A Comprehensive Study of multicast Routing Protocols in the Internet of Things

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Abstract. IP multicast is a desired communication feature in the Internet of Things (IoT) as it provides noticeable resource savings, especially for Low-power and Lossy Networks (LLNs). Indeed, multicast allows cost-, energy-, and time-efficient networking for a multitude of LLN applications ranging from over-the-air programming and information sharing to device configuration and resource discovery. In this context, several multicast routing protocols have been recently proposed for LLNs including Stateless multicast RPL Forwarding (SMRF), Enhanced SMRF (ESMRF), Bi-Directional multicast Forwarding Algorithm (BMFA), and multicast Protocol for LLNs (MPL). Nevertheless, each protocol has been evaluated under different conditions, topologies, and traffic flow, which prevents making comprehensive comparisons of their characteristics and performance. In this paper, we provide an overview of recent LLN multicast protocols followed by a multidimensional performance evaluation of the most popular ones to extract their advantages and drawbacks under different traffic conditions, routing scenarios, and network topologies. Obtained results from extensive realistic simulations using Cooja show that, although each protocol is dominant under specific conditions, MPL remains the best in terms of packet delivery ratio in all scenarios at the expense of extra energy consumption, which requires new resources-aware multicast solutions for the IoT.

Keywords: Internet of Things · IP multicast · MPL · SMRF · ESMRF · BMFA

1 Introduction

The Internet has now connected the whole world starting from mainframes and servers to personal devices and objects. This is become possible thanks to the massive explosion of low-cost smart objects in our lives along with their inevitable connection to the global Internet to offer unprecedented opportunities and services in a multitude of fields, including smart healthcare, smart agriculture, and smart surveillance. Such opportunities have given rise to the so-called Internet of Things (IoT). The things in the IoT are made up of sensors and/or actuators that perform a specific function and they are part of an infrastructure allowing the transport, storage, processing, and access to gathered data [4].

Such objects, however, usually operate under limited resources in terms of energy, computation, storage, and bandwidth.

These constraints impose strict challenges on all the layers of the TCP/IP networking stack, especially at the network layer, which needs to provide efficient routing protocols adapted to the constraints of this environment. Depending on the need, we have two main types of routing, the first is unicast and the second is multicast. Unicast is the most used mode for data exchange and it is fulfilled by the recently standardized Routing Protocol for Low-power and Lossy Networks (RPL) [12]. Nevertheless, other real-world IoT functionalities and applications, such as network configuration, resource discovery, and security management would be better served by efficient multicast routing protocols like SMRF [9], ESMRF [1], and MPL [7]. This mode of IoT routing is still challenging, under active research, and is the main focus of this paper.

In order to guide future work and optimize the use of object resources within multicast routing protocols a comprehensive study of their performance should be conducted. Currently, and to the best of our knowledge, no quantitative comparison is available in the IoT literature. Therefore, we conducted this work to provide the research community with such insights.

The remainder of this paper is organized as follows. Section 2 gives a background on representative multicast routing protocols in the IoT, details their operations, and discusses their features. This is followed by the design of our comprehensive study in Section 3, and the discussion of the obtained results under different network settings in Section 4, respectively. The paper ends in Section 5 with a conclusion and ideas for future research.

2 Background on multicast routing in the IoT

IP multicast is a form of diffusion of IP datagrams from a transmitter (single source) to a group of interested receivers in a single transmission [3, 6]. Each group is identified by a single multicast address that is used as a destination address by each host that is member of the group, as shown in Fig. 1. This technique allows the efficient use of bandwidth and energy and prevents duplicate transmissions [2]. Multicast routing is very different from unicast and hence more challenging. First, the source sends the traffic to a group of dynamic receivers. To reach all the members, the multicast delivery path must create multiple branches across the network to build a distribution tree. Second, the source address plays an important role in the creation of the distribution tree, hence multicast routing paths are generally shaped by the source, instead of the destination. Third, multicast routing, generally, relies on a unicast routing protocol to optimize

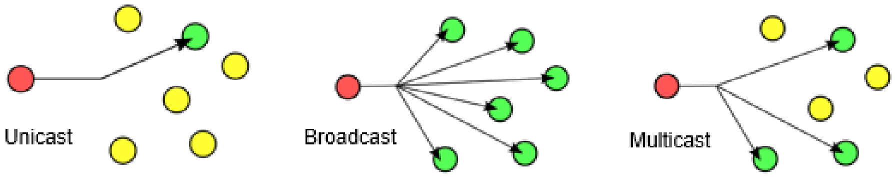

Fig. 1. IP packet routing primitives

generated overhead. These challenges are intensified taking into account the limitations of IoT devices.

