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# Data Fusion and the Impact of Group Mobility on Load Distribution on MRHOF and OF0

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***Abstract*: *Many routing algorithms proposed for IoT are based on modifications on RPL objective functions and trickle algorithms. However, there is a lack of an in-depth study to examine the impact of mobility on routing protocols based on MRHOF and OF0 algorithms. This paper examines the impact of group mobility on these algorithms, also examines their ability in distributing the load and the impact of varying traffic with the aid of simulations using the well-known Cooja simulator. The two algorithms exhibit similar performance for various metrics for low traffic rates and low mobility speed. However, when the traffic rate becomes relatively high, OF0 performance merits appear, in terms of throughput, packet load deviation, power deviation, and CPU power deviation. The mobility with higher speeds helps MRHOF to enhance its throughput and load deviation. The mobility allowed MRHOF to demonstrate better packets load deviation.*

***Keywords*: *IoT, MRHOF, OF0, load distribution.*

## 1. Introduction

IoT can be thought of as a massive number of interconnected devices. Alternatively, we can look at it as a collection of connected systems consisting of networked devices that exchange data to provide services for users' applications. Due to its potential valuable applications, IoT gained attraction from researchers in the past few years; these applications include healthcare, medical services, smart homes, intelligent transportation, and smart cities [1, 2]. However, in IoT systems, many devices are constrained in terms of power and radio links. Also, their topology may frequently change [3]. Of course, these devices should have a communication interface and be connected to a communication infrastructure such as the Internet to be managed remotely. They could also interact by exchanging information or triggering actions in communication known as Machine-to-Machine (M2M) interaction [4]. The number of connected devices over the Internet is growing exponentially, and it is expected to reach 75 billion devices by 2025 [5, 6]. This is driven by the fact that our everyday devices such as lights, fans, kitchen appliances, TVs, and many others are becoming connected to control systems connected to the Internet.

IoT nodes usually have limited resources, including limited energy, CPU power, and memory [7]. Its dynamic and lossy nature usually comes from various factors, including channel fading, mobility, and channel interference, making it characterized as Low-power Lossy Networks (LLNs). The communication between devices may require a multi-hop path, which requires employing a routing protocol to establish the path between the communicating devices. However, this is not an easy task considering the dynamic network topology and lossy channels, especially with low-power devices, in addition to the security threats that routing protocols may suffer from. Therefore, an efficient routing protocol must be capable of dealing with such constrained nodes and should be reliable, energy-efficient, and handle various networking scenarios.

The development of efficient routing protocols for IoT has ranged from deriving variations of protocols originally made for MANETs and VANETs, including [8, 9], or the design of new protocols designated for IoT such as RPL [10]. RPL is considered an experimental standard for IoT, and it utilizes the Objective Function in selecting the best parent nodes to construct paths. Routes are built according to a parent selection process made by the Objective Function. The interesting design of RPL allows employing different metrics implemented within the Objective Function in the process of parent selection. This flexibility allowed researchers to perform easy modifications on this component in addition to its significant impact on the routing efficiency. Many routing protocols have been proposed to tackle this issue [11-15]. However, there is a demand to investigate the performance of these protocols [16-19].

In the course of studying the performance of the routing algorithm objective functions, different studies have attempted to study their performance [20-24]. However, with the advance in IoT applications development and their potential mobility requirements, there is a need to study the impact of mobility on the performance of routing algorithms. Lamaazi, Benamar and Jara [24] have studied the impact of different mobility models, including random waypoint and reference group mobility models, for only one of the objective functions. The evaluation measured control traffic overhead, expected transmissions, hop count, lost packets, and Energy. However, the network size has been too small of 10 and 20 nodes. In addition, there has been a lack of clarity on the network area of operation, mobility parameters, traffic rate, and communication pattern. Furthermore, the study has not considered the impact of load distribution. Qasem et al. [25] investigate the performance of MRHOF and OF0 in random and grid topology scenarios. The evaluation has measured the packet delivery ratio and power consumption. However, their study has studied only the behavior of RPL for static network scenarios.

Some studies have considered sink mobility such as in [26, 27]. Wadhaj et al. [26] have considered the scenarios when the sink node is static or mobile. The results have shown that the static sink scenarios outperform the mobile scenarios. Saad and Tourancheau [27] have investigated sink mobility to enhance the performance of RPL by attempting to increase the leaf nodes' lifetime. This is conducted by making the sink move towards the leaf nodes. Although the experiments have shown an increase in network lifetime, this behavior can be affected by the network structure, and therefore the results might be restricted to specific scenarios.

