IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

SPECIAL SECTION ON MOBILE EDGE COMPUTING AND MOBILE CLOUD COMPUTING: ADDRESSING HETEROGENEITY AND ENERGY ISSUES OF COMPUTE AND NETWORK RESOURCES

Received July 15, 2019, accepted July 28, 2019, date of publication August 2, 2019, date of current version August 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2932718

Improving the Performance of LOADng Routing Protocol in Mobile IoT Scenarios

JOSÉ V. V. SOBRAL[1,2], JOEL JOSÉ P. C. RODRIGUES[1,3,5,6], (Senior Member, IEEE), RICARDO A. L. RABÊLO[4], KASHIF SALEEM[5], AND SERGEI A. KOZLOV[6]

[1]Instituto de Telecomunicações, Universidade da Beira Interior, 6201-001 Covilhã, Portugal
[2]Department of Education, Federal Institute of Maranhão (IFMA), São Luís 65010-030, Brazil
[3]PPGEE, Federal University of Piauí (UFPI), Teresina 64049-550, Brazil
[4]PPGCC, Federal University of Piauí (UFPI), Teresina 64049-550, Brazil
[5]Center of Excellence in Information Assurance (CoEIA), King Saud University, Riyadh 11653, Saudi Arabia
[6]International Institute of Photonics and Optoinformatics, ITMO University, 197101 St. Petersburg, Russia

Corresponding authors: Joel José P. C. Rodrigues (joeljr@ieee.org) and Kashif Saleem (ksaleem@ksu.edu.sa)

This work was supported in part by the Brazilian National Council for Research and Development (CNPq) under Grant 201155/2015-0 and Grant 309335/2017-5, in part by the National Funding from the FCT—*Fundação para a Ciência e a Tecnologia* under Project UID/EEA/50008/2019, in part by the Government of the Russian Federation under Grant 08-08, and in part by the Deanship of Scientific Research at King Saud University through the Research Group under Grant RG-1439-022.

ABSTRACT Routing protocols represent an important issue on the Internet of Things (IoT) scenarios since they are responsible for creating paths and forwarding data packets among the network nodes. In mobile IoT scenarios, the topology changes caused by the movement of nodes makes the work of routing protocols more difficult. Thus, the current IoT routing solutions tend to present strong limitations and a poor performance in these scenarios, generally requiring complex additional improvement to better support the mobility of the devices. In this context, the Lightweight On-demand Ad hoc Distance-vector Routing Protocol – Next Generation (LOADng), is an emerging solution for IoT networks that despite being adequate for a mobile environment due to its reactive functioning still lacks in performance. Thus, this paper proposes a novel solution to enhance the performance of LOADng in mobile IoT networks. The improved version, LOADng-IoT-Mob, introduces a mechanism that permits nodes to be aware of the availability of their neighbors through the harnessing of control messages. As a result, these nodes can shorten paths and avoid sending data packets through broken routes due to the movement of the nodes. Additionally, a short periodical control message is introduced, allowing the nodes to update their routing table, even with a low control message frequency. Furthermore, a new routing metric is proposed for creating routes based on the reliability of the link and proximity of the neighboring nodes. Finally, through computational simulations, the performance of the LOADng-IoT-Mob is studied under multiple scenarios varying the network size, the number of mobile devices, and maximum nodes' speed. The results obtained demonstrate the efficiency of the proposed solution in terms of packet delivery ratio, latency, and power and overhead efficiency, with a slight increase in memory consumption.

INDEX TERMS Internet of Things, LOADng, low power and lossy networks, routing protocol, wireless network.

I. INTRODUCTION

In recent years, Internet of Things (IoT) has grabbed the attention of both the scientific community and business sector for its great potential and research and business opportunities [1], [2]. From a simple smart temperature control system [3] all the way to a city entirely operating on smart technology [4], [5], IoT covers a vast range of applications. However, along with the opportunities of IoT emerge the technical challenges of the existing technological limitations. From these, it is possible to detach the issues related to the networks that interconnect IoT devices.

In general, IoT devices are miniaturized and suffer from severe limitations of hardware (processing and memory) and energy. In a broad set of IoT environments, network devices can have mobility capacity, which makes hardest the network functioning [6]. Thus, due to these characteristics, IoT networks are categorized as Low power and Lossy

The associate editor coordinating the review of this manuscript and approving it for publication was Raja Wasim Ahmad.

Networks (LLNs). In an IoT context, routing protocols are responsible for providing routes and forwarding data packet among the connected devices [7]. Thus, regarding the characteristics of LLNs, routing protocols need to be simple to fit and perform efficiently in any IoT device with the lowest computational cost possible. In addition to device level performance, routing protocols should be able to self-adapt to the typological changes caused by the mobility of IoT devices.

The IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [8], although considered as the standard routing protocol for IoT networks [9], does not efficiently support mobility because it has been particularly designed for static networks [10]. In addition, it has limitations regarding multicast data forwarding [11], [12], memory usage [13], [14], and point-to-point traffic pattern [9], [15]. Thus, as an alternative to RPL, the Lightweight On-demand Ad hoc Distance-vector Routing Protocol – Next Generation (LOADng) [16], provides a lightweight, modular, and simple routing solution for LLNs.

LOADng is a reactive routing protocol that was initially designed for Mobile Ad-hoc Networks (MANET) and efficiently manages high point-to-point (P2P) data traffic. However, its main limitations, as mentioned in [17], are delay in constructing routes and problems provoked with inefficient flooding consuming high energy, with massive overhead and packet collision.

Although designed for networks composed by mobile nodes, to the best of authors' knowledge, the current literature does not address any comprehensive study to assess the performance of LOADng in IoT networks with mobile devices. The low performance of existing IoT routing solutions in mobile scenarios makes emerging the need for less complex improvements to fulfill the requirements of these networks. Therefore, this work aims to study the performance of LOADng in mobile IoT scenarios and additionally propose a novel mechanism to improve protocol performance. The proposed LOADng-IoT-Mob introduces a new mechanism that allows the nodes to harness control messages to help the routing table management and adapt to the dynamic changes in the topology. This mechanism also allows the nodes to shorten paths to destinations that have come closer. Further, the LOADng-IoT-Mob uses a new short periodical control message that can be used when the regular control message exchange is not enough to maintain the routing table of the nodes updated. These periodic messages are controlled and can be suppressed to avoid an increase in the network overhead. Moreover, the proposed solution includes an additional routing metric that seeks to build reliable routes composed of the nearest neighboring nodes. Thus, the main contributions of this work are as follows:

- LOADng routing protocol performance analysis and highlight key issues in supporting mobile nodes in IoT networks;
- Propose a novel solution known as LOADng-IoT-Mob based on the harnessing of control messages to improve the performance of LOADng. This enhanced control messaging supports mobility in IoT scenarios and keeps track of the changes in the location of its mobile neighbors.
- Creating a new periodic control message to trigger the control message harnessing mechanism and permit the routing table management without significantly increasing the message overhead.
- Introducing a new routing metric in the LOADng-IoT-Mob based on the received signal strength, which increases network reliability and the Quality of Service (QoS).
- Last but not least, the proposed solution's network performance is studied for memory consumption, packet delivery ratio, latency, and power and overhead efficiency.

TABLE 1. List of acronyms and abbreviations.

Index	Meaning
AMI	Advanced metering infrastructure
AODV	Ad-hoc On-Demand Distance Vector
CCR	Check channel rate
COB	Control bit overhead per delivered data bit
CSMA	Carrier Sense Multiple Access
CTP	Collection Tree Protocol
DEST	Destination
ESB	Energy spent per delivered data bit
ExpRing	Expanding Ring
IC	Internet-connected
IoT	Internet of Things
kB	Kilobytes
LLN	Low power and Lossy Networks
LOADng	Lightweight On-demand Ad hoc Distance-vector Routing Protocol – Next Generation
LR	Live routes
LTE	Long Term Evolution
MAC	Medium access control
MANET	Mobile Ad-hoc Networks
mJ	Millijoules
MNB	Maximum number of broadcasts
Mob	Mobile
MP2P	Multipoint-to-point
OS	Operating system
P2P	Point-to-point
PDR	Packet delivery ratio
PLL	Packets delivered with low latency
Pos	Position
QoS	Quality of Service
RAM	Random access memory
RDC	Radio duty cycle
RE	Residual energy
RPL	IPv6 Routing Protocol for Low-Power and Lossy Networks
RREP	Route Reply
RREQ	Route Request
RSSI	Received signal strength indicator
SRC	Source
UDGM	Unit Disk Graph Model

Table 1 presents the list of acronyms and abbreviations adopted in this work. The rest of the paper is organized as follows. Section 2 discusses the LOADng routing protocol and details the mobile IoT network model while

Section 3 reviews the literature and relevant improvements for LOADng. Section 4 presents the proposed LOADng-IoT-Mob with a novel route discovery mechanism, control message harnessing function, and routing metric and the performance assessment of the proposed solution is analyzed in Section 5. Finally, Section 6 concludes the paper and suggests some future recommendations.

II. BACKGROUND AND SYSTEM MODEL

This Section discusses the LOADng routing protocol and the model of mobile IoT network considered on this work.

A. LOADng ROUTING PROTOCOL

LOADng is a routing protocol that simplifies the AODV (Ad-hoc On-Demand Distance Vector) [18] to attain and efficiently handle the requirements of LLNs. Its reactive feature constructs a route among the nodes only when data packets need to be transferred. Thus, a source (SRC) node that needs to transmit a data packet needs to commence a route discovery process to find and construct a path till the destination (DEST) node. This process is performed using a core structure comprising control messages and an Information Base. The main elements for route discovery are the Route Request (RREQ) and Route Reply (RREP) message and the Routing Set (also termed as routing table), which can comprise several route entries [19]. While control messages are exchanged among the nodes to discover and construct paths, the Routing Set is used to store the information about the created routes, handle control message flooding, and provide information to the forwarding of data packets.

Simply stating, in the LOADng protocol, when a node wants to send a data packet to a destination and the path is unknown, it should store the data packet in a queue and start a route discovery process. Thus, the packet originator should create and broadcast an RREQ addressed to the packet destination indicating the necessity of route creation. Every node that receives the RREQ should process the message, create or update an entry in the Routing Set to the message originator, and verify if it is the message destination before deciding to drop or rebroadcast the route request. An RREQ is dropped mainly when its hop limit expires, or when the node has already received the same message. The route request is rebroadcasted when not dropped.

