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Congestion-Aware RPL for 6LoWPAN Networks

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Abstract—**IPv6 over low power wireless personal area network (6LoWPAN) is promising to be used in many different IoT applications. Recently, many protocols have been proposed for 6LoWPAN networks such as RPL routing protocol which is developed by the ROLL working group and expected to be the standard routing protocol for 6LoWPAN. Many problems are facing 6LoWPAN as it connects to the Internet such as congestion. In this paper, we propose a new RPL routing metric called Buffer Occupancy which reduces the number of lost packets due to buffer overflow when congestion does occur. Also, a new RPL objective function called Congestion-Aware Objective Function (CA-OF) is presented. The proposed objective function works efficiently when congestion occurs by selecting less congested paths. Simulation results show that CA-OF improves performance in the presence of congestion by an overall average of 37.4% in term of number of lost packets, throughput, packet delivery ratio and energy consumption.**

I. INTRODUCTION

The Internet of Things (IoT) is an emerging paradigm that a variety of things or objects such as wireless sensor nodes, radio frequency identification (RFID) tags and near field communication (NFC) devices are able to interact with each other and cooperate to achieve a common goal [1]. These things are connected to the Internet where they can collaborate and provide services such as smart environments (home, office, and building), health care, etc. [1], [2]. Wireless sensor networks (WSNs) are considered as one of the most important elements in the IoT [3]. 6LoWPAN is used for full integration of WSN with the Internet where sensor nodes implement the Internet Protocol (IP) stack though it has been originally designed for wired networks. However, the implementation of TCP/IP model in 6LoWPAN has many issues and problems due to the limitation of energy and buffer resources. TCP requires connection setup and termination before and after the data transmission and UDP does not provide a congestion control mechanism. Thus, TCP and UDP are not efficient for 6LoWPAN [1], [4]. Therefore, one of the main issues in 6LoWPAN is congestion that causes packet loss, energy consumption and degrades throughput.

Integration of WSNs with the Internet has sparked research interest in recent years. However, it is known that existing protocols and the architecture of the Internet are inefficient for WSNs. Recently, the Internet Engineering Task Force (IETF) has developed a set of IP based protocols for Low power and Lossy Networks (LLNs) through the 6LoWPAN and ROLL (Routing Over Low power and Lossy networks) working groups [5]. One of the main protocols the IPv6 Routing Protocol for LLNs (RPL) [6], which was developed in March 2012, is expected to be the standard routing protocol for 6LoWPAN networks [7]. Many metrics have been proposed to be used with RPL that can be divided into link and node metrics e.g. hop count, Expected Transmission Count (ETX), node energy, latency, link quality and throughput [8].

In this paper, we are addressing the congestion problem in 6LoWPAN networks and improving the network performance when congestion occurs. In our work [9], we did experiments to assess and analyse network conditions with congestion. We have concluded that with high network traffic, the majority of packets are lost at node buffers due to buffer overflow. Therefore, it is important to take the buffer occupancy into account to reduce the number of dropped packets at the buffer. To the best of our knowledge, this is the first work that considers the buffer occupancy as a metric in the RPL objective function. This scheme can improve network performance by reducing the number of lost packets due to buffer overflow. Thus, in this paper, we propose a new objective function called Congestion-Aware Objective Function (CA-OF) which combines two metrics: Buffer Occupancy (BO) and ETX. With the proposed objective function, packets are forwarded to a sink node through less congested nodes.

The remainder of the paper is organized as follows: in section 2, a brief overview of RPL is given. In section 3, we provide a literature review of related work about the proposed objective functions in RPL. A new objective function with a new metric is proposed in section 4. In section 5, simulation scenarios and results are given. Finally, section 6 concludes this paper and discusses future work.

II. RPL OVERVIEW

RPL is a distance-vector routing protocol which is designed on the basis of IEEE 802.15.4 physical and MAC layers [6]. In RPL networks, there are three types of nodes: root nodes which provides connectivity to other networks, intermediate nodes which forwards packets to the root and leaf nodes [10]. RPL is designed to be quickly adaptive to network conditions and to provide an alternative path to the root node when the default path is not available [7].

