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Mohamed Ghazi Amor

Anis Koubâa

Eduardo Tovar

Mohamed Khalgui

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CISTER Research Center

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail: mhgha@isep.ipp.pt, aska@isep.ipp.pt, emt@isep.ipp.pt

http://www.cister.isep.ipp.pt

Abstract

RPL is the standard routing protocol for the Internet of Things. It is designed for low-power and lossy networks. Several works designed different objective functions for RPL to optimize routing decisions for a particular category of applications. However, these objective functions do not take into account the cyber-physical properties of the environment. In addition, they are tailored to satisfy a particular application requirement (e.g. energy efficiency or delay), so are not adaptive to possible changes of data criticality. This paper improves on the state-of-the-art with the design of a cyber-physical objective function tailored for smart city applications, that addresses the aforementioned gaps. Initial simulation results demonstrate the effectiveness of Cyber-OF in coping with dynamic changes of the criticality of events data and in providing a good performance trade-off between conflicting performance metrics, namely energy.

Cyber-OF: An Adaptive Cyber-Physical Objective Function for Smart Cities Applications

Med Ghazi Amor§ Anis Koubaa§*, Eduardo Tovar§, Mohamed Khalgui ||
§CISTER/INESC TEC and ISEP-IPP, Porto, Portugal
* Prince Sultan University, Saudi Arabia.
|| INSAT, University of Carthage, Tunisia.
Email: (mhgha, aska, emt)@isep.ipp.pt, akoubaa@psu.edu.sa, khalgui.mohamed@gmail.com

***Abstract*—RPL is the standard routing protocol for the Internet of Things. It is designed for low-power and lossy networks. Several works designed different objective functions for RPL to optimize routing decisions for a particular category of applications. However, these objective functions do not take into account the cyber-physical properties of the environment. In addition, they are tailored to satisfy a particular application requirement (e.g. energy efficiency or delay), so are not adaptive to possible changes of data criticality. This paper improves on the state-of-the-art with the design of a cyber-physical objective function tailored for smart city applications, that addresses the aforementioned gaps. Initial simulation results demonstrate the effectiveness of Cyber-OF in coping with dynamic changes of the criticality of events data and in providing a good performance trade-off between conflicting performance metrics, namely energy**

I. INTRODUCTION

The Internet-of-Things (IoT) is increasingly gaining popularity in both academia and industry enabling a large number of applications that integrate both the cyber-world and the digital world, namely the Internet. Gartner predicts that the value add of the IoT by 2020 would reach $1.9 Trillion whereas CISCO estimates to reach 50 billions devices by 2020 [1]. Smart cities is one of the most promising applications of the IoT and according to IoT Analytics, it is considered as the second most popular application in 2015 [2]. One of the most influencing driving factor of the IoT is the development of standard protocols stack that copes with IoT applications requirements in terms of scalability, energy-efficiency, Quality of Service (QoS) and security, including the IEEE 802.15.4 protocol and its variants for lower communication layers, and then its integration to the Internet through the 6LoWPAN initially, and later with RPL routing protocol [3] at the network layer. CoAP and MQTT were proposed as alternatives to HTTP for Internet application layer and transport layer protocols in the IoT.

RPL is a source-based distance-vector routing protocol that was designed for low-power and lossy networks, such as wireless sensor networks. RPL attracted a lot of attention in the literature considering the open design of its objective function that is responsible for shaping the routing decision. Several works (e.g. [4] [5] [6] [7] [8]) have been proposed around the specification of objective functions that improve over those specified in the standard namely OF0 and MRHOF based on ETX metric. However, most of these objective functions adopt a static behavior that intends to optimize either a single-metric or multi-metric objective function without being adaptive to the events data carried out. In addition, the proposed objective functions in the literature do not consider the cyber-physical properties of the environment such as climate conditions, that in the context of a smart city applications, may infer about the criticality of an event (e.g. high temperature would mean a fire event).

To illustrate the problem, consider an RPL-based sensor network for weather and climate conditions monitoring. Typical objective functions would be designed to optimize a certain metric of interest such as energy consumption, or delay, or throughput, or hop count, etc. Some others like in [6] proposed a fuzzy logic objective function that combines several metrics of interest like energy consumption, or delay using fuzzy rules. However, these objective functions would behave exactly the same as if they carry a normal data packet or a critical-event data packet, which might not be appropriate. In fact, in case of normal conditions, it is wiser to focus more on optimizing the energy consumption, however, when a critical event occurs, (e.g. a fire) it would be more appropriate to optimize the end-to-end delay. Thus, an adaptive behavior would fit better this dynamic nature of events in the context of IoT applications in general and smart cities applications in particular. This represents the main motivation of this paper, where we contribute with the design and development of a new objective function that (1) takes into account the cyber-physical properties of the environment, (2) provides an adaptive behavior based on the criticality of the event. We also provide initial simulation results that demonstrate the effectiveness of our approach.

