Fault-Tolerant RPL Through Context Awareness*

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***Abstract*— The Routing Protocol for Low power and Lossy Networks (RPL) has recently been considered as the standard routing protocol for wireless sensor networks (WSN). RPL builds routes between nodes based on specific metrics that reflect arbitrary optimization objectives through the RPL Objective Functions (OFs). In this paper, we propose a Context-Aware Objective Function (CAOF) that takes into account the limited resources of the sensor nodes and their temporal changes. The proposed CAOF optimizes the power exploitation as a critical resource by taking the battery level into consideration in the routing decision. Simulation results show that our CAOF increases the network lifetime by up to 44% compared to non-context-aware OFs of RPL. Furthermore, CAOF ensures more fairness in the exploitation of batteries of the different nodes in the network more than non-context-aware OFs. In addition CAOF enhances the delivery ratio when compared with RPL non-context -aware OFs.**

Keywords—routing; RPL; context-aware; Wireless Sensor Networks (WSN)

I. Introduction

The Routing Protocol for Low power and Lossy Networks (RPL) has been developed by the Internet Engineering Task Force (IETF) as the standard routing solution for IPv6-Based smart object networks [1][2]. In order for RPL to suite a wide variety of applications, it was designed to separate the packet processing and forwarding mechanisms from the routing optimization objective [3]. Consequently, RPL can be designed to satisfy arbitrary objectives, such as minimizing the energy consumption and minimizing latency, or satisfy any imposed constraints of the application.

In this paper, we consider context-awareness as the optimization objective of RPL. Such an objective is critical for different Internet of Things (IoT) applications which are inherently prone to frequent failures in the heterogeneous battery-operated network elements. Node failures due to the limited available resources can lead to a dramatic deterioration in the overall network performance, despite the large node population of IoT networks [4].

We propose a new fault-tolerant RPL objective function (OF). An RPL objective function defines how the routing metrics, optimization objectives, and related functions are used to form a routing tree. Individual nodes use the OF to select their respective parents. We incorporate the context-awareness approach of the Context-aware Adaptive Routing (CAR) [5] and Sensor Context-aware Adaptive Routing (SCAR) [6] schemes into an RPL OF. CAR and SCAR were initially designed to achieve delay-tolerance in mobile wireless sensor networks. In such networks, node mobility is the main source of loss of connectivity. In contrast, we consider fixed networks in which the limited node resources are the sole cause of dis-connectivity.

The proposed OF enables the nodes to select their parents based on the nodes' capabilities, available resources and relative location with respect to the sink node. This is achieved via a weighted summation of utilities defined in terms of the above context information. We use extensive simulations to evaluate the performance of the proposed context-aware OF (CAOF). Our simulation results show that CAOF outperforms RPL basic OFs that are based on hop-count or expected transmissions in terms of the network-wide delivery ratio, the network lifetime, and the fairness in resource exploitation.

The remainder of the paper is organized as follows. Section II presents the necessary preliminaries of RPL and context-aware routing. In Section III, we present the proposed fault-tolerant RPL OF. We present an extensive set of simulation results in Section IV and conclude the paper in Section V.

II. Preliminaries

In this section we present the necessary background discussion of both RPL and context-aware routing.

A. RPL: Routing Protocol for Low power and Lossy Networks

RPL represents the fundamental routing protocol for IPv6-based low power and lossy networks (LLN). RPL is a proactive distance vector routing protocol which constructs its routes once the network is initialized forming a loop-free tree-like graph called Directed Acyclic Graph (DAG) rooted at a sink node as shown in Fig 1.

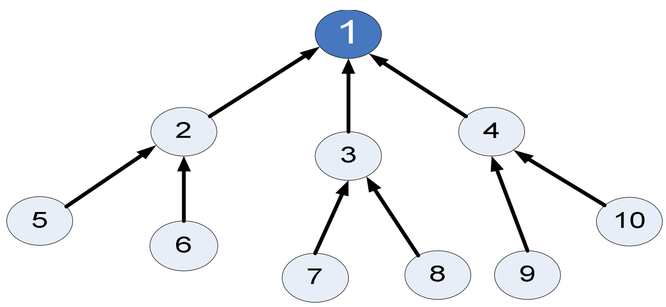

Fig 1. DODAG rooted at node 1.

