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ELITE: An Elaborated Cross-Layer RPL Objective Function to Achieve Energy Efficiency in Internet of Things Devices

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***Abstract*—Energy consumption is a major challenge in IoT devices, which was aimed to be improved by employing energy-efficient Objective Functions (OF) in the structure of RPL routing protocol. Meanwhile, the majority of the existing OFs mainly perform the parent selection based on the gathered information from the routing layer. Nevertheless, based on our investigations, there exists a series of transmission operations in the MAC layer, which significantly affects the energy consumption in IoT devices. Therefore, in this paper we propose ELITE, an energy-efficient cross-layer OF, which introduces a novel routing metric, called Strobe per Packet Ratio (SPR). SPR indicates the number of transmitted strobes per packet due to Radio Duty Cycling (RDC) policies in the MAC layer. This newly defined metric, which has been designed to be coupled with asynchronous MAC protocols, could be differentiated node by node and based on the existing relative phase shift between the communicating nodes. In this regard, ELITE tries to select a path, which imposes less number of strobe transmissions to its nodes. According to the evaluation results, while ELITE could reduce the average amount of required strobes per packet by up to 25%, it can significantly improve the average amount of consumed energy in an IoT node by up to 39% compared to its counterpart OFs.**

***Index Terms*—Internet of Things, Communications, Routing, RPL, Asynchronous MAC, ContikiMAC, RDC, Objective Function, Energy Consumption, Reliability.**

I. Introduction

BARRIERS and distances will be pushed away by means of how IoT is connecting humans to humans, humans to devices and devices to devices. IoT is an emerging topic of computing, which has gained a significant attention due to its widespread applications in various domains, e.g., buildings, farms, hospitals, and environment. According to a published report by the McKinsey Global Institute®, the financial impact of IoT on the global economy may reach as high as $3.9 to $11.1 trillion dollars at the end of 2025 [1].

Basically, creation and establishment of an IoT infrastructure depends on the communication of many resource constrained embedded devices in terms of processing power, memory, energy (battery powered or harvester), data rate, and transmission range, through the wireless mediums [2]. It has been estimated that we are going to face a network consisting more than 100 billion smart embedded devices at the end of 2025 [3]. The rapid growth in the number of connected smart devices in such systems arises significant considerations in the area of communications. Therefore, it is essential for IoT infrastructures to be assigned with a standard, comprehensive, and flexible layered architecture [4]. Nevertheless, despite of many efforts on providing a standard architecture for IoT, a unified model has not been introduced yet. As it has been illustrated in Fig. 1, among the previously proposed architectures, three layers are in common: 1) Perception, 2) Network, and 3) Application.

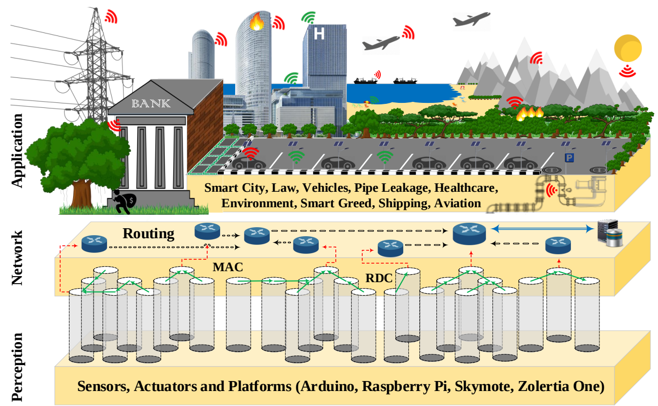

Fig. 1: Basic IoT architecture.

Each layer in the IoT architecture has a specific set of responsibilities, which will directly affect the amount of resource consumption in the IoT nodes. In many of the IoT applications, nodes are distributed in environments, where the battery maintenance (either charging or replacement) is inconvenient or even impractical. Hence, every layer should employ energy-efficient techniques to prolong the lifetime of the network. Depletion of a node's energy may lead into catastrophic incidents, where a part of the topology would be disconnected from the remainder.

In the layered architecture of IoT, the role of network layer on the amount of consumed energy is indispensable. This layer itself could be divided into several sub-layers. However, its routing and Medium Access Control (MAC) layers play an essential role in providing an energy-efficient communication for delivering data packets from their sources to their destination(s). The MAC layer has an important responsibility in controlling the most energy-hungry component in the nodes, i.e., the transceiver. This responsibility is upon Radio Duty Cycling (RDC) protocols to keep off the radio module as long as possible. While RDC protocols are generally categorized as synchronous, and asynchronous, it has been shown that the asynchronous RDC mechanisms impose less overhead in terms of bandwidth, and complexity [5]. In addition, among the existing asynchronous RDC protocols, the ContikiMAC

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[6] has shown to be energy-efficient, reliable, and fast, which makes it an attractive option for IoT infrastructures.

On the other hand, the IPv6 Routing **P**rotocol for **L**ow-power and lossy networks **(RPL)** was introduced to provide flexible and low-power routing in IoT infrastructures [7]. The component, which provides this flexibility in RPL, is known as the Objective Function (OF). Based on a single or a set of node/link metrics, which are determined according to the application requirements (e.g., stability, reliability, energy efficiency, performance), the OF is responsible for specifying a set of policies for path selection in the network. As a result, the existing embedded nodes would be able to forward their packets to their destinations(s) in an optimized manner. Hence, an OF could have a significant impact on the energy consumption of the IoT nodes. Although, there have been a number of efforts on providing OFs, which consider power consumption or the residual energy of the nodes as one of their routing metrics to reduce the overall energy consumption, they all concentrate on the routing layer specifications [8]. Therefore, there is a lack of novel OFs, which exploit a cross-layer paradigm to involve contributing factors from other layers in the path selection procedure to further mitigate the amount of energy consumption.

In this paper we propose ELITE, an elaborated cross-layer objective function to achieve energy efficiency in IoT applications. To this end, we first investigate the significant impact of sending a group of packets, known as strobe, on the nodes energy consumption. These packets are continuously sent to the one-hop receiver until it wakes up and gets informed about the incoming packet. Strobes are transmitted as part of the RDC protocol in the MAC layer, which in this study, the ContikiMAC has been selected. Then, we explain that this amount of energy consumption is due to the inappropriate selection of candidate parents with considerable amount of relative phase shift with the sending node, which enforces the sender to transmit more number of strobes to the receiver. To solve this problem, ELITE employs a novel routing metric called **S**trobe per **P**acket **R**atio (SPR), which operates based on the number of transmitted strobes per each transmitted packet. Accordingly, ELITE is able to significantly reduce the number of required strobes, and consequently reduces the amount of consumed energy by the sender.

We evaluate ELITE against a number of well known OFs through a set of comprehensive experiments in an IoT network via Cooja simulation environment [9] running RPL over IEEE 802.15.4 standard. Cooja is a Java-based, and cycle accurate IoT simulation environment, which is part of the Contiki operating system [10]. Our simulation results, which were obtained through various network configurations, have shown that ELITE improves the average amount of consumed energy in an IoT node by up to 39% compared to its counterpart OFs. This amount of improvement is due to its reduction in the average amount of SPR by more than 25%. Further observations have shown that ELITE can also improve other network specifications such as reliability, End-to-End (E2E) delay, and topology control overhead.

The remainder of this paper is organized as follows: Section II represents a background on RPL and its structure. Section

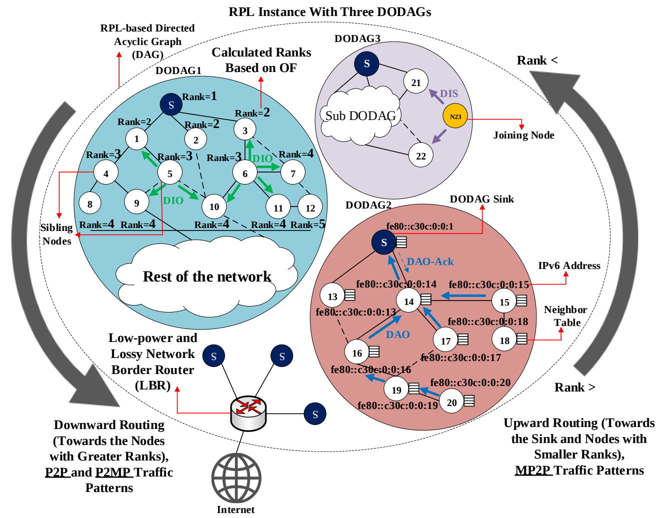

Fig. 2: The structure of RPL in an IoT network.

