Wireless Personal Communications
https://doi.org/10.1007/s11277-020-07088-6

FreeBW-RPL: A New RPL Protocol Objective Function for Internet of Multimedia Things

Hadjer Bouzebiba[1] · Mohamed Lehsaini[1]

Abstract
Most of the current research has been restricted to scalar sensor data based IoT applications. However, today's research and development activities rely on multimedia-based services and applications while this kind of applications has several requirements in terms of storage, bandwidth, latency, etc. Furthermore, protocols dedicated to IoT applications have proved their weakness in multimedia environments. Hence, a new paradigm called internet of multimedia things (IoMT) has been proposed to fulfill the requirements of multimedia applications. In this paradigm different multimedia things can interact and cooperate with each other over the Internet. Moreover, IETF ROLL working group standardized an IPv6 routing protocol for low-power and lossy networks (RPL for LLNs) for resource constrained devices. In this paper, we propose an enhanced version of RPL for IoMT called free bandwidth (FreeBW)-RPL in which the sensed data is essentially provided by multimedia devices. FreeBW-RPL protocol proposes a new objective function called FreeBW that takes the FreeBW calculation in the network layer. We set the QoS routing challenge as the amount of the bandwidth while selecting the routing path in order to measure the maximum FreeBW so as to deliver better performance of the multimedia applications. Simulations have been conducted over COOJA simulator. The obtained results proved that our proposal outperforms the basic ones in terms of end-to-end delay, throughput, packet delivery ratio and energy consumption and provides better performance than other protocols.

Keywords FreeBW-RPL · IoT · IoMT · IPV6 · RPL · LLNs · Network layer · QoS · OF

1 Introduction

With the explosive growth of smart devices, mostly called smart things which can interact with the physical environment and communicate with other things via Internet in so called 'internet of things' (IoT) world [1, 2]. These physical objects or things can significantly

✉ Mohamed Lehsaini
m_lehsaini@mail.univ-tlemcen.dz

Hadjer Bouzebiba
hadjer.bouzebiba@univ-tlemcen.dz

[1] STIC Laboratory, University of Tlemcen, Chetouane, Algeria

Published online: 17 January 2020

affect our lives by having the capability to communicate with other devices such as sensors, actuators, mobile phones, home automation devices and smart grid devices [3, 4].

With the same definition as IoT system, internet of multimedia things (IoMTs) is considered as an interconnection of multimedia objects in which they are able to acquire multimedia contents from the real world being equipped with multimedia devices [5]. Moreover, with the growth of this type of smart devices, the tendency of IoMT applications become much more important recently by getting involved in many fields such as smart homes, smart health, smart vehicles, smart cities... etc. This diversity may bring new stringent requirements than the IoT environment, mostly due to the increase of multimedia content in the network. The multimedia content can refer to a combination of two or more different media contents such as text, audio, image, video, etc. [5], by giving a mixture of real time and non-real time applications. For example, some surveillance cameras in a smart home application record images and audio at once or a complete video scenario of what happening up there. Recent studies that have recorded a definite boost in multimedia traffic flow, report that the multimedia traffic specially the video type dominate significantly the IP traffic on the Internet [6]. This kind of traffic called in [7] big-volume-of-data (BVD) multimedia communications in IoMT, which is considered as a limited resource and a complex task to manage.

IoT systems are based on the low power and lossy networks (LLNs) and inherit their constrained resources, making any routing protocol adaptable to limited-resource applications. While meeting the LLNs requirements, the routing protocol for low-power and lossy networks (RPL) [8, 9] is standardized as a routing protocol for the IoT, defined by the IETF working group routing over low power and lossy networks (ROLL). RPL is a proactive distance vector routing protocol that organizes the network into a tree structure called destination oriented acyclic graph (DODAG). In RPL each node selects its preferred parent based on some specific routing policies. The standard employs multiple routing metrics and constraints that are translated into one objective function in aim to select the best path. RPL is characterized by its flexibility to choose the appropriate objective functions as per the application requirements.

Furthermore, wireless communication are known by some limitations such as bandwidth, limit processing units, energy consumption, etc [10]. Besides of these constraints, multimedia streams add more load which exceeds the capability of IoT to satisfy higher bandwidth, memory space, and energy [11]. Projecting these requirements to the routing protocols result in a necessity to have an efficient routing protocol that endures QoS mechanisms of IoMT applications. Therefore, most of the routing protocols proposed in IoT doesn't appear adequate to satisfy the multimedia constraints because of the stringent requirement of QoS parameters such as bandwidth, delay and packet loss rate [12]. Among these protocols, we cite RPL protocol which has been well-known in IoT networks, but few research tried to improve it objectively for IoMT applications. Several issues remain open to improve some routing protocols that guarantee sets of QoS requirements of constrained networks.

An important challenge for supporting multimedia applications in IoT is the bandwidth limitation available on the internet [13]. The available bandwidth estimated in most of works relies on the implementation of the QoS aware protocol using cross-layer design. In other words, the MAC layer estimates the available bandwidth along the paths and the routing layer routes information according to the bandwidth required by applications [14]. Available bandwidth may be used to analyze the network performance, as it can be used for the applications which require large bandwidth by improving it QoS of multimedia services and video streaming over a network [15]. Moreover, the available bandwidth have been addressed in multiple prior studies however, and to the best of our knowledge no RPL objective function implementation have been proposed in order to calculate the effective bandwidth in the network layer. Therefore, and after getting inspired on how is it important to know whether a path can provide enough of free available bandwidth before routing a multimedia flow.

In this paper, we design a new QoS aware objective function based on free bandwidth in an enhanced version of RPL protocol called FreeBW-RPL. Our proposed routing protocol chooses a preferred parent by considering the free space of the maximum bandwidth (BW) proposed around its neighborhood during the whole network path (from the source node to the sink node). The FreeBW-RPL optimization have been based on requirement of the smart home monitoring in aim to drive a large amount data flow. Furthermore, FreeBW-RPL distributes the traffic load in the network and borrows in dynamic way several paths for routing the heavy traffic by creating energy-balanced paths. In our study, we present an end-to-end free-bandwidth based on a proactive routing protocol (RPL) for a prototype of Internet of Multimedia networks. After intensive simulations, we concluded that FreeBW-RPL protocol maintains the best data-forwarding path comparing it to the default RPL's objectives functions.

The remainder of this paper is organized as follows. Section 2 provides background information and an overview about the RPL protocol. Section 3 surveys the related work. Section 4 describes our proposed FreeBW-RPL protocol specification. Section 5 discusses in details the FreeBW-RPL protocol performance evaluation and discussion. Finally, we conclude this paper in Sect. 6.

2 Overview of RPL Routing Protocol

RPL [8] is a distance vector routing protocol that operates in top of both of the IEEE 802.15.4 PHY and MAC layers. RPL builds a tree shape topology known as directed acyclic graph (DAG) composed of one or more sink nodes; in a case of one single root, it is called a destination oriented directed acyclic graph (DODAG). The sink node can be also known as LLN border router (LBR) when it acts like a bridge between the LLN and Internet. With its robust topology over lossy links, RPL updates the routing information in order to maintain network state information. RPL supports different types of traffic such as multipoint to point (M2P), point to multipoint (P2M) and point to point (P2P).

