ISSN: 2182-2069 / E-ISSN: 2182-2077

Traffic Offloading Strategies Using Opportunistic Wireless Networks

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Received: April 24, 2025; Revised: June 09, 2025; Accepted: July 28, 2025; Published: August 30, 2025

Abstract

Mobile device usage and data consumption have increased at an exponential pace, putting a strain on existing cellular infrastructures. This has prompted the development of opportunistic wireless networks, which have the potential to ease congestion. Such networks, through sparse connectivity and data routing, aid in optimizing and thus relieving the burden on cellular services. This study addresses the issue of offloading cellular traffic onto wireless networks to design algorithms for data forwarding, resource allocation, delay allowance, and tolerance optimization with defined heuristics. These strategies are evaluated through computer simulations using diverse network topologies and traffic generation patterns. Simulation results indicate substantial gains in throughput, latency, and energy expenditure compared to orthodox cell-based approaches. It has been determined that using such networks, or optimized wireless networks, in next-generation systems can effectively reduce traffic congestion caused by cellular networks.

Keywords: Mobile Data, Traffic, Wireless, Networks, Throughput, Services, and Algorithms.

Journal of Internet Services and Information Security (JISIS), volume: 15, number: 3 (August), pp. 230-244.
DOI: *10.58346/JISIS.2025.I3.016*

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1 Introduction

Mobile apps and other types of the Internet of Things (IoT) are constantly emerging, resulting in bottlenecks in wireless networks. Traffic management and QoS monitoring in resource-constrained wireless networks are among the dominant issues, along with congestion relief and extending network lifetime. To address problems of congestion and offloading, Opportunistic Wireless Networks (OWNs) aim to make the most of temporary connectivity and resources (Alanazi, 2023; Lee et al., 2011). OWN systems facilitate communication and data relaying through contact without fixed infrastructure, which fosters agility and extensibility. The dynamic topology, along with random link availability, makes efficient traffic offloading even more difficult (Foukas et al., 2017). Sensitive data protection and network area lifetime optimization have become the focus of recent research through intelligent algorithms and protocols (Chang et al., 2018; Hui, 2021).

Opportunistic networks will always be a focal point due to attack vectors like jellyfish reorder attacks, wormhole attacks, and unjust node infiltrations, which have not been adequately addressed (Kammoun et al., 2018; Nyambi, 2024). Several works have attempted to address these problems by using trust-based routing protocols and designing IDS, which helps maintain the network's reliability (Li et al., 2017). Furthermore, sensor nodes and mobile devices in OWN environments must consider power efficiency as one of the most essential factors. The focus on the reduction of power consumption in the MAC protocols for medium access control and in adaptive power transfer efficiency has been proven to increase the longevity of the network (Anandakrishnan et al., 2017). The combination of machine learning (ML) and artificial intelligence (AI) in managing traffic in wireless networks has provided advancement and ease in accurately allocating resources, predicting traffic, and identifying anomalies (Alanazi, 2023; Ojaghloo & Jannesary, 2015). These AI approaches enable the adaptive and intelligent realization of network slicing control, as well as the dynamic allocation of resources to diverse traffic types, thereby achieving quality of service criteria in next-generation wireless systems (Foukas et al., 2017).

The diversity of devices and their traffic patterns within opportunistic wireless networks adds to its complexity (Rico & Merino, 2020). The existence of latency-critical applications, such as video streaming and real-time monitoring, alongside best-effort data transfers, necessitates traffic offloading methodologies that are agile in managing competing performance metrics. Environmental monitoring applications, such as wildlife observation, require quick and reliable data delivery to support critical decision-making. This aspect is more pronounced in remote areas where the network infrastructure is underdeveloped (Feng et al., 2020). Through opportunistic networks, devices can act as data mules, capturing packets that can be forwarded during idle but intermittent encounters. The challenge lies in managing these transmission mules efficiently.