III, addresses the problem statement, while Section IV represents the motivation. A detailed description of ELITE has been provided in Section V. System setup and experimental results are stated in Section VI. Section VII, presents the related studies. Finally, the paper is concluded in Section VIII.

II. IPv6 Routing Protocol for LLN (RPL)

Fundamentally, RPL is an IPv6-based and distance-vector routing protocol, which was designed to be adopted by stationary unstable networks, where the traditional routing mechanisms are not applicable [8]. This protocol is part of the network layer and it is capable of operating on top of MAC and IEEE 802.15.4 PHY layers [7]. The tree shape structure of RPL organizes the embedded nodes in form of a graph, which is known as a Directed Acyclic Graph (DAG). Every DAG could be composed of a single or multiple sink nodes as the root(s) of the tree. In case of having a single sink in the DAG, the graph would be called Destination Oriented DAG (DODAG). In this structure, the end-nodes (leaves) can transmit their data packets through the existing paths towards the sink or any other destinations.

The routing metrics, which are considered in the OFs have an important role in the construction and appearance of the DODAG. Based on the intended IoT application and its specifications, an OF assigns a path cost to every available path and tries to optimize the path selection process according to a single or set of routing metrics. The construction of the DODAG, routing, and packet transactions have been facilitated via four ICMPv6 control messages in RPL: 1) DODAG Information Object (DIO), 2) DODAG Information Solicitation (DIS), 3) Destination Advertisement Object (DAO), and 4) DAO-Acknowledgment. The complete structure of RPL has been illustrated in Fig. 2.

A key element in initiating the construction of the DODAG and its maintenance is the DIO control message. DIO's mission is to provide the nodes with adequate configuration information to be able to join an RPL instance, connect to a DODAG, select a preferred parent, and forward their data packets towards their destination(s). Metric Container and

DODAG Configuration Option are couple of the most vital sections in the structure of DIO, which contain necessary information (including the OF) for a node to create a parent set among its accessible neighbours and select one as its preferred parent. Upon receiving a DIO and selecting a preferred parent, the node calculates its rank by monotonically increasing its parent's rank and updates its routing information. Afterwards, the node prepares and broadcasts a DIO message to inform its neighbours about its decision. This procedure will be iterated until the DODAG is constructed. In order to mitigate the control overhead as well as the amount of consumed energy due to transmission of control messages, RPL employs a trickle timer algorithm to increase the transmission interval of DIOs in an exponential manner with regards of the stability of the DODAG. In order to join a DODAG, nodes can broadcast DIS messages to inform their neighbours about their request. Any node, which receives a DIS, will send back a unicast DIO to the solicitating node and provides it with essential information for joining the DODAG. Consequently, the solicitating node can decide on selecting its preferred parent.

DIO and DIS are the building blocks of upward routing in a DODAG to enable Multi-Point to Point (MP2P) traffic flows (Fig. 2). Nevertheless, RPL is capable of handling Point-to-Point (P2P) and Point to Multi-Point (P2MP) traffic patterns as well. Accordingly, to provide the required information for downward routing, it employs the DAO control message. RPL supports downward routing in two Modes of Operation (MoP): 1) Storing, where intermediate nodes can store the routing information carried by the DAOs, and 2) Non-Storing, where the intermediate nodes do not have the sufficient space for storing the routing information. The fourth control message that has been applied in the structure of RPL is DAO-Ack, which will be transmitted by the receiving side upon an explicit request from the sender or through occurrence of an error in sending a DAO message.

A. *Objective Function*

According to the specific requirements of an IoT application, the path selection procedure should be optimized based on a single or set of node/link metrics. The OF's duty is to exploit these metrics to assist the embedded nodes through the path selection procedure. Meanwhile, metric is a concept, which is used to measure and assign a cost value to the available paths in the topology. A number of supported node/link metrics have been introduced in [11]. Furthermore, an OF is responsible for defining how routing metrics, optimization objectives, and other relevant functions should be used to compute the rank of a node [7]. The first step towards establishment of a successful communication between the existing nodes in a DODAG, is to select one of the neighbouring nodes as the preferred parent. In this regard, RPL creates and stores three relevant sets in every node: 1) Neighbour Set, 2) Parent Set, and 3) Preferred Parent Set [12]. This responsibility is upon the employed OF in an RPL instance. It is worthy to mention that according to the principles of the standard RPL, every RPL instance employs a single OF for determining its routing policies [7]. Because in case of employing more than one OF in the DODAG, there will be a number of consequences due to their conflicts. One of these consequences is the rank miscalculation, which could lead into loop creation in the network. Therefore, the standard version of RPL employs only a single OF in every instance. Furthermore, for the sake of flexibility, the RPL standard does not enforce adopting any specific OFs, and it has separated the OF's implementation from the other fundamental functionalities of RPL. Consequently, in every RPL instance we can design and employ customized OFs, which could fulfill the corresponding IoT application requirements.

There are two types of OFs, which are being frequently used in RPL-based IoT infrastructures: 1) Objective Function Zero (OF0) [13], and 2) Minimum Rank with Hysteresis Objective function (MRHOF) [14]. The simplest form of OF in the standard RPL is OF0, which does not employ any metrics in its structure. The path selection process in OF0 is based on the shortest path, which is not appropriate for many contemporary IoT applications. On the other hand, MRHOF has the ability to employ various node/link metrics and is more complicated than OF0. According to [14], different metrics, i.e., Expected Transmission Count (ETX), Hop Count, or Latency could be adopted by MRHOF. These metrics, which are known as additive metrics (They are added along the path, in a hop by hop manner), shall be used individually. The default metric, which has been considered in the structure of MRHOF is ETX. ETX refers to the minimum expected number of packet transmissions to a specific destination in order to reach a successful transmission. Paths with higher amounts of quality in terms of reliability and Packet Delivery Ratio (PDR) would have lower ETX. Thus, they have higher chances to be selected as the preferred path.

Generally speaking, OFs have a critical role in the construction of the DODAG and activity of the nodes. Consequently, they can significantly affect the amount of energy consumption in the existing embedded devices in IoT infrastructures [15], [16]. Therefore, they should be carefully designed and implemented in order to meet the IoT requirements.

III. PROBLEM STATEMENT

Typically, the transmission and reception activities consume the major portion of the energy in IoT and WSN platforms [17]. According to [18], the amount of consumed energy in the transmission (E_{tx}), and reception (E_{rx}) phases are obtained via Equations (1), and (2), respectively.

$$E_{tx} = \Big(P_{sv} + (\frac{\gamma.r.d^n}{\eta})\Big).T_{tx} \quad (1)$$

$$E_{rx} = (P_{sv} + P_{rx}).T_{rx} \quad (2)$$

Where, P_{sv} is the amount of consumed power in the transceiver's synthesizer, and voltage-controlled oscillator, η corresponds to the amplifier efficiency factor, γ relates to the antenna specifications, r is representing the data rate, d is the distance, and n is the path loss exponent [18]. Furthermore, P_{rx} is the integration of power consumption in different building blocks of the receiver. Finally, T_{tx}, and T_{rx} are indicating the amount of time that the transceiver is

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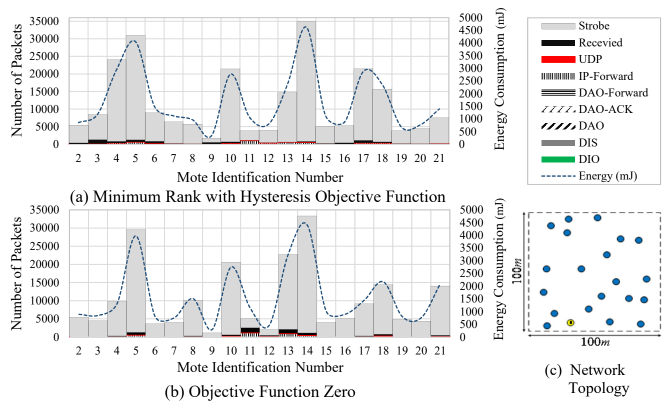

Fig. 3: OF and strobe's effect on energy consumption trend.

active in each of these two modes of operation. As it could be observed from Equations (1), and (2), the more time the transceiver spends in these two phases, the more energy will be consumed. Meanwhile, one of the factors that leads into more transmission and reception activities in the nodes, is the increment of the packet transmissions.