The construction of RPL network topology is based on the DAG (Directed Acyclic Graph) concept where every node selects a neighbour as its parent based on the objective function which defines how nodes translate one or more metrics (delay, link quality, hop count, etc. ...) into rank. RPL organises nodes as Destination Oriented DAGs (DODAG) where a sink node works as the root of the DAG which is responsible to start forming a network topology. The DAG root broadcasts a DIO (DODAG Information Object) control message which contains its rank and ID to other nodes in the network. When an intermediate node receives the DIO message, it replies to the root node with DAO (Destination Advertisement Object) for joining the DODAG. Then, the intermediate node computes and updates its own rank and sends a DIO message with its rank to all neighbours. This process continues until the DIO message reaches the leaf nodes. When a node receives a DIO message from more than one neighbour, it selects its parent with best rank. Also, when a node does not receive a DIO message within a specific time, it starts to send a DIS (DODAG Information Solicitation) message to solicit DIO message from neighbours.

III. RELATED WORK

Many routing metrics and objective functions have been proposed to be used within the RPL routing protocol in LLNs and 6LoWPAN networks. In this section, a discussion and review of these routing metrics and objective functions are given.

In [11], the default objective function for RPL, called objective function zero (OF0), is developed. OF0 is designed to find the nearest path to the root node in terms of distance by using the hop count as a metric. In OF0, a node selects its preferred parent with minimum rank which is increased by a strictly positive normalised scalar called rank_increase to obtain the node's rank. OF0 does not use the link and node metrics which are defined in [8]. Thus, OF0 does not reflect the node and link conditions and characterisations such as when a high packet loss occurs in a wireless link or at a parent node.

In [12], ETX-OF is proposed where it is based on the ETX metric. ETX describes the expected number of transmissions to successfully transmit a packet on a link. ETX-OF finds a path which can deliver a packet from a node to the sink node with minimum number of transmissions. A node computes the ETX path value for a path through each candidate neighbour by adding two components: the ETX value of a link to a candidate neighbour and the ETX value of the path, which is advertised in a DIO message, from the selected neighbour to the sink. The node selects its preferred parent with minimum ETX path value. In other words, ETX-OF selects a path which has least packet channel loss. Thus, ETX-OF reflects how much the wireless link or channel is congested. However, it does not reflect how much a node is congested which is where the majority of packets are lost when congestion occurs.

In [13], a new RPL metric called Averaged Delay (AVG_DEL) has been proposed. This metric aims to minimise the delay from a node to the root node. AVG_DEL is computed as the cumulative sum of link-by-link delays along the path to the root node. The proposed metric has been compared with ETX in terms of delay over a 19 node network. In [14], a new objective function is developed based on remaining energy as a metric. The path cost from a node to the root node is defined as the minimum value between the preferred parent path cost and the node's energy. A node selects its parent that has maximum path cost value. The energy-based objective function is compared with ETX-OF within a 20 sensor network.

In [15], combined methods are proposed to quantify and combine one or multiple RPL routing metrics in an additive or lexical manner according to system user requirements. The routing metrics used in this paper are: hop count, ETX, link quality level (LQL) and nodes' available energy. The lexical combination manner provides a metrics prioritisation to ensure application's requirements while, the additive method offers a flexible way to combine metrics using a metric weight pair. In [16], two RPL metrics are proposed based on the link performance at the MAC layer. The first metric called R-metric which includes ETX and packet losses due to the MAC contention. The second metric called Q-metric which provides a balanced load distribution in the network by selecting the lowest traffic loaded parent. The proposed metrics are implemented and tested within a seven mote testbed network and compared with the back-pressure algorithm [17] which uses a weighted ETX cost.

In [18], a new RPL routing metric called PER-HOP ETX is proposed. The proposed metric distributes the ETX value to each node along a path from a node to the root node instead of using the additive ETX metric, as in [12]. The PER-HOP ETX metric works better when the network scale becomes large. The proposed metric is compared with OF0 and ETX-OF. In [8], the authors propose a set of link and node RPL routing metrics and constraints which are suitable to be used with 6LoWPAN. The proposed metrics are divided into node metrics and link metrics. The node metrics include node state and attribute (NSA), node energy (NE) and hop count (HP). The link metrics are throughput, latency, link reliability, which includes LQL and ETX, and link color (LC). LC is a 10 bit value which indicates the link characteristics e.g. whether the link supports encryption.