There are several multicast routing protocols proposed in the IoT, which usually follow one of the two basic modes: dense or sparse, with the dense mode as the most deployed one. Indeed, all the prominent Iot multicast solutions discussed below fall under this class. Nevertheless, they differ w.r.t. the dependence on the unicast routing protocol (RPL), as shown in the taxonomy of Fig. 2.

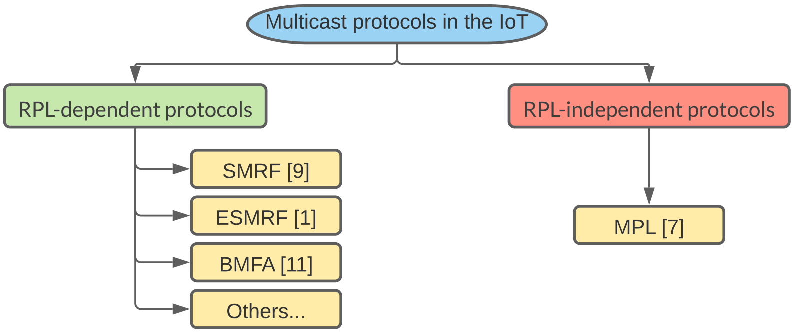

Fig. 2. Taxonomy of multicast protocols in IoT.

2.1 RPL-Independent Multicast

There is only one IoT multicast routing protocol falling under this category, namely the Multicast Protocol for Low-Power and Lossy Networks (MPL), which was standardized in 2016 by RFC 7731 [7]. MPL avoids the need to build or maintain a multicast topology, by broadcasting messages using the Trickle algorithm [8] to all MPL forwarders in an MPL Domain. The protocol presents a proactive and a reactive mode of operations along with blind flooding. It should be noted that reactive and proactive modes can be enabled simultaneously [7].

In the proactive mode, if a MPL Seed (source node) wants to transmit a multicast message in an MPL domain, it generates an MPL Data Message. If the destination address is different from the MPL Domain Address, IP-in-IP tunneling is used to encapsulate the multicast message in an MPL Data Message, preserving the original IPv6 destination address. Upon receipt of an MPL Data Message, the MPL Forwarder extracts the MPL Seed ID and message sequence number and determines whether the message has been received previously based on the MPL Seed Set and the Buffer Messages Set for a given MPL domain. If the sequence number is less than a lower bound kept in the MPL Seed set or if a message with the same sequence number exists in the Buffer Message set, the MPL Forwarder marks the MPL Data Message as old. If not, the message is marked as new and it updates the MPL Seed set, adds the MPL data message to the Buffer Message set, and performs its processing and multicast of the message.

In the reactive mode, a MPL Forwarder periodically broadcasts information contained in the MPL Seed set and the Buffer Message set of a MPL domain to the local neighbors using MPL Control Messages. MPL Forwarder determines whether or not there are new MPL data messages that have not yet been received by the control message source, and multicasts these MPL data messages.

2.2 RPL-Dependent Multicast

In this category, a multitude of solutions have been proposed. The following subsections detail the most deployed ones.

Stateless multicast RPL Forwarding: Stateless multicast RPL Forwarding (SMRF) is a lightweight stateless multicast forwarding algorithm presented as an alternative to MPL for RPL networks [9]. It uses RPL's storage mode of operation with multicast support (MOP 3) [10], and works on the basis of RPL parent information and multicast group membership. Thus, parent nodes are supposed to know the multicast group addresses of their children and make entries for those advertised multicast group addresses in their routing tables.