A smart embedded device in an RPL-based IoT infrastructure transmits different types of packets during its lifecycle. These packets could be either data driven or due to controlling and management of the DODAG. Fig. 3 represents the amount of transceiver activity in terms of transmitted and received packets in every node of the topology with regards of type of the OF[1]. In order to get into more detail, the type of the transmitted packets has been also declared in Fig. 3. The observations in Fig. 3 could be analyzed from two perspectives. First is the impact of OFs on the amount of consumed energy in the corresponding nodes, which could reach as high as 55.5%. This amount of influence is due to the OF's duty, which is to dictate how embedded nodes select their path in order to forward their data packets across the DODAG. Hence, OFs have a direct impact on the amount of transceiver activity and consequently the energy consumption of the nodes.

Second is the significant contribution of the number of transmitted strobe packets on the amount of consumed energy in the nodes. According to Fig. 3, the trend of the consumed energy in the nodes completely complies with the number of transmitted strobes in the corresponding node. In other words, the more number of strobe packets a node sends, the more energy it will consume. A deeper insight into Fig. 3 clarifies that the amount of consumed energy is directly affected by the number of transmitted strobe packets in the MAC layer, where the typical OFs in the routing layer are not aware of them. Indeed, The mentioned problem is due to inappropriate design of OFs in the structure of RPL. Thus, to conduct energy-efficiency in IoT infrastructures, it is crucial to adopt an intelligent cross-layer OF, which conserves more energy through mitigation of strobe packet transmission in the MAC layer.

[1]The information is obtained through a set of preliminary evaluations on a random topology containing 20 Zolertia One platforms [19] with a transmission interval of 12 seconds (Reader is referred to section V for more details on the simulation environment).

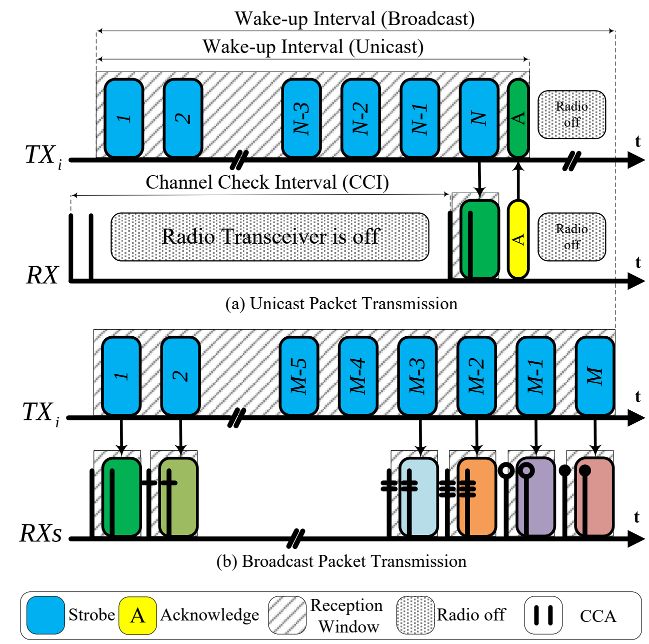

Fig. 4: ContikiMAC architecture.

IV. Motivation of the Proposed Method

Generally, based on our experiments and as it was mentioned in [20], it could be assumed that the process of listening to the channel for detecting and receiving the probable incoming packets consumes the same amount of energy as the transmission procedure. Therefore, in order to reduce the energy consumption, the radio module should be kept off as long as possible. This responsibility is upon a part of the MAC layer, which is known as the Radio Duty cycling protocols (RDC). An RDC protocol is a fundamental aspect of IoT infrastructures with the aim of turning the transceiver on and off based on a time-line, which could be synchronous or asynchronous. In synchronous RDC protocols, the existing nodes would synchronize their clocks to be awaken simultaneously for potential communication. This synchronization will impose extra overhead to the network in terms of bandwidth and complexity [5]. To overcome this overhead, asynchronous RDC protocols were introduced to enable the nodes to communicate in an independent manner. Accordingly, in asynchronous approaches, nodes have their specific sleep time-line and they will be woken up based on the policies of the RDC protocol to check the channel for probable packets.

In the past few years, a number of RDC mechanisms have been designed and implemented in the MAC layer [6], [21], and [22]. Among them, ContikiMAC is an asynchronous RDC protocol, which has been proven to be very reliable (in terms of PDR), fast, and energy-efficient due to its fast sleep mechanism, which shortens its wake-up period and also efficient transmission procedure in single channel medias [23]. Hence, ContikiMAC is being broadly used as the RDC protocol in many IoT infrastructures. In this regard, we have chosen ContikiMAC as our underlying MAC layer RDC mechanism.

The structure of ContikiMAC has been depicted in Fig. 4. Accordingly, by employing ContikiMAC, every node will turn on its radio module after an interval, which is called the

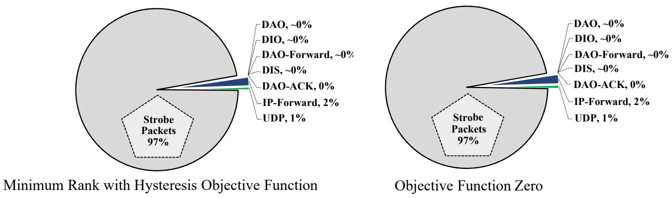

Fig. 5: Strobe abundance against different packets.

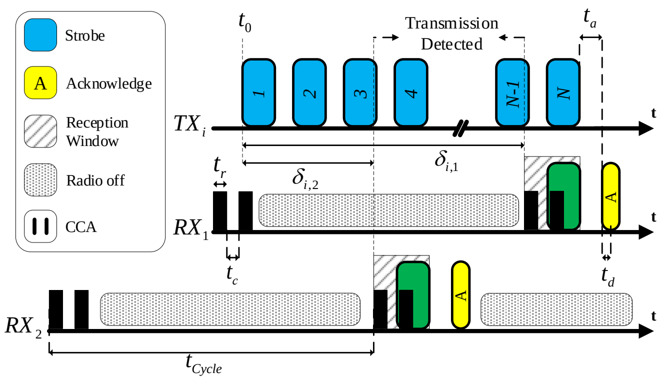

Fig. 6: Illustration of relative phase shift in ContikiMAC.

Channel Check Interval (CCI), in order to check the probable channel activities via two consecutive channel samplings. On the other hand, whenever a source node decides to transmit a packet, it tries to inform the receiver about the upcoming data packet by periodically sending a packet with an equal size to the corresponding packet. These repeatedly sent packets are known as the *Strobe* packets. Based on the *Channel Check Assessment (CCA)* procedure, whenever the receiver wakes up for checking the channel and detects that the strength of the existing signal is above a predefined threshold (strobe packets are being sensed), it will keep turning on its radio module, checks the incoming destination field of the packet and evaluates whether it is the destination or not. Upon reception of a unicast packet, the receiver will send back an ACK to prohibit the transmitter from further strobe transmissions. However, since broadcast packets must be received by all of the neighbouring nodes, the transmitter has to traverse its entire wake-up interval with no ACK expectations, which results in more transmission cost and energy consumption.

Although RDC protocols reduce the amount of energy consumption in the receiving nodes, and strobe packets improve the reliability of the packet transmissions, but the repetition of the strobe's transmission imposes significant amount of energy consumption to the transmitting nodes [24]; Especially, with keeping in mind that in ContikiMAC, the size of the strobe packets is equal to the size of the transmitted packets. As it has been illustrated in Fig. 5, independent from OF varieties, strobe packets have the most contribution among the different types of transmitted packets in the nodes energy consumption with nearly 97%. This amount of contribution is due the asynchronous nature of ContkiMAC protocol, which has been presented in Fig. 6. According to this plot, there is a relative phase shift interval ($\delta_{i,j}$) between the time instance that the transmitter (TX_i) is beginning its strobe transmission (t_0) and

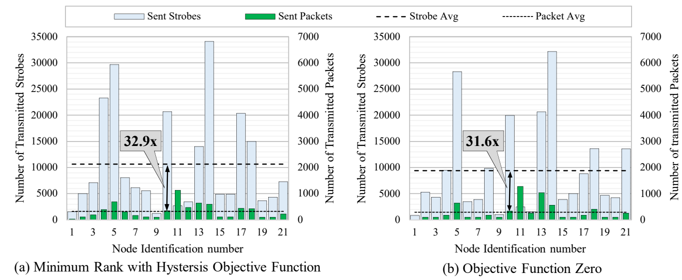

Fig. 7: Comparing number of transmitted strobes against transmitted packets.

the time instance that the receiver (RX_j) starts checking the channel and detects the transmission. According to this time interval, which is between $[0, t_{cycle})$, the total number of sent strobes could be risen or fallen; (t_{cycle} indicates the time interval that a node periodically conducts the CCA procedure). In addition, the relative phase shift is not a constant value and it could be changed due to several factors, e.g., the clock drifts throughout the node's lifetime [25], node reset, software delays, CSMA back-off, and burst transmission (use of pending bit).