A node may belong to multiple RPL instances in the same network able to be run concurrently, and each instance is identified uniquely by RPL_InstanceID. RPL instance consists of one or more DODAGs using an independents root, which helps to satisfy multiple QoS of IoT applications. Each node own a rank value, which is increased in a downward direction that helps it to maintain its position and relation with other nodes in the DODAG. The construction of the DODAG is based on the objective function (OF) which deploys a set of routing metrics to build the DODAG based on algorithms or calculation formula. As well, the OF optimizes the path costs according to the intended application requirements, for example the IoMT requirements are more constrained than the IoT's one. The process of building the DODAG structure begins at the root node by broadcasting a control message named DAG information object (DIO). This kind of messages contains some configuration parameters (such as the DODAG roots identity, routing metrics, as well as the rank) needed to build the topology. Once the neighboring nodes receive DIO message, the node that tends to join the DODAG exploits the provided information in the DIO message by adding the sender of the DIO message to its candidate parent list. After computing its own rank based on the objective function (OF), it selects one of parents list as its preferred parent. After that, the node transmits the DIO message with the updated information to its neighbors and repeats the same process until all nodes will possess an upward route to forward the traffic towards the root. In a case that a joined node may receive more than one DIO message, it has to select even to process the received DIO message (improve its position to a lower rank according to the objective function) or discard it. Another type of ICMPv6 control message named DAG information solicitation (DIS) which is provided by the node that does not receive a DIO message. It requests the neighbors for a DIO message. In addition to that, RPL specifies a mechanism for applications requiring downward traffic from the gateway to a node wherein a node sends a destination advertisement object (DAO) control message as a unicast packet in aim to create a reverse path information.

3 Related Work

Several issues are still open for more improvement and specification in internet of multimedia things. Thereby, actually routing a multimedia content using RPL protocol in a required environment such as the IoMT networks is still a challenging task due to the difficulty of meeting certain levels of QoS. Moreover, the transmission of this required type of data is more bandwidth hungry when comparing it to the conventional scalar data traffic in IoT networks [6]. Considering RPL as an IoT routing protocol, it is characterized by it flexibility to not restrict any routing metrics nor parameter settings during the routing selection process [8]. In other words, IETF ROLL working group did not require any specific usage of objective function which makes RPL highly adaptable as per the application and network requirements for IoMT systems.

Numerous surveys have focused on the core of RPL and its deployment in various environments so as to shed light its characteristics and limitations [16–18]. Another RPL review was presented in [9] where authors provided a comprehensive review about the diferents RPL application domain and challenges. However, the survey in [19] gives a large focus on the existing objective functions by highlighting the advantages and the shortcoming of each studied solution by giving a comparative study of the existing OFs also a classification of the used metrics. Another survey [20] that presented the most relevant routing solutions for LLNs networks by identifying the requirements and the most issues studied by the current routing protocols proposed for IoT scenarios, in particular the RPL enhancements.

Moreover, several optimizations in RPL taking the QoS as routing metrics have been studied, such as [21–23] when each of these works tried to satisfy a specific QoS. Starting by [21], authors derived from the conventional RPL's OF "minimum rank with hysteresis objective function (MRHOF)", a new OF called OFQS to be compliant of the RPL supporting the multi-instance approach. The OFQS is based on multi-objective metrics taking into account the delay and the remaining energy of the battery nodes alongside with the quality of link. In [22], the authors measured the RPL performance in terms of the quality of service parameters such as the packet delivery ratio, the network convergence time, the remaining energy, the latency and the control traffic overhead. These QoS measurements were done using Cooja simulator and Wireshark network analyzer. In another work [23] which authors used several QoS properties as metrics such as the delay and the energy, in which an enhanced RPL protocol for IoT environment has been proposed named E-RPL. The E-RPL reduced the routing overhead in the network, besides it improves the energy consumption and end-to-end delay be compared with the existing RPL OFs (OF0 and MRHOF).

Another proposed RPL extension named clustered additive RPL (CA-RPL) [24] which applies a clustering technique to achieve network scalability. The proposed technique selected the cluster head basing on the battery power and the connectivity degree of a node. The simulation results show an outperforming of the proposed approach CA-RPL when comparing it with the conventional RPL approaches. Another approach is presented in [25], where authors aimed to optimize the performance of RPL under mobility by proposing a game theory based mobile RPL (GTM-RPL). The game theory method has found an optimal solution for routing by using a mobility metric and a density metric which depends on specific application parameters. The mobility is monitored via received signal strength indication (RSSI) readings. Results showed an improved performance of RPL under mobility in terms of energy consumption, throughput and end to-end-delay. The advantage of GTM-RPL is that even in the presence of a mobile environment, nodes can cover large areas and communicate in an efficient and reliable manner.

Accordingly, some approaches proposed some enhancements of RPL in order to fulfill the challenges imposed by the IoMT networks such as [26, 27]. In [26], authors designed a QoS aware objective function (OF-FL) based on fuzzy logic that combines set of metrics like ETX, hop count, end-to-end delay and battery level. The proposed OF-FL uses fuzzy parameters that allow the configuration of the routing decision. This protocol improves packet delivery rate (PDR), delay and energy consumption compared to the standardized OF (MRHOF and OF0). However, the behavior of the proposed objective function is the same whether it carries a normal data packet or a critical event data packet. Additionally, in [27] authors proposed an enhanced version of RPL protocol named Green-RPL in which they aim to minimize carbon footprint emission and energy consumption by ensuring the QoS requirements. Green-RPL protocol relies on a set of metrics used along the path towards the root that are the delay, battery consumption and types of energy source. Simulation results show that Green-RPL protcol outperforms OF0 in energy efficiency and number of successful packet transmissions; though ETX outperforms Green-RPL protocol in terms of energy efficiency but not in number successful packet transmissions. Another enhancement of the RPL protocol which considers the remaining energy of nodes when routing the IoT traffic is proposed in [28]. The proposed method was compared with ETX-based RPL in which experimental results showed an improvement in terms of the network lifetime, while the proposed method consumed nearly the same as the total energy consumption of ETX based RPL.

IoMT applications require the bandwidth satisfaction as a QoS constraint. In this context, numerous cross-layer routing solutions have been proposed in literature [14, 29–33]. In these solutions, the network layer extracts useful information from the MAC layer about the available bandwidth and by return the source node can easily adapt its sending rate. Moreover some studies in IoMT networks has included a cross layer communication based on physical, data link, network and application layers. The routing protocol proposed in [29] bears high heterogeneity besides of it ability to choose the optimal routing path which exchanges multimedia data. Even though, they included the security bit in the frame in order to recognize the authenticated data. The bandwidth estimation mechanism were used in AODV protocol to get a new QoS routing protocol named AQA-AODV [30]. This protocol relies on link and path available bandwidth estimation mechanisms. Besides of an adaptive scheme that can help source node get informed about the current network state and whose main purpose is to adjust the transmission rate according to the application QoS requirements.

Authors in [14] proposed a link capacity estimation scheme based on a novel passive available bandwidth estimation by considering the back-off and retransmission information. Moreover authors in [31] proposed an on-demand routing protocol called M-QoS-AODV with a multichannel MANETs based on a distributed channel assignment scheme. In [32], authors proposed a QoS-aware AODV routing-based admission control (QAODV-AC) which achieves a cross layer cooperation between IEEE 802.11 MAC and AODV-QoS routing protocol. They take into account as a value of available bandwidth estimation the variable of saturation throughput of IEEE 802.11 MAC. Another technique in [33] includes the IEEE 802.11 MAC layer parameters in computing the available bandwidth.

In another case and more particularly, the bandwidth can be considered as an achieving requirement for the benefit of the total power consumption [34]. In this work, the authors proposed a cooperative multi-path routing (CMPR) in order to save power consumption while ensuring the bandwidth constraint and designed a heuristic CMPR algorithm that constructs energy-efficient node-disjoint cooperative multi-path routing. An enhancement of RPL named power controlled RPL (PC-RPL) protocol [35] which adaptively controls the routing topology via transmission power and received signal strength indication (RSSI) threshold of individual nodes in order to improve the delivered bandwidth and fairness by achieving a better throughput.