With SMRF, multicast traffic can only flow downward in the Destination Oriented Directed Acyclic Graph (DODAG). The root of the RPL network is the only node capable of generating a multicast message. The other nodes only accept multicast packets received from their preferred parent in the DODAG tree. Subsequently, the node checks if it is a member of the multicast group indicated in the received packet, if so, it processes the multicast packet in its network stack. In the end, instead of blindly forwarding all datagrams to all nodes, and based on the information provided by the RPL, the node checks if there is at least one child node interested in this traffic to forward the packet, if not it drops it. Multicast datagrams in SMRF will only reach those parts of the network that have expressed interest in the flow by joining a multicast group.

Enhanced SMRF: Qorany and al. [1] proposed an improvement of the SMRF protocol in their Enhanced SMRF (ESMRF) protocol that supports bidirectional multicast traffic flows downward and upward in the DODAG. The main idea of ESMRF is that sources of multicast traffic encapsulate their packet in an ICMPv6 delegation packet and send it to the root of the RPL tree, which transmits the multicast packet on behalf of the original source.

Bi-Directional multicast Forwarding: Georgios and al. [11] proposed Bi-directional multicast Forwarding Algorithm (BMFA) for RPL based netowrks. In order to support bidirectional traffic and avoid routing loops, BMFA uses the 20-bit flow label of the IPv6 header. A node will accept an incoming message if the Link Local address (LLA) of this message is the LLA of the preferred RPL parent or the LLA of one of its children, and if and only if the value of the flow label in the IPv6 header does not contain its own LLA. BMFA also uses the information provided by the RPL group membership system.

In BMFA, a source can use flow label to tag a packets for which the source requests a special treatment by IPv6 nodes. For example, a source may require a default quality of service or a real-time service. The disadvantage of BMFA is that it is impossible to uses the flow label in a non-standard way and hence might prevent interoperability. Table 1 summarizes the main objectives, strengths, and weaknesses of the studied protocols.

Table 1. Summary table of the studied multicast routing protocols.

Protocol	Objectives	Strengths	Weaknesses	Year
MPL [7]	-Ensure multicast data transmission in LLNs without maintaining a routing table.	-Ensures retransmission of packets in case of loss and provides a high delivery rate thanks to the buffering principle. -Maintains network consistency and ensures reliability. -Fast update and adaptation to network mobility and density.	- Can cause communication overhead due to retransmission of lost packets also control packets consumes resources. -Low device storage capacity can limit buffer size, resulting in reduced performance. -High end-to-end latency.	2016
SMRF [9]	-Lightweight algorithm for multicast data transmission based on RPL.	-Reduced resource consumption. -Easy and simple to implement and understand. -Transfer messages in the right order.	-Only allows multicast transmission downwards. -No retransmission mechanism in case of loss.	2013
ESMRF [1]	-SMRF enhancement to enable upstream and downstream multicast data transmission.	-Resolves the SMRF gap by allowing upward multicast traffic.	-Monitors communication by using the root node to route all multicast traffic. -May result in high end-to-end latency. -Additional control messages.	2015
BMFA [11]	-An alternative solution to improve the SMRF to ensure upward and downward packet delivery.	-Bidirectional. -Reduced consumption of resources. -No additional control messages.	-No retransmission mechanism -Misuse of the IPv6 Flow field	2017

3 Experimental Design and Tools

To achieve the objectives of this study we evaluate the performance of the studied multicast routing protocols using the Contiki operating system. Contiki is a lightweight open source operating system designed for the IoT, which includes the kernel, libraries, program loader and a set of processes, developed by the Swedish SICS research team designed for the resource-constrained device [5]. We perform the simulations using the Cooja simulator.

3.1 Experimental protocol

In order to compare the performance of the studied protocols, it is necessary to measure them under the same conditions in different scenarios. We studied the performance of the protocols with the variation of the parameters shown in the Table 2. The reception probability is a configurable simulation parameter that defines the probability of receiving a transmitted message from a neighbor.