Fig. 6 contains a number of ContikiMAC timing parameters. t_r represents the minimum longevity required for a stable RSSI-based channel sampling, while t_c is the time interval between two consecutive channel samplings in each CCA. t_a is the required time for sending an Acknowledgement after reception of the packet, and t_d is the required time for detecting the Acknowledgement packet. Meanwhile, according to Fig. 6, assume that there are two receiving neighbours (RX_1 and RX_2) in the transmission range of TX_i. Let's assume that the $\delta_{i,1}$ is longer than $\delta_{i,2}$. In this case we will have:

$$\delta_{i,1} > \delta_{i,2} \rightarrow R \times \delta_{i,1} > R \times \delta_{i,2} \rightarrow$$
$$N_{i,1} > N_{i,2} \rightarrow \alpha_{i,1} > \alpha_{i,2}$$
$$\therefore E_{tr_{i,1}} > E_{tr_{i,2}}$$

where R is indicating the transmission rate of strobe packets in ContikiMAC, $N_{i,j}$ represents the number of transmitted strobes in the $\delta_{i,j}$ interval, and $\alpha_{i,j}$ is the amount of imposed activity to the radio module in TX_i for sending the strobes to RX_j. As a result, by intensification of the relative phase shift, more number of strobes shall be required to inform the receiver and thus, more amount of energy will be consumed by the transmitting node. According to Fig. 7, the existence of this problem has enforced the nodes to send more than 31x of more strobes, on average, against the other packets, which will directly affect the amount of their energy consumption. To take control of this problem, this paper proposes a routing policy, which selects those of paths with less $\delta_{i,j}$ between their involving nodes with the hope of decreasing the overall amount of strobe packets in the MAC layer during the packet transmission.

V. The ELITE Approach

In this section, we will introduce ELITE, an RPL-based objective function, which conducts energy-efficiency in IoT infrastructures. ELITE is a cross-layered OF, which employs the

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obtained information from the RDC protocol in the underlying MAC layer, and transforms them to a path selection metric at the routing layer. In section III, we discussed that strobe packets are the most important contributors to the energy consumption of the nodes in IoT infrastructures. We have also shown that the intensification of the relative phase shift between the transmitter and the receiver would increase the number of required strobe packets for informing the receiver, and consequently more amounts of energy will be consumed by the sending node. Accordingly, ELITE considers the existing relative phase shift between the transmitter and receiver nodes by employing the number of required strobes per each of the transmitting packets as the RPL path selection metric. More number of strobes per packet indicates higher amount of relative phase shift between the sender and the receiver. Fig. 8 represents the structural architecture of an ELITE-enabled IoT infrastructure and the cross-layered connections between ELITE and lower-level layers.

According to Fig. 8, RPL has two responsibilities: 1) *Packet processing and forwarding*, and 2) *Routing optimization*. The first task is accomplished through a set of functions implemented in the *Processing Manager*, while the later has been handled through a set of operations in the *Routing Manager*. Meanwhile, ELITE has been implemented in the routing manager in the standard RPL (RFC6550). The Metric Container in the body of ELITE has been modified in a way to involve a novel cross-layer, and additive metric, which considers the information of strobe transmissions in the underlying MAC layer. This newly defined metric is called Strobe per Packet Ratio (SPR) and it is calculated via Equation (3). SPR indicates the number of required strobes per each packet to be sent to the one-hop receiver until it would be awaken based on the RDC protocol policies and receives it. In order to calculate SPR, the node counts the number of transmitted strobe packets until it receives an ACK from the receiver side. To accomplish the path selection procedure, RPL assigns a path cost to every possible path. Accordingly, to calculate the path cost in ELITE, every node of the DODAG $(Node_i)$ should first calculate the values of SPR for its recently sent packets to its candidate parents $(SPR_{Node_i \to CP_j})$. Then, according to Equation (4), it should add the calculated SPRs to their corresponding Strobe Path Metrics (SPM) received from each of the candidate parents (SPM_{CP_j}). The SPM values are extracted from the DIO messages that have been sent by the candidate parents. At the next step, the resulting SPM values for $Node_i$ to each of its candidate parents are compared in order to select the node's preferred parent. Finally, the resulting SPM corresponding to the preferred parent will be informed to the neighbouring nodes via DIO messages. It is noteworthy that the SPM of Node_0 (Sink) is considered to be zero in Equation (4).

$$SPR_{Node_i} = \frac{Number\ of\ Recently\ Sent\ Strobes}{Number\ of\ Recently\ Sent\ Packets} \quad (3)$$

$$SPM_{Node_i \to CP_j} = SPM_{CP_j} + SPR_{Node_i \to CP_j} \quad (4)$$

The main contribution of ELITE is its algorithm, which enables the nodes to route the packets across the DODAG in an IoT infrastructure. This algorithm is implemented in the Objective Function module and will be discussed in the following sub-section.

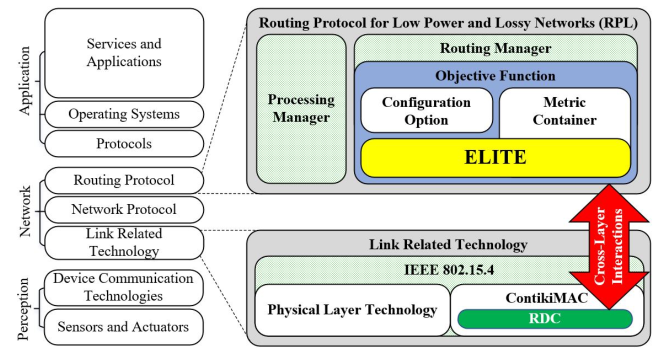

Fig. 8: The structural architecture of an ELITE-enabled IoT infrastructure.

A. ELITE's Algorithm

The algorithm of ELITE, which is designed to achieve energy-efficiency in IoT systems, is shown in Algorithm 1. This algorithm is executed in each of the IoT nodes. The input of the ELITE algorithm is the entries of the node's parent table. As a result of running this algorithm on the nodes of the DODAG, each node selects the best parent, which satisfies the SPM constraints, and updates its routing information.

Invoking Algorithm 1 in an ELITE-enabled node i, triggers the search of its parent table for finding an energy-efficient path towards the sink. To this end, ELITE algorithm first evaluates whether the ParentTable of the node has any members or not (Line 1). Then, if there were any member(s) in the node's ParentTable, ELITE computes the average amount of $(SPM + SPR)$ corresponding to the existing candidate parents in the ParentTable. This calculated value is represented by Δ_{th} and it will be used as a threshold for our routing decision makings in ELITE (Line 7). Routing metrics that are highly sensitive to network dynamics, could enforce the nodes to switch their parents even with trivial alterations. This issue could lead into unstable topologies. Accordingly, since SPM is inherently a time-variable metric, it could create more parent switches in the network. Therefore, employment of Δ_{th} in the structure of ELITE provides it with hysteresis. Hence, in case of confronting negligible alterations in the SPM, the nodes will not instantly change their parents. Consequently, with having a more stable DODAG, not only the number of disseminated control packets will be reduced, but more energy will be conserved in the nodes. Furthermore, the dynamic calculation of Δ_{th} based on the average amount of $(SPM + SPR)$ (instead of assigning it with a constant value) has enabled this threshold to never loose its effectiveness in the network. Note that in Algorithm 1, the $\text{SPR}_{i,ParentTable.Entry}$ indicates the strobe per packet ratio between node i, and the candidate parent, which is currently under evaluation in its ParentTable list.