When RREQ reaches its destination, the receiver node generates an RREP message as a feedback to the request source address. The RREP is then unicasted through the same path traveled by the RREQ. On the way, every intermediate node that receives the message verifies and update its Routing Set before forwarding the reply message to the destination. When the RREP reaches its RREQ source, the route discovery process is completed, and the data packets are then unicast over the recorded path. Figure 1 exemplifies the route discovery process of LOADng, where node SRC needs to send a data packet to the DEST node. LOADng presents considerable simplifications concerning AODV, one of the most relevant being the non-use of periodical HELLO messages.

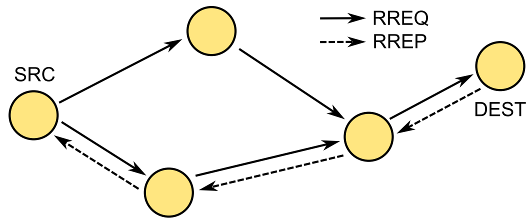

FIGURE 1. LOADng route discovery process. SRC creates and broadcasts an RREQ that floods the network to the point of reaching the destination node DEST. DEST replies the request of SRC using an RREP that is unicasted through the path constructed by RREQ.

This simplification helps reduce the network traffic overhead and, consequently, reduces the energy consumed. However, it also implies a lesser exchange of control information, which is crucial in mobile networks.

B. MOBILE IoT NETWORK AND APPLICATION MODEL

This work seeks to study and improve LOADng specifically for IoT networks with mobile devices. Therefore, in this paper, the mobile IoT network model considered comprises devices with movement and variation in the availability of Internet connection. The network consists of Internet-connected and simple nodes. The Internet-connected (IC) nodes are equipped with IEEE 802.15.4 radio and an additional communication interface (*e.g.* LTE and Wi-Fi) that allows the nodes to communicate directly with the Internet. In contrast, simple nodes are equipped with an IEEE 802.15.4 radio but do not have direct Internet-connection, making it necessary to use an IC node as a gateway to forward the messages addressed to the Internet. Both types of nodes can be mobile.

In the considered IoT scenario, the nodes can send two types of data packets: Internet packets and simple packets. The Internet packets are addressed to an external Internet destination or service located outside the local network. Consequently, these Internet packets can generate multipoint-to-point (MP2P) traffic once sent from simple nodes to IC nodes that should forward them to the Internet. Contrarily, the simple packets are destined for any local network nodes in a P2P traffic pattern. All network nodes, Internet-connected or not, can create, send and forward both packet types.

Figure 2 presents an IoT smart home scenario with mobile nodes that can encompass the previously described network and application. In the scenario, devices can communicate amongst themselves to reach a common objective. For example, an air conditioner can use a laptop as a gateway for sending an Internet packet to consult the weather condition during daytime. A smart TV, an IC device, can directly access the streaming services and at the same time provide a connection to a smart refrigerator to consult the prices of and order groceries that are out of stock. Smartphones can also be used to activate/deactivate a robotic vacuum cleaner both locally or through the Internet.

The IoT network and application model presented here have numerous applications. Also, the given model can

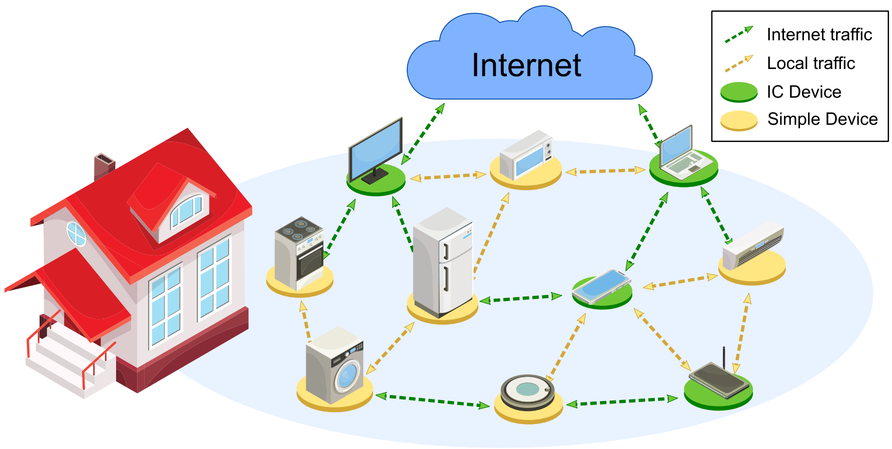

FIGURE 2. **Smart home IoT scenario composed by devices with different capacities. Note: This image has been designed using resources from Freepik.com.**

encompass the concepts of IoT edge and fog computing, where devices exchange data in a closer way to reduce the latency and the required bandwidth to communicate with data centers [20]. Thus, it is "common sense" that due to the deployment cost, not all IoT devices will be directly connected to the Internet. Hence, an efficient solution is required to help these resource-limited devices connect and communicate with the Internet. Further, considering the mobility of devices, the adopted routing solution should self-adapt to autonomously maintain its functioning with minimum human intervention and fulfill the application's requirements in an optimal manner.

III. RELATED WORKS

LOADng presents essential changes in AODV to create a more lightweight and reliable protocol to meet the requirements of LLNs. However, this protocol still has drawbacks that sharply limit its performance. Although LOADng has been most studied in recent years and regarded a promising protocol for IoT networks, mainly with P2P traffic, the proposed improvements for the protocol are still few in number.

A performance comparison between LOADng and RPL is presented in [21]. In their work, the authors have assessed the performance of both the protocols regarding packet delivery ratio, control overhead, average path length, and end-to-end delay. The obtained results showed that LOADng overcomes RPL mainly in P2P scenarios, where the proactive solution has recognized lower performance. The performance of LOADng was also studied in IoT scenarios with P2P and MP2P traffic in [22]. Based on the limitations of LOADng in MP2P scenarios, Yi and Clausen [23] have proposed a collection tree extension for the protocol. This proposal, named LOADng-CTP, introduces proactive features to LOADng and helps the nodes create a routing tree to forward data packets from the leaves (nodes) to a root (sink) node. The proposed approach has performed similar to RPL regarding packet delivery ratio and delay, but with a lower control overhead. The performances of RPL and LOADng-CTP were also compared in an advanced metering infrastructure (AMI) scenario in [24].

The default LOADng proposal is modular and permits the use of different routing metrics to construct paths among the nodes. The native routing metric of LOADng is the hop count, which is not reliable and takes into account the number of hops between the nodes only once to select the best route. Thus, Sasidharan and Jacob [25] proposed LRRE, a new routing metric based on the number of live routes (LR), residual energy (RE), and hop count. Here, the referred metrics are merged in addition to hold the monotonicity and isotonicity properties of routing algebra [26]. The evaluation results exhibited that the proposed LRRE obtained better results when compared with each one of the metrics used separately. The performance of LOADng with different routing metrics was also studied in [27]. LOADng, due to its reactive features, produces a considerable control message overhead during its functioning. To mitigate this problem, Yi *et al.* [28] have proposed the SmartRREQ mechanism to limit the broadcasting of messages during the route discovery process. This solution uses the already existent information about the routes in the intermediate nodes to control the number of RREQ broadcasts. Thus, when an intermediate node, which is neither the RREQ originator nor the destination, receives an RREQ, it should perform additional processing to verify if there is any entry in its Routing Set to the RREQ destination. If an entry is found, then the RREQ message should be forwarded in unicast to the destination using the next hop node stored in the route entry or else, the message will be normally forwarded in broadcast as the default implementation of LOADng. The obtained results compared with default LOADng and AODV show this simple mechanism can reduce the number of broadcast transmissions, contributing to the decrement of packet collisions and traffic overhead.

Still seeking to reduce the control traffic overhead of LOADng, Bas *et al.* [29] introduced the Expanding Ring flooding extension for LOADng to perform the discovery process using flooding of control message based on rings that can grow progressively. Thus, the Expanding Ring creates a new field on the RREQ messages known as the maximum number of broadcasts (MNB) (or `mnb-value`) to control the range of RREQs in the number of hops. Also, the authors introduced three new parameters to adjust the mechanism's functioning: MNB_START is used to define the initial `mnb-value`; MNB_INCREMENT is used to define the increase in range after a route discovery fault; and MNB_THRESHOLD is used to define the maximum value of MNB. When the process of route discovery is initiated, the `mnb-value` field of the RREQ is initialized with the MNB_START value and, then, the message is sent in a broadcast. The RREQ originator should also define a timer to wait for a reply to the generated request. Each intermediate node that receives the RREQ should verify the existence of some entry for the message destination into its Routing Set. If found to be true, the node should use the SmartRREQ mechanism to transmit the message to the destination, otherwise the node will verify if the `mnb-value` field is higher than 0. If found positive, the `mnb-value` is decreased by one, and the message is broadcasted. In contrast, the received RREQ is dropped. When the timer defined by the RREQ originator expires, the originator starts a new route discovery using the `mnb-value` field added to the MNB_INCREMENT value. This process occurs until the MNB reaching the MNB_THRESHOLD value or the desired route is constructed. The Expanding Ring mechanism can regulate the area of the RREQ messages and reduce the control overhead. However, if the message destination is not found in the initial discovery tentative, the mechanism can produce a reverse effect, increasing the network overhead and energy consumption. Compared with SmartRREQ, Expanding Ring can reduce the number of collisions, but this leads to an increase in the end-to-end delay.

Considering IoT scenarios with different types of nodes and traffic patterns similar to that described in the subsection II-B, Sobral *et al.* [30] proposed the LOADng-IoT. The proposed improvement for LOADng in IoT scenarios comprises three different mechanisms that can enhance the network performance regarding QoS and energy efficiency. The introduced Internet route discovery mechanism allows the network nodes to find a route to IC devices without a previous definition of a gateway. For this purpose, both RREQ and RREP messages received an additional flag known as `iot` to indicate that messages are used to discover an IC node. RREQ messages with `iot` flag true does not have a defined destination, and any device Internet-connected can reply to it using an RREP message with IoT flag true. Further, the authors have introduced a new Internet Route Cache mechanism that allows the nodes to store the main information about a previously known Internet route removed from the Routing Set. This feature enables the nodes to reduce the number of broadcasts required to find an Internet path and contributes to a lower energy consumption and control overhead, although there is a slight increase in the memory usage. Finally, the authors also proposed a new error code to advise the network nodes about the status of the Internet connection of the devices working as gateways.

