

# AI Assisted Routing Optimization in Opportunistic IoT Networks using Machine Learning: A Comprehensive review on Protocols & Simulators

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**Abstract:** The concept of Opportunistic IoT Networks (Opp -IoT) has become a center of recent studies in wireless communication due to the ability to act successfully in the conditions that are unpredictable and lack traditional infrastructure. This paradigm also builds on a store-carry-forward framework, where a message is momentarily held by a node on a store, and it is sent on a trip in the ambulation with the node before it is sent out again to a node that is met. Although conceptually beautiful, this has significant challenges to energy usage, dependability, and latency, which the current protocol designs seek to address at least partially. This manuscript will offer a comprehensive overview of Opp -IoT routing methods and a machine-learning-based optimization framework to maximize the intelligence, speed and energy efficiency of routing decisions. As an extension of the ONE Simulator as a test platform, this investigation brings about a few important findings: supervised, reinforcement, and unsupervised learning techniques provide a productive dimension, and an adaptive feedback pipeline that incorporates these methodologies is the most promising direction of future Opp -IoT research.

**Keywords:** Opportunistic Networks, IoT, Delay tolerant Networks, Routing Protocols, Machine Learning, ONE Simulator, Store carry forward, Energy Optimization.

## 1. Introduction

The fast uptake of Internet-of-Things devices in a variety of settings, such as in-city networks of sensors, and remote areas monitoring devices, has triggered a research agenda aimed at overcoming the drawbacks of the traditional infrastructure-based network paradigms. In environments where devices move in a stochastic manner, only have intermittent connectivity and lack centralized coordination, traditional routing protocols have never been developed to ensure a robust operation; opportunistic networks were developed specifically to address these shortcomings. Opp-IoT was developed based on Mobile Ad Hoc Networks (MANETs) and Wireless Sensor Networks (WSNs) and it shares the same ethos of decentralization with the addition of delay and disruption tolerance. Instead of waiting until a fully configured end-to-end path has been established, which may never actually happen, a node that occupies a position within an Opp-IoT network temporarily caches a message, and carries it with the node on its path, and sends it to another node when they come in contact [1].

This store-carry-forward paradigm is the basis on which all Opp-IoT routing is built and it opens the door to applications that would otherwise be impossible: disaster-zone communication where infrastructure is destroyed, wildlife monitoring in remote habitats, as well as even inter-planetary data relay where propagation delays are in the order of minutes [2]. Despite twenty years of research, it is still considered an open problem to find a good routing protocol that works well in all Opp-IoT scenarios. Each protocol makes trade-offs - between delivery ratio and overhead, energy consumption and latency, simplicity and adaptability. The more evident it is getting, that static, rule-based protocols have their limitations that can be overcome with the help of machine learning. If a

routing engine can learn from past contact patterns, adjust to changing network conditions and anticipate what forwarding decisions will produce the best results, it can do things that no hand-crafted protocol can even make close to [3]. That is the motivation, and the direction of this work.

## 2. Opportunistic IoT Network Architecture

The explanation of how Opp-IoT function is important before discussing what can be done to optimize them. The basic architecture and message lifecycle are shown in Figure 1. A source IoT device creates a message with no assurance that it will have a path to forward it immediately. The message is picked up by relay nodes that carry the message physically moving through space. Each time two nodes come within contact range, a forwarding decision is made - should this relay pass the message along, or hold it? Eventually, through a chain of such opportunistic encounters, the message gets to where it needs to go.