Table 2. Comparison parameters.

parameter	Range of variation
Reception probability	[0.2, 1.0]
Number of senders	{1, 2, 4, 8, 16}
Number of nodes	{25, 50, 100, 400}

For the simulations where we study the effect of varying the loss rate, the number of sources and the number of members, we used a topology with 100 nodes of type Z1 and a density of 9. Concerning the variation of the number of nodes, we used 4 topologies: 25, 50, 100 and 400 nodes with a density of 3, 6, 9 and 16 respectively, the simulation setup and approximate current consumption of the Z1 mote are shown in Table 3.

Table 3. Simulation setup.

Simulation setup		
Duration		10 minutes
Number of repetitions (RandomSeed)		5 times
Transmission rate of the multicast source		1 pkt / 40 sec
Network layer protocol (unicast)		RPL - MOP3
MAC		CSMA - MAX_FRAME_RETRIES = 5
PHY & RDC		802.15.4 with CX-MAC
BMFA, SMRF, ESMRF and MPL		Default parameters
Zolertia Z1 hardware features		
IC	**Notes**	**Current Consumption**
CC2420	TX Mode @ 0 dBm	17.4 mA
	RX Mode	18.8 mA
MSP430f2617	Active Mode @ 8MHz	4 mA
	Low-power Mode	0.5 uA

3.2 Comparison criteria

- Energy consumption: the average energy consumption (CPU and radio activity) per node, we use the "energest.h" library and extract the energy consumption in (mW) by the following formula:

$$\frac{ENERGEST\_TYPE \times Current \times Voltage}{RTIMER\_SECOND \times simulation\ \ time} \tag{1}$$

- Packet delivery ratio (PDR):

$$\frac{total\ \ number\ \ of\ \ messages\ \ received}{10\ (messages) \times number\ \ of\ \ members} \tag{2}$$

- End-to-End delay: the average time it takes for a message to be received by all members.
- Number of packets sent: the average number of multicast packets sent by each node.

4 Performance evaluation results

According to the theoretical study, SMRF only works in RPL networks where the DODAG root is the multicast data source, and in this case, SMRF and ESMRF work in the same way. Our study focuses on real cases where the data source is not necessarily the root node. Therefore, we have studied only the ESMRF protocol.

4.1 Variation of the reception probability

In this experiment, We varied reception probability in the interval [0.2, 1.0]. Fig. 3 present the obtained results.

As can be seen in this figure, when the reception probability is equal to 0.2, all protocols except MPL show a decrease in PDR until it reaches about 0. This

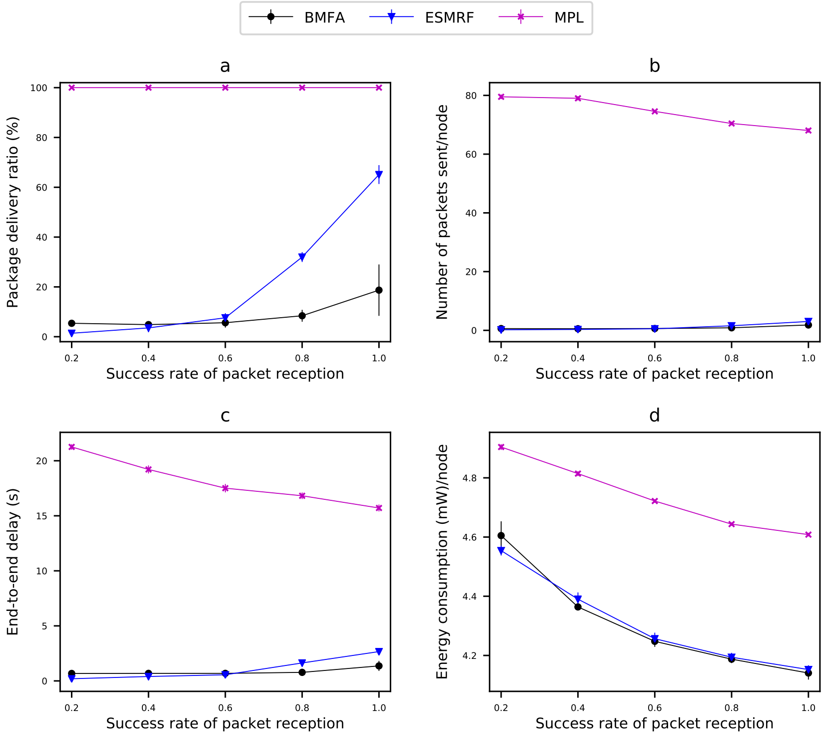

Fig. 3. Variation in message reception probability.