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Fig. 1 shows a Destination Oriented DAG (DODAG) that supports Point-to-Multipoint and Multipoint-to-Point communication. On network initialization, each node in the RPL network advertises itself using a control message called the DODAG Information Object (DIO) that contains the node's information. Then, it chooses a preferred parent to maintain in its one-entry routing table through which it forwards packets to the sink. Parents in turn choose their preferred parents and the cycle goes on until reaching the sink node constructing the shown DODAG [7].

RPL constructs DODAGs aiming to minimize the path cost to the DAG root according to set of routing metrics like throughput, latency, number of hops, etc. Consequently RPL allows the use of objective functions [7].

An Objective Function (OF) is the rule a node uses to calculate its rank and choose the best parent out of multiple candidate neighbors to be its preferred parent accordingly. Thus, the OF is the key of how the RPL DODAG tree is constructed initially and updated occasionally. Objective Function Zero (OF0) is an already-implemented example of OFs. It aims to minimize the number of hops towards the sink node [7].

B. Context-Aware Routing

Intermittently-connected IoT networks are susceptible to discontinuities due to node failures, changes in the topology, etc. Thus motivated, Context-aware Adaptive Routing (CAR) [5] and Sensor Context-aware Adaptive Routing (SCAR) [6] have emerged as key approaches for achieving delay tolerance based on the nodes' conditions and constraints in mobile ad-hoc and sensor networks. The main sources of network discontinuities addressed by CAR/SCAR are the limited battery capacities of the nodes and node mobility. In such networks, the goal is to select the next best mobile carrier of the data which will "most probably" deliver the data message to the sink node among the current neighbors.

CAR/SCAR use multi-criteria prediction and decision-making techniques [5]. Context-awareness is derived from the dependency of these techniques on context attributes such as the change degree of connectivity of the node, its colocation with sink, and its battery level. Each attribute is represented by a utility function $U_{atttibute}$ that takes a value between 0 and 1. Each node of a SCAR-based network locally calculates its attributes. The delivery probability $P(n_i)$ of sensor node n_i is the weighted sum of the individual utilities of the context attributes:

$$P(n_i) = W_{cdc} * U_{cdc}(n_i) + W_{coloc} * U_{coloc}(n_i) + W_{batt} * U_{batt}(n_i) \quad (1)$$

where $W_{atttibute}$ are the weights that reflect the importance of a given attribute in defining the context of the node. Sensors exchange $P(n_i)$ with each other periodically while moving across the network. Each node builds a routing table that lists its immediate neighbors and their corresponding delivery probabilities. A node selects the best carrier of a the message to be transmitted as the neighbor with the highest delivery probability among all neighbors in the routing table [6].

III. The Proposed Context-AWARE Objective Function (CAOF) for RPL

RPL objective functions aim to optimize a certain metric on routing paths, either to fit a specific application, or to minimize the path cost from this metric's point of view. Typically, it neglects the nodes' capabilities or context changes that might be known a priori, such as initial battery level of nodes, or can happen a posteriori, such as the node's sleeping mechanism for saving power. These events could lead to dis-connectivity, and result in a similar behavior as mobile networks. For example, sleep and awake mechanisms may change the nodes' neighbors each time the node awakes, exactly like nodes of mobile networks. For that purpose, we introduce the Context-Aware Objective Function (CAOF) for RPL.

CAOF takes context awareness into account in RPL DODAGs construction, with a view to make RPL more flexible to node failures and operate more efficiently with context changes in sensor networks dealing wisely with their limited resources in routing decisions. The idea behind the proposed objective function and implementation issues will be explained in the following subsections.

A. CAOF

CAOF captures the context of the sensor nodes defined by the attributes that cause connectivity intermittence in non-mobile sensor networks as follows:

Drained Battery: Wireless sensor networks consist of low-memory low-power sensor nodes mainly battery-operated. Being battery-driven results in this major dis-connectivity problem where the communication range of a node may be reduced or the node may totally detach from the RPL DODAG on battery death.

Dis-continuous Connectivity: In sink-centered WSNs, the traffic is directed towards the sink node(s). Hence, nodes that are closer to the sink(s) need to be awake more often compared to other nodes far away from the sink(s) in order to forward all the traffic to the sink(s). This leads to variable duty-cycles throughout the WSN. Duty-cycling may be synchronous or asynchronous. The latter cannot guarantee that each node will see the same neighbor nodes each time it wakes up.

