overhead ratio when one or two mechanisms are used.

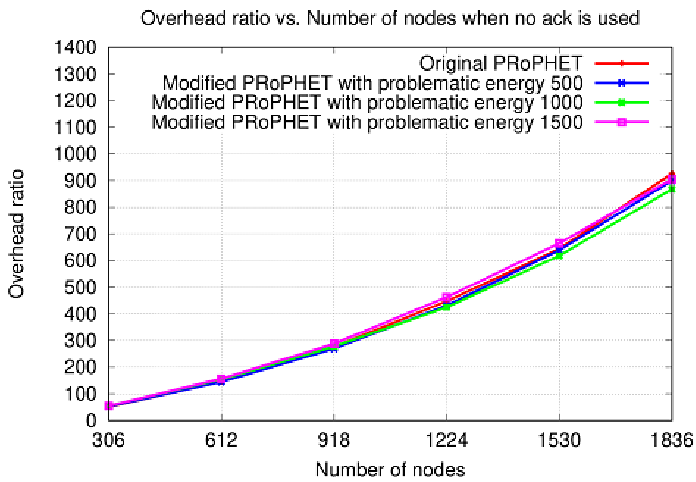

Figure 3. Overhead ratio vs. No. of nodes when no ACK is used.

When comparing the overhead ratio results in Figure 3 and Figure 4, better performance is achieved when both mechanisms are used. The overhead ratio is almost the same for the original PRoPHET and the modified versions.

However, the overhead ratio increases as the network becomes denser. This is because a larger number of nodes leads to more frequent encounters and more opportunities for message replication in opportunistic forwarding protocols. As a result, a greater number of copies of each message are generated and propagated throughout the network. While this can enhance the chances of successful delivery, it also significantly increases the number of transmissions relative to the number of successfully delivered messages, thus raising the overhead ratio.

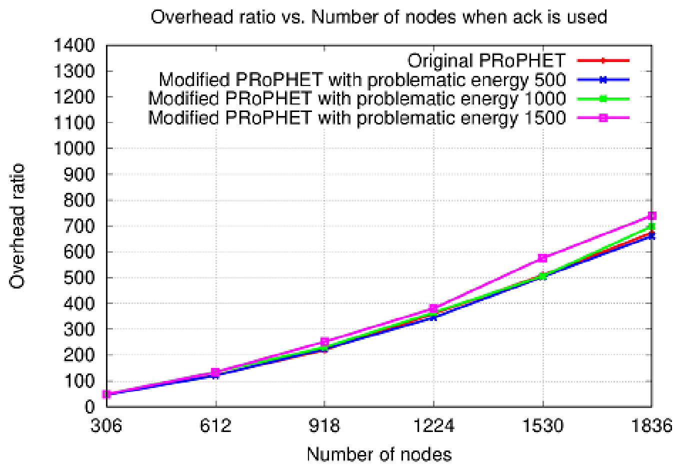

Figure 4. Overhead ratio vs. No. of nodes when ACK is used.

A comparison between Figure 3 and Figure 4 shows that the overhead is consistently higher in Figure 3 for the same number of nodes. This is primarily due to the difference in buffer management strategy: Figure 3 presents results from the scenario where no acknowledgment (ACK)-based buffer cleaning mechanism is applied, which allows messages to remain in node buffers even after successful delivery. As a result, nodes may continue to forward already delivered messages, leading to increased redundancy and higher transmission overhead. Conversely, Figure 4 incorporates an ACK-based buffer management system, which promptly removes delivered messages from all buffers upon acknowledgment propagation. This reduces unnecessary message forwarding, lowers buffer occupancy, and leads to a significant reduction in overall overhead.

Figure 5 and Figure 6 present the results for average buffer time vs. number of nodes when one or both mechanisms are used.