Although LOADng-IoT has presented significant improvements to the use of LOADng in IoT scenarios, it still has some limitations in mobility scenarios since it has been projected for static networks. The LOADng-IoT performance evaluation study presented by the authors showed that the proposal overcame the compared solutions in several situations, including one with mobile nodes. However, in the mobility scenario, only a small number of Internet-connected nodes managed to move across the studied area. Furthermore, the authors have not addressed any solution to mitigate the decrease in performance due to the dynamicity in the network topology, which occurs with the movement of the nodes.

The limitation presented by the current literature solutions, mainly related to the lack of mobility support, have motivated this work. The proposed solution to improve the performance of LOADng in mobile IoT networks has been thoroughly described in the following section.

IV. PROPOSED LOADng-IoT-Mob

This work proposes an improvement for LOADng protocol in mobility IoT scenarios. The proposed approach, LOADng-IoT-Mob, introduces a new mechanism that allows nodes harnessing the control messages, exchanged during the route discovery process, to manage the information of its Routing Set to better support the topology changes due to the mobility of devices. Further, it allows the nodes to shorten paths to a known destination that can grow closer because of its movement. Moreover, LOADng-IoT-Mob also includes a new routing metric based on the received signal strength indicator (RSSI) to help the nodes construct paths with more close and reliable nodes.

In addition to mobility support, LOADng-IoT-Mob includes features of SmartRREQ, Expanding Ring, and LOADng-IoT to provide an improved and efficient network performance, specifically for IoT applications. Thus, some fields are added into default LOADng control messages and Routing Set. In both RREQ and RREP, the fields `smart-rreq`, `mnb-value`, and `iot` are inserted to support SmartRREQ, Expanding Ring, and LOADng-IoT proposals. Further, in the Routing Set, the field `R_internet_conn` is inserted to support the LOADng-IoT. Finally, the novel mechanism proposed by LOADng-IoT-Mob requires the addition of a new fields, namely `R_next_hop_valid_time`, in the Routing Set to record the valid time of each next hop node.

The following subsections describe the proposed approach functioning and indicate how both control message and Routing Set additional fields are used to improve the network performance.

A. ROUTE DISCOVERY IN LOADng-IoT-MOB

LOADng-IoT-Mob, as previously explained, encompass other improvements to offer an improved performance in IoT networks similar to the shown the subsection II-B. Thus, the proposed solution allows the use of two different types of route discovery processes.

The first, known as simple route discovery process, is dedicated to create paths to forward the local data packets. Thus, when a node intends to send a simple packet to a destination not found on its Routing Set, it should kick off with a simple route discovery process using the Expanding Ring flooding mechanism, as shown in Figure 3. In this process of route discovery, the SRC node generates an RREQ with `mnb-value` field equal to one and broadcasts it. If the node that receives the RREQ contains a route to the desired DEST, it unicasts the RREQ by means of the SmartRREQ mechanism to the DEST. The DEST node receives the RREQ and replies it with an RREP message. After receiving the RREP, the SRC node completes the discovery process by updating the Routing Set with new information and can start sending the data packets to the DEST node. Note that other neighbor nodes that receive the RREQ and do not have a route to DEST drop the RREQ packet due to the MNB limitation.

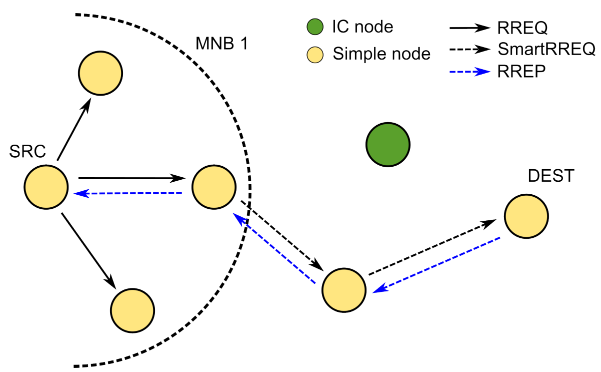

FIGURE 3. **LOADng-IoT-Mob simple route discovery process using expanding ring flooding for constructing a path for a simple node.**

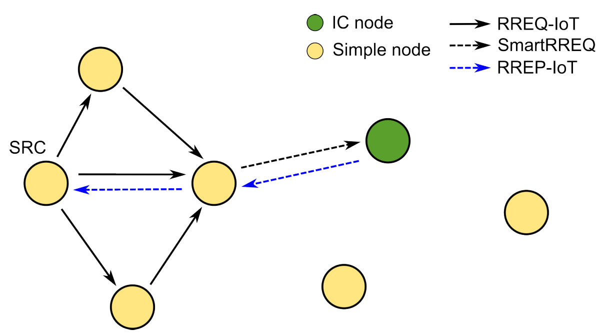

FIGURE 4. **LOADng-IoT-Mob Internet route discovery process for constructing a path for an Internet-connected node.**

The second process, termed Internet route discovery, is used when a node needs to send a data packet to an Internet address. Hence, the node performs an Internet route discovery process, as proposed by the LOADng-IoT and exemplified in Figure 4. At the time, when the SRC node needs to send a data packet to an Internet address, the node generates and broadcasts an RREQ-IoT (RREQ with `iot` flag = 1) in the network. Note that as the interest of SRC is to find an IC node to forward the message to the Internet, RREQ-IoT does not indicate any specific destination inside the local network. The neighbor node receiving the RREQ-IoT and knowing a path to an IC node transmits the request in unicast similar to the SmartRREQ mechanism. The IC node receiving the request generates an RREP-IoT (RREP with `iot` flag = 1) and sends it to the SRC node. Finally, the SRC, after receiving the RREP-IoT, sends the Internet data packets through the found IC node, using it as a gateway. It is important to highlight that in the Internet route discovery, flooding is not limited by the MNB value because the Expanding Ring mechanism is not used.

Note that the LOADng-IoT-Mob does not create new route discovery mechanisms but has already merged existing efficient solutions. However, in order to fulfill its aim and allow support mobility, the proposed solution introduces an additional field for each entry in the Routing Set to manage the availability of the next hop node in the path to each destination. Thus, during both the route discovery processes, whether simple or Internet, each new entry added in the Routing Set should include the `R_next_hop_valid_time` field. The value of the new field value is set according to the value of NEXT_HOP_VALID_TIME parameter, which is represented in seconds, plus one hysteresis value.

The NEXT_HOP_VALID_TIME parameter, which is better explained in the next subsection, should initially be defined in the network deployment phase and accessible to the whole network's nodes. The following subsection also describes the use of control messages to manage the availability of routes and the refreshing procedure of `R_next_hop_valid_time` values.

B. CONTROL MESSAGES HARNESSING FOR ROUTES MANAGEMENT

LOADng in scenarios with mobile nodes suffers from topology changes during data forwarding. A route discovered in an instant can become unavailable a few seconds after its creation. The simplification that led the AODV toward LOADng has removed the use of periodical HELLO messages to reduce the control overhead and the protocol complexity. Contrarily, this change makes the protocol lose its capacity of self-adaption to topology changes, suffering decrease in notable performance in high mobility scenarios.

To confront the presented challenge and provide adequate mobility support for mobile IoT networks, LOADng-IoT-Mob proposes a mechanism that can harness all control messages used during the network functioning for managing the Routing Set. Thus, during the route discovery processes (both simple and Internet), after receiving a control message, the nodes should perform an initial procedure, before handling the message content, to refresh the `R_next_hop_valid_time` field of the Routing Set related to the message sender. The `R_next_hop_valid_time` is used to indicate the valid time of the next hop of a route. Thus, while this valid time does not expire, the node considers the next hop to be on its communication range. In other words,

---

Algorithm 1 Algorithm for Next Hop Valid Time Refresh and Path Shorten Executed for Each Received Control Message

---

```
Input: Received control message
msg ← received control message;
previous_hop ← address of node from the message
was received;
for each entry of Routing Set do
    if entry.R_next_addr = previous_hop
    then
        entry.R_next_hop_valid_time ←
        NEXT_HOP_VALID_TIME + 1;
    end
    if entry.R_dest_addr = previous_hop and
    entry.R_next_addr ≠
    entry.R_dest_addr then
        entry.R_next_addr ← previous_hop;
        entry.R_next_hop_valid_time ←
        NEXT_HOP_VALID_TIME + 1;
        entry.R_hop_count ← 1;
        entry.R_metric_type ← HOP_COUNT;
        entry.R_metric ← MAX_DIST;
    end
end
```

R_next_hop_valid_time can indicate the presence of the next hop node in the area of the route entry owner.

The R_next_hop_valid_time value is updated every second, decreasing by one. When a node receives a control message from its neighbor, the R_next_hop_valid_time value of the route entries related to the message sender are refreshed. This procedure is exposed in Algorithm 1. For each route entry existing on its Routing Set, the node should verify if the previous hop node (i.e., the message sender) is the next hop for reaching the destination of the entry. If yes, then that node should refresh the R_next_hop_valid_time according to the NEXT_HOP_VALID_TIME parameter plus one hysteresis value which, in the algorithm, is 1.

When a R_next_hop_valid_time is decreased to zero, the node should assume that the neighbor node defined as the next hop of the route entry lies outside the communication range. Thus, the route entry of the expired R_next_hop_valid_time is considered invalid and should be used neither for data forwarding or path construction. Hence, if the node to need to send a message, the invalid route should not be considered, and a new route discovery process should be performed. This mechanism, although forces the execution of new route discoveries, ensures that the data packet is not being sent through an unreachable next hop, provoking data packet loss. However, note that this invalid route should not be removed from the Routing Set but only maintained as inexistent. In this way, if the node receives a control message from the next hop of the invalidated route entry, the route can be reactivated by refreshing the entry's R_next_hop_valid_time. This behavior avoids the data packets from being forwarded for destinations with an inaccessible next hop. At the same time, it permits the node to recover route to nodes that have regressed to the communication range without the need of performing a new route discovery process.