is because MPL, unlike the others, tries to maintain consistency between nodes in terms of data through a retransmission mechanism implemented using the trickle algorithm. To ensure this functionality, MPL needs a higher number of multicast messages sent than other protocols, and with the decrease of packets reception probability more packets are lost, so the number of these messages increases and the End-to-End delay also increases. On the other hand, ESMRF and BMFA do not have a retransmission mechanism for lost packets. Thus, as the reception probability value decreases, the PDR decreases and more multicast messages are sent, justifying the short end-to-end delay compared to MPL.

4.2 Variation of the density and the number of nodes

This time we tested the behavior of each protocol in four different topologies: 25 nodes desity equal to 3, 50 nodes desity equal to 6, 100 nodes desity equal to 9 and 400 nodes desity equal to 16. Results are depicted in Fig. 4.

In the case of MPL, we notice that with the increase in the number of nodes, PDR remains equal to 100%, and the end-to-end delay increases and this is quite logical. The average number of multicast messages sent by each node in the 25-nodes topology is approximately 62.17 messages, with the increase in the number of nodes and to maintain a PDR equal to 100%, MPL needs more multicast messages, with a topology of 400 nodes, a total of about 30,000 multicast messages sent in the network, or 78 messages per node.

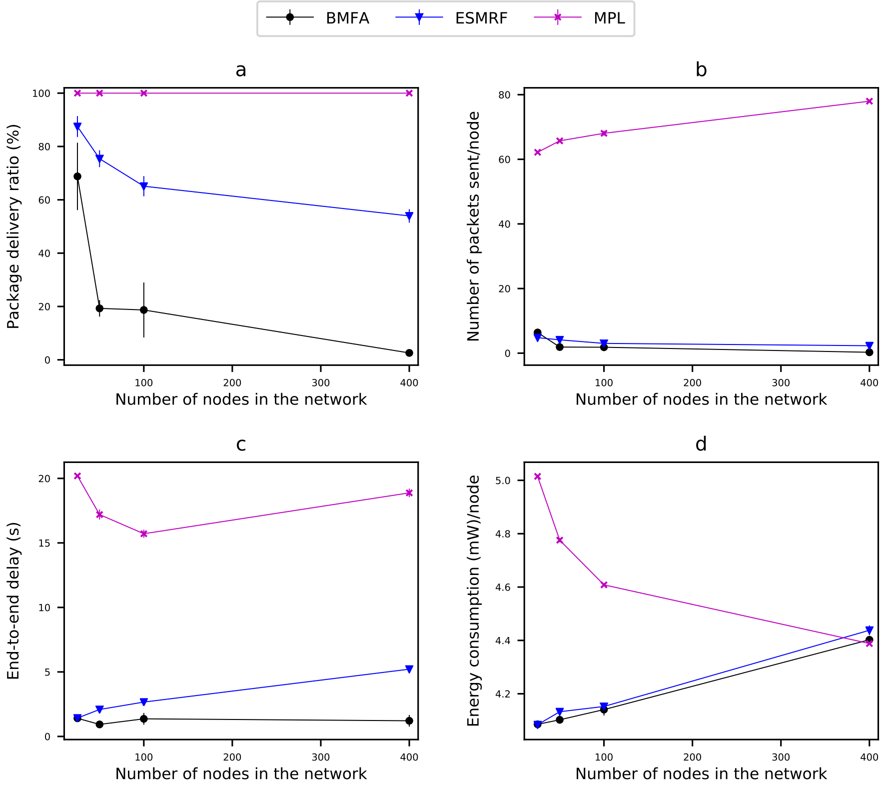

Fig. 4. Variation of the density and the number of nodes.

In the other case, we notice that the other protocols have lost their performance in terms of packet delivery ratio with the increase in the number of nodes, and this is mainly due to the increase in the number of messages sent which generates more collisions and a large part of the messages sent are lost. Noting that BMFA is the weakest protocol, it has the lowest PDR, especially in large topologies.