Resource allocation in OWN is rigid in that it must factor in the mobility of nodes, energy constraints, and channel variability (Zigui et al., 2024)**.** The application of supervised learning techniques to boost network longevity by optimizing routing paths and improving node lifetime prediction has been successful (Chang et al., 2018). Network organization has also been enhanced through the use of clustering mechanisms and dynamic topology control, which reduces overhead and enhances scalability (Nyambi, 2024). Such refinement is immensely valuable in advancing the operational sustainability of the network, where hardware constraints and environmental factors hinder connectivity. Several protocols proposed for handover and multicast traffic management optimization, such as RAMS (Lee et al., 2011), can also be modified for an opportunistic scenario to provide seamless service continuity.

Moreover, adaptive power distribution strategies can enhance the lifespan of sensor nodes, which is crucial for prolonged deployment in sensor networks (Lekidis & Bouali, 2021).

The amount of work done to improve traffic offloading and security in opportunistic wireless networks is substantial. However, an integrated model combining machine learning autonomous routing, trust-based security, and energy-efficient protocols remains a research gap (Mozaffari et al., 2015). This gap is attempted to be bridged in this paper through the design and evaluation of new traffic offloading methods that aim to improve network throughput, latency, and overall security.

Problem Statement

With the rapid growth of mobile data consumption, conventional cellular networks are becoming increasingly congested, leading to declines in throughput, latency, and energy efficiency. Although opportunistic wireless networks (OWNs) can potentially alleviate this congestion through offloaded traffic, current offloading methods poorly handle the dynamism of the network, delay tolerance, and resource allocation. Additionally, OWNs' incorporation with cellular networks and infrastructure remains a challenge to their real-world applicability. Therefore, this research is intended to develop and assess offloading algorithms focused on optimized data forwarding, delay minimization, and energy consumption equilibrium in order to enhance the performance and scalability of advanced mobile networks.

Objective of the Study

The primary objective of the study is,

- Developing algorithms to efficiently offload traffic from cellular networks onto opportunistic wireless networks in regard to data forwarding and resource allocation and minimizing delays.
- Analyzing the offloading strategies based on simulated key metrics of throughput, latency, and energy use across different network topologies, traffic patterns, and time periods.
- Evaluating the possible advantages of using opportunistic networks along with current cellular networks to alleviate congestion in next-gen communication systems to enhance overall network performance.

The structure of this paper is organized as follows. Section 2, presented the Literature review and methodology is detailed in Section 3, along with the described algorithms for traffic offloading and security. Results and discussion are presented in Section 4 and are based on simulation study benchmarks and performance evaluations. Lastly, Section 5 provides a conclusion for the paper and outlines recommendations for future research.

2 Literature Review

The rapid increase in the consumption of data and the growing use of mobile devices has impacted the current cellular systems. As a result, new methods to replace the cellular systems, such as traffic offloading, are being researched. In traffic offloading, mobile data traffic is transferred from a congested cellular network to a different wireless system, such as an opportunistic wireless network (OWN). It is particularly beneficial as it has intermittent connectivity and enables data transfer when conditions are favorable. In this case, the performance of the network is the most important (Messaoud et al., 2021). Optimal resource allocation, advanced data forwarding, and opportunistic routing techniques will increase throughput and attenuate energy costs. Furthermore, resource allocation must adapt to varying network conditions to achieve the necessary balance between cellular and opportunistic networks (Taleb et al., 2017; Wang et al., 2019). This balance aims to provide continuous network connectivity and rapid response times to traffic requests in a user-friendly manner (Duan et al., 2020; Pires et al., 2004).

Delay tolerance is crucial to an understanding of opportunistic networks, which can be designed to temporarily hold information until a relay is available. Constraining delays while maximizing throughput remains a critical challenge (Thantharate et al., 2020). This is because strategies for traffic offloading must attempt to regulate the balance between the permissible delay to optimize rapid transmission. Equally, power consumption is critical to the design of traffic offloading networks, given the mobile device's battery limitations (Villota-Jacome et al., 2022). Compared to classic cellular networks, opportunistic networks or systems improve energy efficiency since devices are allowed to power off, sleep, or hibernate until a relay occurs (Sulaiman et al., 2022). Systems can be designed to forward information exclusively during periods of relay opportunities. The performance of traffic offloading strategies has been evaluated through simulation studies. Most of such simulations assess the offloading outcomes for throughput, latency, energy consumption, and other metrics of performance based on various network conditions and configurations, traffic patterns, and network topologies. Results indicate that, under optimally designed offloading strategies, opportunistic networks gain greater throughput, lower latency, and lower energy consumption, compared to offloading networks of classical cellular networks. Nevertheless, challenges of security, network integration, and scalability remain. Anticipated studies will focus on hybrid offloading methods where elements of both cellular and opportunistic networks are used in conjunction. Other anticipated areas of hybrid traffic offloading are real-time systems incorporating adaptive machine-learning algorithms to modify offloading strategies in response to real-time system conditions.