Colocation: The location of a neighbor node with respect to the sink node is an important attribute when selecting which parent to forward messages through to the sink node.

B. Suitability

SCAR adopts prediction techniques over the context of the sensor node to compute its probability of message delivery. Meanwhile, CAOF computes the instantaneous suitability S_i of a node to be a parent based on its survivability in the DODAG, as represented by its battery level, connectivity (duty-cycle), and colocation with the sink (rank). Each of these metrics is expressed in the suitability equation by its corresponding utility function and weight as

$$S_i = W_{dc} * U_{dci} + W_{coloc} * U_{coloci} + W_{batt} * U_{batti} \quad (2)$$

Nodes of an RPL network calculate their attributes locally and exchange them with neighbors via DIOs. Each node then computes the suitability of its neighbors individually, and hence, decides which one of the neighbors is the most suitable to be the preferred parent.

C. Implementation issues

1) Colocation Utility Function

CAR/SCAR sets the colocation utility function to "1" if the node is directly connected to the receiver (i.e., the sink node), and to "0" otherwise. This leads to a faulty/in-accurate indication about the position of the node in the network. Neighbors that are two hops away from the sink are of the same weight in the delivery probability as those of N-hops away from it. Consequently, routing decisions based on such a criterion may exhaust the network resources, waste a lot of unnecessary power and lead to longer routes, and hence, lower delivery ratios and network life-times. This motivates us to use the idea of leveling in order to know how far a node is from the sink. CAOF uses this different representation for calculating the colocation utility. We assume that our network is divided into levels. Nodes of the same rank are at the same level, i.e., they are at the same logical distance from the sink and have the same colocation. With this representation, the colocation of nodes is more meaningful and causes the nodes to decide to forward packets through lower-level nodes since they are closer to the sink than the outer or same rank nodes.

2) Battery Utility Function

In order to get a reasonable representation for battery death and decay granularity, we defined a battery model that starts with a value representing the maximum number of seconds the modeled battery can hold. On the other hand, the model calculates how many seconds a node uses its transceiver for transmission and reception. The model continuously subtracts the time (in seconds) taken in transmission or reception from the latest battery value.

IV. Performance Evaluation

We next evaluate the performance of CAOF against OF0 running over native RPL. Our goal is to assess their efficiency in the adaptation to the network changes and limited resource restrictions. Simulations were carried on COOJA simulator which is a JAVA based simulator designed for simulating WSNs [8]. We consider node running the Contiki operating system [9]. We use the network topology depicted in Fig. 2 that is a three-hop sensor network composed of twenty-two nodes (white and grey nodes) and a sink (the black node). This topology – while a synthetic one to study the performance – is common in applications such as environment/agricultural monitoring and buildings automation where sensors are spread over the area of interest gathering information. This information is then sent to a central sink node connected with a backend system for processing and digesting the collected data. For this sensor network we assume the following:

- The sink node is mains-operated while all other nodes are battery-operated with a draining strategy based on the battery model explained above.
- The sink node is the only receiver in the network. Other nodes are either acting as both traffic sources and forwarders, as the case with the grey nodes, or acting as traffic sources only, as the case with the white nodes.

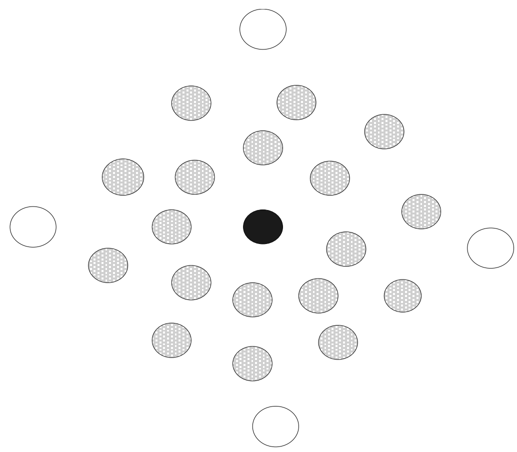

Fig. 2. Sink-centered network topology wherein all traffic is directed to the centric sink node.