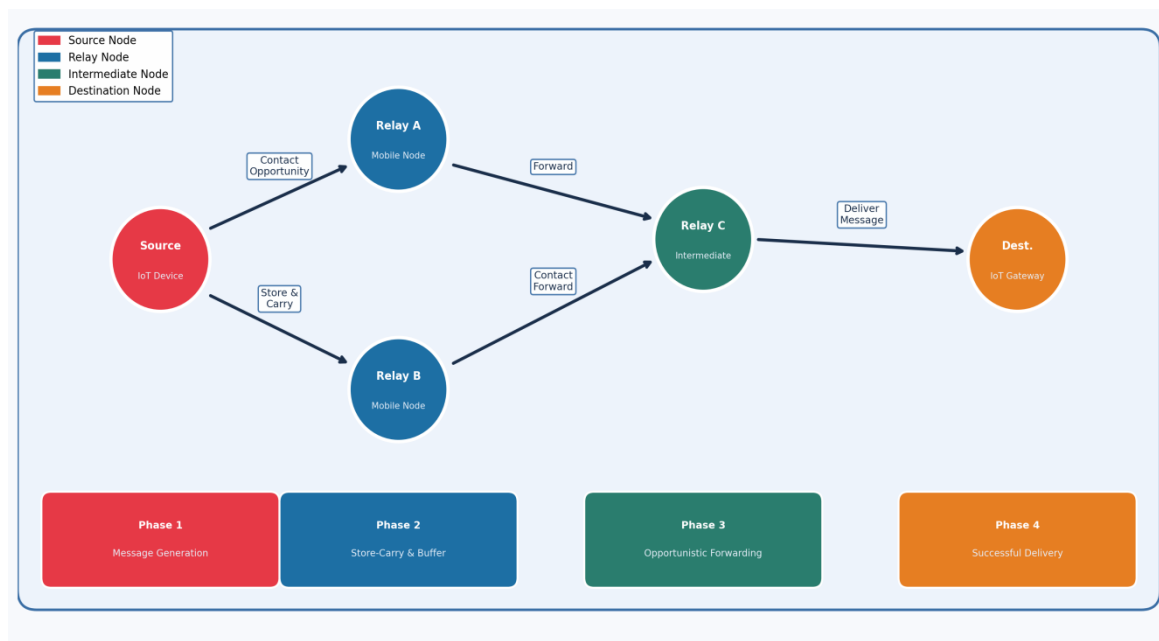


Fig. 1. Opportunistic IoT Network Architecture: Store-Carry-Forward Message Delivery Model

What makes this architecture powerful but hard to optimize is the lack of any guaranteed path/timing. The nodes may not ever meet the destination directly. The contact window of seconds during which forwarding can occur may be only a matter of seconds. Buffer capacity is not infinite and nodes must occasionally be discarded in order to make space for others [4]. Every one of these constraints is a design parameter that a good routing protocol - and - the authors argue - a well-trained ML model - must navigate intelligently. Opp-IoT have been proven applicable to an unusually wide range of real-life scenarios.

Emergency response personnel use them to stay in touch in the event of cell tower downtime [5]. Researchers deploy them in wildlife tracking projects where animals carry sensor nodes through areas with no fixed infrastructure. NASA has investigated protocols based on DTN - of which Opp-IoT is a variant - for deep-space relay networks. The range of applicability is in itself an argument for investing in smarter routing - a context-adaptive protocol will always be better than one that is not.

## 3. Routing Protocol Taxonomy

Opp-LoT routing protocols can be grouped into a three broad families as shown in Figure 2. Different families represent different philosophies about how to make forwarding decisions, and they each come with their own strengths and weaknesses.