Sanshi and Jaidhar [28] consider nodes' mobility using Random Walk, Gauss-Markov, and Random Waypoint mobility models. However, they have not considered full network mobility; they have considered only half of the mobility of the nodes. They measure power consumption, packet delivery ratio, and latency. However, there has been a lack of clarity about the traffic communication settings such as communication pattern and traffic rate.

Enhancing the operation of RPL has the focus of many studies [29, 30] which are considered slight adjustments to its operation. However, to develop a comprehensive enhancement that considers the limitations of IoT in terms of throughput and load distribution a thorough evaluation of the protocol is needed. RPL remains the most important protocol to be studied and enhanced as it is the experimental standard for IoT. So, the focus of the evaluation is to examine two crucial algorithms, namely MRHOF and OF0, as these two algorithms have been the center of development for enhancing the operation of routing under the limited resources in the IoT environment. In this paper we extend the work in [31] to thoroughly investigate the performance of these counterparts in terms of their efficiency and load distribution under a variety of working scenarios, including the impact of mobility scenarios.

This paper studies the performance of these counterparts under the impact of the group mobility model and the impact of varying traffic with the aid of simulations using the well-known Cooja simulator [32]. This has been examined using various performance metrics, including power consumption, CPU power consumption, throughput, power deviation, CPU power deviation, and packets load deviation. Power deviation is vital to measure the network ability to stay in operation for a longer time. It is important to measure the routing algorithm's ability to distribute the load. The distribution of power consumption would extend the nodes and network lifetime. CPU power deviation estimates the routing algorithm's ability to distribute its computational load among the participating nodes, which affects the power consumption. Packets load deviation is used to estimate the routing algorithm's ability to distribute the traffic load.

The rest of this paper is structured as follows. Section 2 introduces routing algorithms presented in the literature. Section 3 provides an overview of RPL and describes the operation of MRHOF and OF0. The subsequent Section 4 illustrates the reference point group mobility model. Section 5 explains the simulation environment, the performance metrics and presents the evaluation results. Finally, Section 6 concludes the work.

## 2. Literature review

Based on the operation of the routing protocols for LLNs and how they keep updated routes, they can be classified mainly into reactive and proactive. Another way to categorize routing protocols is based on their utilization of location information known as geographic routing. Many reactive protocols proposed for LLNs have been developed as modifications on well-known MANET routing protocols, this includes LOAD(ng) [8] and TinyAODV [9], which are enhancements over AODV routing protocol [33] to provide the routing support for LLNs. Proactive routing protocols such as ZigBee cluster-tree [34] and Collection Tree Protocol (CTP) [35] intend to keep up-to-date routes all the time. Other protocols try to combine the two approaches forming a hybrid approach such as Hydro [36]. On the other hand, geographic routing utilizes location knowledge in building routes, Beacon Vector Routing (BVR) [37] is an example of this category.

LOADng [8] supports different communication patterns, including point-to-multipoint and point-to-point. However, it is important to note that the routing overhead for point-to-multipoint communication pattern is considered high. This comes from the large amount of needed route discovery packets to support this communication pattern. TinyAODV and NST-AODV [9] are other derivatives of AODV. The reason for naming it so is because it has been implemented in the MICAz's TinyOS to utilize link failure detection mechanism. Like AODV, route reply messages are only generated by the destination node. However, it is important to note that TinyAODV targets static networks but local repairs are not supported. The latest release supports both point-to-multipoint and point-to-point communication.

BVR [37] is an example of geographical routing protocols. The geographic approach is greedy by nature, so to deliver packets, a node selects, as its next hop, the closest node to the required destination. Although geographic routing might look scalable, it does not consider the lossy nature of wireless links in selecting the next node to the destination. Also, some geographic routing protocols may require periodic exchange of neighboring nodes' information for up to two hops [38], which indeed would affect the network constrained resources.

CTP [39] is a proactive protocol designed for data collection communication pattern, which is a multipoint-to-point pattern. This kind of communication is very common for application communication patterns in LLNs. CTP is a tree-based protocol; it utilizes what is commonly known as the ETX as a metric in the selection decision of the next hop along the path to the destination. It uses data and control packets in estimating the wireless link cost (link lossy rates). Based on the lowest accumulated ETX value, the next hop is selected. However, it suffers from routing loops and packet duplications [35].

The main efforts in proposing a routing algorithm have been based on enhancing the objective function operation in RPL, which utilizes metrics composition in the objective function. These compositions are categorized into fuzzy, additive, lexical, and hybrid composition [40]. In the fuzzy composition, the fuzzy logic is employed to calculate the parents' ranks. The additive composition [41] is based on adding the participating nodes' metrics weighted values to form one value, with which the parent selection is made. In lexical composition [42], the parent selection is based on the first metric; however, if parents are equal, the second metric is used to select one. In the hybrid approach [40, 43], a combination of previous categories combines participating metrics.