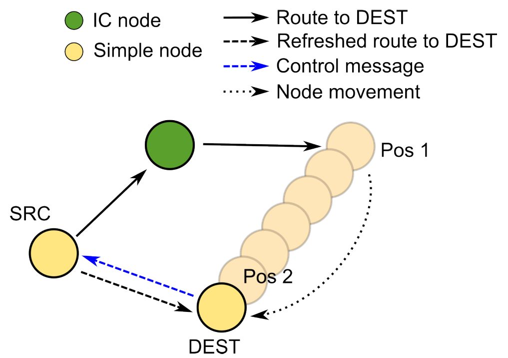

FIGURE 5. Path shorten mechanism proposed by LOADng-IoT-Mob. The SRC shortens the path constructed to the DEST node when it moves from Pos 1 to Pos 2.

Algorithm 1 also shows an important feature provided by the LOADng-IoT-Mob to shorten previously constructed paths. When a control message is received, in addition to the procedure previously described, the node should check if the previous hop node is the destination of some entry in the Routing Set. If yes, then the node should update the route entry information, shortening the path to just one hop, and updating some other data of the entry to maintain it coherence. Figure 5 exemplifies this procedure. Initially, when the route is created, the DEST node is in Pos 1, and the path from SRC to DEST have two hops. Seconds after, DEST moves to Pos 2, which is the nearest to the SRC node. At this point, the DEST node broadcasts a control message (*e.g.*, discovering a route for another node outside the figure). The SRC node receives the control message from DEST and, then, executes the procedure described in Algorithm 1. The SRC, verifying the existence of a route entry to the DEST on its Routing Set, refreshes and shortens the path. Thus, a future message from the SRC to the DEST can be sent using the new and most suitable one hop path.

The use and frequency of control messages during network functioning can vary according to several parameters, such as the network application, data traffic, and quantity of nodes. Thus, to allow the nodes to maintain its Routing Set refreshed even in a network with little control messages usage, LOADng-IoT-Mob has adopted periodical control messaging, where the introduced HELLO_MOB messages are simpler and shorter than the previously known HELLO messages from AODV. The proposed new control message is formed by only two fields, message type and originator address. Thus, the unique function of HELLO_MOB is to make the message receiver execute the procedure that refreshes the R_next_hop_valid_time value and shorten existent paths when possible.

HELLO_MOB messages are generated and scheduled to be sent in a fixed interval based on the HELLO_MOB_INTERVAL parameter, whose value represents seconds. To avoid the generation of excessive control message overhead, the HELLO_MOB messages sent can be suppressed when another control message is sent in broadcast within the HELLO_MOB sending interval. Thus, when a node sends a control message in broadcast, the scheduled HELLO_MOB message is delayed with an additional HELLO_MOB_INTERVAL. This practice presumes that as the neighbors have received a control message and executed the Algorithm 1 procedure a few moments ago, the reception of the HELLO_MOB only represents an unnecessary overhead. Contrarily, when the use frequency of the control message is low, the HELLO_MOB generated in a fixed interval can help the nodes refresh and maintain its Routing Sets. It should be highlighted that the HELLO_MOB suppression is only performed by the transmission of control messages in broadcast. It is because unicast transmissions, different from broadcasts, cannot be received by all nodes in the area and, thus, it is not possible to assume that all the neighbors have received the communication.

The proposed solution helps LOADng better self-adapt to the topology changes that occur with the movement of nodes. The `R_next_hop_valid_time` field introduced in the Routing Set and refreshed by harnessing control messages allows the nodes to be aware of the availability of the next hop and avoid sending data packets through broken paths. At the same time, the mechanism to shorten paths can help the nodes reduce the transmissions required for reaching a destination. It is important to highlight that the path shortening forces the route entry to use the hop count routing metric, which is the basic and default metric of LOADng. Also, it is recommended to adjust the NEXT_HOP_VALID_TIME and HELLO_MOB_INTERVAL parameters with equal values to ensure synchronicity between the valid time of the next hop and HELLO_MOB sending. Finally, the experiments performed during the proposed solution design exposed that HELLO_MOB message usage strongly decreases in dense networks with reasonable use of control message, becoming almost unused in some cases. Thus, the authors indicate that the overhead generated by the proposed periodic message is insignificant regarding the benefits of its usage.

Taking into account that default route metric of LOADng cannot be reliable for mobile IoT networks, the next subsection presents the proposed routing metric to be used with the LOADng-IoT-Mob.

C. WEAKRSSI ROUTING METRIC

The default LOADng uses the hop count as the routing metric for selecting the best route between two nodes. This metric, although simple and easily implementable, can neither represent the real distance or the quality of the links that compose a path. However, the core structure of LOADng permits the creation and use of different routing metric without significant modifications in the protocol. Thus, LOADng-IoT-Mob introduces the new weakRSSI routing metric that allows the nodes to create routes based on the distance among the nodes and the strength of the received transmissions.

The weakRSSI is a minimizable routing metric (lower values is better) based on the RSSI, which is a value computed in the reception of a transmission indicates the strength of the received signal. RSSI values vary according to the used radio interface; *e.g.*, in the CC2420, the RSSI ranges from 0 to 100 (nearest to the value zero is better) [31]. Frequently, RSSI values are used both for distance [32] and link quality [33] estimation. However, the measured RSSI values represent only the communication between two nodes. Thus, to measure the quality of a whole path, weakRSSI uses a simple aggregation mechanism that counts the "weak" RSSI values along the path. Under this mechanism, the RSSI of a link is counted as "weak" if its value is above a threshold value defined through the WEAKRSSI_THRESHOLD parameter.

In the course of the network functioning with the use of weakRSSI, the nodes should define the metric in the generation of each RREQ and RREP using the `metric-type` field, which already exists in the message. Thus, during the route discovery processes, each node that receives an RREQ or RREP should calculate the RSSI value for the received message and verify if it is lower than the defined threshold. If true, the RSSI value is considered "weak" and, the `route-metric` field, which already exists in both the messages, should be incremented by one. In contrast, the field is not modified. In the following, the message is normally handled, the route is created or updated, in the case of an already existent path having a higher weakRSSI value. Figure 6 helps exemplify the use of weakRSSI routing metric. Considering the weakRSSI threshold as −30, all RREQ or RREP received within an RSSI lower are computed as "weak" and incremented in the `route-metric` message field. Thus, the route constructed by DEST to reach SRC is the DEST-D-C-SRC once the weakRSSI value is 1.

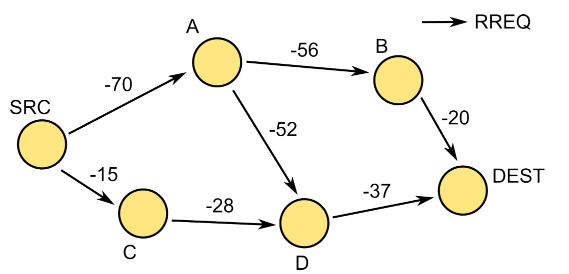

FIGURE 6. Best path selection using weakRSSI routing metric. If the WEAKRSSI_THRESHOLD is defined as −30, then the selected path from DEST to SRC should be DEST-D-C-SRC.

Note that neither LOADng or LOADng-IoT-Mob are multipath and, thus, the Routing Set only stores one entry for each destination. Hence, when forwarding data packets, the nodes do not need to choose the best path because this task is already done in the moment of route discovery, and only one path should exist.

The simple but efficient proposal of weakRSSI allows the nodes to choose the best route to a destination based on a metric that collects aspects both distance and link quality. High RSSI values indicate transmissions received from the nearest nodes and also with lesser probability of the loss provoked by signal attenuation. Thus, constructing paths avoiding the use of "weak" RSSI links consequently implies more reliable and adequate routes for data transmissions.

The next Section is dedicated to present the study conducted to assess the performance of the proposed LOADng-IoT-Mob.

V. PERFORMANCE EVALUATION

To assess the performance of the proposed LOADng-IoT-Mob in mobile IoT scenarios, the authors have conducted several simulation studies using Cooja Simulator [34], which is a part of Contiki OS [35]. Cooja is a well known and widely used tool that allows the emulation of the real behavior motes, (*e.g.* TMote Sky and Zolertia Z1), in terms of processing power, memory, and energy consumption. Although simulation tools may not constitute a real wireless environment, they represent a critical tool that can reproduce equivalent conditions to compare different protocols, making the study more reliable, fair, and free from the interference of external factors.

TABLE 2. Considered network scenarios.

Scenario Name	Network Area	Num. Nodes	Speed Min-Max	Mobility Config.	% of Mobile Nodes
Scenario 1		10, 20, 30, 40, 50	1∼3 m/s	All moves	100%
Scenario 2	200 m			Only simple moves	80%
Scenario 3				Only IC moves	20%
Scenario 4		30	1∼1, 1∼3, 3∼5, 5∼7, 7∼9 m/s	All moves	100%
Scenario 5				Only simple moves	80%
Scenario 6				Only IC moves	20%

In the performed study, the proposed solution was compared with the default LOADng, LOADng with SmartRREQ, LOADng with Expanding Ring, and LOADng-IoT. The application and network model considered was the same presented in subsection II-B. Although in the scenarios described in the referred subsection did not regard the mobility of all network devices [36], this study considers a "worst case" scenario, where all nodes can move in the network area. Thus, six different scenarios that varied in the number of nodes and the maximum speed of the mobile devices were created. In all scenarios, the Internet-connected nodes were 20% of the network devices. Table 2 presents all considered scenarios. The mobility pattern of the nodes was generated based on the Random Waypoint mobility model [37] using the BonnMotion 3.0.1 [38] tool. Table 3 exposes the most relevant parameters adopted in the study common to all scenarios. Table 4 shows the configuration parameters

TABLE 3. Network parameters common to all scenarios.

Parameter	Value
Network Execution Time	600 s
Traffic Pattern	P2P and MP2P
Data Packet Frequency	10 s ∼ 15 s
Data Packet Length	512 bits
Medium Access Control (MAC) Protocol	Carrier Sense Multiple Access (CSMA)
Radio Duty Cycle (RDC) Protocol	ContikiMAC
Check Channel Rate (CCR)	16 Hz
Radio Environment	Unit Disk Graph Model (UDGM) - Distance Loss
Transmission Range	50 m
Interference Range	50 m
TX and RX Chance	90%
Mote Type	Tmote Sky

TABLE 4. Configuration parameters of compared approaches.