In [7], a new objective function called QoS-Aware Fuzzy Logic (OF-FL) is developed based on the fuzzy logic concept. The proposed objective function combines a set of RPL metrics (end-to-end delay, hop count, ETX and battery level) to produce a single output metric called neighbour quality by using a fuzzy inference system which includes fuzzification, fuzzy rules and defuzzification. However, it is very difficult to implement the fuzzy logic system, which requires high computational processing capabilities, on a sensor node that has very limited processing resources.

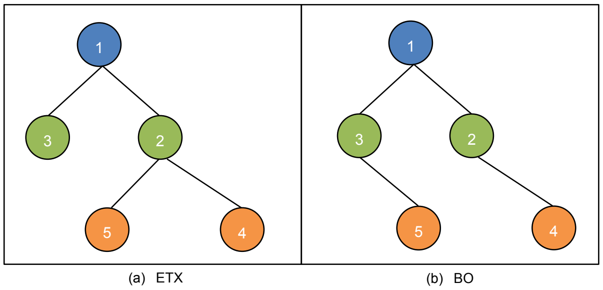
Recently, in [19], a new RPL routing metric called DELAY_ROOT, which minimises an average delay towards the DAG root, is proposed. The proposed metric can reduce the time delay between DODAG nodes and DODAG root based on the ContikiMAC radio duty cycle protocol. DELAY_ROOT is combined with three other metrics: ETX, rank and number of received packets to develop a new RPL based routing protocol called congestion avoidance multipath routing protocol (CA-RPL). CA-RPL is tested and compared with RPL which uses ETX metric. Simulation results show that CA-RPL reduces the number of lost packets and the time delay from original RPL by an average value of 20% and 30% respectively. However, the proposed routing protocol does not use the buffer occupancy as a metric where the majority of packets are lost when congestion does occur and it does not reflect how much the nodes are congested. Therefore, CA-RPL does not select less congested paths from nodes to the root but, it selects a path with least time delay.

IV. CONGESTION-AWARE OBJECTIVE FUNCTION DESIGN

In RPL, the objective function, which is completely responsible for network topology construction, is separated from the core protocol specifications. This allows easy design and implementation of a new objective function that satisfies the application and network requirements. The objective function combines one or more RPL routing metrics to produce a rank value which is advertised by a DIO control message. The majority of packets are lost at node buffers when congestion occurs in 6LoWPAN networks. Hence, it is important to consider the node's buffer occupancy as a metric in the objective function calculation in order to make the RPL routing protocol aware of the dropped packets. Therefore, the objective function reflects how much the node is congested.

To explain the importance of the buffer occupancy metric in RPL when congestion occurs, consider the following simple scenario with a network of one sink node, two intermediate nodes and two leaf nodes. At the network topology construction stage, nodes 2 and 3 select the sink node (node 1) as parent and nodes 4 and 5 choose node 2 as parent as shown in Fig. 1(a). Firstly, the intermediate and leaf nodes send packets to the sink node with low data rate. In this case, with ETX metric, the packets are delivered successfully to the sink node and buffer overflow does not occur since the nodes' buffer is almost empty. After that, when an event occurs at the leaf nodes, they start to send packets at high data rate. In this situation, both node 4 and 5 send high data rate packets to their parent, node 2, where buffer overflow occurs. On the other hand, node 3 has no child node and its buffer is completely empty. With ETX-OF, which does not reflect the buffer overflow, nodes 4 and 5 continue to send their packets to node 2 where the majority of packets are lost at its buffer. Node 5 will not change its parent to node 3 where its buffer is empty since ETX-OF does not take the buffer occupancy into account. However, if the buffer occupancy is considered in the objective function as a metric, node 5 will change its parent to node 3, when high buffer overflow occurs at node 2, as the rank value of node 3 is smaller than the rank value of node 2 as shown in Fig. 1(b). In this case, the network load is distributed between node 2 and 3, hence buffer overflow is reduced significantly.