In [44], a fuzzy logic reasoning is used to estimate neighbors quality using various routing metrics, including delay, ETX, and energy. The implementation has been in two stages: stage for computing Quality of Service (QoS) considering ETX and delay metrics, followed by another stage to combine energy into computing neighbors' quality. However, this may result in additional computation overhead. Also, based on fuzzy logic, OFFL is another solution presented in [45]. It combines link and node metrics, including hop count, battery level, end-to-end delay, and ETX, to produce a single metric that defines the neighbors quality. Also, OFEC [46] utilizes fuzzy logic, it uses ETX and hop count metrics, but energy consumption has been utilized in a different way to be the energy consumed in transmission and reception and energy consumption in low and full power mode. CMOF [47] also applied fuzzy logic. It combines latency and ETX to optimize packet delivery and delay based on using good connectivity paths with lower traffic. The latency is estimated by summing time spent by packets in the transmission queue and the channel access time based on CSMA channel access under heavy traffic, and fuzzy logic is then applied. However, the threshold values used have not appropriately justified, making their accuracy arguable.

EAOF [42] is an example of the lexical approach. It integrates ETX with nodes' residual energy. The node selects a subset of neighboring nodes with the lowest ranks based on ETX. Among these nodes, the one with the maximum residual energy is chosen as the preferred parent. The ETX implementation used is based on MRHOF ETX. The evaluation has shown improved network lifetime with a slight degradation in packet reception ratio since EAOF might consider lower quality paths to reduce energy consumption.

Based on the additive approach, C h a n g et al. [41] propose a weighted energy-oriented metric that utilizes residual energy and ETX to tackle the energy consumption distribution over nodes. Their study is based on that depending only on ETX could result in excessive use of good-quality paths, which might affect the network lifetime. QU-RPL [48] is another example of this approach; it distributes the traffic load within the routing tree by employing the queue utilization factor and a threshold to reflect network congestion. The queue utilization factor is combined with both ETX and hop count to calculate the nodes' rank to select the best parent. However, this requires high interaction between the link and routing layers. IRPL [49] utilizes a metric named LCI index for the purpose of enhancing path selection based on the transmission life cycle. The purpose of this index is to improve the rank calculation method by including the node's successful link transmission cost. It computes various aspects, including data throughput, average transmission rate, and node energy. However, including all these aspects may result in additional overhead. CAOF [50] employs ETX and buffer occupancy in building paths. It relies on ETX in the event of low traffic, but if links appear to be congested, it relies only on buffer occupancy in the selection process.

SCAOF [43] is a technique based on the hybrid approach; it combines various metrics to select paths that avoid low power nodes. The combination includes ETX, remaining energy, availability, number of restarts, and affordable workload. According to its evaluation, it could increase network lifetime, enhance QoS and reduce network churn in agriculture applications. However, exchanging a high number of metrics may be affected by packet errors or loss, which is common in lossy networks. Nonetheless, the conducted evaluation h limited. Another example in [40], the technique attempts to avoid selfish or malicious nodes; it combines the hop count and packet forwarding indication to build shorter paths. It utilizes the residual energy and hop count for load distribution. However, the impact of this combination has not been studied thoroughly, in addition to the lack of clarity on the usage of residual energy metric.

It is worth noting that combining metrics may serve certain performance goals depending on the targeted network application. However, we should be aware of keeping the number of involved metrics at a minimum; otherwise, the complexity would increase. In addition, the more metrics to combine, the larger the size of the DIO messages, which may increase the fragmentations risk and routing errors [51]. Furthermore, in the case of additive composition, the process becomes very complicated as we increase the number of metrics involved, and as so assigning weights for these metrics gets more complex. Hence, the way we combine metrics is crucial for the success of the enhancement being developed. Table 1 illustrates and summarizes the differences between the studies mentioned above in terms of composition type, node metrics, link metrics, and provides some feedback on these proposed solutions.

Table 1. Comparative of Routing Algorithms based on objective function enhancements

| Algorithm | Node metrics | Link metrics | Composition type | Drawback |
|---|---|---|---|---|
| OFFL [45] | Hop count and Battery life | ETX Delay | Fuzzy | Composition complexity. Paths with poor quality might be selected |
| Fuzzy [44] | Energy | ETX Delay | Fuzzy | Composition complexity |
| OFEC [46] | Hop count and Energy consumption | ETX | Fuzzy | Composition complexity. |
| CMOF [47] | Latency | ETX | Fuzzy | Threshold values are not appropriately justified, which makes their accuracy arguable |
| EAOF [42] | Residual energy | ETX | Lexical | Paths with poor quality might be selected |
| QU-RPL [48] | Hop count and Queue utilization | ETX | Additive | Composition complexity |
| CAOF [50] | Buffer occupancy | ETX | Additive | Paths with poor quality might be selected |
| IRPL [49] | Node energy, Data throughput and Data transmission rate | ETX | Additive | Composition complexity |
| Chang et al. [41] | Remaining energy | ETX | Additive | In the attempts to handle load balancing, poor-quality paths might be selected |
| Karkazis et al. [40] | Hop count and packet forwarding indication Hop count and residual energy | ETX | Additive and Lexical | In the attempts to handle malicious nodes and load balancing, paths with poor quality might be selected |
| SCAOF [43] | Remaining energy, availability, number of restarts, and affordable workload | ETX | Additive and Lexical | Composition complexity and communication overhead. Paths with poor quality might be selected |