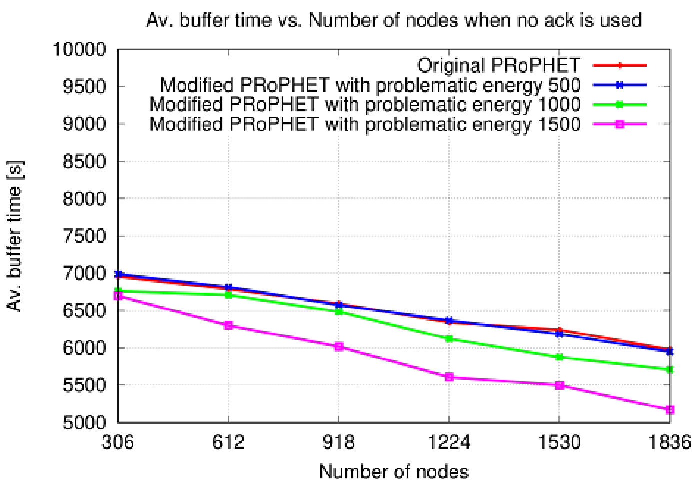

Figure 5. Av. Buffer Time vs. No. of nodes when no ACK is used.

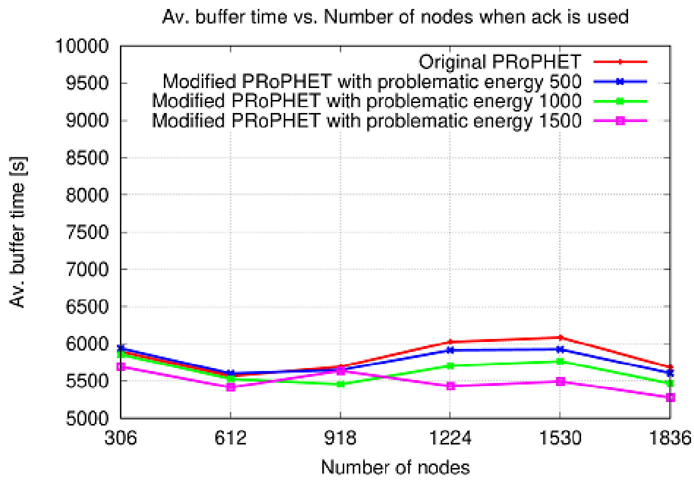

Figure 6. Av. Buffer Time vs. No. of nodes when ACK is used.

The average buffer time improves when both mechanisms are applied to PRoPHET. The ACK messages will be distributed in an epidemic manner in the network and if a node, during the update, finds a packet that is the same as the ACK in the buffer, it will reduce the Time to Live (TTL) to the initial value, making that packet drop in the next update.

The best results are achieved with a problematic energy threshold of 1500 J and when both mechanisms are used. In Figure 5, the average buffer time decreases as the number of nodes increases because a larger number of nodes leads to more frequent contacts and forwarding opportunities, which help to quickly deliver messages and reduce their residence time in buffers. The best results are observed at the energy threshold of 1500 J because this threshold ensures that nodes participate in forwarding only when they have sufficient energy reserves, thereby maintaining network stability and preventing premature node failures that could delay message delivery.

In contrast, Figure 6 does not show a continuous decrease in average buffer time with an increasing number of nodes due to varying network dynamics and buffer management policies. Fluctuations may arise from factors such as temporary buffer congestion, uneven node distribution, or energy depletion causing some nodes to drop out or reduce participation intermittently. These factors can cause irregularities in message holding times despite the increase in node density. While both figures demonstrate trends in buffer time with increasing node count, it is evident that for the same number of nodes, the average buffer time in Figure 5 is consistently higher than in Figure 6. This discrepancy arises primarily due to the absence of the ACK-based buffer management in Figure 5. Without ACK support (Figure 5), once a message is delivered to its destination, intermediate nodes retain copies of that message in their buffers until their TTL expires. This results in longer message retention periods and increases average buffer occupancy, especially in denser networks where contact opportunities are more frequent but without an efficient mechanism to purge obsolete data.

Conversely, in Figure 6, the ACK mechanism ensures that once a message is delivered, the corresponding ACK is propagated throughout the network. Nodes that receive the ACK can immediately identify and delete the delivered message from their buffers. This prompt message removal greatly reduces the average time messages spend in the buffer, particularly in larger networks where ACKs spread quickly due to increased node interactions. We evaluated the effectiveness of the proposed method by comparing it with the original PRoPHET protocol, a well-established routing scheme in DTNs.