After calculating the Δ_{th}, ELITE checks whether the node has already a preferred parent (BestParent) or not (Line 14). The current entry of the ParentTable will be set as the BestParent of the node, if it has not selected any parents yet, e.g.,

Algorithm 1: ELITE Routing Algorithm

```
   Input: Node i Parent Table Entries
   Output: Update Routing Information
   /* The following code is running on each node
      */
1  while ParentTable.Entry ≠ NULL do
2      Δ_th+=ParentTable.Entry.SPM+SPR_{i,ParentTable.Entry};
3      ParentTable.Entry=ParentTable.Entry→next;
4      count++;
5  end
   /* Calculating the average amount of (SPM+SPR)
      among the ParentTable entries                  */
6  if count != 0 then
7      Δ_th = Δ_th / count;
8  else
       /* There is no member in the ParentTable  */
9      exit();
10 end
   /* Reset the ParentTable.Entry to point to the
      beginning of the list                          */
11 reset(ParentTable.Entry);
12 while ParentTable.Entry ≠ NULL do
13     SPM ← ParentTable.Entry.SPM+SPR_{i,ParentTable.Entry};
14     if (BestParent = NULL) then
15         BestParent ← ParentTable.Entry;
16         Node_i.SPM ← SPM;
17         Rank ← SPM;
18     else
           /* We try to decide based on the strobe
              packets for reducing the energy
              consumption                            */
19         if (BestParent.SPM+SPR_{i,BestParent}) < SPM < Δ_th
            then
               /* BestParent will not be changed!  */
20         else if SPM < (BestParent.SPM+SPR_{i,BestParent})
            < Δ_th then
21             BestParent ← ParentTable.Entry;
22             Node_i.SPM ← SPM;
23             Rank ← SPM;
24         else if SPM ≤ Δ_th then
25             BestParent ← ParentTable.Entry;
26             Node_i.SPM ← SPM;
27             Rank ← SPM;
28         else
               /* Neither of the both current
                  candidates are promising to be
                  selected as the best parent. Thus,
                  we will pass the current
                  BestParent to compare with other
                  candidates in the following
                  iterations of while loop           */
               /* BestParent will not be changed!  */
29         end
30     end
31     ParentTable.Entry=ParentTable.Entry→next;
32 end
   /* Generate and send a new DIO                    */
33 dio.mc.strobe ← SPM;
34 SendDIO();
```

during the time that the DODAG is being constructed. If the node has already assigned with a BestParent (line 18), ELITE will compare all of the entries of the node's ParentTable with the current BestParent to find a probable new alternative in part of a while loop (lines 18 to 30). Accordingly, ELITE compares the SPM values of the two paths (which now include their corresponding SPRs from node i to the parent that establishes the path) with Δ_{th}. In each iteration of the while loop, if any of the two candidate paths provide less SPM than the Δ_{th}, ELITE can switch to the new parent based on the SPM to provide energy-efficiency, otherwise it will keep its current BestParent with the hope of finding a better parent in the future

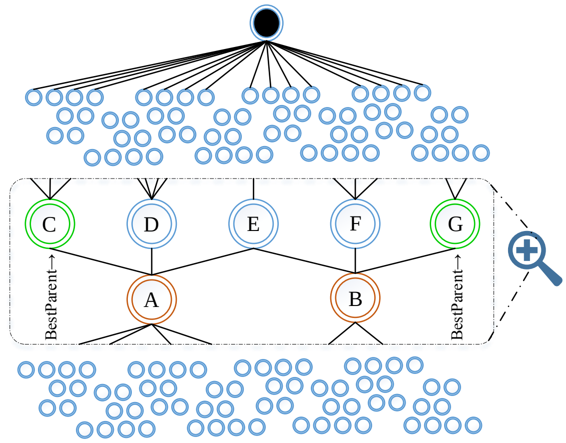

Fig. 9: A case study scenario for ELITE.

iterations of the while loop. It is noteworthy that by taking SPR into account, ELITE selects those of paths with the minimum amount of relative phase shift between their involving nodes and thus, the overall transmission activity of the nodes in the DODAG would be significantly reduced. This will directly mitigate the amount of energy consumption in the nodes of the DODAG.

Accordingly, considering Lines 18 to 30 of the Algorithm 1, if both of the candidate parents or either of them provide(s) less SPM than the Δ_{th}, the parent with lower SPM or the one, which provides less SPM than the Δ_{th}, will be selected as the BestParent. If both of the candidate parents (including the current BestParent) impose more amounts of SPM than the Δ_{th} or in cases, where only the current BestParent is providing a lower SPM against Δ_{th}, the ELITE will keep the current BestParent unchanged with the hope that a new BestParent could be found in the following iterations of the while loop (Lines 12 to 32). Finally, as it can be seen in Algorithm 1, if the node switches its preferred parent, it will initialize the Metric Container with the new SPM value and updates its routing information to further inform its neighbouring nodes about its decision through dissemination of DIO messages (Lines 33 and 34). We will check the functionality of ELITE with an example scenario in the following subsection.

B. Case Study Example

Fig. 9 depicts a case study scenario in an ELITE-enabled IoT infrastructure, where a number of nodes are connected based on the ELITE principles. In the following, we will discuss on how ELITE's algorithm decides to change a path from a source to the destination (black filled colored node) for conducting strobe and energy-efficiency. Accordingly, we have considered a snapshot of an inner zone of this network containing 7 nodes. In this scenario, two nodes, i.e., A, and B, are considered as child nodes, while the remaining five nodes, i.e., C, D, E, F, and G are the members of the parent sets. The existing candidate parents (ParentTable contents in Algorithm 1) of node A, are C, D, and E, while the candidate parents of node B are E, F, and G. Let's assume that node C is the BestParent of node A, and node G is the BestParent of node B. The information that has been delivered to nodes A and B

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TABLE I: The case study numerical information.

	Received SPM from DIO
node A	$SPM_C = 1068, SPM_D = 924, SPM_E = 204$
node B	$SPM_E = 924, SPM_F = 800, SPM_G = 800$
	Calculated SPR
node A	$SPR_{A,C} = 80, SPR_{A,D} = 20, SPR_{A,E} = 90$
node B	$SPR_{B,E} = 83, SPR_{B,F} = 33, SPR_{B,G} = 69$

through DIO messages and the calculated SPR values in each of these nodes could be seen in Table I. The information in Table I shows that the Δ_{th} (the average $(SPM + SPR)$) for nodes A and B are 759 and 903, respectively.

Accordingly, when node A executes Algorithm 1, the sum of SPM and SPR values for each of the candidate parents will be calculated. Considering node A, the value of $(SPM + SPR)$ for the paths passing through nodes C, D, and E are 1148, 944, and 294, respectively. As a result, node E provides the most efficient path among the entries of the node A's ParentTable and its $(SPM + SPR)$ value is less than $\Delta_{th_A} = 795$. Thus, node E will be announced as the new BestParent of node A. Note that, since ELITE considers all of the existing links' SPR along the path from node A to the sink, although the SPR of the link connecting node A to node D is much better than the SPR value of the link connecting node A to node E, ELITE selects node E as the BestParent of node A. On the other hand, considering node B, although node G (The current BestParent of node B) still provides the minimum SPM among the other entries of node B's ParentTable, since node F provides a better SPR than node G, the value of $(SPM + SPR)$ in the path passing from node F becomes lower than the path passing from node G (and also lower than $\Delta_{th_B} = 903$). Hence, ELITE will switch the BestParent of node B from G to F. As it was shown in this case study scenario, Algorithm 1 conducts energy-efficiency over an ELITE-enable IoT infrastructure by selecting the paths with the minimum amount of relative phase shift and consequently minimum amount of SPR between their involving nodes. In the next Section we will evaluate the results of implementing ELITE in an IoT simulation environment.

VI. System Setup and Results

In order to evaluate ELITE, we have exploited Contiki's built-in IoT simulation environment known as Cooja [10], [9]. Cooja is a cycle accurate Java-based simulator, which is able to emulate off-the-shelf IoT platforms considering their implementation details. Since in this simulation environment, the nodes are carefully emulated based on their manufactured specifications, while developing the intended algorithm and applications, we also take into consideration the applicability and portability of the proposed method in real-world experiments [26]. To conduct our simulations, we have employed a class of IoT platforms known as Zolertia One (Z1) developed by Zolertia®. Z1 exploits the second generation of the low power Texas Instruments® MSP430 micro-controller as its CPU, and employs the Chipcon® CC2420 radio module for its wireless communications. The CC2420 is an IEEE 802.15.4 compliant RF transceiver manufactured by the Texas Instruments, which is designed for low-power and low-voltage wireless applications, and it is broadly used in real-world

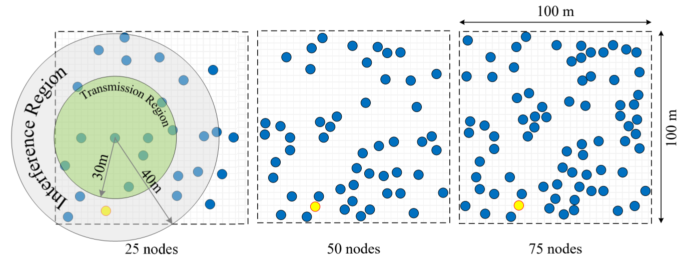


Fig. 10: Random IoT topologies with different densities.