It is worth noting that there are other enhancements on OFs based on multipath routing, including LB-RPL [52], M-RPL [53], CA-RPL [54], OMC-RPL [55]. These protocols target load distribution through using multipath routing. Although these protocols might help in load distribution, there is high complexity associated with selecting these multipaths, especially that this process may depend on the composition and exchange of various metrics. Not to mention the probability of packet loss and errors, which would indeed create additional overhead that needs to be avoided at any cost [51]. In addition, it is not enough to distribute traffic load, but also ensure network stability [48]. Some studies also focus on load balancing either using multipath routing or through using multiple gateways to distribute the traffic load to more than one sink [56]. Others have investigated traffic distribution using single gateway [57-59].

## 3. RPL overview

RPL is a routing protocol designed by the IETF ROLL working group for LLNs on top of IPv6 [10]. The routing protocol is optimized for the multipoint-to-point traffic, the main communication pattern in LLNs, by creating a Destination-Oriented Directed Acyclic Graph (DODAG). It also supports point-to-multipoint and peer-to-peer communication patterns.

The operation of RPL uses a group of ICMPv6 messages to exchange the required information to build the DODAG, including:

- DODAG Information Solicitation (DIS)
- DODAG Information Object (DIO)
- Destination Advertisement Object (DAO)

To solicit a DIO message, a DIS message is sent by any node in order from neighboring nodes, usually when it joins a stable network. The DIO messages are transmitted from senders to the sink node, while DAO messages are used to build routes from the sink node to other nodes and build routes between nodes.

RPL uses the trickle algorithmic component to control the transmission of data traffic. Various studies have investigated the optimization and enhancement of this component. It has been implemented in RPL to regulate the transmission of routing traffic by controlling DIO broadcasts. It also controls the sending and listening of nodes, and by randomly selecting the transmission time in half of an interval, it tackles the short-listen problem [60].

### 3.1. Objective functions

The objective function determines the path cost calculation, parents' selection, rank computation, and how to broadcast the path cost. It also defines how a node converts one or more metrics into a rank value [61]. Among a group of candidate nodes, the node with the minor rank is selected as the parent and so on, and since the rank corresponds to the position of nodes in the DODAG, the rank should be decreasing for nodes along the path towards the root node.

The operation of the objective function depends on the routing metrics, which are interpreted into a rank value. Nodes use this value to select the best parents to build the DODAG. The node with the minor rank is chosen as the best parent. These metrics can be categorized into node metrics and link metrics. Node metrics may include power consumption, hop count metrics, etc. Link metric is related to link cost estimation such as latency, throughput, and Expected Transmission Count (ETX). There are two standardized objective functions, namely, the Minimum Rank with Hysteresis Objective Function (MRHOF) [61, 62] and the Objective Function Zero (OF0) [63].

### 3.2. Objective Function Zero (OF0)

OF0 is designed to choose the nearest node based on its rank to the DODAG root as the best or preferred parent. However, it keeps another parent as a backup in case the connectivity with the best parent is lost. The *rank* is calculated for a given node using equations (1) and (2), where $R_n$ represents the rank for node *n*, *rank_increase* is a positive scalar value, $R_\mathrm{p}$ represents parent rank, $S_\mathrm{p}$ is the *step-of-rank* which is a value associated with the parent link metric such as the hop-count, and two normalization factors $R_\mathrm{f}$ and $S_\mathrm{r}$ representing represents *rank factor* and *stretch of rank*, in addition to MHRI which is a constant number representing the *Minimum Hop Rank Increase*. The settings of these parameters can be found in detail in [63]:

(1) $$R_n = R_\mathrm{p} + \text{rank\_increase},$$

(2) $$\text{rank\_increase} = \left(R_\mathrm{f} \times S_\mathrm{p} + S_\mathrm{r}\right) \times \text{MHRI}.$$

### 3.3. Minimum Rank with Hysteresis Objective Function (MRHOF)

MRHOF is designed to reduce the frequent excessive change of preferred parent, known as churn in the network topology. The node evaluates the path cost through candidate parents by adding up to two components; the value of the candidate parent and the value advertised in the *metric container* of the selected metric. After that, the parent associated with the lowest path cost is selected as the preferred parent. However, unlike in OF0, with MRHOF, if a new minimum path is found that has a smaller path cost than the preferred parent path, it will change to this new path. The complete description of MRHOF operation can be found in detail in [61, 62].