The aforementioned research have largely depend on some useful information extracted from the MAC layer in order to estimate the available bandwidth. In which it can lead to some network performance degradation such as the exchanged amount of overhead caused by the exchanged messages between different layers, more energy resource and security breaches. However, to the best of our knowledge, none of these research have employed the estimation of free bandwidth in the network layer, as a basic objective function in RPL protocol. Exceptionally in [32] where the idea of FreeBW was implicitly looked but it was not discussed more deeply besides it was not dedicated for RPL nor for the multimedia IPv6 routing process. Our proposed enhanced protocol FreeBW-RPL is dedicated for routing large information sensed from an IoMT's environment, without depending on information collected from the MAC layer.

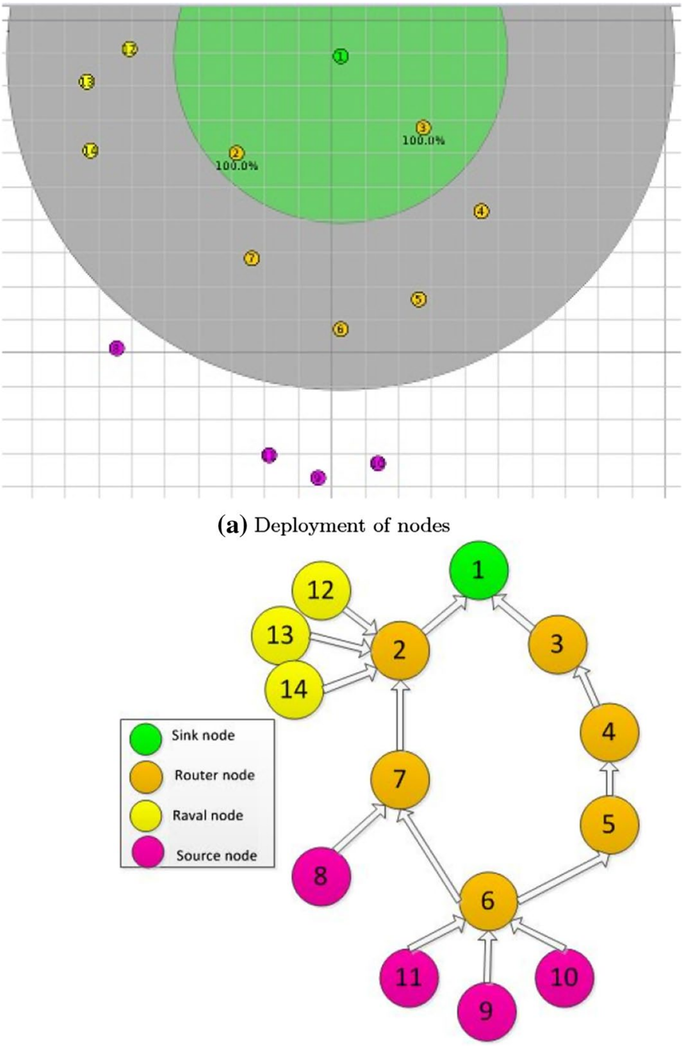
4 FreeBW-RPL Protocol

The ideal channel condition has been pointed in some research such as [36] when comparing to the raw channel bandwidth, that it cannot be saturated by the maximum throughput and that may still be far below to the maximum capacity of bandwidth and this may depend significantly on the change average of packet length during the transmission. Therefore, from this result we can dedicate that the effective estimation and the good management of the bandwidth in the network should take into account the amount of packet sent.

In this section, we discuss about our FreeBW-RPL protocol improvement by giving more insight about the network scenario and the proposed objective function called free bandwidth.

4.1 Network Model

We consider an IoMT static network with a fixed number of nodes (14 nodes) including the DAG root; where the RPL nodes are organized in the following Fig. 1a, b. The root is suitably considered as static node and it is linked to the Internet gateway. Nodes in the network are running the FreeBW-RPL protocol, more precisely the data routing relies on the free-bandwidth objective function.



(b) Network generated

Fig. 1 Scenario of the routing process

4.2 QoS Aware of Based on Free Bandwidth

The bandwidth metric, in the network layer, means the allocated bandwidth between the different nodes in the network provided for an IoMT' service.

In our proposition, we respect the general concept of the bandwidth calculation in the lower layers such as the MAC layer. In which in QoS design, it is considered that any constrained service requires high bandwidth in each link between the different nodes in the network. Indeed, any emission of packet can have an impact on the available bandwidth by reducing the amount of free bandwidth in this link. Therefore, we propose FreeBW-RPL protocol by creating a new objective function (OF) named free bandwidth. The main idea is to find an optimal path by selecting the maximum free bandwidth in the whole path (from source to sink). We illustrate in Fig. 2a, b an example for the bandwidth selection in the entire routing path. Once node (C) or (D) want to send a DIO message, it should choose the minimum value between its bandwidth value and its parent's value in order to keep track of this minimum value for the descendant nodes. Once node (E) receives this DIO message from both (C and D) with two different minimum values (3, 2) respectively, it must take the maximum bandwidth value between it and select them as Best_parent. Subsequently, upon the send operation (broadcast of DIO message), node (E) will eventually send the updated DIO to the neighbors with the maximum value of the free bandwidth received in the whole path which is 3, as illustrated in Fig. 2b.

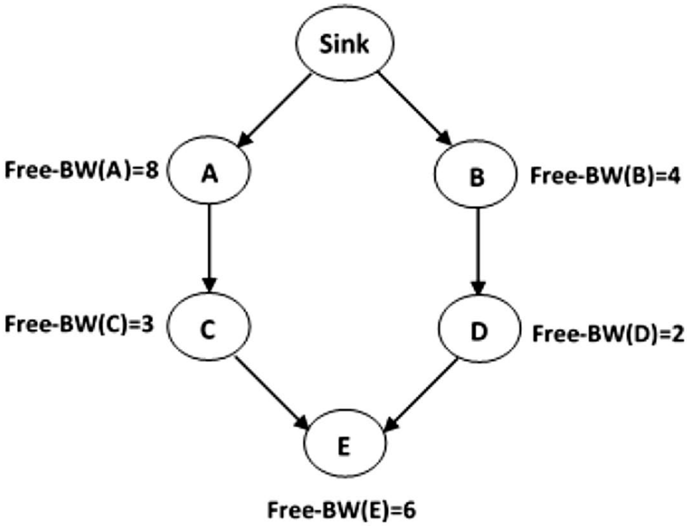
The value of the free bandwidth is calculated according to the Eq. 1 wherein $Link_{Rate}$ depends on mote characteristics and represents the total amount of packet supported by the channel, and $Send_{Rate}$ represents the bandwidth usage during the routing process. In addition, Algorithm 1 illustrates the computing of the free bandwidth (described in the next Sect. 4.3).