LOADng parameters	
Parameter	**Value**
NET_TRAVERSAL_TIME	2 sec
RREQ_RETRIES	1
RREQ_MIN_INTERVAL	2 sec
R_HOLD_TIME	60 sec
MAX_DIST	65535
B_HOLD_TIME	4 sec
MAX_HOP_LIMIT	255
RREQ_MAX_JITTER	1 sec
RREP_ACK_REQUIRED	FALSE
USE_BIDIRECTIONAL_LINK_ONLY	FALSE
RREP_ACK_TIMEOUT	2 sec
LOADng-ExpRing parameters	
Parameter	**Value**
MNB_START	1
MNB_INCREMENT	2
MNB_THRESHOLD	7
LOADng-IoT parameters	
Parameter	**Value**
USE_INTERNET_ROUTE_CACHE	TRUE
R_INTERNET_HOLD_TIME	120 sec
NUM_ROUTE_CACHE_ENTRIES	2
LOADng-IoT-Mob parameters	
Parameter	**Value**
NEXT_HOP_VALID_TIME	60 sec
HELLO_MOB_INTERVAL	60 sec
WEAKRSSI_THRESHOLD	-50

defined for each studied approach. The values were defined in an empirical way to allow all the approaches reaching a consistent performance. Note that all the proposals of improvement adopt parameters from the default LOADng. Moreover, LOADng-IoT-Mob uses the parameters of all the available approaches (as common) and only the last three parameters are introduced by the new proposed solution. Furthermore, LOADng-SmartRREQ approach does not need any configuration parameter using only the one provided by the default LOADng. The studied routing solutions were compared regarding five metrics: packet delivery ratio, packet delivered with low latency, control bit overhead per delivered

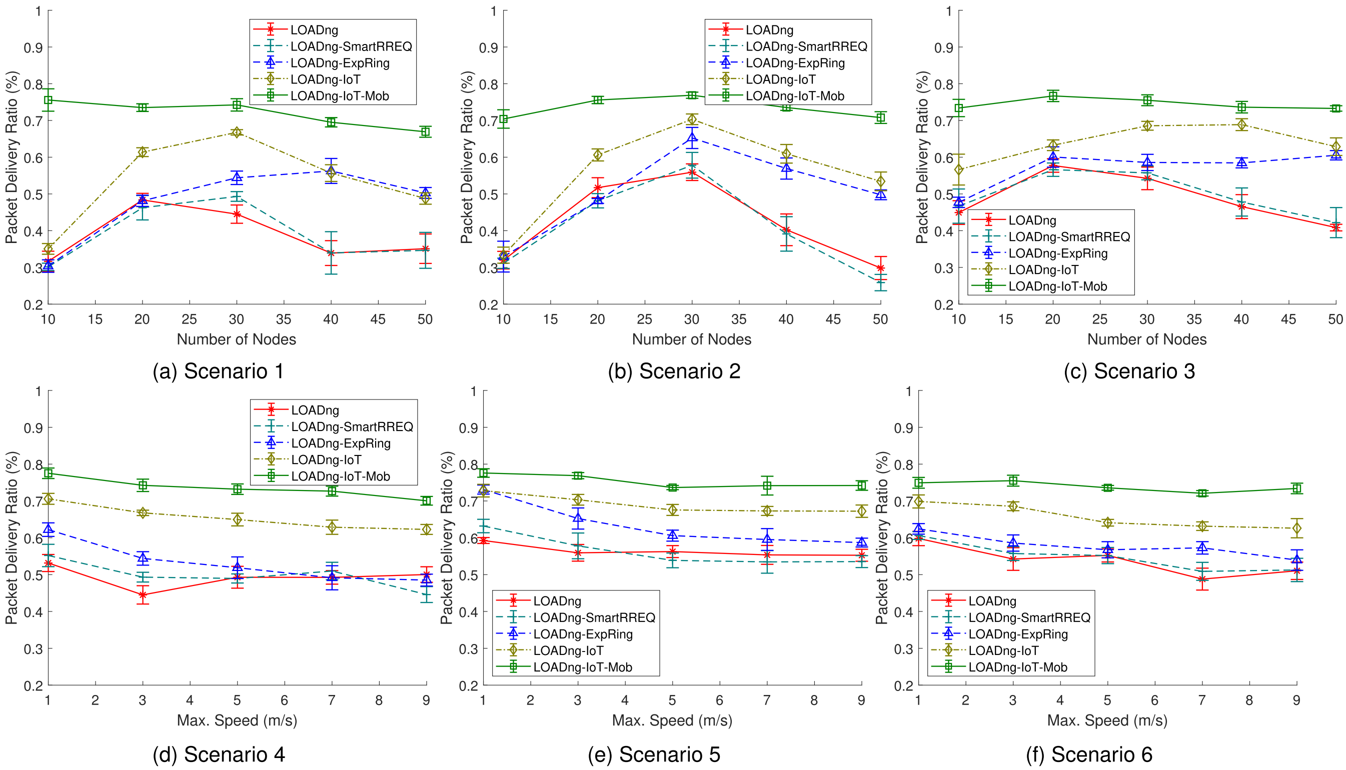

FIGURE 7. Packet delivery ratio in function of the number of nodes (a, b, c) and maximum nodes' speed (d, e, f) for LOADng, LOADng-SmartRREQ, LOADng-ExpRing, LOADng-IoT, and LOADng-IoT-Mob.

data bit, energy spent per delivered data bit, and memory usage. The obtained results for each metric have been presented and analyzed separately. For all studied scenarios, the simulations were executed 30 times, and the results show a confidence interval of 95%.

Figure 7 exposes the results for the metric of packet delivery ratio (PDR), which presents the ratio between the data packets that were successfully delivered to its final destination and all the data packets sent. The obtained results show that the proposed LOADng-IoT-Mob can overcome all other studied proposals in all studied scenarios. The mechanism proposed to harness the control messages were seen to be efficient to the Routing Set management, avoiding the sending of data packets through broken paths. With the use of the proposed solution, the message sender can know about the availability of the next hop and, thus, start a new discovery process when detects that the previously existent path was broken. The proposed solution also exposed to be consistent in scenarios with mobility of the whole network devices, different from the other compared solutions. It is also important to note that in the scenarios with 10 nodes, the other solutions exposed a very low PDR, mainly in Scenarios 1 and 2, when the percentage of the mobile nodes was over 80%. This has been justified by the low density of the nodes in the area, where the number of available routes was limited and the inability of self-adaption to the topology changes provoked by the mobility of the nodes led the solutions without mobility support to a poor performance. In the networks with 20 and 30 nodes, the majority of the studied solutions presented the best results. It was observed that this reasonable quantity of nodes exposed a proper balance between density and the interference produced by the devices. In the network with more than 30 nodes, the proposals that did not implement an efficient flooding mechanism presented a considerable performance decrement. The high number of broadcasts required by the route discovery processes were executed almost at the same time by several nodes generating a high probability of packet collisions, contributing to the PDR decrease. The proposed LOADng-IoT-Mob, in contrast, has not suffered from this problem since it has adopted features both from the Expanding Ring and LOADng-IoT for performing efficient route discoveries. These features, with the addition of weakRSSI and the control message harnessing mechanism, have permitted the LOADng-IoT-Mob to have a reliable and adequate performance regarding the PDR in the studied scenarios. In Scenarios 4, 5, and 6, where the number of nodes is fixed in 30 and the speed of the nodes is variable, all studied approaches have exposed a few variations in the results, proposed solution reaching the best ones. Thus, it was noted that the PDR performance of the studied solutions are few affected by the speed of the nodes when varied below 9 m/s, according to the obtained results.

Figure 8 presents the results obtained to the metric of packets delivered with low latency (PLL). This metric exposes the percentage of data packets successfully delivered with latency lower than a predefined threshold. The threshold value should

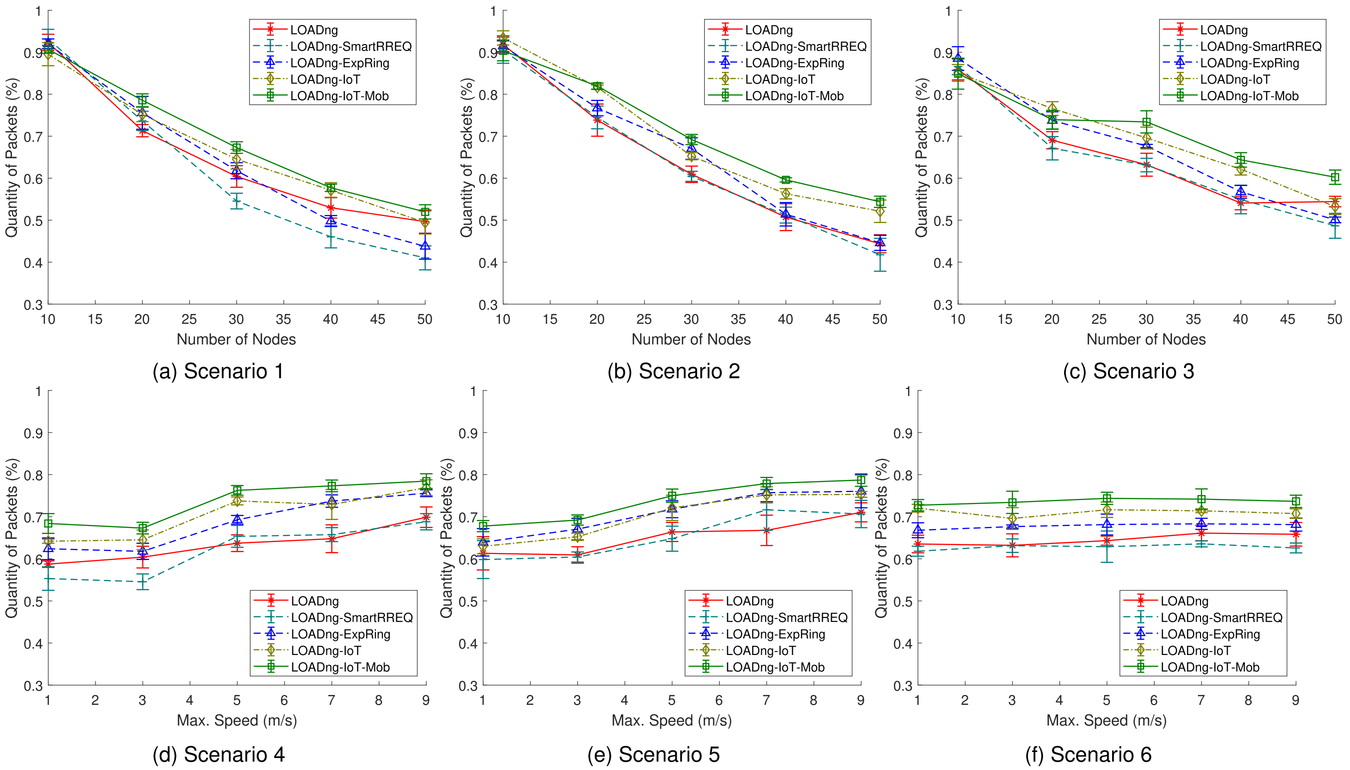

FIGURE 8. Quantity of data packets delivered with latency lower than 0.5 seconds in function of the number of nodes (a, b, c) and maximum nodes' speed (d, e, f) for LOADng, LOADng-SmartRREQ, LOADng-ExpRing, LOADng-IoT, and LOADng-IoT-Mob.