## 4. Reference point group mobility model

Reference Point Group Mobility Model (RPGM) [64, 65] is a well-known mobility model that simulates group behavior for nodes mobility. For each group, there is a group leader, where other nodes move freely around it, considering the group leader as their reference point to establish their mobility. Hence, they would likely be following the group leader. However, it is important to know that each node has its movement direction and speed, but this movement is derived from the group leader's direction and speed. The group mobility models play a crucial role in simulating real-life scenarios such as search and rescue crews, army-based vehicles' movement, playing teams, etc.

The group leader movements can be defined using a speed vector *S*. Group members follow the group leader mobility with some deviation degree. The group leader movements utilize the random waypoint model [66]. The deviation distance obeys a uniform distribution with interval (0, $m$] where $m$ is the maximum allowable deviation distance from the group leader, with uniformly distributed direction. The movement characteristics of group members are defined in the next equations:

$$S_i^t = S_l^t + \text{rand}() \times \text{SDR} \times \max S, \quad (3)$$

$$D_i^t = D_l^t + \text{rand}() \times \text{ADR} \times A. \quad (4)$$

The deviation from the group leader is represented in two parameters: Speed Deviation Ratio (SDR) and Angle Deviation Ratio (ADR). Both have a value between 0 and 1 to make the group member speed and direction associated with the group leader. Where $S_i^t$ represents the speed vector at time $t$ of group member $i$, $S_l^t$ represents the speed vector at time $t$ for group leader $l$, max$S$ represents the maximum speed, $D_i^t$ represents group member $i$ direction vector at time $t$, $D_l^t$ represents the direction vector at time $t$ for the group leader $l$, and $A$ represents the angle.

# 5. Performance evaluation

## 5.1. Simulation model

The simulation experiments have been conducted with the well-known COOJA simulator Contiki 3.0 [32], which is the most recent release of the simulator. This simulator is a recognized simulation tool that has been extensively used in IoT research [67]. Both OF0 and MRHOF are implemented and validated within Contiki 3.0 code. Various node types are supported within the simulator, including Skymotes designed for IoTs. The network topology scenario can be set manually, randomly, or with the aid of a scenario file, that has the nodes' distribution and their movement during the simulation time over the simulation area. The Bonnmotion tool [65] has been used to create group mobility scenarios. The scenarios can be characterized by: mobility model, simulation time, simulation area, the number of nodes, and average node speed. The node's movement and distribution followed the RPGM mobility model. Since the collective communication mode is the leading traffic pattern for this kind of networks, the generated traffic follow this mode. The traffic rates and mobility speed have been varied to conduct a thorough performance investigation.

## 5.2. Simulation parameters

The performance analysis is conducted by simulating a network of 50 nodes scattered across a 250×150 m area for 500 s of simulated time. These settings simulate real-world scenarios involving motes in open terrains, such as on a playing field, or search and rescue operations in a limited region, where communication between nodes is required to collect information inside a certain area. Although the number of nodes or the simulation period might be increased, but this is done to keep the processing time manageable. Both OF0 and MRHOF have been challenged under identical environmental conditions and identical traffic loads to enable a direct and fair comparison between them.

The RPGM mobility model is used to mimic node mobility, with each group of nodes arranging their motions based on the movement of the group leader. Each group consists of three nodes. Group members travel to a maximum distance of 50 m from the group leader's location, while the group leader moves to a randomly determined point inside the simulation area. The nodes' speed is set randomly, where the mean speed has been varied between 1, 5, 10, 15, and 20 m/s. Nodes average moving speed ranges from normal walking speed to regular vehicle speed limit. The traffic rate has been set to 1 packet/interval, where the interval has been varied between 1, 5, 10, 15, 30, and 60 s. Simulation parameters are illustrated in Table 2. A 95% confidence interval has been ensured for the results; however, the error bars are not shown in the figures for the sake of clarity.

Table 2. The simulated experiments parameters.

| Parameter | Values |
|---|---|
| Number of nodes | 50 |
| MAC layer | IEEE 802.15 |
| Simulation area | 250×150 m |
| Simulation time | 500 s |
| Mobility model | RPGM |
| Distance deviation | 50 m |
| Average speed | 1, 5 ,10, 15, 20 m/s. |
| Pause time | 0 s |
| Packet size | 30 bytes |
| Packet interval | 1, 3, 5, 10, 15, 30, 60 s |

### 5.3. Performance metrics

The evaluation of OF0 and MRHOF has been conducted through various potential scenarios. The performance measures include throughput, power consumption, CPU consumption, CPU power deviation, power deviation, and packets' load deviation.