$$Free\ bandwidth = Link_{Rate} - Send_{Rate} \tag{1}$$

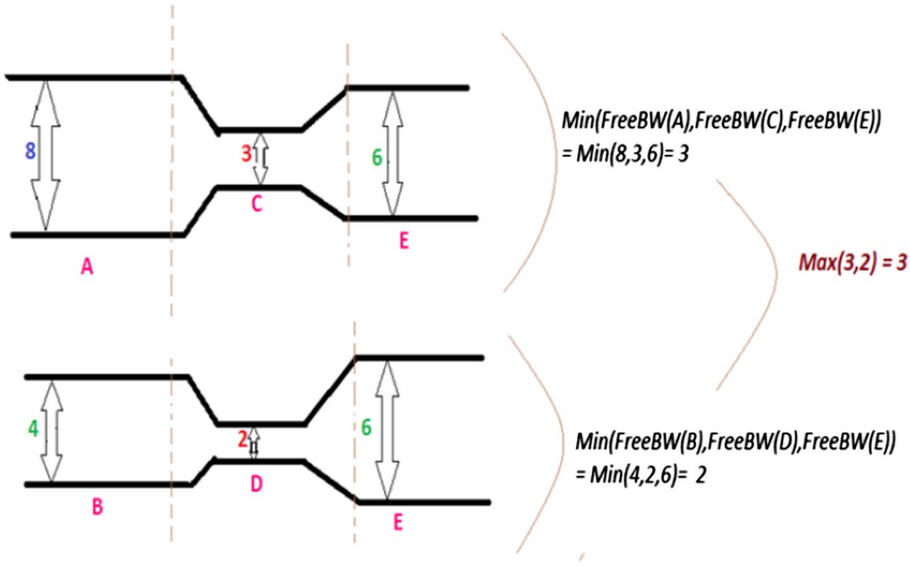
In addition, we tried in our proposed scenario (depicted in Fig. 3 to saturate node 2 by putting 3 sender nodes in order to see how will be the choice of the routing path selected by each of the OFs: ETX, Energy, None and our proposed FreeBW-OF. As shown in Fig. 3, once the usual path chosen by the default OFs is congested, FreeBW-OF chose the non-congested one by switching into the blue colored path by choosing another preferred parent. Thus, we can deduce that our proposed FreeBW-OF depends on a multipath choice during the routing process by giving more load balance to the network.

4.3 FreeBW-RPL Algorithm

Our FreeBW-RPL protocol includes new mechanism that calculates the free bandwidth in a distributed manner. Each RPL router listens to the DIOs messages from neighboring nodes. After that, it processes the DIO parameters such as OF and parent_rank. When a RPL router receives the first DIO message, it adds the DIO sender ID to the parent list and selects directly the sender as the best parent. Otherwise, it joins the parent that provides the higher free bandwidth in the whole path from the selected parent to the sink. Then, it computes its rank by using the BW objective function. Before the broadcast operation of the updated DIO message, the sending node should compare its own minimum free bandwidth (FreeBW) to the one already maximized (best parent's



(a) Bandwidth selection in the entire routing path



(b) Detailed example for the bandwidth selection

Fig. 2 Bandwidth selection

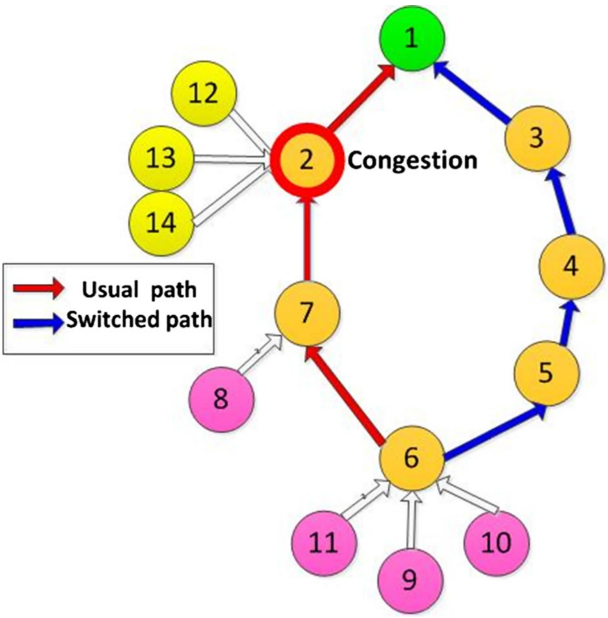


Fig. 3 Usual path chosen by ETX, ENERGY and NONE Vs switched path by FreeBW-OF

FreeBW). Eventually, these new parameters will be transmitted in new DIO message to the neighbors. This process is illustrated in Algorithm 1.

Algorithm 1 : FreeBW-RPL protocol optimization

Begin
Receive DIO;
Process DIO (get parameters from DIO buffer)
- Candidate.path_metric = dio.path_metric
- Candidate.parent_id = dio.node_id

if Best_parent == NULL **then**
  Add the DIO sender as a candidate parent ;
  $Best\_parent.path\_metric = candidate.path\_metric$;
  $Best\_parent.id = candidate\_parent.id$
else
  $Diff = abs(Best\_parent.path\_metric - candidate.path\_metric)$;
  - Min_diff is used to maintain stability of the preferred parent choice
  if $(Diff > Min\_diff)$ **then**
    $best\_parent = Max(candidate.path\_metric, Best\_parent.path\_metric)$;
  end if
end if
- Update DIO parameter;
$dio.path\_metric = Min(Best\_parent.path\_metric, FreeBW)$
$dio.node\_id = current\_node.id$
Broadcast DIO;
End

5 FreeBW-RPL Performance: Evaluation and Discussion

5.1 Working Environment

We evaluated the performance of FreeBW-RPL protocol by extending its code under COOJA Network simulator [37], in order to illustrate the impact of the new free bandwidth OF on different aspects of IoMT systems characteristics. COOJA is considered as an emulator because it tests exactly the binary code of a class that would run on real hardware of IoT nodes known as Z1 motes running Contiki operating system [38]. Moreover, it gives us full flexibility in evaluating radio environments and topologies. For the radio propagation model, we use unit disk graph model: distance loss [39].

In our simulation network, we used two scenarios: in the first one we included 14 nodes over a square space (100 m × 100 m); node 1 is a sink node located at the edge of the network and in the second, we implemented the scalability in several network scenarios comprising from 10 to 50 nodes in which the source node varied from 3 to 10 nodes. The nodes are arranged as depicted in Fig. 1b. The radio communication range is 50 m. Five levels of traffic rates, i.e., (1 pkt/s, 2 pkt/s, 3 pkt/s, 4 pkt/s and 5 pkt/s) has been considered in the simulation with a data size of 50 bytes. In the second scenario, we varied the size of network from 10 to 50 with a data size of 100 bytes and a data rate 5 pkts/s. Finally, the simulation duration was lasted for 300 s. The remaining simulation' parameters are summarized in Table 1.

5.2 Performance Metrics

We evaluate the routing performance of the defaults OFs of RPL protocol and our proposed FreeBW-RPL protocol in terms of packet delivery ratio (PDR), end-to-end delay, throughput and energy Consumption.

- *Packet delivery ratio (PDR)* PDR is defined as the ratio of the number of received packets to the number of sent packets.

Table 1 Simulation parameters

Parameters	Values
Network simulator	COOJA under Contiki OS (2.7)
Radio environment	Unit disk graph medium (UDGM)
Emulated nodes	Z1
Network area	100 m × 100 m
Number of nodes	10, 14, 20, 30, 40, 50
Number of sink nodes	1
Number of source nodes	3, …, 10
Transmission range	50 m
Total frame size	127 bytes
Data packet size	(50, 100) bytes
Traffic rate	1, 2, 3, 4 and 5 pkts/s
Simulation time	300 s

- End-to-end delay: The end-to-end delay (packet delay) is another evaluation metric used for measuring the total time taken by packets in order to be successfully delivered from a source node to the sink node.
- *Throughput* Throughput is the amount of bytes received by the sink node to the whole value of time needed by the packets from its send time till the end of simulation. These bytes come from the data packets. Throughput is calculated as:

$$Throughput\,(KB/s) = \frac{\sum size\,(received_{packet}) * Count\,(received_{packets})}{duration\ of\ simulation} \tag{2}$$

- *Energy consumption* In order to compute the energy consumption of the network, we use a novel technique of software named Powertrace which is a available tool in Contiki [38]. This tool tracks the power state by estimating the energy consumption for CPU processing, CPU in a low power mode, packet transmission and listening. As well, the power trace mechanism provides CPU, low power mode (LPM), radio listen and radio transmit values; which gives the total time consumed in each power trace interval. The total energy consumption is computed according to the Eq. 3. Moreover, we take the average percent radio represented by average power consumption (APC) on time of each type of nodes (source, routers and servers) during the whole network setup according to Eq. 4.

$$Energy\ consumption = \sum_{i=1}^{n} (LPM + CPU + RadioListen + RadioTransmit) \tag{3}$$

$$APC = \frac{\sum_{i=1}^{n} (LPM + CPU + RadioListen + RadioTransmit)}{n} \tag{4}$$

where n represents the number of nodes

- *Energy consumed per packets received* We measured a new evaluation metric by calculating the energy consumed for the total amount of the packets received successfully following Eq. 5. The results of this metric is depicted in Fig. 8c.

$$Energy\ consumed\ per\ packet = \frac{Power\ consumption}{Amount\ of\ packets\ successfully\ received} \tag{5}$$

5.3 Simulation Results and Discussion

In order to study the impact of data transmission rate on the network behavior, we varied data rate from 1 to 5 packets per second and measured PDR, end-to-end delay, throughput and energy consumption.