The remainder of the paper is organized as follows. Section II presents an overview of previous works on design of objective functions of RPL and contrast it against the proposed cyber-physical objective function. Section III presents the cyber-physical objective function. Simulation study and performance evaluation are presented in Section IV. Section V concludes the paper and outlines future works.

II. RELATED WORK

Routing metrics and objective functions are the responsible features for the Directed Acyclic Graph (DAG) construction in RPL. However, the standard defined by the IETF in [4] did not impose any routing metric to use. Thus, the parent selection is implementation-specific which makes it an open research issue worth of being investigated. In this section, we briefly review the Objective Functions (OF) proposed in the literature.

Initially, the IETF defined two specifications which describe the default objective function for RPL implemented in Contiki OS, referred to as Minimum Rank with Hysteresis Objective Function (MRHOF) and the OF0.

In [5], MRHOF was proposed. It is an objective function based on the ETX metric which is the number of transmissions a node expects to make to a destination in order to successfully deliver a packet. It uses a metric container to specify the routing objects which are located in a DIO packet. Besides the ETX, MRHOF may be used with any routing metric defined in RFC 6551.

As for the OF0 which is defined by the IETF in [9], it does not consider any routing metric, instead it chooses the neighbor with the minimum rank as the preferred parent. The goal of the OF0 is for a node to join a DODAG Version that offers good enough connectivity to a specific set of nodes.

In [10], the authors defined a new extention for RPL called Co-RPL. It is designed for mobile low power and lossy WSN. Its main purpose is to maintain the connectivity between the nodes while providing QoS guarantees in a mobile network. Their solution is to modify the trickle timer which will depends on the speed and mobility of the node.

In [11], the authors tackled the problem of using one metric to construct the DAG and to optimize paths to the root. They considered four routing metrics for their solution to select the best neighbor. It consists on combining the Hop Count, End-to-End delay, Energy and the ETX (expected transmission count) using an artificial intelligence technique which is the fuzzy logic. This algorithm will convert these links and node metrics into one output value which will decide whether the neighbor parent deserves to be a preferred parent or no.

In summary, when studying the mentioned OFs, we notice that they do not take in consideration the cyber-physical properties of the environment. Therefore, relying on one metric or more in a critical condition (storm, fire, disaster ...) may be inefficient and does not satisfy the requirements of the smart cities application profiles. For example, the use of the hop-count metric in an emergency situation may not choose the fastest way to advertise the network. In addition, the use of one static objective function would not fit the requirements of the same applications having different types of event criticality.

III. CYBER-PHYSICAL OBJECTIVE FUNCTION

We designed the Cyber-Physical objective function (Cyber-OF) to adapt the network tree structure in real-time to the cyber-physical properties of the environment based on the event criticality. In fact, for normal data packets, the objective is to maximize the network lifetime, thus, the objective function optimizes the energy consumption. In case of a critical event, the network should adapt its topology to minimize the end-to-end delays. Therefore, we adopt an adaptive behavior by considering two routing objective functions, each uses a particular metric of interest, namely:

- **Energy Metric:** this metric represents the energy consumption in an RPL node. With this metric, it is possible to extend the network lifetime. It is essential to consider this metric for applications with energy-efficiency concerns.
- **End-To-End delay:** The end-to-end delay is the average time taken by a packet to be sent from node to sink. This metric should be minimized for applications that require real-time guarantees.

The flowchart in the Figure 1 summarizes the operations of the cyber-physical objective function.

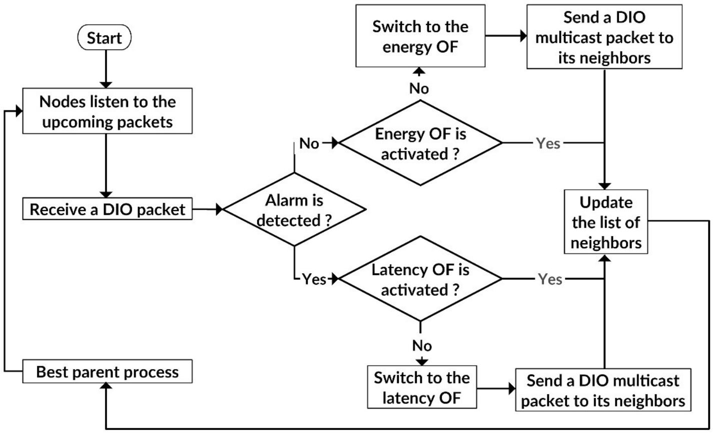

Fig. 1. Flowchart of the Cyber-Physical objective function

First, the objective function (OF) based on the energy metric is activated. Second, RPL switches to the latency OF only if a critical event is detected which will allow RPL to find the stable minimum-latency paths. The metric used by the Cyber-OF is determined by the metrics located in the DIO metric container.

For example, in normal conditions, the objective function maximizes the network lifetime. In case of an emergency situation where a critical event is detected, nodes involved in forwarding this event to the border router must use a new objective function that reduces the end-to-end delays.