be defined according to the goals of the application to measure how much the proposal can fulfill its requirements. This work set the threshold value for low latency as 0.5 seconds once the considered network was used by a smart home IoT application. According to the obtained results, the LOADng-IoT-Mob has accomplished, in majority, the best results compared to the other studied approaches. However, a decrement in performance was observed with the increasing number of network nodes. This behavior is already expected since the increasing of the network density in a wireless environment can provoke the increasing of the end-to-end latency as a whole [39]. Contrarily, in the scenario with variable speed and mobility over 80%, all studied approaches presented slightly better PLL values with increasing device speed. It was noted that in the higher speed scenarios, the number of messages delivered in one-hop transmission increased in comparison with messages delivered through multi-hop. Thus, the percentage of packets delivered with lower latency increased. In general, the capacity of path shortening of the proposed approach contributed to the faster data packet delivery. Also, the use of combined flooding control mechanism has reduced the overhead and, consequently, the size of the contention window for performing the transmissions. As a result, the time for message forwarding and the latency was also reduced.

Figure 9 shows the results obtained for the metric of control bit overhead per delivered data bit (COB). COB metric represents the average control overhead needed to provide each data bit successfully. The metric value is computed based on the ratio between the sum of the control bit transmitted by all the network and the amount of data bit successfully delivered. Thus, this metric exposes the network efficiency concerning overhead. The results obtained for the metric of COB exposed that for all the studied scenarios, the proposed solution required less control overhead to deliver each data bit. The mechanism proposed for managing the Routing Set and topology changes helps the node detect broken path and create new routes to send data packets. Thus, although the nodes are forced to perform new discovery processes and use more control messages, the proposal allows the nodes to find new paths and successfully deliver the data packets. Further, the proposed LOADng-IoT-Mob introduced a new HELLO_MOB control message to boost the Routing Set refreshing mechanism. In the first impression, one can assume that the use of a periodical control message can increase the overhead. However, the obtained results showed the opposite. In the proposed solution, the HELLO_MOB messages were only used when the control overhead was not sufficient enough to maintain the information about the availability of the next hop nodes updated. Thus, even when used, HELLO MOB messages have shown more benefits than harm, allowing the nodes to know about the movement of their neighbors and avoiding sending of data packets through broken paths.

The results obtained to the metric of energy spent per delivered data bit (ESB) are shown in Figure 10. The ESB

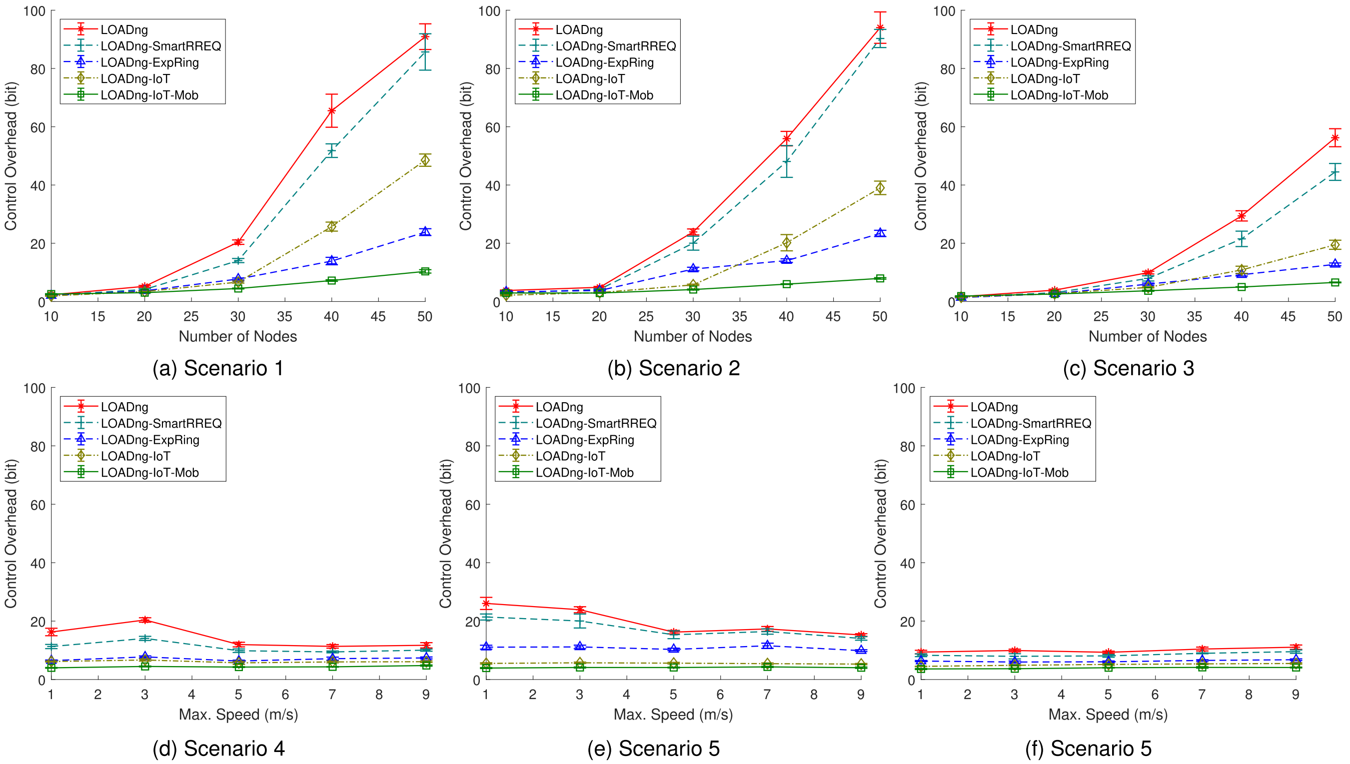

FIGURE 9. **Control bit overhead to delivery each data bit in function of the number of nodes (a, b, c) and maximum nodes' speed (d, e, f) for LOADng, LOADng-SmartRREQ, LOADng-ExpRing, LOADng-IoT, and LOADng-IoT-Mob.**

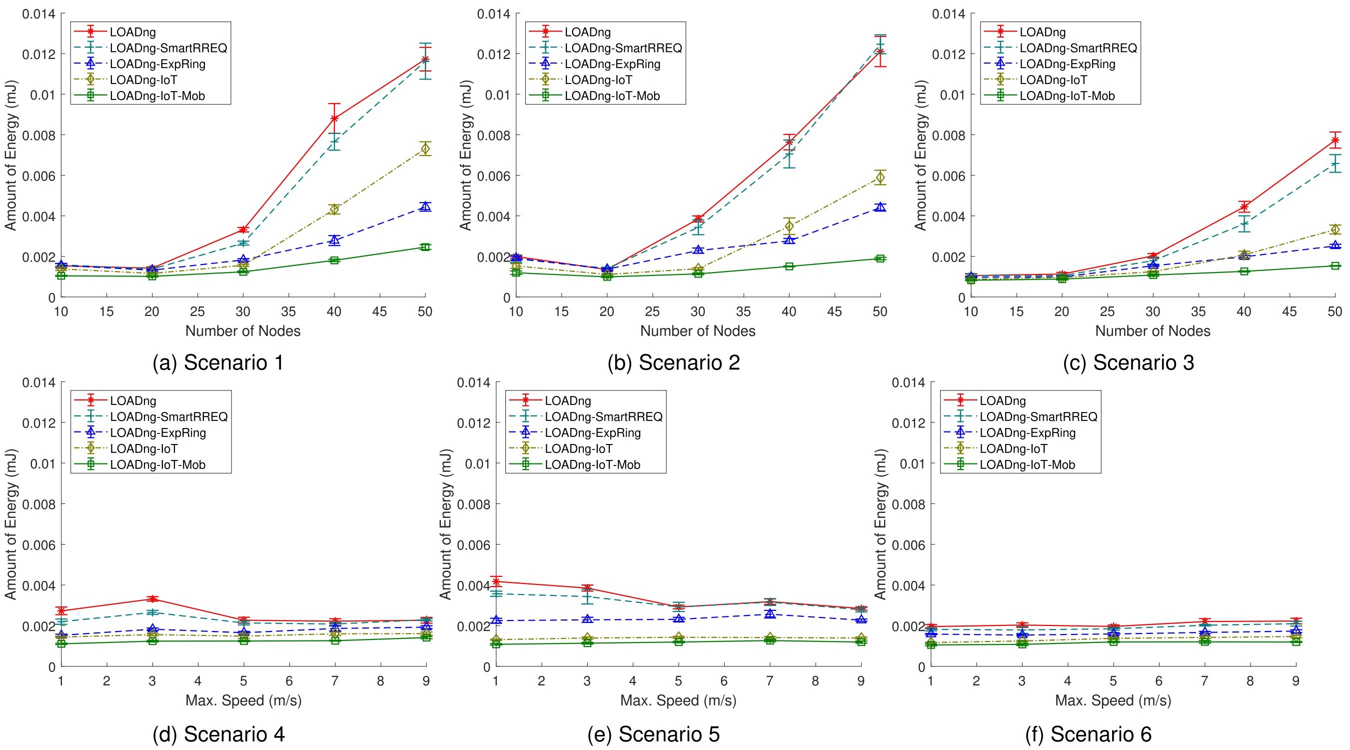

FIGURE 10. **Energy spent to delivery each data bit in function of the number of nodes (a, b, c) and maximum nodes' speed (d, e, f) for LOADng, LOADng-SmartRREQ, LOADng-ExpRing, LOADng-IoT, and LOADng-IoT-Mob.**