5.3.1 Packet Delivery Ratio

The simulation results in Fig. 4 show that the packet delivery ratio of the new OF (free bandwidth) is better than the RPL OFs (ETX, Energy and NONE). The main reason for that is that FreeBW-RPL protocol has more effective mechanism than RPL with its defaults OFs, in which it avoids the congested path by switching the path into a new parent node which provides a path with higher Free-BW. This mechanism allows the packet flow to

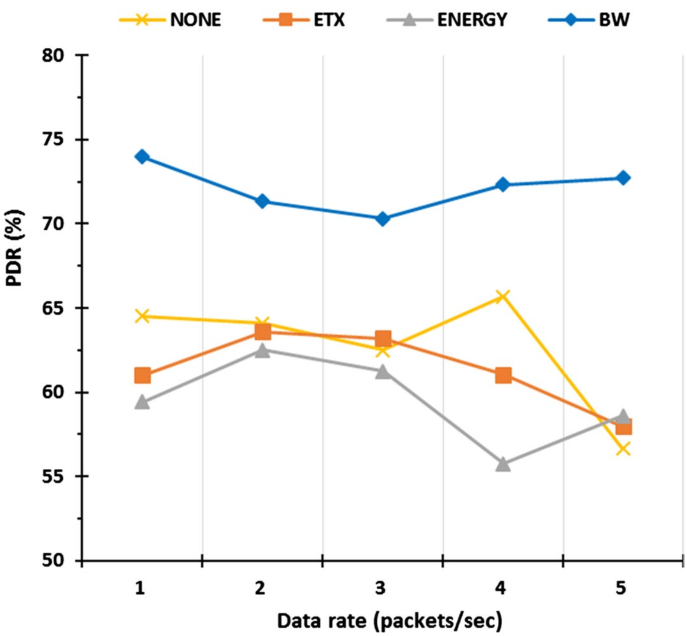


Fig. 4 Packet delivery ratio versus data rate

find an alternative path by gaining more chance to get delivered and not to be overlapped with other packets comparing to the congested path, leading into a higher success of packet delivery. Moreover, FreeBW-RPL protocol is shown to be the most effective protocol to transfer packet with a difference of PDR rate (11%, 12,5%, 9,5%) higher than ETX-OF, Energy-OF and None-OF) respectively, and this can be arguing that with this new protocol FreeBW-RPL the network is more reliable.

Figure 5 depicts our second scheme which comprises from 10 to 50 nodes, by evaluating the PDR in terms of the scalability of nodes. The evaluated OFs behave in the same way by showing a decrease in PDR since the number of nodes increases, and this due to the increment rise expansion of packet collision that takes the same path. By giving a chance to the packets to avoid the congested path and switch to the less one, the FreeBW-RPL shows better results in terms of PDR comparing to the default OFs.

5.3.2 End-to-End Delay

As shown in Fig. 6 RPL with OFs (ETX, Energy and NONE) has the highest delay because they doesn't take into account the Free BW which leads the packets to go through the congested path by taking more delay in the queue list waiting to get served. Whereas FreeBW-RPL has lower delay than the default RPL OFs. And this mainly because of the switching mechanism used by FreeBW-OF, once the node confront a congested link it tries to find another parent in order to switch the path to a less congested link. Therefore, the time taken by a source's packet to be forwarded until the sink node using the FreeBW-OF is less than the one taken by the other OFs. Indeed, because all OFs (ETX, Energy and None) are executed under the same context, keeping the same congested path with minimum hop account, in most cases with a congested link, which must have more time to transmit and

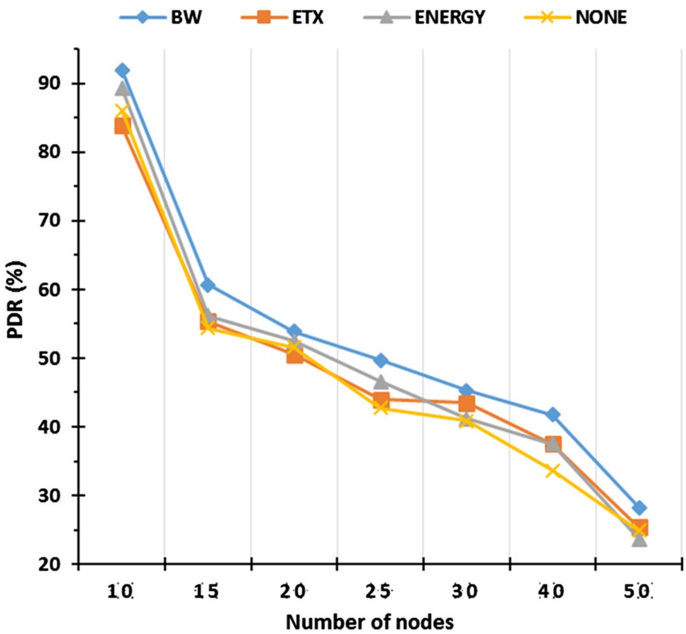


Fig. 5 Packet delivery ratio versus number of nodes with data rate=5 pkts/s

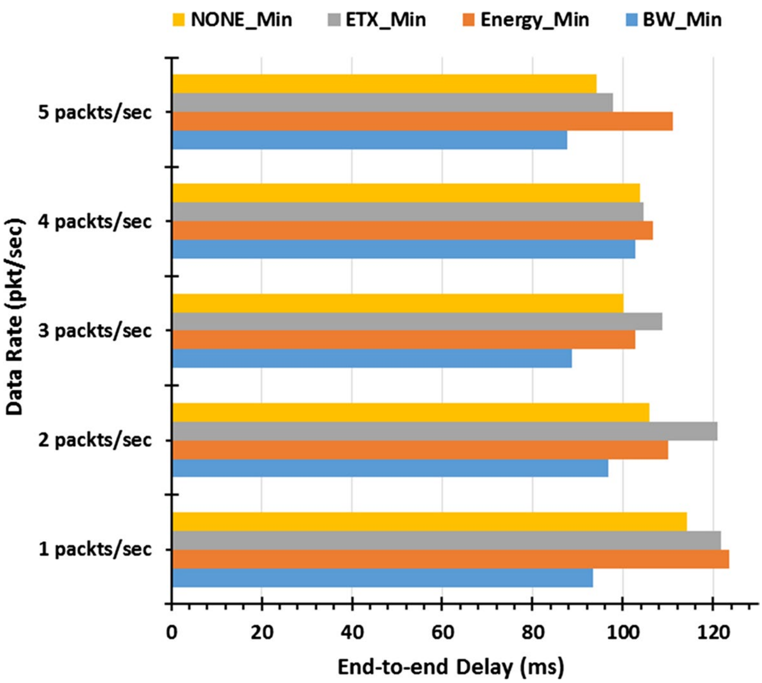


Fig. 6 End-to-end delay versus data rate

causes higher delay. In both send rate (2 and 4 pkts/s) the delay of FreeBW-OF increases, otherwise the delay reaches its minimum values which makes the data rates (1, 3, 5 pkts/s) are the best rates in terms of delay. ETX and Energy OFs have the highest delay, and for the overall OFs they reached their minimum delay at the data rate (3 pkts/s).