TABLE II: Zolertia One specifications.

Parameter	Value
Micro-Controller Unit (MCU)	MSP430 (2^{nd} generation)
Architecture	16 bit RISC (Upgraded to 20 bits)
Radio Module	CC2420
Operating MCU Voltage Range	1.8V$<V<$3.6V
CC2420 Voltage Range	2.1V$<V<$3.6V
Operating Temperature	-40$^\circ C<\theta<$+85$^\circ C$
Operating System Clock Frequency	$f<$16MHz
MCU Active Mode Current @ V_{cc} = 3V (I_a)	2mA
MCU Low Power (Standby) Mode Current (I_{lpm})	0.5μA
Off Mode Current	0.1μA
Radio Transmitting Mode Current @ 0dBm (I_{tr})	17.4mA
Radio Receiving Mode Current (I_{rc})	18.8mA
Radio IDLE Mode Current	426μA

wireless network implementations [27]. A number of major specifications related to the Z1 platform (extracted from the data-sheets of its own and its interior hardware modules), which are considered in the simulations are illustrated in Table II.

According to Table III, in order to conduct our experiments, we have simulated an IoT network in an area with a size of $10000m^2$ (as in [28], and [29]) considering various network scenarios. Based on the previous studies in the context of RPL, the number of deployed nodes in the IoT infrastructure has been varied between 7 to more than 250 nodes; Nevertheless, according to the conducted survey on more than 39 published papers before 2017, the average number of employed nodes in RPL-related studies was 49.4 [30]. With respect to this issue, we have varied the number of nodes by 25, 50 and 75, which are randomly distributed in the intended IoT simulation area (Fig. 10). The only sink in the DODAG takes control of the nodes through the RPL's ICMPv6 control messages. In our simulations, nodes are obliged to transmit User Datagram Protocol (UDP) packets with 52 Bytes of payload to the sink with three levels of data rates, which have been selected and classified intuitively: 1) low (0.5 Packet/Minute), 2) Moderate (1.5 Packet/Minute), and 3) High (2.5 Packet/Minute) to generate different traffic rates. Furthermore, the Z1 nodes are set to send their data packets with a transmission power of 0dBm, as it is the default transmission power in most of the employed radios in WSN and IoT applications [31]. These IoT platforms have been set to cover an area with a radius of 30m

TABLE III: Simulation environment parameters.

Parameter	Value
Sensing Area	10000m^2
Number of Transmitter Nodes	25, 50, 75
Number of Sink Nodes	1
Communication Range	30m
Interference Range	40m
Transmission Power	0dBm
Traffic rate	0.5Pkt/Minute, 1.5Pkt/Minute, 2.5Pkt/Minute
UDP Payload Size	52Bytes
Simulation Time	3600s

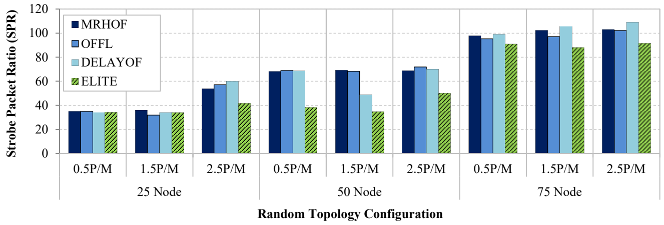


Fig. 11: Number of transmitted strobes per packet in each node in different network scenarios.

with an interference range of 40m. Finally, in order to have a fair comparison, all of the simulations were lasted for 3600 seconds considering the network's convergence time.

A. Experimental Results

The efficiency of ELITE has been investigated through its comparison with three state-of-the-art OFs, i.e., MRHOF [14], OFFL [8], and DelayOF [32]. Where, MRHOF represents the standard OF in RPL, OFFL is a delegate for energy-aware and reliable OFs, and DelayOF is representing the OFs with high performance. We have evaluated the efficiency of ELITE in IoT infrastructures from Strobe per Packet Ratio, Energy consumption, Reliability, Performance, and Control Overhead perspectives. In the following, we will discuss the simulation results.

1) Energy Efficiency Evaluation: As it was mentioned earlier, strobe packets have the most contributing impact on the energy consumption of IoT nodes. In this regard, the fundamental goal of ELITE was to mitigate the amount of transmitted strobe packets by the sender to decrease its energy consumption. Hence, in the first place, we have analyzed the efficiency of ELITE in terms of SPR. As it has been depicted in Fig. 11, in less dense topologies (25 nodes) with low data rates (0.5 P/M), despite of a slight improvement (nearly 2.5%) in the SPR by employment of ELITE, all the OFs are acting relatively the same; Because, due to presence of few nodes in the network, there will be a lack of path diversity, which prevents the nodes to have a wider set of options in their candidate parent set. Hence, they may have no other option to switch their preferred parent based on the OF. In other words, in case of having few nodes in the environment, the nodes may only have one candidate parent in their transmission range. Therefore, independent from employing which OF, the node will select that particular candidate as its best parent. In addition, exploiting low data rates in low density networks, inherently reduces the number of strobe packets, which prevents the SPR to get fully affected by the ELITE.

On the other hand, by increasing the number of nodes and data rates in the network, the amount of strobe transmission will be significantly escalated. In this regard, deploying more number of nodes in the DODAG would have two consequences: 1) Paths would involve more number of nodes, which will enforce them to forward more packets (especially in those nodes, which are closer to the sink), and 2) More amounts of control packets would be required to maintain the DODAG. In either of these situations, due to more packet transmissions (whether data packets or control packets), more strobe packets will be transmitted by the nodes across the DODAG. In the meantime, increasing the data rates will also intensify the strobe dissemination. Furthermore, in moderate and high density IoT infrastructures, due to presence of path diversity, ELITE-enabled nodes will have this opportunity to select their preferred parent among a broader range of neighbouring nodes with probable minimal relative phase shift. Hence, in such circumstances, the ELITE OF could significantly reduce the amount of strobe packet transmissions. As it has been illustrated in Fig. 11, ELITE can improve the average amount of SPR against MRHOF, OFFL, and DelayOF by 25.1%, 25%, and 24.7%, respectively. According to the results, this amount of improvement may reach as high as 49.6%, 49%, and 44.3% based on the configuration of the network.

In order to measure the amount of consumed energy by each of the deployed motes, we have employed the On-Line Node-Level Energy Estimation technique [33] in which, the overall energy consumption (E_{total}) is computed according to Equation 5.

$$E_{total} = V.[I_a t_a + I_{lpm} t_{lpm} + I_{tr} t_{tr} + I_{rc} t_{rc} + \sum_{i=1}^{n} I_p t_p] \quad (5)$$

Where, E_{total} is the total amount of consumed energy in the node, V is the platform's supply voltage, I_a is the draining current from the processor in active mode, I_{lpm} is the drained current in low power mode (LPM), I_{tr} and I_{rc} are the drawn currents from the transceiver module in transmission and reception phases, respectively, and the I_p corresponds to the current of peripherals (e.g., LEDs and buttons). Further more, t represents the amount of spent time by each module in a certain mode.