- Traffic sources send packets (pkts) with different rates. The white nodes send with a ratio of 4:1 to the grey nodes. This means that if the white nodes are sending with a rate of 4 pkts/sec, the grey nodes then send with a rate of 1 pkts/sec.
- All battery-operated nodes are running with 8 Hz duty-cycle. As we have fixed duty-cycles for all nodes, giving a weight to the dis-connectivity due to duty-cycling utility function will not affect the decision. This eliminates the first term $W_{dc} * U_{dci}$ in equation (2).
- The weights of the colocation and battery utilities are 80% and 20%, respectively. We did a sweep of the weights to find their best values. We omit the details of such experiments for space limitations. In short, when the battery utility is assigned a higher weight than the colocation utility, longer routes are taken since nodes sometimes neglect candidate forwarder nodes' lower ranks for better battery values.

Our CAOF evaluation metrics are inspired by its motivation to preserve the sensor node power resources by taking the battery levels into account in the routing decisions. More specifically, we consider the network lifetime as our primary performance measure. One way to assess the network lifetime is through the Time To First Failure (TTFF) which is the time until the first node in the network runs out of battery. Another important metric that is widely used to measure the network lifetime is the network survivability after the first failure. We define the network survivability as the time until 20% of the network nodes are down due to dead batteries. We also evaluate the fairness in exploiting the batteries of different nodes in the network. Finally, we consider the delivery ratio as a measure of the throughput performance of the network. We next report the simulation results and comparison between CAOF and OF0 according to the above metrics.

A. Delivery Ratio

Fig. 3 shows the delivery ratios achieved by both CAOF and OF0 after 10 minutes of simulation. The delivery ratio achieved by CAOF is slightly higher than that achieved by OF0. Unlike OF0, CAOF distributes the load over different parents, causing less possibility of interference per parent than

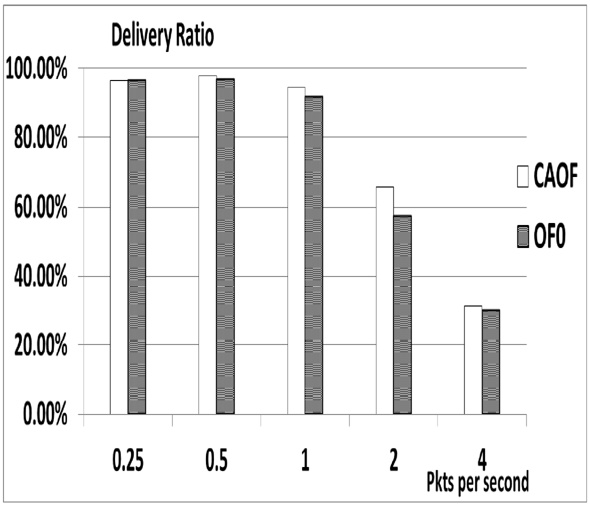

Fig 3. The delivery ratio of both CAOF and OF0 versus the rate of the leaf nodes (the white node in Fig. 2).

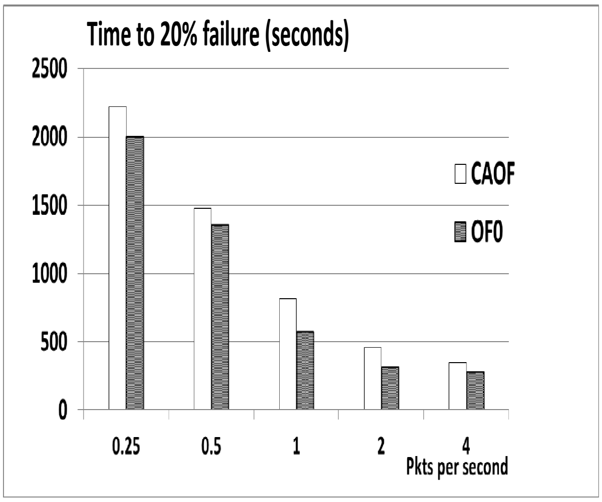

Fig 4. The network survivability both CAOF and OF0 versus the rate of the leaf nodes

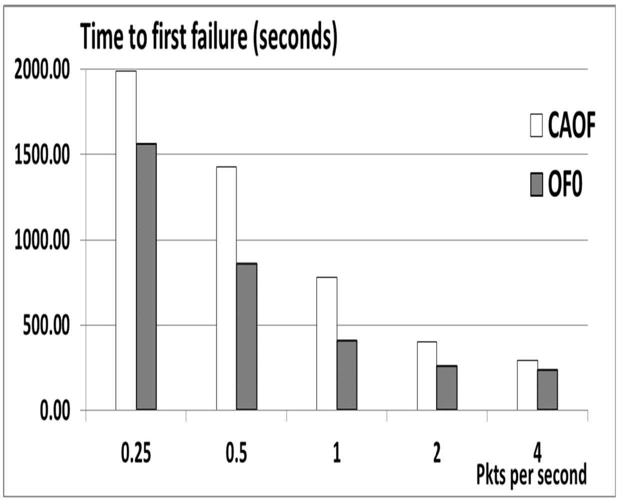

Fig 5.The TTFF of both CAOF and OF0 versus the rate of the leaf nodes.