- *Throughput* is the amount of successfully received data in bytes during the simulation time.
- *Power Consumption* is the average of power used by all nodes in the network. It includes all types of power consumption, including CPU power, Low Power Mode (LPM), radio transmission, and radio listening. The LPM represents the sleep mode power consumption.
- *CPU Power Consumption* is the average power consumption resulting from nodal processing used by all nodes in the network; it includes processing packets, calculating metrics, etc.
- *Packets Load Deviation* (*PLD*) is the deviation of successfully forwarded packets toward the desired destinations. Nodes may vary in their participation in packet forwarding to their destination. The ideal scenario is that all nodes have equal participation in network traffic. Therefore, PLD is used to estimate the routing algorithm's ability to distribute the traffic load. PLD is calculated using the equation

(5) $$\text{PLD} = \frac{1}{m} \times \sum_{i}^{m} |l_i - \mu|,$$

where $l_i$ is the amount of successfully forwarded packets by node $i$, $\mu$ is the average of these packets, and $m$ is the number of participated forwarding nodes.

- *Power Deviation* (*PD*) is the deviation of power used by the participated forwarding nodes in the network. This is important to measure the ability of the network to survive for a longer time by measuring the ability of the routing algorithm in distributing the load. Distributing power consumption would extend the nodes and network lifetime. PD is calculated using the equation

(6) $$\text{PD} = \frac{1}{m} \times \sum_i^m |P_i - \mu|,$$

where $P_i$ is the amount of power consumption by node $i$, $\mu$ is the average of these consumptions, and $m$ is the number of participated forwarding nodes.

- *CPU Power Deviation* (*CPD*): is the deviation of CPU power consumption used by the participating forwarding nodes in the network. This is an important measure since it estimates the routing algorithm's ability to distribute its computational load among the participating nodes, which affects the power consumption. CPD is calculated using the equation

(7) $$\text{CPD} = \frac{1}{m} \times \sum_i^m |\text{CP}_i - \mu|,$$

where $\text{CP}_i$ is the amount of CPU power consumption by node $i$, $\mu$ is the average of these consumptions, and $m$ is the number of participated forwarding nodes.

### 5.4. Impact of varying traffic

The impact of varying traffic rates has been examined using an average speed of 1m/s. The traffic rate is varied by traffic intervals of 1, 3, 5, 10, 15, 30 and 60 s, with an interval of 1 second corresponding to the heavy traffic rate of 1 packet per 1 s, while traffic interval of 60 s corresponds to very lightweight traffic of 1 packet every 60 s. Fig. 1 shows the throughput achieved by both OF0 and MRHOF. As the figure illustrates, both techniques achieve close behavior for medium and light traffic, which is considered normal considering the low amount of traffic injected into the network. However, OF0 clearly outperforms MRHOF by up to 37% for heavy traffic rates.

Fig. 2 shows the CPU power consumption used by OF0 and MRHOF. As the figure depicts, OF0 exhibits lower consumption with a difference of up to 34%. The difference becomes lower as the traffic rate gets lower. However, it is worth noting that both exhibit relative values for traffic interval of 1 second, but we should bear in mind that OF0 is delivering much more data than MRHOF, so it is normal to consume more power. Similar behavior is depicted for power consumption in Fig. 3.

Packets load distribution is intended to see the ability to distribute traffic load over participating nodes in the network. Fig. 4 clearly shows that OF0 outperforms MRHOF for different traffic rates with a difference that reaches 67%, except for lower traffic rates where the latter shows comparable performance, which is considered normal since the network is not experiencing a large amount of traffic. On the other hand, when considering CPU power deviation and power deviation in Figs 5 and 6, OF0 is a clear winner with a difference that reaches 75% and 79%, respectively. It is important to note that with the relatively heavy traffic, MRHOF could not deliver most of the traffic on the contrary of OF0, which managed to deliver 50% of the traffic for the first traffic interval. MRHOF managed to deliver comparable traffic compared to OF0 after 3rd traffic interval. This explains spike in CPU power deviation and power deviation associated with MRHOF. This measure is different from Packets Load Deviation since it considers all types of traffic, including control messages exchanged to build paths to the destination.