metric presents the energy efficiency of the network showing the average amount of energy, in millijoules (mJ), required to provide each data bit successfully. The value is obtained with the ratio between the amount of energy spent by the whole network and the amount of data bit delivered. Thus, a high PDR together with a low energy consumption represents better ESB values. In this work, the values obtained by the ESB metric were a ''shadow'' of the values obtained for the COB metric. These results exposed that in the studied scenarios, the majority of the energy consumption was related to the transmission and reception of control messages. Thus, the proposal with lower overhead generated also presented lower energy consumption. The results obtained exposed that the proposed solution attained better energy efficiency compared to the other approaches in all the studied scenarios. Also, the proposed approach has exposed to be less affected by the network density growth and the increase in the number of mobile devices in the scenario when compared with the other solutions. LOADng-IoT-Mob, by using different methods for reducing and controlling the flooding of control messages, was able to require fewer transmissions, which implies a lesser energy consumption, to execute the route discovery processes. Thus, together with the high PDR values obtained, the proposed solution was able to attain the best ESB values. Regarding the scenarios with variable speed, all the studied solutions presently do not show considerable changes with the increase in the average speed of the nodes.

TABLE 5. Memory usage.

Proposal	Flash (kB)	RAM (kB)
LOADng	29.47	5.28
LOADng-SmartRREQ	29.79 (+ 1.09 %)	5.28
LOADng-ExpRing	29.87 (+ 1.35 %)	5.28
LOADng-IoT	31.94 (+ 8.38 %)	5.33 (+ 0.85 %)
LOADng-IoT-Mob	32.35 (+ 9.77 %)	5.36 (+ 1.55 %)

Table 5 presents the memory usage of the implemented and studied routing proposals. The exposed values, expressed in kilobytes (kB), cover all codes deployed in the nodes comprising the application, routing protocol, network stack, and operational system. The Flash column represents the amount of memory used for code implementation, *i.e.*, the read-only data. The RAM column, in contrast, shows the read-write data that is manipulated according to the code execution. The percentage inside the parenthesis gives the increased memory usage about the default LOADng implementation. The proposed LOADng-IoT-Mob required almost 10 % more Flash memory, which represents 2.88 kB, in comparison with the default LOADng. Further, the proposed approach increased the RAM usage by only 1.55 %. The presented memory usage increase is already expected due to the code increments required to reach the goals of the proposal and provide several benefits to the network. Considering that the performance assessment study has used Tmote Sky motes, which have 48 kB of Flash capacity and 10 kB of RAM, it is possible to observe that the proposed approach has consumed 67.3 % of the device Flash memory while the default LOADng has consumed 61.3 %. Concerning RAM usage of Tmote Sky, the proposed solution required 53.6 % while the default proposal demanded 52.8 %. Thus, although it has presented a higher memory usage, the proposed mobility improvement does not jeopardize all devices' memory and leaves a considerable portion of memory free to be used by more complex applications and future updates in the device firmware. Also, the increased memory usage can be seen as a reasonable trade-off or an ''necessary evil'' by all improvements provided to the network performance. Based on the exposed results, the next section in dedicated to present the conclusions of the work and show important future issues to be developed.

Based on the exposed results, the next section presents the conclusion of the work and shows important future issues that need to be studied.

VI. CONCLUSION AND FUTURE WORK

This work proposed a new improvement method for LOADng protocol in IoT scenarios with mobile devices. The LOADng-IoT-Mob proposal was designed to cover the lacks presented by the default LOADng regarding the mobility of nodes and to provide an efficient and reliable routing solution for the considered scenarios. The proposed solution merged features of other important enhancements for LOADng in the state-of-the-art and proposed new mechanisms for reaching a suitable performance in mobility environments.

The LOADng-IoT-Mob adopted the flooding controlling mechanism from the Expanding Ring and the SmartRREQ and inherited the Internet route discovery mechanism from the LOADng-IoT to create a solution that is able to find routes for different traffic types with low overhead and high reliability. Also, the proposal introduced a new mechanism of control message harnessing to allow the nodes to manage the discovered routes and self-adapt to the topology changes provoked by the movement of devices. Thus, the LOADng-IoT-Mob permitted the nodes to manage the information about the next hop of the paths existent on the Routing Set without additional fields in the control messages. Further, within of the procedure of control message harnessing, a new mechanism was introduced to permitted the nodes to shorten the path for destinations that had moved to near to them, reducing the route to one-hop. Considering that the control message harness mechanism depends on the overhead generated by the nodes, a new HELLO_MOB message was also introduced to be used when the usual network overhead is not sufficient to maintain the information of the neighbors' nodes updated in the Routing Set. Finally, a new weakRSSI routing metric was introduced to allow the nodes to construct more reliable and nearest paths to avoid an earlier break in the route. The proposed solution was compared with different approaches existent in the literature in scenarios with various node densities and speeds. For the metric of PDR, PLL, COB, and ESB, the proposed solution was able to present a significant and considerable performance increase. Thus, based on the obtained results in the studied scenarios, the LOADng-IoT-Mob was able to attain better data delivery reliability, lower latency, lower control overhead, and better power efficiency compared with the other studied solutions in the considered mobile IoT network scenarios. As a negative point, the proposed solution required increased memory usage; however, it can present a good trade-off based on the obtained benefits.

For future work, the authors intend to optimize the source code implementation to reduce the required memory usage and assess the proposed solution in real testbeds. The authors also detach the necessity of the development of new studies and improvements for the LOADng becomes more reliable and efficient, mainly concerning the flooding mechanism.

REFERENCES

[1] E. Borgia, "The Internet of Things vision: Key features, applications and open issues," *Comput. Commun.*, vol. 54, pp. 1–31, Dec. 2014.

[2] I. Bisio, C. Garibotto, A. Grattarola, F. Lavagetto, and A. Sciarrone, "Exploiting context-aware capabilities over the Internet of Things for industry 4.0 applications," *IEEE Netw.*, vol. 32, no. 3, pp. 101–107, May/Jun. 2018.

[3] Q. Liu, Y. Ma, M. Alhussein, Y. Zhang, and L. Peng, "Green data center with IoT sensing and cloud-assisted smart temperature control system," *Comput. Netw.*, vol. 101, pp. 104–112, Jun. 2016.

[4] L. Sanchez, L. Munoz, J. A. Galache, P. Sotres, J. R. Santana, V. Gutierrez, R. Ramdhany, A. Gluhak, S. Krco, E. Theodoridis, and D. Pfisterer, "SmartSantander: IoT experimentation over a smart city testbed," *Comput. Netw.*, vol. 61, pp. 217–238, Mar. 2014.

[5] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[6] T.-A. Do, S.-W. Jeon, and W.-Y. Shin, "How to cache in mobile hybrid IoT networks?" *IEEE Access*, vol. 7, pp. 27814–27828, 2019.

[7] M. Z. Hasan, F. Al-Turjman, and H. Al-Rizzo, "Analysis of cross-layer design of quality-of-service forward geographic wireless sensor network routing strategies in Green Internet of Things," *IEEE Access*, vol. 6, pp. 20371–20389, 2018.

[8] R. Alexander, A. Brandt, J. P. Vasseur, J. Hui, K. Pister, P. Thubert, P. Levis, R. Struik, R. Kelsey, and T. Winter, *RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks*, document RFC 6550, Mar. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6550.txt

[9] O. Iova, P. Picco, T. Istomin, and C. Kiraly, "RPL: The routing standard for the Internet of Things. . . or is it?" *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 16–22, Dec. 2016.

[10] M. Bouaziz, A. Rachedi, and A. Belghith, "EKF-MRPL: Advanced mobility support routing protocol for Internet of mobile things: Movement prediction approach," *Future Gener. Comput. Syst.*, vol. 93, pp. 822–832, Apr. 2019.

[11] K. Q. A. Fadeel and K. El Sayed, "ESMRF: Enhanced stateless multicast RPL forwarding for IPv6-based low-Power and lossy networks," in *Proc. Workshop IoT Challenges Mobile Ind. Syst. (IoT-Sys)*, New York, NY, USA, 2015, pp. 19–24.

[12] G. G. Lorente, B. Lemmens, M. Carlier, A. Braeken, and K. Steenhaut, "BMRF: Bidirectional multicast RPL forwarding," *Ad Hoc Netw.*, vol. 54, pp. 69–84, Jan. 2017.

[13] W. Gan, Z. Shi, C. Zhang, L. Sun, and D. Ionescu, "MERPL: A more memory-efficient storing mode in RPL," in *Proc. 19th IEEE Int. Conf. Netw. (ICON)*, Dec. 2013, pp. 1–5.

[14] C. Kiraly, T. Istomin, O. Iova, and G. P. Picco, "D-RPL: Overcoming memory limitations in RPL point-to-multipoint routing," in *Proc. IEEE 40th Conf. Local Comput. Netw. (LCN)*, Oct. 2015, pp. 157–160.

[15] M. Zhao, A. Kumar, P. H. J. Chong, and R. Lu, "A comprehensive study of RPL and P2P-RPL routing protocols: Implementation, challenges and opportunities," *Peer-Peer Netw. Appl.*, vol. 10, no. 5, pp. 1232–1256, Sep. 2017.

[16] T. Clausen, J. Yi, and U. Herberg, "Lightweight on-demand ad hoc distance-vector routing—Next generation (LOADng): Protocol, extension, and applicability," *Comput. Netw.*, vol. 126, pp. 125–140, Oct. 2017.

[17] Y. B. Zikria, M. K. Afzal, F. Ishmanov, S. W. Kim, and H. Yu, "A survey on routing protocols supported by the Contiki Internet of Things operating system," *Future Gener. Comput. Syst.*, vol. 82, pp. 200–219, May 2018.

