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Abstract—In this paper, we assess the energy performance of TSCH and 6TiSCH using the Contiki-NG operating system on Zolertia RE-mote (Rev. B) nodes.

These boards are part of the IoT hardware family, and they allow for the creation of a network minimizing energy consumption. The paper is subdivided into three main sections: in the first one, we will compare the energy consumption of the leaf and root node (LLC) at first using up to the MAC TSCH layer, and then using the full stack.

In the second section, we will analyze the TSCH joining process and relative energy consumption. Further, in the final section, we will assess the performance of the TSCH mode over various distances.

Index Terms—6TiSCH, Contiki-NG, Energest, IEEE 802.15.4, Power Consumption, Range, Time Slotted Channel Hopping, TiSCH, TSCH, Zolertia

I. INTRODUCTION

The IETF IPv6 over the TSCH mode of IEEE802.15.4e (6TiSCH) working group has standardized a set of protocols to enable low power industrial-grade IPv6 networks. 6TiSCH proposes a protocol stack rooted in the Time Slotted Channel Hopping (TSCH) mode of the IEEE802.15.4-2015 standard, supports multi-hop topologies with the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) routing protocol, and is IPv6-ready through 6LoWPAN [2].

Contiki-NG is an operating system for resource-constrained devices in the Internet of Things. Contiki-NG contains an RFC-compliant, low-power IPv6 communication stack, enabling Internet connectivity. The system runs on a variety of platforms based on energy-efficient architectures such as the ARM Cortex-M3/M4 and the Texas Instruments MSP430. The code footprint is on the order of a 100 kB, and the memory usage can be configured to be as low as 10 kB.

This paper serves as an initial look at the performance of TSCH on the Contiki-NG operating system. Specifically, we're going to look at the energy consumption by the TSCH network stack vs the 6TiSCH network stack. We'll also analyze the TSCH joining process. Finally, we'll see how much impact the distance between node has on the network.

The hardware in use are Zolertia RE-Mote boards, designed jointly with universities and industry partners in RERUM European project, to ease the development of private and secure applications for IoT and Smart City applications.

The RE-Mote packs several onboard resources, like an RTC,

external WDT, Micro-SD, RF switch, and a Shutdown mode to reduce its power consumption down to 150nA [1].

II. RELATED WORK

A. Accurate energy consumption using Energest

In section III of this paper, we focus on the analysis of the energy consumption between leaf and root node. This analysis can be done by knowing different parameters like current, tension, and time.

tension is always 3.3V, current instead should be correctly provided in the board datasheet, previous works have shown that real current consumption values are different from the datasheet provided ones [4], in this paper, we are going to use such current measurements to determine the energy consumption.

B. Throughput Analysis

In this paper, an analysis of the throughput performance of TSCH networks is made. They show which parameters of the TSCH networks (node count, hop count, ...) influence the throughput metric in what way. Our research focuses on different performance characteristics of the TSCH implementation and can be useful alongside these results [5].

III. ANALYSING THE 6TiSCH ENERGY CONSUMPTION

In the first analysis, we compared the energy consumption during a certain time period of the entire 6TiSCH stack to when only enabling the TSCH MAC layer (without link-layer security) after network convergence.

The full stack can be seen as in Figure 1.

For both analyses, we report on the consumption of the root and the leaf node separately.

Following we remark differences in energy consumption between the root and the leaf node in the two different scenarios.

The Time-Slotted Channel Hopping (TSCH) mode for medium access control (MAC) included in the standard IEEE 802.15.4 has been designed as the multichannel MAC protocol for Low-power and lossy networks (LLNs), a key component of the Internet of Things (IoT). Its flexibility makes the TSCH mode a very promising candidate for the future of the MAC layer in LLNs. As such, its performance under different conditions must be assessed, so that accurate guidelines for its application can be drawn [6].

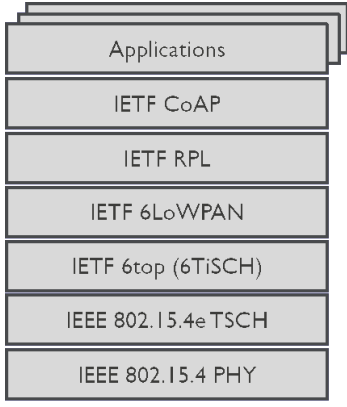


Fig. 1. 6TiSCH Protocol Stack [3].

the physical setup of the experiment consists of two Zolertia Remote RevB boards placed at a fixed distance of approximately 20 cm as shown in Figure 2.

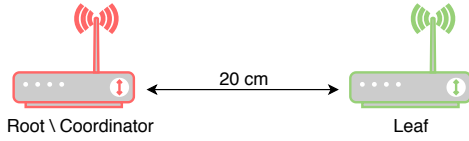


Fig. 2. Network topology for 6TiSCH energy consumption analysis.

The basic setup for the following analysis are a root (coordinator) node and a leaf node that exchange the same amount of data packets.

Both nodes are configured to measure the energy consumption by the Energest¹ module available in Contiki-ng².

The Energest module can be used to implement lightweight, software-based energy estimation approach for resource-constrained IoT devices. By tracking the time various hardware states such as the radio is turned on, and by knowing the power consumption of the state, it is possible to estimate the energy consumption [1].

The energy consumption is measured referring to the following formula:

$$E_{tot} = \sum_{s \in state}^{N_s} E_s = \sum_{s \in state}^{N_s} I_s \cdot V_{cc} \cdot t \quad (1)$$

Where V_{cc} is the supply voltage, fixed as a constant at the value 3.3V, I_s is provided by the Table I column *Device profiling* [4], and t is measured using Energest.

All measurements are performed in a span of 15 minutes each.