To develop a new objective function which works efficiently under low and high data conditions when congestion occurs. We must consider both the ETX metric which is important with low data rate (as the majority of packets are lost at the wireless channel) and the Buffer Occupancy (BO) metric (which is important to consider with congestion occurrence where the majority of packets are lost due to buffer overflow). Thus, it is better to combine both metrics ETX and BO to develop a new objective function that works efficiently with different conditions. The modified objective function can be describes as:



(a) ETX (b) BO

Fig. 1: Network topology within congestion

$$combined\_metric = w1 * ETX + w2 * BO \qquad (1)$$

Where $w1$ should be high with low data rate and $w2$ should be high during periods of congestion i.e. high traffic load. Hence, the buffer occupancy has been utilized as an indicator to realize the probability of buffer overflow. Thus, $w1$ and $w2$ are equal to buffer free space and buffer occupancy respectively. For instance, with low traffic where buffer is empty, $w1$ becomes 100% while with high network traffic as the buffer is full, $w2$ equals 100%. Therefore, the proposed objective function is aware of congestion and reflects how much the node and wireless channel are congested by using BO and ETX metrics respectively.

V. PERFORMANCE EVALUATION

The proposed objective function has been tested and evaluated on two different network scenarios through simulation. The two networks were chosen to demonstrate performance on a small network of 19 nodes and a larger network of 35 nodes. CA-OF is compared with three objective functions: OF0, ETX-OF and ENERGY-OF. In all networks, we have used one

TABLE I: Protocol stack

Layer	**Protocol**	**Parameter value**
Application	Every node periodically send packet to sink node	
Transport	UDP	
Network	uIPv6 + RPL	
Adaptation	SICSlowpan layer	compression method = HC06
Data Link	CSMA (MAC layer) Contikimac (RDC layer) 802.15.4 (framer)	buffer size = 8 packets CCA count = 2 MAC retransmission = 3 channel check rate = 8 Hz
Physical	CC2420 RF transceiver	Max. packet length = 127 byte

TABLE II: Simulation parameters

Parameter	Value
Operating system	Contiki 2.7 [20]
Simulator	Cooja [21]
Simulation time	30 minutes for each simulation
Ratio model	UDGM - Distance Loss
Node type	Tmote Sky
Transmission range	50 m
Interference range	100 m

sink node, a set of intermediate nodes which send packets to the sink node every minute and a group of leaf nodes which send packets at high data rate (4 packets/s) to create a congested situation. During the simulation, intermediate and leaf nodes start sending packets after 60 s as the network topology construction is completed. The protocol stack and simulation parameters used in the simulation are shown in tables I and II.

The first network consists of a sink node, 12 intermediate nodes and 6 leaf nodes. We have counted the number of buffer overflow packets and channel loss packets in the network for CA-OF and compared it with three other objective functions as shown in Fig. 2. This result shows that CA-OF loses less packets at the buffer than others as CA-OF considers the buffer occupancy as a metric in its objective function. Consequently, CA-OF tries to forward packets to the sink node through less congested nodes leading to reduced buffer overflow. Fig. 3 shows network throughput which is measured as the number of successfully received packets at the sink node every minute. According to this figure, CA-OF has better network throughput than others for the reasons stated above. Fig. 4 illustrates the ratio of the total number of received packets by the sink to the total number of sent packet in the intermediate and leaf nodes. It is clear that CA-OF has higher ratio with value of 79.57% than ENERGY-OF, ETX-OF and OF0 where they have a ratio of 58.19%, 51.67% and 44.44% respectively. During the simulation time, we have measured the total energy consumption due to transmission and reception at the intermediate and leaf nodes. Fig. 5 shows the energy consumed in transmission and reception per successfully delivered packet. We note that with CA-OF, the energy consumption in the network is less than others as ENERGY-OF, ETX-OF and OF0 waste energy by transmitting and receiving packets which are then lost due to buffer overflow on the path without successful delivery because the buffer occupancy has not been considered.