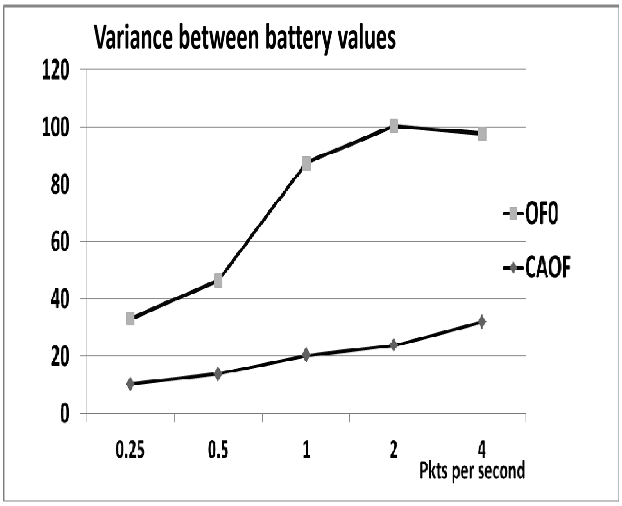

Fig 6. The variance of the battery levels across the network according to both CAOF and OF0.

the case with OF0. This causes slightly higher delivery ratios in CAOF especially at high rates.

B. Network Lifetime

Fig. 4 shows the significant TTFF improvement due to CAOF as compared to OF0. The TTFF due to CAOF increases by at least 22% more than the TTFF of OF0 at the highest data rate, and reaches a maximum of 44% improvement at rates of 1 pkt/sec and 0.5 pkt/sec. Moreover, Fig. 5 shows that CAOF increases the network survivability by at least 10% more than OF0 at the lowest rate, reaches 30% at rate of 1 pkt/sec, and drops to 20% at the highest data rate. These results show how important considering the nodes' limited resources in the routing decisions is for the network survivability. This is due to decreasing the potential intensive use of some part(s) of the network as illustrated by the next experiment.

C. Fiarness in Node Resource Exploitation

Since we are taking nodes' resources into account, a very important metric of evaluation is how fair the resources of the different nodes in the network are exploited. Our fairness indicator is the variance of the battery levels of all the nodes in the network after 20% failure occurs. Fig. 6 shows that according to OF0 there is a great variation between nodes' battery levels; which indicates a severe exploitation of the batteries of certain nodes/parts of the network and a light exploitation of the other nodes. Such unfairness quickly exhausts some nodes and causes the TTFF of OF0 to be less than CAOF. This is because routes are never motivated to change due to the exhausted resources due to OF0 which does not take the battery level into account in the routing decision.

On the other hand, CAOF battery level variance is nearly linear and slowly increases with the data rate. Furthermore, the CAOF variance of the battery level is significantly lower than the variance of OF0. This indicates the wise balance in load distribution over the whole network due to CAOF. In CAOF fairness in resource exploitation is highly achieved since routes are initially built based on the degree of resources' usage. If a parent has lower battery level than another, this means it was exhausted. Therefore, CAOF will choose the other parent if they have the same rank level.

V. CONCLUSIONS

In this paper, we have proposed the Context-Aware Objective Function (CAOF) for RPL. The CAOF allows RPL to take the sensor node limited resources, such as the battery level, into the routing decision. Simulation results show a significant improvement of CAOF over RPL-OF0 in both the network lifetime and fairness in resource exploitation. CAOF TTFF increases with at least 22% more than that of OF0 and reaches a maximum of 44% at lower data rates. Such an improvement in the TTFF increases the ability of the network to survive even with high data rates. The longer lifetime of CAOF is attributed to its ability to wisely distribute the loads over the network without exhausting certain nodes as the case with OF0. For future extension, we plan to investigate the effect of the duty-cycling on the performance of CAOF.

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