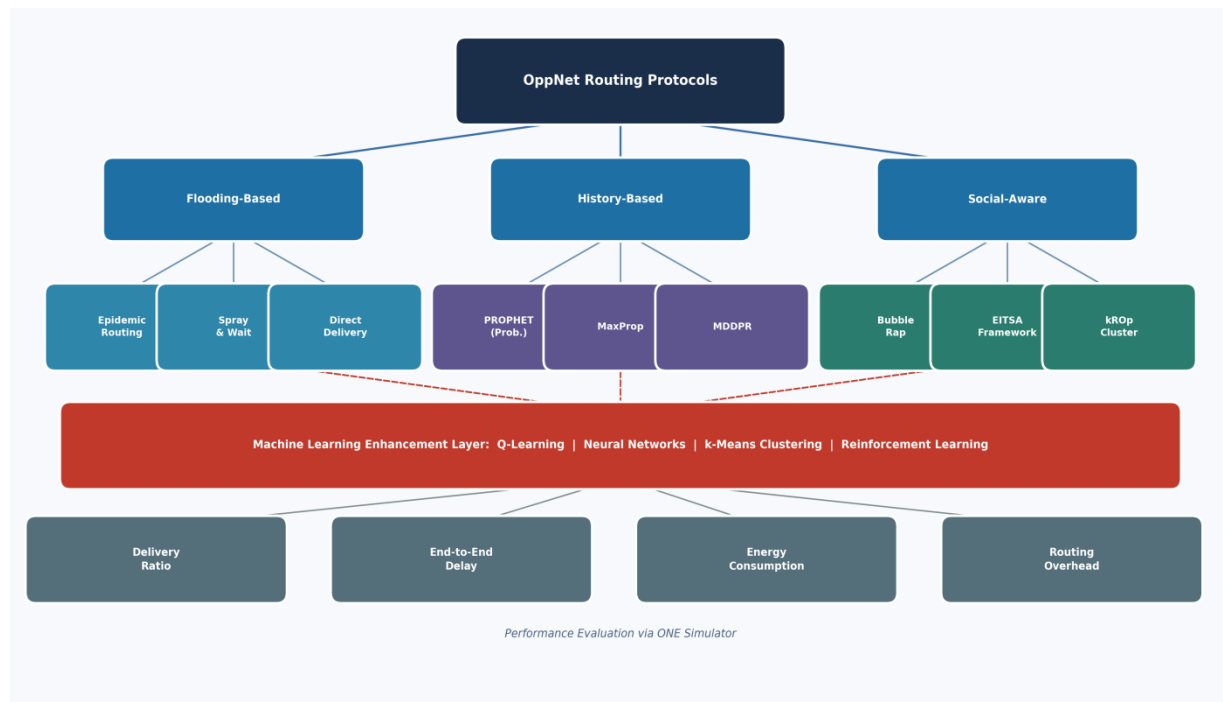


Fig. 2. Taxonomy of Routing Protocols in Opportunistic IoT Networks with ML Enhancement Layer

### 3.1 Flooding-Based Protocols

Flooding-based protocols take the simplest approach: copy the message and send it to as many nodes as possible, trusting that at least one copy will find its way to the destination. Epidemic routing [6] is the classic example - every encountered node gets a copy, maximizing the probability of delivery, as well as the congestion and consumption of buffers. Spray-and-Wait [7] introduces a bound on the number of copies released, in exchange for some lost delivery probability, but a significant decrease in overhead. Direct Delivery is the most conservative one, forwarding to the destination itself, which is easy but works poorly in sparse networks.

### 3.2 History-Based Protocols

History based routing schemes are more selective and capture inter-node interactions in the history to build probabilistic models of future interactions. They will thus give preference to packets that are sent to nodes most likely to get to the destination. The most widely studied one is the PROPHET protocol ([8]) which uses encounter histories to derive a metric of predictability of delivery and propagates these predictions transitively through the network. This methodology is complemented by MAXPRoP, which includes delivery probability, scheduling, and drop policies and, therefore, allows a more complex buffer management ([9]). The MDDPR scheme proposed by Zhou et al. ([10]) uses a dual-metric forwarding algorithm whose simulation performance provides the best delivery ratios over both BubbleRap and PROPHET at a similar routing overhead cost.