Simulation results demonstrated that the proposed method outperforms the original PRoPHET in terms of delivery probability, overhead ratio, and average buffer time across varying network sizes and energy configurations. While the original PRoPHET does not consider the residual energy of nodes or provide mechanisms to remove already delivered messages, our approach ensures that low-energy nodes are excluded from forwarding responsibilities, and redundant messages are eliminated through acknowledgment dissemination. These enhancements lead to more efficient buffer use, lower network congestion, and improved message delivery, especially in scenarios with constrained energy resources.

The results confirm that integrating energy-awareness and buffer management significantly enhances the protocol's robustness and efficiency compared to traditional methods.

DISCUSSION

The simulation results show that combining energy-aware forwarding with ACK-based buffer management improves network performance by enhancing message delivery, reducing buffer time, reducing overhead and conserving node energy. The addition of the ACK mechanism increases delivery probability compared to using the energy-aware mechanism alone. This improvement primarily results from buffer freeing once messages are acknowledged, intermediate nodes can remove them from buffers, allowing space for new messages and enabling more effective forwarding. Additionally, the combined mechanisms reduce redundant transmissions, lowering network overhead by approximately 10–15% in dense networks. The energy-aware forwarding mechanism further ensures that low-energy nodes refrain from unnecessary forwarding, conserving energy and improving overall network efficiency. Average buffer residency time also decreases, especially in high-density networks, because delivered messages are promptly removed, facilitating faster and more reliable message propagation.

The proposed approach also has several practical implications. By prioritizing nodes with higher residual energy and removing delivered messages from buffers, the protocol reduces unnecessary transmissions and conserves energy across the network. Low-energy nodes extend their operational lifetime by limiting their forwarding activity, which improves overall network longevity and reliability. From an environmental perspective, these energy savings can translate into a reduced IoT carbon footprint compared to the standard PRoPHET protocol. Finally, these mechanisms are particularly relevant for battery-powered IoT devices in industrial monitoring or smart city applications [34], where energy efficiency and reliable message delivery are critical for sustainable long-term operation.

CONCLUSION

In this work, we proposed a modified version of the PRoPHET protocol that integrates energy-aware message forwarding with ACK-based buffer management. By considering the residual energy of nodes, the protocol reduces the burden on low-energy nodes, preventing premature depletion while maintaining network connectivity. The ACK mechanism ensures that successfully delivered messages are promptly removed from buffers, freeing space for new packets and reducing redundant transmissions.

Simulation results demonstrate that the proposed protocol outperforms the standard PRoPHET in terms of delivery probability, buffer efficiency, and energy utilization. The energy-aware forwarding mechanism helps maintain long-term network functionality, while the ACK-based buffer management reduces congestion and unnecessary retransmissions. Together, these enhancements optimize bandwidth and buffer usage, resulting in more reliable and efficient operation in energy-constrained Delay-Tolerant Networks.

The findings suggest that combining energy-awareness with buffer management can improve the sustainability and performance of IoT and vehicular networks, providing a practical approach for resource-constrained environments.

Future work will focus on developing new energy-efficient routing strategies for battery-powered IoT devices, aligning with green computing trends. The aim is to further optimize resource utilization, reducing energy consumption across network nodes while maintaining high message delivery rates. Potential approaches include multi-objective optimization or AI-driven predictive models that adapt forwarding decisions based on node energy, mobility patterns, and network conditions.

AUTHOR CONTRIBUTIONS

Conceptualization, E.S, O.J, K.T. and A.I; Methodology, O.J.; Validation, K.T, A.I.; Investigation, E.S, O. J.; Resources, K.T., A.I; Data Curation, O.J.; Writing–Original Draft Preparation, E.S., O.J; Writing–Review & Editing, E.S, O. J.; Supervision, E.S.

CONFLICT OF INTERESTS

The authors confirm that there is no conflict of interest associated with this publication.

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