[18] S. R. Das, C. E. Perkins, and E. M. Belding-Royer, *Ad hoc On-Demand Distance Vector (AODV) Routing*, document RFC 3561, Jul. 2003. [Online]. Available: https://rfc-editor.org/rfc/rfc3561.txt

[19] D. Sasidharan and L. Jacob, "A framework for the IPv6 based implementation of a reactive routing protocol in ns-3: Case study using LOADng," *Simul. Model. Pract. Theory*, vol. 82, pp. 32–54, Mar. 2018.

[20] G. Premsankar, M. Di Francesco, and T. Taleb, "Edge computing for the Internet of Things: A case study," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1275–1284, Apr. 2018.

[21] J. Yi, T. Clausen, and Y. Igarashi, "Evaluation of routing protocol for low power and Lossy networks: LOADng and RPL," in *Proc. IEEE Conf. Wireless Sensor (ICWISE)*, Dec. 2013, pp. 19–24.

[22] J. V. V. Sobral, J. J. P. C. Rodrigues, K. Saleem, and J. Al-Muhtadi, "Performance evaluation of LOADng routing protocol in IoT P2P and MP2P applications," in *Proc. Int. Multidisciplinary Conf. Comput. Energy Sci. (SpliTech)*, Jul. 2016, pp. 1–6.

[23] J. Yi and T. Clausen, "Collection tree extension of reactive routing protocol for low-power and lossy networks," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 3, 2014, Art. no. 352421.

[24] S. Elyengui, R. Bouhouchi, and T. Ezzedine, "A comparative performance study of the routing protocols RPL, LOADng and LOADng-CTP with bidirectional traffic for AMI scenario," in *Proc. Int. Conf. Smart Grid Clean Energy Technol. (ICSGCE)*, Oct. 2015, pp. 43–49.

[25] D. Sasidharan and L. Jacob, "Improving network lifetime and reliability for machine type communications based on LOADng routing protocol," *Ad Hoc Netw.*, vol. 73, pp. 27–39, May 2018.

[26] J. L. Sobrinho, "Algebra and algorithms for QoS path computation and hop-by-hop routing in the Internet," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, vol. 2, Apr. 2001, pp. 727–735.

[27] J. V. V. Sobral, J. J. P. C. Rodrigues, N. Kumar, C. Zhu, and R. W. Ahmad, "Performance evaluation of routing metrics in the loadng routing protocol," *J. Commun. Softw. Syst.*, vol. 13, no. 2, pp. 87–95, 2017.

[28] J. Yi, T. Clausen, and A. Bas, "Smart route request for on-demand route discovery in constrained environments," in *Proc. IEEE Int. Conf. Wireless Inf. Technol. Syst. (ICWITS)*, Nov. 2012, pp. 1–4.

[29] A. Bas, J. Yi, and T. Clausen, "Expanding ring search for route discovery in loadng routing protocol," in *Proc. 1st Int. Workshop Smart Technol. Energy, Inf. Commun.*, 2012, pp. 1–8.

[30] J. V. V. Sobral, J. J. P. C. Rodrigues, R. A. L. Rabêlo, K. Saleem, and V. Furtado, "LOADng-IoT: An enhanced routing protocol for Internet of Things applications over low power networks," *Sensors*, vol. 19, no. 1, p. 150, 2019.

[31] *2.4 GHz IEEE 802.15.4 / ZigBee-Ready RF Transceiver*, Chipcon Products, Texas Instrum., Dallas, TX, USA, 2006.

[32] A. Booranawong, K. Sengchuai, and N. Jindapetch, "Implementation and test of an RSSI-based indoor target localization system: Human movement effects on the accuracy," *Measurement*, vol. 133, pp. 370–382, Feb. 2019.

[33] R. D. Gomes, D. V. Queiroz, A. C. L. Filho, I. E. Fonseca, and M. S. Alencar, "Real-time link quality estimation for industrial wireless sensor networks using dedicated nodes," *Ad Hoc Netw.*, vol. 59, pp. 116–133, May 2017.

[34] J. Eriksson, F. Österlind, N. Finne, N. Tsiftes, A. Dunkels, T. Voigt, R. Sauter, and P. J. Marrón, "COOJA/MSPSim: Interoperability testing for wireless sensor networks," in *Proc. 2nd Int. Conf. Simulation Tools Techn. (Simutools)*. Brussels, Belgium: Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2009, pp. 27:1–27:7.

[35] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki—A lightweight and flexible operating system for tiny networked sensors," in *Proc. 29th Annu. IEEE Int. Conf. Local Comput. Netw.*, Nov. 2004, pp. 455–462.

[36] G. Porcu, J. Buron, and A. Brandt, *Home Automation Routing Requirements in Low-Power and Lossy Networks*, document RFC 5826, Apr. 2010. [Online]. Available: https://rfc-editor.org/rfc/rfc5826.txt

[37] C. Bettstetter, G. Resta, and P. Santi, "The node distribution of the random waypoint mobility model for wireless ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 2, no. 3, pp. 257–269, Jul. 2003.

[38] N. Aschenbruck, R. Ernst, E. Gerhards-Padilla, and M. Schwamborn, "BonnMotion: A mobility scenario generation and analysis tool," in *Proc. 3rd Int. ICST Conf. Simulation Tools Techn. (SIMUTools)*. Brussels, Belgium: Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2010, pp. 51:1–51:10.

[39] J.-C. Kuo, W. Liao, and T.-C. Hou, "Impact of node density on throughput and delay scaling in multi-hop wireless networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 5103–5111, Oct. 2009.

JOSÉ V. V. SOBRAL received the B.S. degree in computer science from the Centro de Ensino Unificado de Teresina (CEUT), Teresina, Brazil, and the M.Sc. degree in computer science from the Federal University of Piauí (UFPI), Teresina. He is currently pursuing the Ph.D. degree with the University of Beira Interior (UBI), Covilhã, Portugal. He is also with the Federal Institute of Maranhão (IFMA), São Luís, Brazil, where he is an Assistant Professor, and he is also a member of NetGNA Research Group. His research interests include the Internet of Things (IoT), routing protocols for low power and lossy networks, wireless sensors networks, RFID systems, and computational intelligence.

JOEL JOSÉ P. C. RODRIGUES (S'01–M'06–SM'06) is currently a Professor with the Federal University of Piauí, Brazil, and a Senior Researcher with the Instituto de Telecomunicações, Portugal. He is also the Leader of the Internet of Things Research Group (CNPq). He has authored or coauthored over 750 papers in refereed international journals and conferences, three books, and he holds two patents. He is a Licensed Professional Engineer (as a Senior Member), a member of the Internet Society, and a Senior Member of ACM. He is also a member of many international TPCs and participated in several international conferences organization. He is the Director for the Conference Development—the IEEE ComSoc Board of Governors, the IEEE Distinguished Lecturer, the President of the Scientific Council at ParkUrbis - Covilhã Science and Technology Park, the Past-Chair of the IEEE ComSoc Technical Committee on eHealth, the Past-Chair of the IEEE ComSoc Technical Committee on Communications Software, Steering Committee Member of the IEEE Life Sciences Technical Community and Publications Co-Chair, and a Member Representative of the IEEE Communications Society on the IEEE Biometrics Council. He had been awarded the several Outstanding Leadership and Outstanding Service Awards by the IEEE Communications Society and several best papers awards. He has been the General Chair and a TPC Chair of many international conferences, including the IEEE ICC, GLOBECOM, and HEALTHCOM. He is the Editor-in-Chief of the *International Journal of E-Health and Medical Communications* and the *Journal of Multimedia Information System*, and an Editorial Board Member of several high-reputed journals.

RICARDO A. L. RABÊLO received the B.Sc. degree in computer science from the Federal University of Piauí, Brazil, in 2005, and the Ph.D. degree in power systems from the São Carlos Engineering School, University of São Paulo, Brazil, in 2010. His research interests include smart grid, the Internet of Things, intelligent systems, and power quality.

KASHIF SALEEM received the B.Sc. degree in computer science from Allama Iqbal Open University, Islamabad, Pakistan, in 2002, the P.G.D. degree in computer technology and communication from Government College University, Lahore, Pakistan, in 2004, and the M.E. degree in electrical engineering—electronics and telecommunication and the Ph.D. degree in electrical engineering from University Technology Malaysia, in 2007 and 2011, respectively. He took professional trainings and certifications from the Massachusetts Institute of Technology (MIT), IBM, Microsoft, and Cisco. He is currently an Associate Professor with the Center of Excellence in Information Assurance (CoEIA), King Saud University, Riyadh, Saudi Arabia. He has authored or coauthored over 100 papers in refereed international journals and conferences. His research interests include ubiquitous computing, mobile computing, the Internet of Things (IoT), machine-to-machine (M2M) communication, wireless mesh networks (WMNs), wireless sensor networks (WSNs) and mobile ad hoc networks (MANETs), intelligent autonomous systems, information security, and biologically inspired optimization algorithms. He has organized, co-organized, and served as a technical program committee member in numerous renowned international workshops and conferences. He acquired several research grants in KSA, EU, and the other parts of the world. He is an Associate Editor of the *Journal of Multimedia Information System* (JMIS), IEEE Access, *International Journal of E-Health and Medical Communications* (IJEHMC), and *International Journal of Cyber-Security and Digital Forensics* (IJCSDF).

SERGEI A. KOZLOV received the engineering degree (Hons.) in quantum electronics from the Leningrad Institute of Fine Mechanics and Optics (currently ITMO University), Saint Petersburg, Russia, in 1982, and the Ph.D. and Dr. Sci. Phys. and Maths. degrees from the Saint Petersburg State University, Saint Petersburg, in 1986 and 1997, respectively. From 1986 to 2002, he was with ITMO University, Saint Petersburg, as an Engineer, an Assistant Professor, an Associate Professor, and a Full Professor with the Physics Department, Natural Science Faculty, where he has been a Full Professor and the Head of the Photonics and Optoinformatics Department, and the Dean of the Photonics and Optoinformatics Faculty, since 2002. He has also been the Head of the International Institute of Photonics and Optoinformatics, ITMO University, Saint Petersburg, since 2013. He has authored more than 250 articles. His research interests include femtosecond optics and femtotechnologies, nonlinear optics of few-cycle pulses and ultrafast data transmission, terahertz optics and biophotonics, and quantum informatics. He is a member of SPIE and D.S. Rozdestvenskiy Optical Society.