4.3 Variation in the number of multicast sources

The goal is to study the performance of multicast routing protocols by varying the number of multicast traffic sources from 1 to 16 sources.

With the hardware characteristics of the Z1 mote, we could not increase the number of MPL multicast sources by more than 4 and the messages buffer is equal to 6 messages.

As can be seen in the Fig. 5, MPL with a saddle or multiple sources remains to provide a PDR equal to 100% contrary to the other protocols that they presented a decrease of the latter.

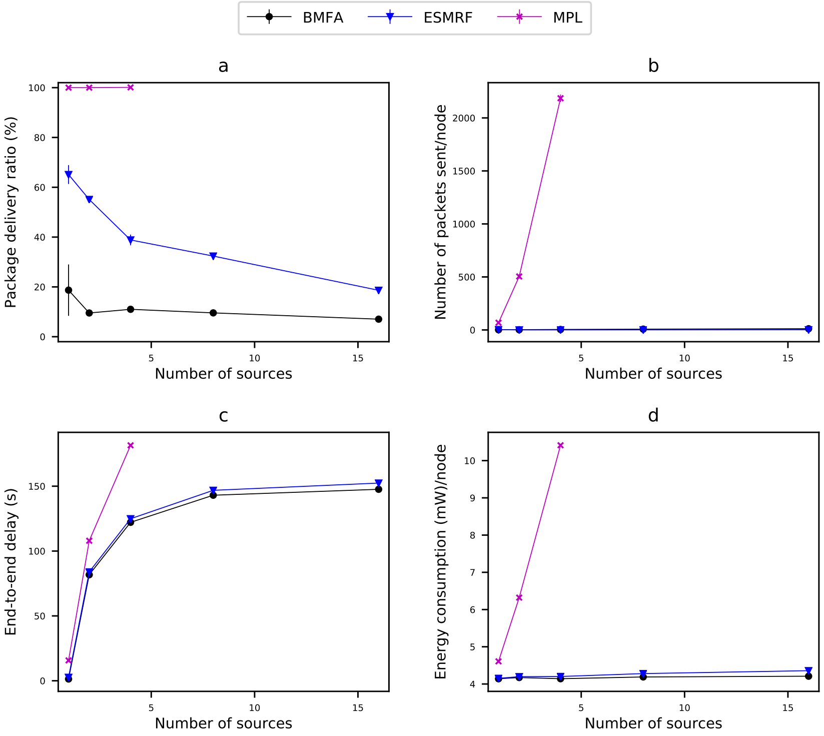

Fig. 5. Variation in the number of senders nodes.

Regarding the number of packets sent in the network, and with only 4 sources and 10 multicast messages sent from each source, MPL achieved over 2185 packets sent per node, which consumes bandwidth and energy of the nodes that are critical constraints in this type of network. The resource consumption in this case is a major drawback of this protocol.

5 Conclusion and future work

In this paper, we analyzed the behavior of the most studied multicast protocols in the literature with respect to several factors that influence their performance. After describing a common comparison metric, we performed extensive simulations for each protocol. The results obtained show that:

1. MPL protocol:
   - Is independent of the unicast protocol used;
   - Was able to maintain a PDR equal to 100% in all scenarios (variation of loss rate, number of nodes, number of senders) which shows the strength of this protocol regarding information delivery;
   - Has a huge consumption of resources, especially energy, network bandwidth and RAM, especially in scenarios where there is a high loss rate, a large number of nodes or multiple multicast traffic streams;
   - Does not support sparse mode.

2. ESMRF and BMFA:
   - They require RPL as a unicast routing protocol;
   - They support the sparse mode by relying on the group member management information provided by the RPL protocol in MOP3;
   - Absence of a control mechanism for packet duplication;
   - ESMRF and BMFA have a lower RDP than MPL, with the increase of the number of nodes or the decrease of the reception probability both protocols and especially BMFA presents a considerable decrease of the PDR what shows the weakness of these protocols in these conditions.

Our future work will focus on the design of a generic multicast routing protocol independent of the unicast protocol used in the network and guaranteeing a good PDR with a reasonable resource consumption, this protocol should support sparse mode.

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