Finally, we have tested CA-OF with a network of one sink, 24 intermediate nodes and 10 leaf nodes (this is formed network 2). Fig. 6 shows the total number of lost packets in the network due to buffer overflow and channel loss. As the proposed objective function reflects how much the nodes are congested by using the buffer occupancy of these nodes as a metric, we can see that CA-OF saves more packets than others by reducing the number of dropped packets at the buffer. Fig. 7 and Fig. 8 show throughput as the number of received packets

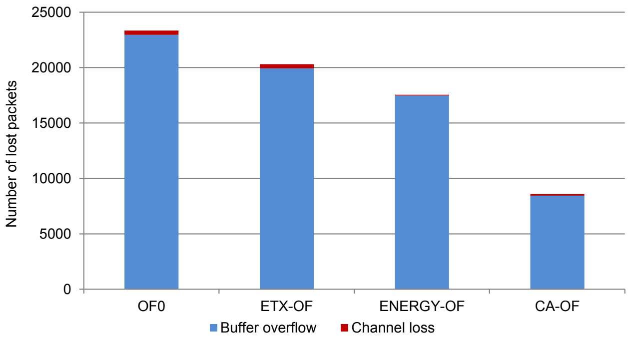


Fig. 2: Total number of lost packets in network 1

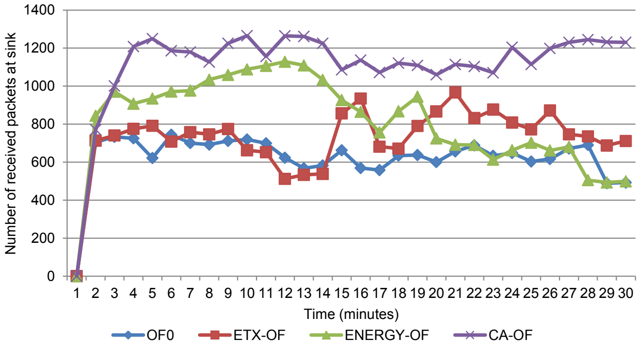


Fig. 3: Network 1 throughput

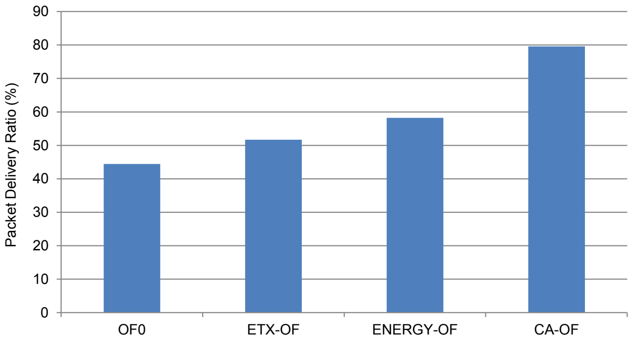


Fig. 4: Packet Delivery Ratio in network 1

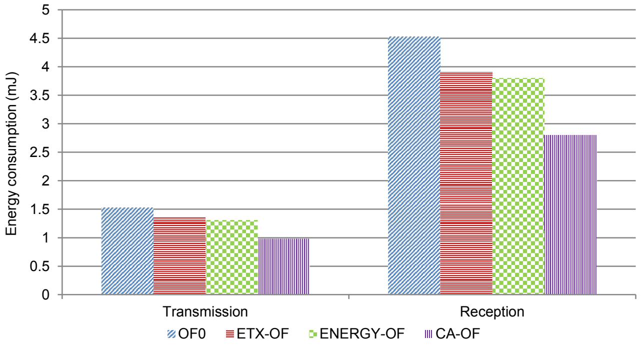


Fig. 5: Transmission and reception energy consumption per successfully delivered packet in network 1