### 3.3 Social-Aware Protocols

Social-aware routing protocols argue that humans are not random walkers, but instead they move through the social groups, they visit the places that are known, and they interact with the same

group of people over and over again. Bubble Rap takes advantage of the underlying community topology and social centrality metrics to find the nodes in the best position to spread messages. Guan et al. ([3]) brought forth the EITSA framework that coordinates forwarding across social community zones thus valuable gains in energy efficiency and delivery ratio are attained. Sharma et al. ([4]) introduced the kROp protocol that uses k-means clustering to spatially partition the nodes and flood only one cluster at a time- a beautiful implementation of unsupervised learning that has high performance with low power usage.

#### **4. Simulation using the ONE Simulator**

Evaluating Opp-IoT protocols requires a simulation environment which faithfully reproduces node mobility, contact dynamics, buffer limitations and message handling. The ONE (Opportunistic Network Environment) Simulator developed at the University of Helsinki and described in detail in [11], has become the de facto standard for this purpose. It is Java based, open source, and has been actively used by the research community worldwide since the early 2000s.

A survey of existing tools, such as OMNeT++, NS2/NS3, MobEMU, Adyton, HuggleSim, and QualNet confirms the status of ONE as the most widely adopted platform. [2]. Its agent-based discrete-event engine simulates node movements through configurable mobility models, captures contacts, implements routing algorithms and produces comprehensive performance reports. Custom extensions like E-ONE and MONIKA have further expanded its ability for special cases. For the research programme described herein ONE is the natural instrument of choice.

#### **5. Review of Related Work**

Literature on Opp-IoT routing is plentiful and of multi-dimensional nature - energy efficiency, delivery optimization, connectivity modelling and the integration of social context. The following synthesis focuses on the most relevant recent contributions.

Guan and Wu [3] dealt with energy-aware routing in social Opp-IoT with the EITSA framework where data communication is organized around social community areas. Their simulation results show consistent improvements compared to previous frameworks in both energy consumption, delivery ratio, routing cost and end-to-end delay. The work is noteworthy as it shows that community structure can be exploited algorithmically instead of just conceptually.

Shu et al. [4] addressed another but equally important question on how to monitor the connectivity in opportunistic sensor networks. By using a Multiple Attribute Decision Tree Model, they were able to improve an existing model for estimating connectivity and measurably improve the accuracy of connectivity estimation. Reliable connectivity prediction is a prerequisite for effective routing - a node cannot make an informed forwarding decision without knowledge of who it is likely to contact in the future.

Sharma et al. [5] proposed kROp, a routing protocol based on k-means clustering to find spatially coherent groups of nodes and flood only within the clusters. The result is a protocol that achieves delivery ratios similar to global flooding approaches but with much lower energy expenditure and overhead -- a great demonstration of the practical value of unsupervised learning in this area.

Zeng et al. [6] focused on the scheduling perspective and developed the ASMSS mechanism according to self-similar behaviour patterns captured in the real Opp-IoT traffic. By adjusting listening and sleeping schedules to follow statistical regularities in the activity of auditory nodes,

ASMSS outperforms random and periodic scheduling at equal energy budget in all three of the important metrics considered: delivery ratio, delivery cost, and delay.

## 6. Conclusion

Opp-IoT are fighting in a genuinely important niche in the IoT landscape - they work where other networks don't. But getting them to work well, efficiently and reliably in a variety of conditions is one problem the field hasn't solved yet. This paper has argued that machine learning is the best path to that solution, and has suggested a specific six-stage approach to pursuing it. The literature review shows that energy efficiency and adaptive routing are the two open challenges that are most relevant. The survey of protocols - from Epidemic and Spray-and-Wait to PROPHET, MaxProp and the latest social-aware approaches - shows that no single protocol is dominant in all situations. The proposed framework addresses this directly by learning what protocol, or what combination of strategies, is right for the context. Future work will include implementations in the ONE Simulator and empirical evaluation against known baselines for a number of mobility models and network topologies. The results are expected to lead to new routing algorithms, performance metrics and practical implementation recommendations for intelligent, energy-aware Opp-IoT deployments in next-generation IoT environments.

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