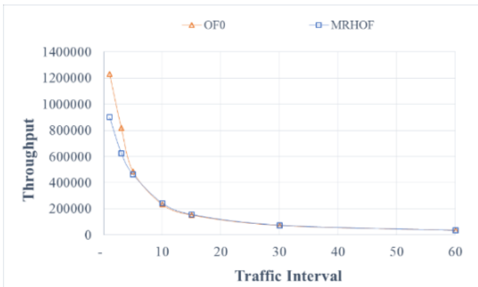


Fig. 1. Throughput with varied traffic intervals

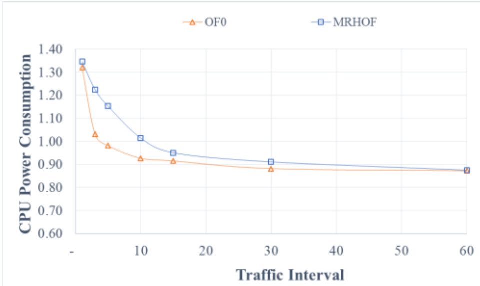


Fig. 2. CPU power consumption with varied traffic intervals

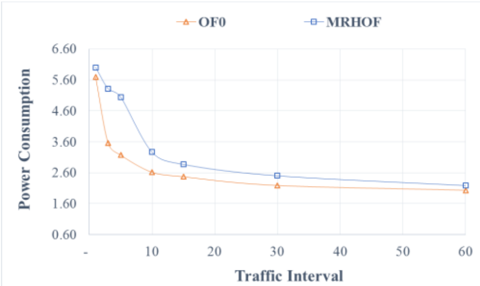


Fig. 3. Power consumption with varied traffic intervals

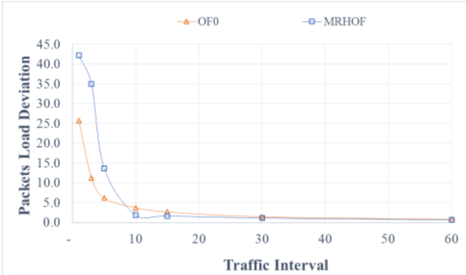


Fig. 4. Packets Load Deviation of OF0 and MRHOF with varied traffic intervals

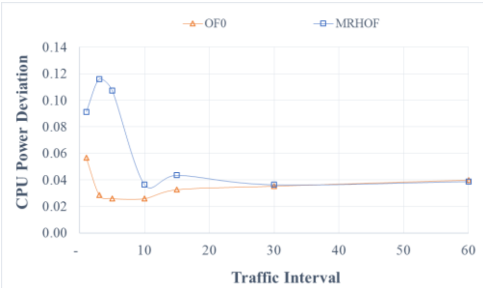


Fig. 5. CPU Power Deviation with varied traffic intervals.

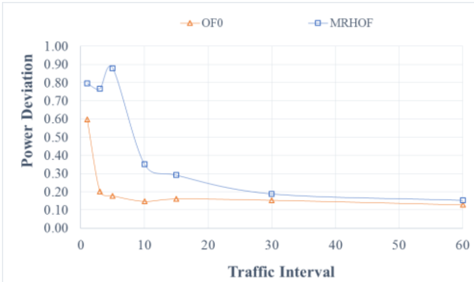


Fig. 6. Power Deviation of OF0 and MRHOF with varied traffic intervals5.5 Impact of varying speeds

The impact of varying mobility speed is studied using average speeds of 1, 5, 10, 15 and 20 m/s. The traffic rate is set to 1 packet per 1 s, corresponding to a relatively heavy traffic rate. Fig. 7 shows the throughput achieved by OF0 and MRHOF. OF0 exhibits clearly better performance for low mobility speed. However, as with the increase in mobility speed, OF0 and MRHOF show close throughput. The mobility with higher speeds helps MRHOF to enhance its throughput.

On the other hand, when considering the CPU power consumption metric, as mobility speed increases beyond 10 m/s, it results in an increase in OF0 CPU power consumption, which makes MRHOF and OF0 perform closely, as shown in Fig. 8. Similar behavior is depicted for the power consumption metric in Fig. 9. This behavior can be explained since mobility forces more frequent updates on the used paths and hence enhance the performance of MRHOF.

The impact of increasing the mobility speed has also been clear on the performance of MRHOF in terms of packets load deviation; as Fig. 10 shows; OF0 outperforms MRHOF for a speed of 1 m/s. However, as the speed increases, MRHOF achieves lower packet load deviation, although both exhibit close throughput. This behavior can be explained since mobility forces a more frequent update on the used paths and hence more load distribution. In terms of CPU power deviation and power deviation, it is clear that OF0 outperforms MRHOF for low mobility speed, as depicted in Figs 11 and 12. However, as the mobility speed increase, they demonstrate close performance. Nonetheless, this would be considered an advantage for MRHOF since it managed to achieve relatively low CPU load deviation, considering its CPU power consumption.