According to Fig. 12, the node density and the data rate are a couple of factors, which affect the amount of consumed energy by the nodes. By deploying more number of nodes in the area and increasing their packet transmission rate, the activity of their transceiver modules will be increased due to transmission and reception of more data packets (mainly due to forwarding operations), and control packets (for maintaining the DODAG). Meanwhile, since MRHOF and OFFL exploit ETX as their routing metric, they would prefer longer but more reliable paths instead of shorter unreliable paths. Hence, unlike DelayOF, which tries to mitigate the E2E delay through shorter and faster paths, MRHOF and OFFL may activate those of paths with more number of nodes. As a result, they have increased the average amount of energy consumption in the nodes by up to 11.5% and 27.6% compared with DelayOF, respectively. Although OFFL considers the residual energy of

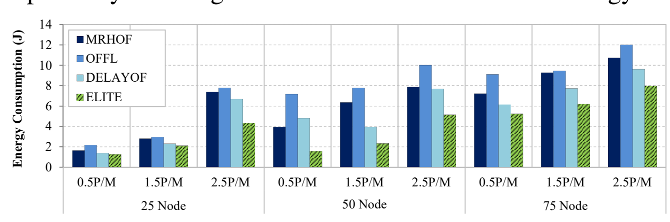
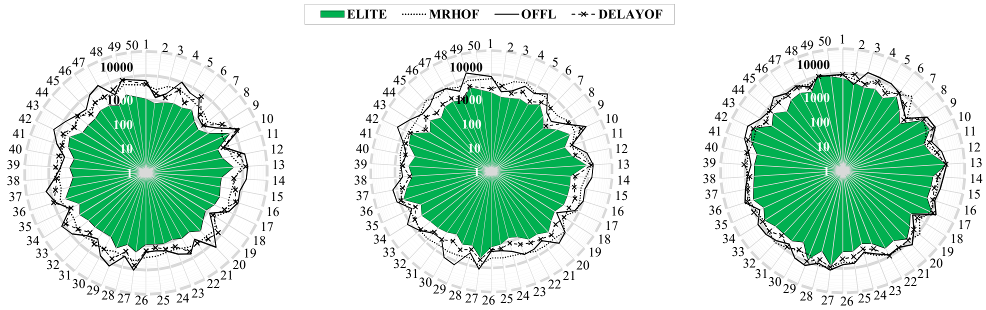


Fig. 12: The average amount of consumed energy by the nodes in different network scenarios.

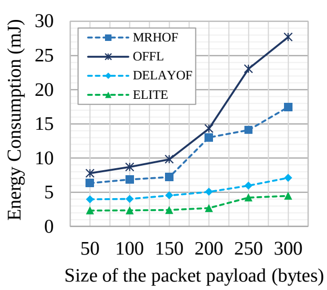


(a) 50 Nodes Topology with 0.5 Packet per Minute Data Rate

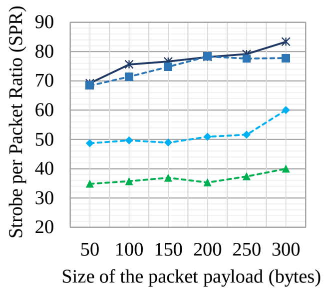
(b) 50 Nodes Topology with 1.5 Packet per Minute Data Rate

(c) 50 Nodes Topology with 2.5 Packet per Minute Data Rate

Fig. 13: The amount of energy consumption in every node of the DODAG (mJ).



(a) Impact of transmitted data size on the consumed energy



(b) Impact of transmitted data size on the SPR

Fig. 14: Impact of data size on the performance of ELITE.

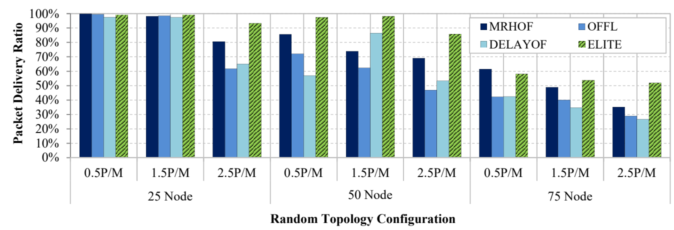


Fig. 15: The average amount of PDR in different network scenarios.

the nodes as one of its routing metrics, the other three routing constraints have prevented an optimized path selection in terms of energy consumption in OFFL.

Beyond all of this, neither of the previously proposed OFs in the literature have considered the concept of relative phase shift and strobe packets as the main reason for energy consumption. In this regard, as it could be seen in Fig. 12, the employment of SPR in the structure of ELITE has enabled it to reduce the average amount of energy consumption in the nodes by 36.9%, 46.7%, and 27.1% in comparison with MRHOF, OFFL, and DelayOF, respectively. Nevertheless, in addition to the average energy consumption, it is highly recommended to evaluate the energy consumption of the nodes individually. In this regard, we have compared the amount of consumed energy in the nodes one by one with respect of different OFs. Considering our moderate network scenario with 50 nodes (Other network scenarios are not presented due to space limitations), Fig. 13 provides a detailed information on the energy consumption of the nodes in a logarithmic manner. According to the green area in this plot, ELITE has provided the minimal energy consumption among the other OFs in most of the nodes while it guarantees that the energy consumption in an ELITE-enabled node never goes beyond the other OFs. This would be very important for preventing the energy-hole problem for providing a more reliable network. According to the results, on average, ELITE has improved the amount of consumed energy in every node by more than 35.2%, 39%, and 25.7% compared with MRHOF, OFFL, and DelayOF, respectively. Furthermore, this amount of improvement may reach up to 64.4%, 71%, and 63.7%, according to the configuration of the network. Finally, in order to provide a more comprehensive investigation, Fig. 14 illustrates the effect of data size on the performance of ELITE against the other OFs in our moderate network scenario. Accordingly, as it could be observed, independent from the size of the transmitted data packets, our proposed OF still dominates the other OFs in terms of both, energy consumption, and strobe per packet ratio.

2) Reliability Evaluation: PDR is an indication of routing reliability in IoT networks [34]. Hence, we have employed Equation 6, to calculate the value of PDR and evaluate the reliability of OFs. Accordingly, PDR is the ratio of successfully received packets by the sink to the total number of transmitted packets towards the sink in the network.

$$PDR = \frac{ReceivedPacketsbytheSink}{TransmittedPacketstotheSink} \tag{6}$$

According to Fig. 15, independent from the type of OF, by assuming a network with a constant number of nodes, increasing the data rate will degrade the amount of PDR. Generally speaking, since IoT platforms are equipped with significantly limited storage, their data buffers are relatively small in size and they could get filled quickly in case of high packet transmission rates. In such circumstances, the nodes will have no other option but to drop their currently stored packets, which results in lower PDR values in the network. In addition, deploying more nodes in the DODAG would also reduce the PDR; Because, more number of nodes in the network will generate more number of data and control packets, which will increase the probability of congestion and consequently packet drops in the nodes' buffers.

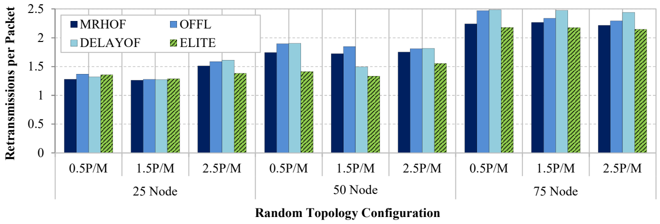


Fig. 16: The average number of retransmissions per packet in different network scenarios.

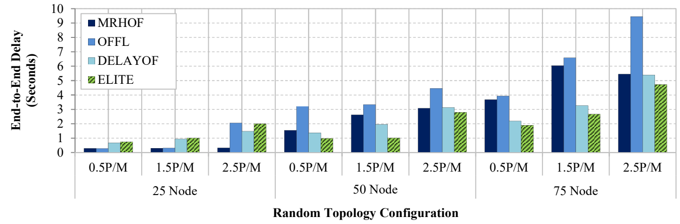


Fig. 17: The average amount of E2E delay in different network scenarios.

We analyze the reliability of ELITE through a simple example. Let's assume we have two nodes, A and B. Based on the topology, node A is obliged to send its packets to node B. The more amount of relative phase shift and SPR between A and B would bring two consequences. First, more strobe packets will impose additional traffic to the radio channel, which may lead to higher channel congestion and consequently lower PDR [35]. Second, since node A itself is a preferred parent for several other child nodes and it has to forward their packets to node B, it has to maintain its received and self-generated packets for a longer period of time in its buffer to apply for strobe transmission. As a result, there will be a high probability that by intensification of the relative phase shift between nodes A and B, due to congestion in the node A's buffer, it will have no other options but to drop the packets, which will lead into reduction of PDR. ELITE overcomes this challenge by selecting the paths with the minimum amount of relative phase shift and SPR in its structure. Hence, as it has been illustrated in Fig. 15, ELITE has improved the average amount of PDR against MRHOF (as one of the most reliable OFs) by more than 11.7%, while it has enhanced the reliability against both, the OFFL and DelayOF by more than 26%. Furthermore, due to selecting paths with higher reliability, ELITE-enabled nodes will have this opportunity to send their packets through paths with higher quality and less packet drops. Thus, they do not need to frequently retransmit their dropped packets due to factors such as congestion in upper layers. As it has been depicted in Fig. 16, ELITE has reduced the average number of retransmissions per each packet by more than 7%, 11.7%, and 10.8% compared with MRHOF, OFFL, and DelayOF, respectively, which is also an indication of establishing higher quality and more energy-efficient communications in ELITE.