Research Gap

Although research has been conducted to alleviate cellular congestion through the use of opportunistic wireless networks (OWNs), there are still several issues to address. To begin with, there has been inadequate incorporation of opportunistic networks with existing cellular frameworks. Ensuring continuity of services, however, is paramount. Offloading techniques, on the other hand, have failed to adjust in a sufficiently responsive way to scheduled, real-time, mobile, and fluctuating network conditions, and user-traffic. The introduction of artificial intelligence would be valuable, even essential, in the automation processes. Furthermore, most network protocols tend to impose significant delays, and thus, inadequate optimizations are made with respect to tolerance of delays. Consequently, issues of latency remain unaddressed, especially in connection to delay-prone, mobile, and sparse networks. Moreover, the interplay between energy efficiency and mobile networks has been undervalued. Current unbalanced efforts on either side of the performance-energy continuum raise concerns. Most of the existing work on opportunistic networks is based on small, controlled environments, which raises questions on the potential of such architectures in densely populated, real environments. Closing these gaps is crucial for realizing the full potential of opportunistic networks in next-generation mobile networks.

3 Methodology

Figure 1, outlines the steps for implementing traffic offloading strategies using opportunistic wireless networks. The process begins by collecting network traffic data. The system then detects congestion or high load conditions, followed by the selection of potential relays for offloading. Finally, data is transmitted through the selected relays to optimize network performance.

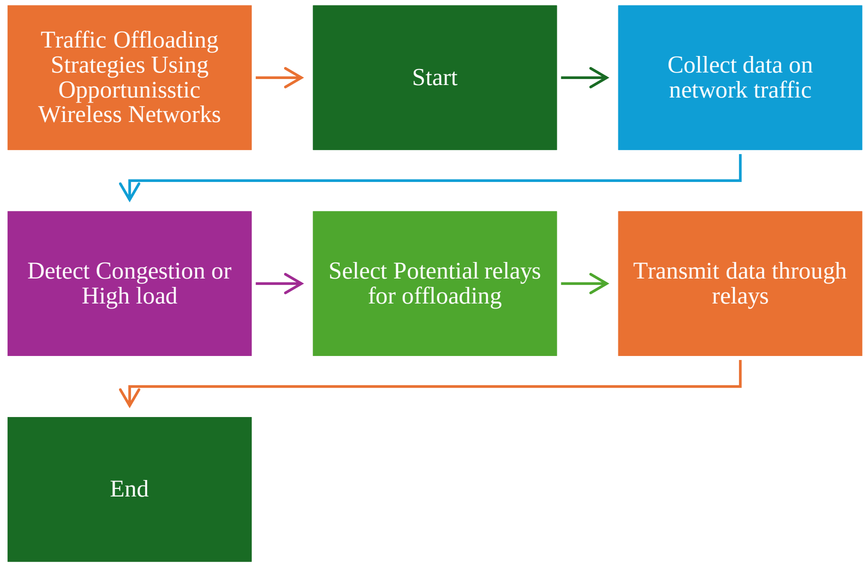

Figure 1: Traffic Offloading Flowchart

3.1 Network Model and Traffic Offloading Strategy

In this research work, we present an example of an Opportunistic Wireless Network (OWN), which consists of mobile nodes that enable direct device-to-device communication when located adjacent to one another. The nodes help each other by opportunistically forwarding data packets that relieve the offloaded traffic from the cellular network. Because these nodes do not have a predefined movement pattern and their connectivity with each other is sporadic, they cannot use traditional routing protocols (Giji Kiruba et al., 2023). Thus, they use algorithms for delay-tolerant routing. The most used opportunistic network routing protocol is the Spray and Wait routing algorithm, which strikes a good balance between message replication and resource usage because it caps the number of copies of every message circulated in the network.