5.3.3 Throughput

Figure 7 shows one of the main advantages of FreeBW-OF. FreeBW-OF guarantees an enhanced amount of network throughput regarding to other OFs(ETX, Energy and None). Indeed, all of the OFs measured decreases when the data packet rate is increasing. Therefore, we can explain that with the increase of data packet rate, there are gradually more data packets transmitting in the network, leading to network congestion and making network throughput decrease. Despite of this decrease, the reason behind the advantage superiority of the throughput given by the FreeBW-OF is that our new OF relieves the network congestion by finding an alternate path less congested with the maximum free bandwidth when sending the packet, thus it increases the average network throughput.

5.3.4 Energy Consumption

In order to estimate the network lifetime with FreeBW-OF, we compared FreeBW-OF with ETX-OF, Energy-OF and None-OF in term of power consumption over time in a network composed of a single DAG.

Figure 8a presents the average power consumption of two distinct nodes that belong to two different paths. The first path (6 → 7 → 2) is used by all of the OFs (ETX, Energy

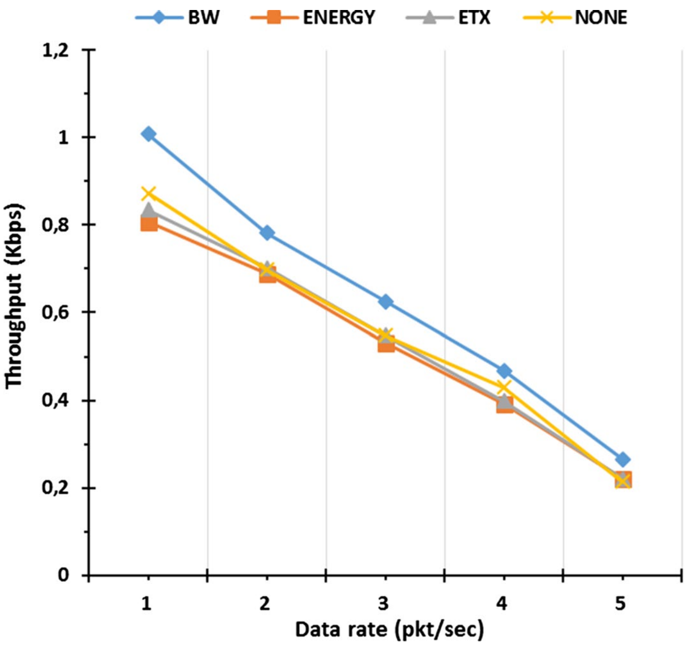
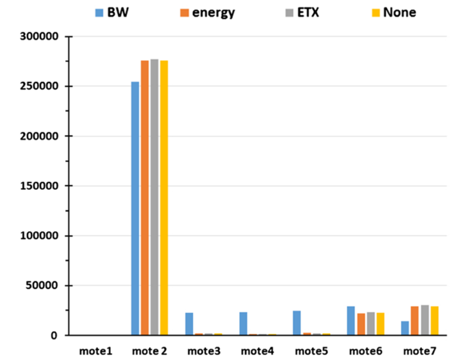
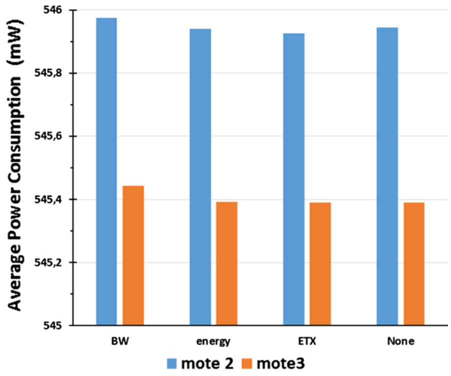


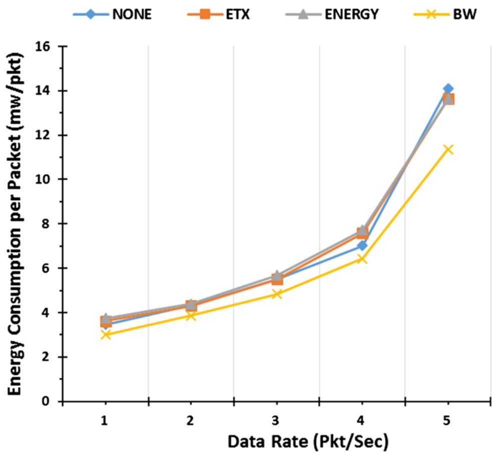
Fig. 7 Throughput versus data rate



(a) Energy consumption for the server and routers



(b) APC for motes 2 & 3



(c) Energy consumed per packet

Fig. 8 Energy consumption (mw)

and None) and the second one (6 → 5 → 4 → 3) is switched dynamically by the FreeBW-OF (we note that these results have been dedicated from the simulation output). From the results, we observe that routing a packet through congested regions may consume more energy than the less congested one. We notice in Fig. 8a that FreeBW-RPL consumes nearly 50% less energy when compared to RPL's OFs. The reason behind the energy consumption of FreeBW-OF is that BW consumes more CPU's energy because it requires more resources in terms of calculation.

Similarly, in Fig. 8b we measure the energy consumed by the closest nodes to the sink (2 and 3) of the two paths chosen by the different OFs. Due to these results referring to Fig. 1, it's much clear that the routed packet takes the path (6 → 7 → 2) while using the RPL's OFs (ETX, Energy, None) whereas it switches the path into (6 → 5 → 4 → 3) when using RPL's FreeBW-OF. Thereby, this could be explained that once the node (2) receives a packet overload it will consume more power and may exhaust the node's energy consumption, in which our proposed protocol FreeBW-RPL takes an advantage in this case by switching the path and balancing the routing charge better than the other RPL OFs.

Another evaluation metric is illustrated in Fig. 8c, in which we tried to evaluate the energy consumed by the successful received packets. It is also shown that FreeBW-OF consumes less energy than ETX-OF, Energy-OF and None-OF. We chose this type of evaluation metric because our network is not a dense network (14 nodes) and we tried to follow the behavior of our proposed OF once it behaves differently than the other OFs of RPL.

As a result, the FreeBW-RPL manages well the network's resources in term of a load balancing, CPU and energy consumption as clearly shown in Fig. 8a.

5.4 Comparative Results

Due to the influence of both of the send rate and the network density values on the IoMT network performance, we provide in this section a comparison between our proposed OF and some recent works which are dedicated to enhance the RPL protocol basing on their objective function, illustrated in Table 2.

The first set of analysis investigated the impact of both of data rate and network density on the PDR. After adjusting our simulation parameters following two comparative works, the first in [40] where the data rate is equal to 1pkt/2sec, 1pkt/5sec and 1pkt/10sec, with network density equal 20, 30, 40 nodes during 900 s of simulation time. The second adjustment were similar to [41] by considering a 30 nodes network size while keeping the same data rate. Interestingly, our proposed FreeBW-OF revealed remarkable results in terms of PDR better than the previous works [40, 41]. The authors in [40] have tended to focus on the performance of both RPL's OFs (OF0 and MRHOF) by fixing the network density and varying the sending intervals whereas the authors in [41] have obtained the PDR results through the test-bed experiments by analyzing the performance of their enhanced routing protocol for low and lossy networks (ERPL), which aims to enhance the peer-to-peer route construction and the data packet forwarding in both of the RPL's operation modes. In our second comparison, we notice how the PDR of our proposed FreeBW-OF decreases when the density of the network increases from 10 to 50 nodes, meanwhile, it provides better PDR performance than the new RPL extension for QoS and congestion-aware (QCOF) defined in [42]. Another findings have confirmed the effectiveness of our proposed FreeBW-OF, in which we have used the same simulation parameters assumed in [43] such as the data rate which has been varied between 2 pkt/min, 3 pkt/min and 6 pkt/min with payload size of 16 Bytes during 600 s of simulation time. Our FreeBW-OF has an advantage in terms of packet drop ratio comparing to the fuzzy logic objective function (OFFL) investigated in [43]. In this comparison, the packet drop ratio results of the FreeBW-OF reflects much higher values of the packet delivery ratio compared to the ones found by the OFFL. The comparison of our results to the above mentioned works proves that our proposed OF (FreeBW-OF) allows a formal solution to the QoS requirements of the IoMT networks while providing satisfactory network performance.