3) Performance Evaluation: E2E delay is a parameter, which should be carefully considered in alarm-based IoT applications such as RHMS *(Remote Health-care Monitoring Systems)* [36]. Hence, we have analyzed ELITE in terms of performance. According to Fig. 17, in a DODAG with relatively limited number of nodes (25 node), ELITE has imposed higher amounts of E2E delay in comparison with DelayOF, which specifically concentrates on the mitigation of latency. Based on the results, ELITE has increased the amount of E2E delay by nearly 13.8% against DelayOF in case of low density topologies. On the other hand, by deploying more number of nodes in the network, due to creation of path diversity, ELITE-enabled nodes can select their preferred parent among a broader range of options, and improve the performance of packet transmissions due to two reasons. First, the nodes with the minimum amount of relative phase shift will be chosen to be set as the preferred parent, which would make the transmitter to waste less time for informing the receiver. Secondly, due to the provided reliability by ELITE, as it was shown in Fig. 16, there will be fewer retransmissions per packet in the network. Each of these issues suffices for the improvement of the performance by ELITE. As it has been depicted in Fig. 17, on average, ELITE not only improves the amount of performance in MRHOF and OFFL by 37.5%, 56.3%, but it also mitigates the amount of E2E delay in DelayOF by more than 22%.

4) Control Overhead Evaluation: More control packets in the DODAG would impose higher amounts of resource consumption in terms of energy and bandwidth to both, the nodes and the links. Accordingly, it is desirable to minimize the amount of control packet overhead in the network. The main solution for overcoming this challenge in RPL is the employment of trickle timer, but it could be further improved by implementing OFs, which bring stability to the DODAG by reducing the inconsistencies, e.g., global repairs and parent switches [12]. The DODAG inconsistencies are mainly driven from alterations in the topology, which are directly affected by OFs. Hence, we have evaluated ELITE in terms of control packet overhead. In this regard, we have calculated the ratio of control packets to the total number of generated packets by the nodes.

As it has been presented in Fig. 18, independent from type of the OF, in a DODAG with constant number of nodes, increasing the data rate would reduce the control packet overhead; Because the rate of the control packets will not be affected as much as data packets. On the other hand, by as-

TABLE IV: Memory footprint of ELITE against other OFs.

	Original version of RPL		RPL extensions		
RPL Objective Function	**OF0**	**MRHOF**	**OFFL**	**DELAYOF**	**ELITE**
Code Size in ROM (bytes)	218	360	1346	260	586
Consumed RAM (Kbytes)	1.69 (21%)	2.16 (27%)	3.16 (40%)	1.92 (24%)	2.5 (31%)

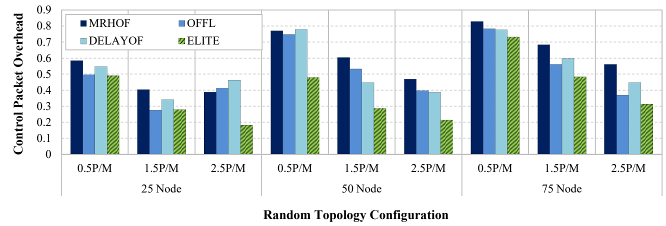


Fig. 18: Comparing ELITE with other OFs in terms of average control packet overhead.

suming a constant data rate, deploying more number of nodes will increase the control packet overhead due to path diversity and more fluctuations in the quality of the nodes and the links from different perspectives. In the meantime, since OFFL uses four constraints in its structure compared with MRHOF, MRHOF would switch the parents with higher probability. Accordingly, OFFL could decrease the control packet overhead by up to 14.3% compared with MRHOF. On the other hand, due to presence of more reliable communications in an ELITE-enabled network, the amount of inconsistencies, which require control packet dissemination, would be lower than other OFs. As it has been illustrated in Fig. 18, on average, ELITE has decreased the amount of control packet overhead by 36.6%, 24.3%, and 29.3% in comparison with MRHOF, OFFL, and DelayOF, respectively.

In addition to the control packet overhead, the size of the control packets, which are used for carrying the routing information (mainly the embedded data in the DIO's metric container) are also important. Accordingly, since ELITE only adds 2 bytes of information to the DIO's metric container, which is identical to the size of the ETX in the standard version of RPL, along with mitigating the control packet overhead, it has been able to reach its goals with imposing minimal costs to the network. Nevertheless, in terms of memory footprint, ELITE imposes an additional code size of nearly 38.6% to the Z1 flash memory in comparison with the MRHOF. Furthermore, as it has been indicated in Table. IV, it has occupied 31% of the RAM (8kB), which is nearly 14% more than the occupied memory space by the MRHOF.

VII. Related Studies

While many of the RPL implementations have employed MRHOF as their OF [37], there have been a number of efforts on designing novel OFs in order to satisfy specific requirements of IoT applications. Accordingly, a number of studies have tried to propose novel OFs to reduce the amount of energy consumption in the nodes with considering the residual energy of the nodes along with other metrics to gain a more energy-efficient routing [8], [38], [39]. Among them, OFFL is a novel and well-known OF, which combines four node/link metrics (including the residual energy of the nodes) by utilizing the fuzzy-logic paradigm [8]. In a relative study, the authors in [40] have proposed Energy and Congestion-aware Routing Metric (ECRM) to be used in Advanced Metering Infrastructures (AMI). The Estimated Remaining Life Time (ERLT), and the Expected Life Time (ELT) are a couple of energy-aware metrics, which could be employed for performing the parent selection to increase the longevity of the network [41], [42]. In all of these studies, the selecting node (the node, who wants to select a parent), considers the energy-efficiency of its parent without taking care of its own energy resources. In other words, the energy consumption of the selecting node should be considered via its children. In contrast, a side from all of the unique specifications of ELITE, the selecting nodes in ELITE-enabled IoT networks not only consider the energy consumption of all the existing nodes in their path towards the sink, but they put their own energy consumption first.

Providing a stable DODAG with less control packet dissemination could also mitigate the amount of energy consumption in the nodes. Hence, a number of studies have tried to provide stability-aware OFs [43], [44]. On the other hand, one of the downsides of RPL is the lack of load balancing mechanism in its OFs, which imposes packet loss, retransmission, and more energy consumption to the nodes. Hence, several studies have tried to propose reliable queue utilization techniques to be adopted in the standard RPL to resolve the congestion and load balancing problems to enhance the PDR and reduce the retranmissions to consequently mitigate the energy consumption in the nodes [37], [40], [45], [46]. A multi-path OF was also introduced in [47] for improving the reliability along with minimizing the jitter in the network. There also exist other types of OFs, designed for IoT applications such as Remote Health Monitoring systems (RHMS), which require both, energy-efficiency, and performance simultaneously [36], [48].

VIII. Conclusion and Future Directions

In this paper we have proposed ELITE, an elaborated cross-layer objective function for RPL to achieve energy-efficiency in IoT applications. ELITE tries to decrease the amount of energy consumption in an IoT node by mitigating the number of required strobe packet transmissions in the RDC mechanism of the MAC layer. To this end, ELITE employs a newly defined routing metric called SPR, which has been designed to be coupled with asynchronous MAC protocols, e.g., ContikiMAC. SPR enforces ELITE to select those of paths, which their involved nodes have to send less number of strobes to their parents to inform them about the incoming packets. Therefore, ELITE decreases the overall transmission activities for sending information from source nodes to their destination(s). The evaluation results show that ELITE reduces the average amount of SPR by up to 25% while it improves the average amount of consumed energy in an IoT node by up to 39% compared to its counterpart OFs. Based on our observations, ELITE gets more effective as the scale of the DODAG increases. This is mainly due to factors such as path diversity, which enables the nodes to have a wider set of options in their candidate parent set with probable minimized relative phase shift, and also due to more data and control packet transactions in the DODAG, which requires more amounts of effort in the RDC layer in terms of strobe transmission.

While there exist other possible metric candidates such as energy per packet, which could consider more contributing factors in the nodes energy consumption, but as it was discussed in the paper, the trend of energy consumption completely complies with the strobe transmissions. Hence, since extracting and utilizing the strobe transmission information from the MAC layer in the routing layer is a straight forward task with minimal overheads, with using the SPR metric, we are able to reach the relatively the same result as energy per packet metric with minimal complexity. Nevertheless, proposing new versions of RPL with considering the amount of consumed energy per packet is a possible field of research for future studies.

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