Critical events :

In the Smart City context, we can identify several unexpected behaviors due to the chaotic nature of cities.

- **Weather disasters:** Floods , storms and earthquakes are some of the critical events that an automation of weather station system can detect. In these systems the weather measurements should be rapidly transmitted in realtime.
- **Accidents :** The first few minutes after an accident are critical to rescue a human life. That is why the emergency response should be fast and efficient.
- **Fires :**Early detection of fires in cities and urban areas is essential in order to prevent more losses and the spread of fire.

All these emergency situations need an early detection to provide an alarm in realtime and that is the main reason why in this paper we proposed an end-to-end delay as a routing metric in the case of a critical event.

IV. SIMULATIONS AND PERFORMANCE EVALUATIONS

A. *Environmental Setup*

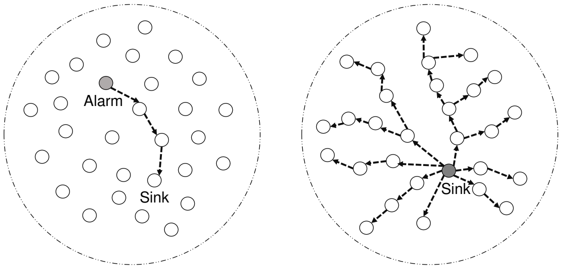

Fig. 2. Simulation scenario : (i) Send the alarm to the sink node (ii) Send a multicast packet to the whole network

We implemented the Cyber-OF in ContikiOS and we used Cooja simulator to evaluate its performance. We evaluated the performance of three implemented objective functions, namely: (1) latency-based objective function (OF), which only optimizes the latency, (2) energy-based OF, which only optimizes the energy, and (3) the Cyber-OF, which implements the adaptive behavior defined in Figure 1.

The simulations scenarios were performed using a 2D-grid surface of a network topology with 10, 20 and 30 sensors. The DAG architecture is composed of one Border Router, which represents the data sink, and the rest are UDP servers generating the data. The depth of the formed DAG is equal to 6. In this simulation, we assumed that a fire alarm will be triggered in node 10, which will send a unicast DIO packet that contains the alarm to the sink. After that, the sink will send the received alarm to all nodes of the DAG to adapt the topology accordingly.

B. *Results*

In this section, we will present the results of the evaluation of the Cyber-OF, and we will examine the impact of the following parameters:

- **End-to-end delay:** It is the duration between starting packet transmission and its reception by the DAG root.
- **Network lifetime** The network lifetime of a WSN is defined as the time collapsed until the first sensor runs out of energy.

1) Average delay: Fig 3 compares the average end-to-end delay of the three objective functions Energy-OF , Latency-OF and the Cyber-OF. It is obivious that they have similar delay values when the network is composed of less than 20 nodes. However , there is a slight difference for the energy OF which allows a higher average delay. This result is expected as the energy OF only maximizes the network lifetime and the choice of the best parent is based only on the energy remaining in the node. We notice also that when the network is composed of more than 20 nodes , the Cyber-OF experiences lower average delay values than the energy OF. This confirms the tendency of the Cyber-OF to minimize the delay when critical events (a fire alarm in our simulation) are detected.

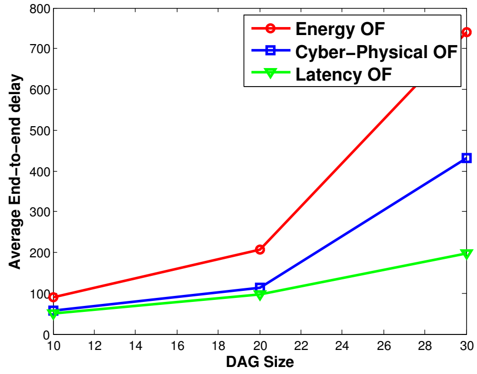

Fig. 3. Average End-to-End delay

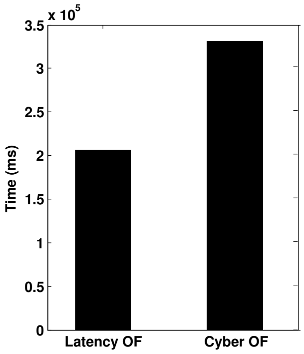

Fig. 4. Comparison between the network lifetime of the Latency-OF and the Cyber-Physical OF

2) Network lifetime: Figure 6 represents the energy consumed by latency OF and Cyber-OF and demonstrates how it can save energy and maximize the network lifetime more than the Latency-OF during 5 minutes of the simulation.

V. CONCLUSION AND FUTURE WORK

In this paper, we presented the initial results and implementations of the cyber-physical objective function to adapt RPL to the properties of the environment. As a future work, the energy metric will be combined with other metrics in order to guarantee an acceptable QoS in the presence of a disaster or in normal conditions. We also aim at storing two parent candidates in the sensor to speed up the advertisement of the alarm. One is used when a critical event is detected and the other is used in normal conditions.

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