6 Conclusion

In this paper, we proposed a novel QoS aware RPL routing protocol for internet of multimedia things (IoMT) with a new objective function named free bandwidth (FreeBW-OF). Our proposed FreeBW-OF allows to select the best forwarding candidate based on the maximum free bandwidth provided from the ascending nodes. Besides of that, the actual free bandwidth takes place at each hop and along all paths, from the source to the

Table 2 Comparison of FreeBW-RPL with others protocols related to the impact of varying the send rate and network size on the RPL performance

Protocol	Performance parameters								
	Packet delivery ratio								
	N = 20			N = 30			N = 40		
	PPS = 2	PPS = 5	PPS = 10	PPS = 2	PPS = 5	PPS = 10	PPS = 2	PPS = 5	PPS = 10
FreeBW-RPL	80.01%	94.88%	98.86%	76.89%	89%	97.72%	68.20%	81.93%	92.05%
MRHOF + OF0 [40]	39%	92%	96%	38%	50%	95%	18%	40%	82%
ERPL [41]	Packet delivery ratio								
	Testbeb results			Network size: N = 30					
				PPS = 2		PPS = 2		PPS = 10	
				70%		75%		80%	
	Packet delivery ratio								
	N = 10		N = 20	N = 30		N = 40		N = 50	
FreeBW-RPL	92.01%		53.9%	45.28%		41.73%		28.22%	
QCOF [42]	16%		17%	18%		20%		22%	
	Packet drop ratio								
	Network size: N = 50								
	PPM = 2 pkts/min			PPM = 3 pkts/min			PPM = 6 pkts/min		
FreeBW-RPL	5%			6%			8%		
OFFL [43]	72%			60%			45%		

destination node (sink). Meanwhile, FreeBW-OF can reduce the congestion problem by switching to a less congested path. We shown, based on experimental evaluation using Cooja, that our FreeBW-OF can reach better results comparing to the default OFs of the RPL protocol in terms of packet delivery ratio, end-to-end delay, throughput and energy consumption. Most of these satisfied evaluation metrics were previously considered as an essential challenge in IoMT networks. Our results can promote the gourmet applications such as IoMT's applications.

In a further proposed approach, instead of combining two routing metrics in an additive manner, we would rather propose an optimized version of the FreeBW-OF during the calculation of the available link capacity (bandwidth) and this is mainly leads to a short path with a maximum free bandwidth optimization. In addition, we intend to improve our proposed OF by taking in consideration the hop account, energy consumption. Besides, it would be interesting to address the application of FreeBW-OF in heterogeneous networks where two types of applications can be deployed: real and non-real applications. Additional tests can be performed to verify the efficiency of the proposed FreeBW-OF through experimental testbeds deployed in realistic scenarios.

References

1. Tan, L., & Wang, N. (2010). Future internet: The internet of things. In: *2010 3rd international conference on advanced computer theory and engineering (ICACTE)* (Vol. 5, pp. 376–380). https://doi.org/10.1109/ICACTE.2010.5579543.
2. Ma, H.-D. (2011). Internet of things: Objectives and scientific challenges. *Journal of Computer Science and Technology*, *26*(6), 919–924. https://doi.org/10.1007/s11390-011-1189-5.
3. Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer Networks*, *54*(15), 2787–2805.
4. Aggarwal, C. C., Ashish, N., & Sheth, A. (2013). *The internet of things: A survey from the data-centric perspective* (pp. 383–428). Boston: Springer. https://doi.org/10.1007/978-1-4614-6309-2_12.
5. Floris, A., & Atzori, L. (2015). Quality of experience in the multimedia internet of things: Definition and practical use-cases. In: *IEEE international conference on communication workshop (ICCW)*, 2015 (pp. 1747–1752). https://doi.org/10.1109/ICCW.2015.7247433.
6. Alvi, S. A., Afzal, B., Shah, G. A., Atzori, L., & Mahmood, W. (2015). Internet of multimedia things: Vision and challenges. *Ad Hoc Networks*, *33*, 87–111. https://doi.org/10.1016/j.adhoc.2015.04.006.
7. Wang, Q., Zhao, Y., Wang, W., Minoli, D., Sohraby, K., Zhu, H., et al. (2017). Multimedia iot systems and applications. *Global Internet of Things Summit (GIoTS)*, *2017*, 1–6. https://doi.org/10.1109/GIOTS.2017.8016221.
8. Winter, T., Thubert, P., Clausen, T., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., & Vasseurr, J. (2012). *RPL: IPv6 routing protocol for low power and Lossy networks*. Technical report, RFC 6550, IETF ROLL WG.
9. Kharrufa, H., Al-Kashoash, H. A., & Kemp, A. H. (2019). RPL-based routing protocols in IoT applications: A review. *IEEE Sensors Journal*, *19*(15), 5952–5967.
10. Wang, J., Liu, Z., Shen, Y., Chen, H., Zheng, L., Qiu, H., et al. (2016). A distributed algorithm for inter-layer network coding-based multimedia multicast in internet of things. *Computers & Electrical Engineering*, *52*, 125–137. https://doi.org/10.1016/j.compeleceng.2015.11.026.
11. Said, O., Albagory, Y., Nofal, M., & Raddady, F. A. (2017). IoT-RTP and IoT-RTCP: Adaptive protocols for multimedia transmission over internet of things environments. *IEEE Access*, *5*, 16757–16773. https://doi.org/10.1109/ACCESS.2017.2726902.
12. Huang, X., Xie, K., Leng, S., Yuan, T., & Ma, M. (2018). Improving quality of experience in multimedia internet of things leveraging machine learning on big data. *Future Generation Computer Systems*, *86*, 1413–1423. https://doi.org/10.1016/j.future.2018.02.046.
13. Elshafeey, A., Elkader, N. S., & Zorkany, M. (2017). Compressed sensing video streaming for internet of multimedia things. *International Journal of Cyber-Security and Digital Forensics*, *6*(1), 44–53.