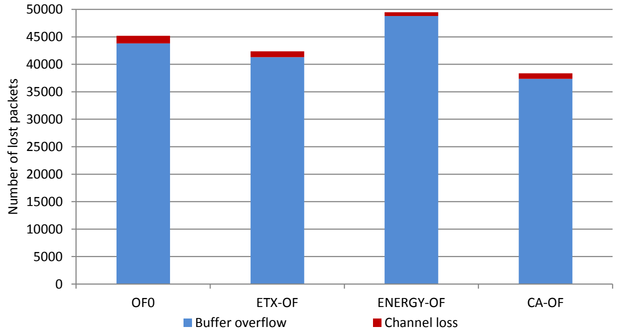


Fig. 6: Total number of lost packets in network 2

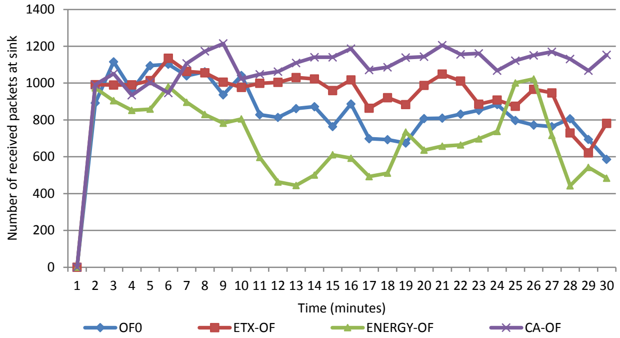


Fig. 7: Network 2 throughput

at the sink per minute in the network and PDR respectively. It is clear that CA-OF has better performance in term of PDR and throughput than ENERGY-OF, ETX-OF and OF0. Lastly, Fig. 9 shows the energy consumed in transmission and reception per successfully received packet. This result demonstrates that CA-OF minimises the energy consumption in the network compared to others.

Overall, based on these simulation results, it is clear that CA-OF improves performance by the average values shown in table III in terms of the number of lost packets, throughput, packet delivery ratio and total communication energy consumption as compared to other objective functions. On the other hand, the limitation of CA-OF is that as the number of intermediate nodes within the coverage area of the sink node is low, the number of possible routes to the sink is reduced. Thus, CA-OF cannot find uncongested nodes to forward high data rate packets to the sink without high packet drops at node buffers. Therefore, the performance advantage of CA-OF increases as the number of nodes close to the sink is high and vice versa.

TABLE III: Improvement in performance offered by CA-OF as compared to the others

Objective function	ETX-OF	ENERGY-OF	OF0
Lost packets	33.5%	36.7%	39.1%
Throughput	34%	45.6%	52.8%
Packet delivery ratio	34.1%	45.4%	52.9%
Energy consumption	17.9%	31.8%	24.4%

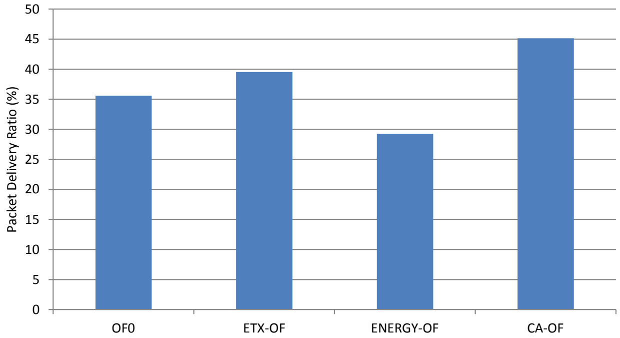


Fig. 8: Packet Delivery Ratio in network 2

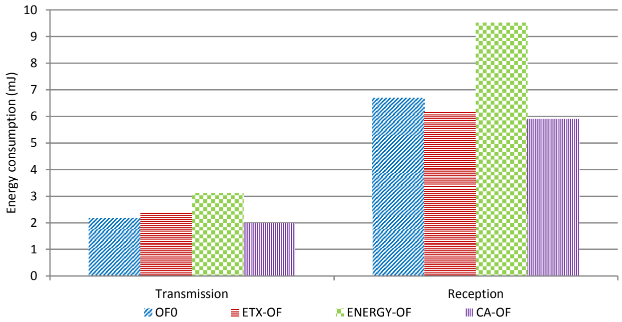


Fig. 9: Transmission and reception energy consumption per successfully delivered packet in network 2

VI. Conclusion and Future Work

In this paper, a new RPL metric called Buffer Occupancy, which is important to consider when congestion does occur in 6LoWPAN network, and a new objective function called Congestion-Aware Objective Function are proposed in RPL routing protocol. The proposed objective function has been implemented and tested in Contiki 2.7 with two different size networks and compared with three objective functions. The simulation results show than CA-OF can choose the least congested path from a leaf node to a sink node by forwarding packets through less congested nodes. Hence, CA-OF improves network performance in terms of packet delivery ratio, throughput and energy consumption.

Finally, in order to prevent buffer overflow, a congestion control mechanism should be invoked where the transmission rate is decreased to a specific value when congestion occurs as an alternative when a non-congested path is not available. So, developing a new congestion control algorithm that uses both traffic control and resource control and supports hybrid application types which are common in the IoT is left for the future.

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