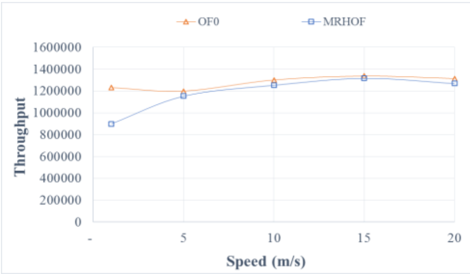


Fig. 7. Throughput with varied speeds

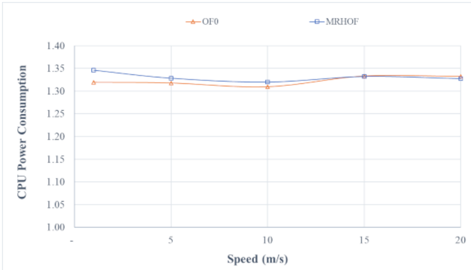


Fig. 8. CPU power consumption with varied speeds

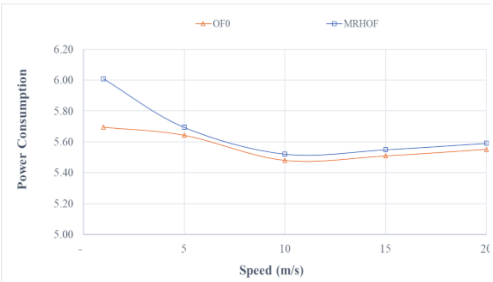


Fig. 9. Power consumption with varied speeds

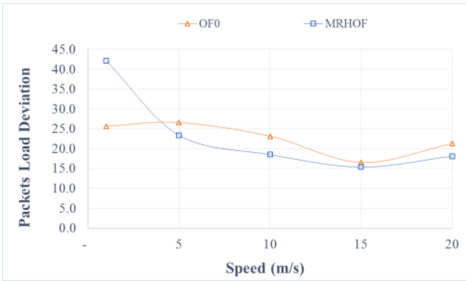


Fig. 10. Packets Load Deviation with varied speeds

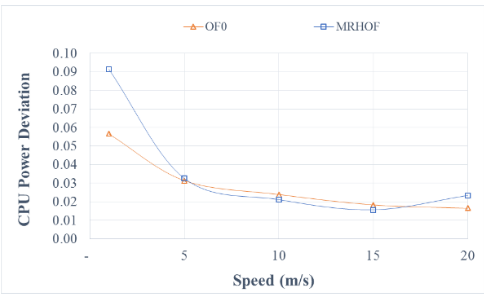


Fig. 11. CPU Power Deviation with varied speeds

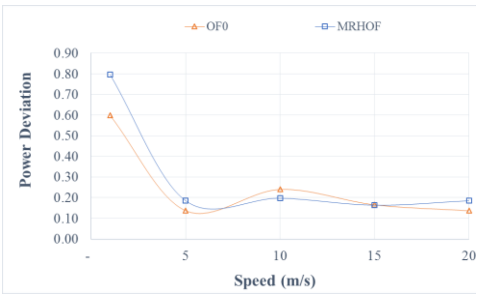


Fig. 12. Power Deviation with varied speeds

## 6. Conclusion and future work

This study has thoroughly investigated the impact of mobility on the performance of two important algorithms, namely MRHOF and OF0, which have been the center of development for enhancing the operation of routing under the limited resources in IoT environment. The study has targeted on their abilities in terms of load distribution and their efficiency in delivering data traffic. It has also investigated the impact of the group mobility model with varied mobility speeds and varied traffic conditions. In addition, the impact of varying the number of sinks has been investigated in static and mobility conditions. For the purpose of investigating their load distribution abilities, new metrics have been derived, including packets load deviation, power deviation, and CPU power deviation. For low traffic rates and low mobility speed, the two algorithms exhibit similar performance for various metrics. However, when the traffic rate becomes relatively high, OF0 performance merits appear, with a throughput that can reach up to 37% better than MRHOF, and also in terms of packet load deviation, power deviation, and CPU power deviation with a difference that can reach 67%, 75%, and 79%, respectively.

The mobility with higher speeds helps MRHOF to deliver more data and hence achieve higher throughput, making them achieve similar performance levels. Also, as mobility speed increases beyond 10m/s, this results in an increase in OF0 CPU power consumption, which makes MRHOF and OF0 exhibit close performance. Furthermore, mobility with higher speeds allows MRHOF to demonstrate better packets load deviation. This behavior can be explained since mobility forces more frequent updates on the used paths and hence more load distribution.

As part of future work, existing load distribution algorithms suffer from high complexity in their operation. Based on this study, one of the directions that we have started working on is deriving a load distribution algorithm, which is likely to be feasible when using an OF0 based algorithm enhancement since it has lower consumption of network resources.

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