14. Zhao, P., Yang, X, Yu, W., Dong, C., Yang, S., & Bhattarai, S. (2014). Toward efficient estimation of available bandwidth for IEEE 802.11-based wireless networks. *Journal of Network and Computer Applications*, *40*, 116–125. https://doi.org/10.1016/j.jnca.2013.08.005.
15. Chaudhari, S. S., & Biradar, R. C. (2015). Survey of bandwidth estimation techniques in communication networks. *Wireless Personal Communications*, *83*(2), 1425–1476. https://doi.org/10.1007/s11277-015-2459-2.
16. Kim, H.-S., Ko, J., Culler, D. E., & Paek, J. (2017). Challenging the IPv6 routing protocol for low-power and lossy networks (RPL): A survey. *IEEE Communications Surveys & Tutorials*, *19*(4), 2502–2525.
17. Zikria, Y. B., Afzal, M. K., Ishmanov, F., Kim, S. W., & Yu, H. (2018). A survey on routing protocols supported by the Contiki Internet of things operating system. *Future Generation Computer Systems*, *82*, 200–219.
18. Ghaleb, B., Al-Dubai, A. Y., Ekonomou, E., Alsarhan, A., Nasser, Y., Mackenzie, L. M., et al. (2018). A survey of limitations and enhancements of the IPv6 routing protocol for low-power and lossy networks: A focus on core operations. *IEEE Communications Surveys & Tutorials*, *21*(2), 1607–1635.
19. Lamaazi, H., & Benamar, N. (2020). A comprehensive survey on enhancements and limitations of the RPL protocol: A focus on the objective function. *Ad Hoc Networks*, *96*, 102001.
20. Sobral, J. V., Rodrigues, J. J., Rabêlo, R. A., Al-Muhtadi, J., & Korotaev, V. (2019). Routing protocols for low power and lossy networks in internet of things applications. *Sensors*, *19*(9), 2144.
21. Nassar, J., Berthomé, M., Dubrulle, J., Gouvy, N., Mitton, N., & Quoitin, B. (2018). Multiple instances QoS routing in RPL: Application to smart grids. *Sensors*, *18*(8), 2472.
22. Charles, A. S. J., & Kalavathi, P. (2018). QoS measurement of RPL using Cooja simulator and Wireshark network analyser. *International Journal of Computer Sciences and Engineering, 6*(4), 283–291.
23. Zier, A., Abouaissa, A., & Lorenz, P. (2018). E-RPL: A routing protocol for IoT networks. In *IEEE global communications conference (GLOBECOM)*. IEEE, pp 1–6.
24. Mishra, S. N., & Chinara, S. (2019). CA-RPL: A clustered additive approach in RPL for IoT based scalable networks. In *International conference on ubiquitous communications and network computing* (pp. 103–114). Springer.
25. Kharrufa, H., Al-Kashoash, H., & Kemp, A. H. (2018). A game theoretic optimization of RPL for mobile internet of things applications. *IEEE Sensors Journal*, *18*(6), 2520–2530.
26. Gaddour, O., Koubâa, A., & Abid, M. (2015). Quality-of-service aware routing for static and mobile IPv6-based low-power and lossy sensor networks using RPL. *Ad Hoc Networks*, *33*, 233–256. https://doi.org/10.1016/j.adhoc.2015.05.009.
27. Alvi, S. A., Shah, G. A., & Mahmood, W. (2015). Energy efficient green routing protocol for internet of multimedia things. In *2015 IEEE tenth international conference on intelligent sensors, sensor networks and information processing (ISSNIP)* (pp. 1–6). https://doi.org/10.1109/ISSNIP.2015.7106958.
28. Mortazavi, F., & Khansari, M. (2018). An energy-aware RPL routing protocol for internet of multimedia things. In *Proceedings of the international conference on smart cities and internet of things* (p. 11). ACM.
29. Rani, S., Ahmed, S. H., Talwar, R., Malhotra, J., & Song, H. (2017). IoMT: A reliable cross layer protocol for internet of multimedia things. *IEEE Internet of Things Journal*, *4*(3), 832–839. https://doi.org/10.1109/JIOT.2017.2671460.
30. Castellanos, W. E., Guerri, J. C., & Arce, P. (2016). A QoS-aware routing protocol with adaptive feedback scheme for video streaming for mobile networks. *Computer Communications*, *77*, 10–25.
31. Zhou, J., Liu, L., Deng, Y., & Huang, S. (2014). A QoS routing protocol with bandwidth allocation in multichannel ad hoc networks. *Wireless Personal Communications*, *75*(1), 273–291.
32. Zhu, H., & Chlamtac, I. (2006). Admission control and bandwidth reservation in multi-hop ad hoc networks. *Computer Networks*, *50*(11), 1653–1674. https://doi.org/10.1016/j.comnet.2005.06.014.
33. Sarr, C., Chaudet, C., Chelius, G., & Lassous, I . G. (2008). Bandwidth estimation for IEEE 802.11-based ad hoc networks. *IEEE Transactions on Mobile Computing*, *7*(10), 1228–1241. https://doi.org/10.1109/TMC.2008.41.
34. Xu, H., Huang, L., Qiao, C., Zhang, Y., & Sun, Q. (2012). Bandwidth-power aware cooperative multipath routing for wireless multimedia sensor networks. *IEEE Transactions on Wireless Communications*, *11*(4), 1532–1543. https://doi.org/10.1109/TWC.2012.020812.111265.
35. Kim, H., Paek, J., Culler, D. E., & Bahk, S. (2017). Do not lose bandwidth: Adaptive transmission power and multihop topology control. In *2017 13th international conference on distributed computing in sensor systems (DCOSS)* (pp. 99–108). https://doi.org/10.1109/DCOSS.2017.23.
36. Zhu, H., & Chlamtac, I. (2005). Performance analysis for IEEE 802.11 e EDCF service differentiation. *IEEE Transactions on Wireless Communications*, *4*(4), 1779–1788. https://doi.org/10.1109/TWC.2005.847113.

37. Osterlind, F., Dunkels, A., Eriksson, J., Finne, N., & Voigt, T. (2006). Cross-level sensor network simulation with COOJA. In *Proceedings of 2006 31st IEEE conference on local computer networks* (pp. 641–648). https://doi.org/10.1109/LCN.2006.322172.
38. Dunkels, A., Gronvall, B., & Voigt, T. (2004). Contiki—A lightweight and flexible operating system for tiny networked sensors. In *29th annual IEEE international conference on local computer networks* (pp. 455–462). https://doi.org/10.1109/LCN.2004.38.
39. Clark, B. N., Colbourn, C. J., & Johnson, D. S. (1990). Unit disk graphs. *Discrete Mathematics*, *86*(1), 165–177. https://doi.org/10.1016/0012-365X(90)90358-O.
40. Mardini, W., Aljawarneh, S., Al-Abdi, A., & Taamneh, H. (2018). Performance evaluation of RPL objective functions for different sending intervals. In *6th international symposium on digital forensic and security (ISDFS)* (pp. 1–6). IEEE.
41. Farooq, M. O., & Pesch, D. (2019). Reduced overhead routing in short-range low-power and lossy wireless networks. *Sensors*, *19*(5), 1240.
42. Aissa, Y. B, Grichi, H., Khalgui, M., Koubâa, A., & Bachir, A. (2019). QCOF: New RPL extension for QoS and congestion-aware in low power and Lossy network. In *14th international conference on software technologies* (pp. 560–569).
43. Safaei, B., Monazzah, A. M. H., Shahroodi, T., & Ejlali, A. (2018). Objective function: A key contributor in internet of things primitive properties. In *Real-time and embedded systems and technologies (RTEST)* (pp. 39–46). IEEE.

Hadjer Bouzebiba holds an academic master's degree in computer science, networks and distributed systems option, at the University of Tlemcen (Algeria) in 2015. Currently, she is member of the research laboratory STIC (Information and Communication Technology Systems) located at the science faculty of Tlemcen University (Algeria) where she has been preparing since the end of 2015 a doctoral thesis on Internet of Multimedia Things. She is author of scientific communications on this topic.

Mohamed Lehsaini received his Ph.D. (2009) from the University of Franche-Comté, France and the University of Tlemcen, Algeria. In June 2013, he was awarded the ''Habilitation à Diriger des Recherches'' (HDR) from Sidi Bel-Abbes University, Algeria. Since 2000, he is a professor at the University of Tlemcen, Algeria, and since 2015, he is the Head of the research STIC Laboratory (Information and Communication Technology Systems) located at the University of Tlemcen. His current research interests include Vehicular Communications, Ad hoc and Sensor Networks, Internet of Things, Internet of Multimedia Things, Wireless and Mesh Networks, Distributed systems, Security in Networks and Performance evaluation. He is the author/coauthor of several research papers in national and international conferences and journals. He is member in several research projects, reviewer in several international conferences and journals.