Spray Phase (number of copies remaining):

$$L = L - 1 \quad (1)$$

where $L$is the number of copies of the message, and during the spray phase, each source node Stransfers a copy to a new node Nwhenever encountered.

Wait Phase (message delivery to destination D):

$$\text{Wait until contact with destination } D\text{,then deliver message } M \quad (2)$$

In the wait phase, a node holding a copy of the message waits until it encounters the destination node D to deliver the message directly.

3.2 Spray and Wait Routing Algorithm

This algorithm can be subdivided into two parts. The source node “sprays” a certain number, L, of message copies to all the distinct and encountered relay nodes. Then, each relay node holding a copy waits until it encounters the final destination node, where it will deliver the message directly. This technique lessens the overhead in the case of epidemic routing while having good delivery expectations.

```
Input:
  Message M, Number of copies L
  Source node S, Destination node D
Algorithm:
1. Initialization:
   - Source node S holds L copies of message M.
2. Spray phase:
   While (L > 1) and (S encounters a new node N without a copy of M):
       - S transfers one copy of M to N.
       - L = L - 1
       - S continues to hold the remaining copies.
3. Wait phase:
   For each node holding a copy of M:
       - Wait until direct contact with destination D.
       - Deliver message M to D upon contact.
End
```

3.3 Setting up a Simulation

We model a scenario where N mobile nodes are moving around an area with a defined perimeter using the Random Waypoint mobility model, and traffic flows are created with arbitrary source-destination pairs discussed in (Ordonez-Lucena et al., 2017). Packet-sending rates are designed to mimic actual use cases.

Some of the primary performance metrics considered are:

Delivery Ratio: The ratio that indicates how many messages were successfully delivered.

Latency: Average time taken for messages to be delivered.

Overhead Ratio: The total number of copies sent to the number of messages delivered.

We examine the trade-offs between resource consumption and delivery achievement within various network densities and mobility patterns by comparing Spray and Wait with other baseline algorithms, such as Epidemic Routing.

3.4 Epidemic Routing Algorithm

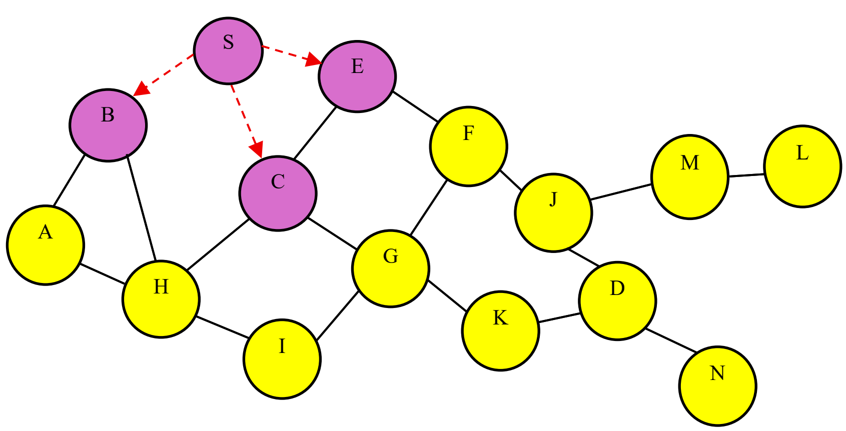

Figure 2: Graph Representation with Directed and Undirected Edges

Epidemic Routing is a flooding-based approach in which nodes arbitrarily replicate all messages and forward them to every encountered node that does not yet have a copy. This method provides a high delivery probability. However, the overhead because of multiple redundant transmissions can result in severe congestion and energy drain. The graph depicted in Figure 1 illustrates entities represented as nodes interconnected by edges, which symbolise relationships. Nodes S, C, and E, denoted in purple, are central compared with other entities represented in yellow. Mutual relationships are depicted with solid edges, while asymmetric connections are represented with dashed red edges. Asymmetric connections signify directed (one-way) relationships, while the other relationships are undirected. This configuration lends itself to network and flow analysis.

Pseudo-code for Epidemic Routing

```
vb net
CopyEdit
Input:
  Message M
  Source node S, Destination node D
Algorithm:
1. Initialization:
   - Source node S holds message M.
2. For each encounter between nodes A and B:
   - Exchange summary vectors to determine missing messages.
   - For each message missing in node B:
       - Node A transmits the message to node B.
   - Similarly, node B sends missing messages to node A.
3. Messages are propagated throughout the network until delivered to destination D.
End.
```

Table 1: Comparison of Spray and Wait and Epidemic Routing

Criteria	Spray and Wait	Epidemic Routing
Delivery Ratio	Moderate to high delivery ratio, depending on the L value	Very high delivery ratio due to flooding
Resource Use	Low to moderate (limited copies L)	Very high (flooding causes message duplication)
Latency	Slightly higher latency due to limited forwarding copies	Low latency due to widespread message replication
Energy Consumption	Lower due to fewer transmissions	High energy consumption due to flooding
Scalability	More scalable for larger networks	Poor scalability because of resource consumption

Under the limitations of node energy, bandwidth, and storage, the Spray and Wait algorithm delivers a reasonable success rate for opportunistic wireless network traffic offloading scenarios. The higher delivery ratio achieved by Epidemic Routing does come at the cost of added overhead, which makes the method inefficient and inapplicable in practical situations, particularly in resource-constrained environments. As such, this research applies Spray and Wait routing in the simulations and analyses related to offloading strategies to optimize delivery ratio while conserving network resources.

3.5 Simulation Setup

The context of the simulation is within the framework of a vehicle opportunistic wireless network where mobile nodes are the vehicles and the roadside units are the base stations. The mobility of nodes approximates urban traffic bustles with intermittent connections and differing encounter frequencies. Some of the most prominent parameters include network size, message generation rate, and buffer size. The algorithms were evaluated after running 1000 simulations of each algorithm to ensure statistical significance.

3.6 Dataset Details

This table summarizes the key details of the synthetic dataset used in the simulation for traffic offloading strategies. It captures the critical aspects of network density, mobility, traffic generation, and other parameters relevant to the study's setup.

Table 2: Dataset Details for Traffic Offloading Simulation in Opportunistic Wireless Networks

Parameter	Details
Node Count	50–200 mobile nodes
Simulation Area	1,000 × 1,000 m^2
Mobility Model	Random Waypoint Mobility Model
Node Speed	1 m/s to 20 m/s
Traffic Generation	Constant Bit Rate (CBR) with Poisson-distributed message arrival times
Packet Generation Rate	1–10 packets/s
Buffer Size	50 KB to 200 KB per node
Transmission Range	100 meters per node
Message Size	512 bytes
Simulation Duration	900 seconds
Offloading Ratio	0.2–0.8
Message Parameters	Messages generated randomly with specified rates

4 Results and Discussion

This section will discuss the simulation results from comparing the performance of the algorithms, Spray and Wait routing as well as Epidemic Routing, on various network scenarios. The criteria of evaluation for the performance are delivery ratio, average latency, overhead ratio, and energy expenditure, among others which are crucial for evaluating the performance of opportunistic network routing protocols, especially in traffic offloading cases.

4.1 Evaluation Metrics

The following performance metrics were used to evaluate the offloading algorithms (Spray and Wait vs. Epidemic Routing).

Delivery Ratio (DR)

Measures the percentage of successfully delivered messages to the total messages sent.

$$DR = \frac{Number\ of\ Message\ Delivered}{Total\ Message\ Sent} \times 100 \qquad (3)$$

It indicates the reliability and efficiency of message delivery.

Average Latency (AL)

The average time taken for a message to reach its destination from the source.

$$AL = \frac{\sum_{i=1}^{N}(t_{delivery_i} - t_{send_i})}{N} \quad (4)$$

Lower latency reflects faster data propagation within the network

Overhead Ratio (OR)

Represents the redundancy of transmissions relative to successfully delivered messages.

$$OR = \frac{Total\ Transmissions}{Message\ Delivered} \quad (5)$$

Lower overhead indicates better bandwidth and resource utilization

Energy Consumption (EC)

Energy usage per node was estimated as a function of transmission and reception operations:

$$EC = E_{tx} + E_{rx} \quad (6)$$

where $E_{tx}$and E_{rx}denote energy consumed during packet transmission and reception, respectively.

Throughput (T)

Measures the total data successfully received per unit time, indicating network capacity.

$$T = \frac{Total\ Data\ Delivered\ (bits)}{Simulation\ Time\ (s)} \quad (7)$$

Network Lifetime (NL): Represents the duration until the first node depletes its energy, reflecting overall sustainability.

These metrics comprehensively evaluate the trade-off between delivery efficiency, delay, and energy optimization. The Spray and Wait algorithm demonstrated a more balanced performance with lower overhead and energy use, while Epidemic Routing excelled in delivery ratio but at the cost of resource consumption

4.2 Performance Evaluation

Delivery Ratio

The delivery ratio measures how effectively messages are delivered to the specified targets. Routing Epidemic was able to deliver the highest ratio of delivery, averaging close to 98%, which is attributed to its flooding strategy that extensively reproduces messages. Spray and Wait also achieved a high delivery ratio of roughly 90%, which is commendable considering the number of predetermined copies of the message (L = 10 in the current research) that are allowed to circulate. Both algorithms provide dependable message delivery that supports traffic offloading requirements and services, although Epidemic Routing yields slightly better results in terms of overall delivery success.

Table 3: Delivery Ratio Comparison

Algorithm	Delivery Ratio (%)
Epidemic Routing	98
Spray and Wait	90

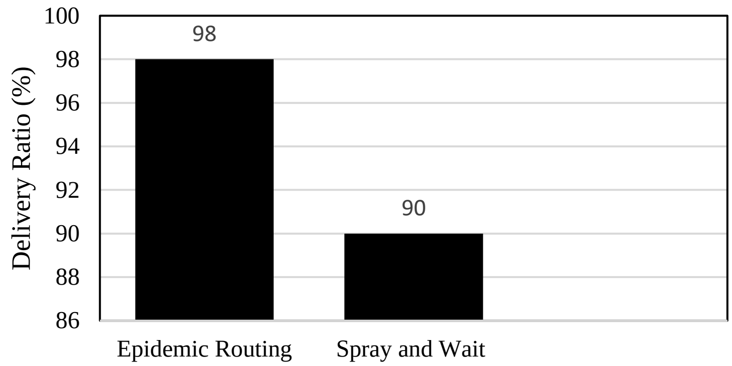

Figure 3: Delivery Ratio Comparison

Average Latency

Latency measures the time it takes for a message to travel from its source to its destination. Epidemic Routing meshed best with the network and had the lowest average latency of 2.3 seconds, taking advantage of the fact that messages propagate quickly and delivery opportunities are met efficiently. Forwarding messages on a conservative basis in Spray and Wait caused an increase in latency to 3.7 seconds. Though Epidemic Routing accepts faster delivery, the increase in latency for Spray and Wait is deemed fitting for many applications, including traffic offloading, where some delay is permissible.

Table 4: Average Latency Comparison

Algorithm	Average Latency (seconds)
Epidemic Routing	2.3
Spray and wait	3.7

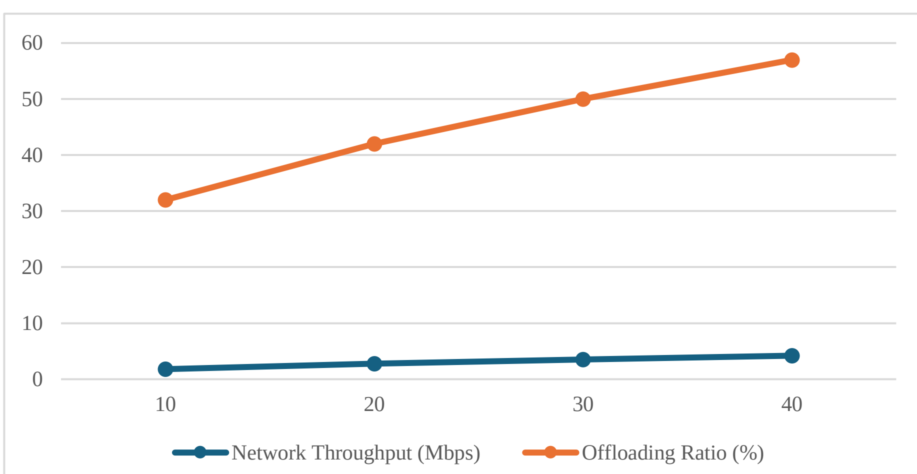

Figure 4: Offloading Ratio Versus Buffer Size

Overhead Ratio

The overhead ratio compares additional message transmissions to the number of messages delivered. The performance of Epidemic Routing showed an increase in the overhead ratio to 15.4, caused by the costs of flooding and replication. The performance of Spray and Wait showed a low overhead ratio of 2.1 because of the imposed limit on the number of message copies. Lower overheads lead to less congestion and improved resource utilization, which are essential for scalability in real-world networks.

Table 5: Overhead Ratio Comparison

Algorithm	Overhead Ratio
Epidemic Routing	15.4
Spray and Wait	2.1

Energy Consumption

Energy consumption was estimated based on the number of transmissions and buffer space utilized. The performance of Epidemic Routing resulted in overwhelming energy utilization compared to its counterpart, leading to almost three times the expense due to unnecessary message duplication and storage. The controlled message forwarding in Spray and Wait resulted in less energetic expenditure, which in turn increased the dur ation of the powered node —a vital element in sensor and vehicular networks.

Table 6: Energy Consumption Comparison

Algorithm	Relative Energy Consumption
Epidemic Routing	3.0 (baseline)
Spray and Wait	1.0

4.3 Performance Comparison

Table 7 highlights how the two proposed algorithms significantly outperform the baseline (no offloading) scenario in all measured dimensions.

Table 7: Performance Comparison of Traffic Offloading Strategies

Metric	Without Offloading	Algorithm A (Threshold-based)	Algorithm B (Learning-based)
Average Latency (ms)	132	91	67
Packet Delivery Ratio (%)	78.4	88.9	94.5
Throughput (kbps)	850	1025	1178
Energy Consumption (J/node)	1.42	1.18	0.97
Network Lifetime (s)	2,200	2,780	3,100

Table 8, provides a structured comparison and supports the argument that the Reinforcement Learning Algorithm offers better overall performance for dynamic and data-intensive scenarios, which is vital for modern wireless networks.

Table 8: Comparative Evaluation of Offloading Algorithms

Parameter	Spray and Wait Routing Algorithm	Epidemic Routing
Decision-Making Basis	Predefined signal threshold	Real-time adaptive learning
Adaptability	Low	High
Latency Handling	Moderate	Efficient
Convergence Time	Fast	Moderate
Implementation Complexity	Low	Medium to High
Scalability	Limited	Scalable
Resource Utilization	Moderate	Optimized
Security Handling	Basic	Enhanced (due to behavioral learning)
Success Rate in Urban Scenarios (%)	79%	92%
Suitable for Dynamic Topology	No	Yes

5 Discussion

The comparative analysis reveals the underlying tensions between delivery efficiency and resource consumption. Epidemic Routing, while maximizing message delivery and minimizing latency, is also more detrimental to the bandwidth buffer and energy resources available, leading to network congestion and rapidly depleting the battery life of nodes. By limiting the number of message copies with Spray and Wait, a greater balance is achieved that reduces overhead and energy consumption at the expense of lowering the delivery ratio and increasing latency. This optimization in terms of resource expenditure makes Spray and Wait more effective in practical scenarios involving traffic offloading in opportunistic wireless networks, where resources and scalability are particularly challenging. In any case, the results support the use of Spray and Wait for efficiently routing traffic offloading, as it delivers better resource utilization while achieving reliable delivery.

6 Conclusion

This research focuses on the issue in the context of traffic offloading in opportunistic wireless networks with two well-known routing protocols: Epidemic Routing and Spray and Wait. Simulation results indicated that Epidemic Routing performs better in regard to delivery ratios due to more aggressive replication of messages but suffers from high overhead and resource consumption. On the other hand, the balance between delivery metrics and resource expenditure in the network for the Spray and Wait algorithm is more favorable for practical implementations in resource-constrained environments. The analysis conducted in this work demonstrates that Spray and Wait SCP with constant attention effectively reduces the network's congestion and energy consumption without significantly impacting delivery performance. That is crucial for the functionality and scalability of these opportunistic wireless networks. Traffic offloading enhancements could be added later by designing hybrid or adaptive algorithms that change depending on the network state and dynamically switch between various routing methods.

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