A. Only TSCH MAC layer

In the first part of the experiment, we used only the stack till the MAC layer (TSCH) as shown in Figure 1. In TSCH networks, every node follows a time-synchronized schedule.

¹<https://github.com/contiki-ng/contiki-ng/wiki/Documentation:-Energest>

²<https://github.com/contiki-ng>

State	CC2538 datasheet	Device profiling
CPU	20 mA	15.35mA
LPM	0.6 mA	9.59 mA
Deep LPM	0.0013 mA	2.58 mA
LISTEN	24 mA	28.32 mA
Rx	27 mA	30.14 mA
Tx	34 mA	31.12 mA

TABLE I
COMPARISON BETWEEN VALUES FROM THE DATASHEET AND N6705B DC POWER ANALYZER RADIO. [4]

This schedule instructs every node about exactly what to do and avoids wasting valuable energy. The TSCH schedule is divided into time slots. The duration of a time slot is typically 10 ms or 15 ms and sufficient to transmit a packet of the maximum size of 127 bytes, immediately followed by an optional acknowledgment frame indicating that the packet was successfully received. Multiple time slots are grouped into a slot frame, and the size of a slot frame defines the width of the schedule. These slot frames repeat continuously over time. TSCH also allows one to use multiple frequencies, leading to a two-dimensional matrix of cells. The number of available frequencies actually determines the height of the schedule [7].

We proceeded as explained in the setup to measure the energy consumption between leaf and root node.

Results are reported in Table II. What we can see is that data

Node	CPU	LPM	Deep	Tx	Rx
Leaf	3.330 mJ	314.385 mJ	85.143 mJ	1.132 mJ	993.527 mJ
Root	3.330 mJ	314.385 mJ	85.143 mJ	1.132 mJ	993.527 mJ

TABLE II
AVERAGE POWER CONSUMPTION COMPARISON BETWEEN ROOT AND LEAF NODE PER STATE, TSCH MAC ONLY.

from root and leaf nodes show no variation, and the energy consumed from both of them is the same.

In a TSCH network The root needs to control the way the network is formed, including how new nodes join and how already joined nodes advertise the presence of the network, this is all encoded in the TSCH RFC³.

The root node during network convergence needs to:

- Define the Information Elements included in the Enhanced Beacons, advertising the presence of the network;
- for a new node define rules to process and filter received EBs;
- Define the joining procedure. This might include a mechanism to assign a unique 16-bit address to a node and the management of initial keying material;
- Define a mechanism to secure the joining process and the subsequent optional process of scheduling more communication cells.

After the network has been formed it must be maintained, this implies that the root node must:

- Manage each node's time source neighbor;

³<https://tools.ietf.org/html/rfc7554>

- Define a mechanism for a node to update the join priority it announces in its EB;
- Schedule transmissions of EBs to advertise the presence of the network.

We can therefore say that, atleast for two node, the workload on the root is not enough to show a difference in energy consumption during the stated time spam.

B. Full stack

The next experiment is as cited in the section III introduction related to the energy consumption once the full 6TiSCH stack has been enabled (except for the security layer).

The setup of this experiment is the same to the previous one. Two boards 10cm apart from each other (2) are running the same source code.

In this scenario, we have a coordinator node and a leaf node. No messages are exchanged between the two if not for standard 6TiSCH service messages.

We proceeded as explained in the setup to measure the energy consumption between leaf and root node.

Results are reported in Table III.

Node	CPU	LPM	Deep	Tx	Rx
Leaf	5.00 mJ	313.341 mJ	85.143 mJ	80.121 mJ	98.362 mJ
Root	3.890 mJ	310.560 mJ	84.209 mJ	0 mJ	33.879 mJ

TABLE III

AVERAGE POWER CONSUMPTION PER STATE BETWEEN ROOT AND LEAF NODE, FULL 6TiSCH STACK.

C. Final comparison

As a final comparison, we compared the total energy usage between root and leaf nodes in the two configurations. What we measured has been reported as Table IV.

Node	MAC only	Full stack
Leaf	1.398 J	0.582 J
Root	1.398 J	0.433 J

TABLE IV

ENERGY COMPARISON BETWEEN LEAF AND ROOT NODE IN MAC ONLY AND FULL STACK CONFIGURATIONS.

IV. ANALYSING RANGE CAPABILITIES

A. Approach

In order to properly analyse the range capabilities, we must first define a test structure that will be repeated at each range. The test in this case is sending 120 packets (1 per second, 52 data bytes each) over a specified range (varying between 1 and 100 meters) so we can show the performance characteristics of TSCH as the distance between nodes varies. The data payload size was chosen out of convenience, as each packet carries metrics from the sender and they happened to be 52 bytes in size. Varying this packet size will result in different performance metrics and so must be addressed V.

Due to time constraints, combined with other obligations, the full scope of the experiments in this section has not yet been carried out. A brief comparison is made (showing the

methodology) between nodes with 1 meter separation and nodes with 5 meters separation. Further work must be done to complete this analysis V.

As of now, though, we can show that the TSCH functionality is essentially unchanged when we're looking at 1 vs 5 meters separation between the two nodes. The power requirements are within margin of error, there is no significant packet loss in either case. The longer distance has a slightly higher latency (potentially caused by more retransmissions, we'll need to look at this V).

For this analysis, we disabled the 6TiSCH stack (using only the TSCH mac layer) and ensured no security was enabled. No further changes to the Contiki-NG network stack were required.

B. Results

1) *1 meter separation:* First, we'll compare the latencies. At 1 meter separation, we found, on average, 9.29 timeslots delay between the enqueueing of the packet on the sender's side and the arrival on the receiver's side ???. Presumably, a majority of this time is spent in the queue (or in re-transmissions), but this will be verified later V. Over the distance of 1 meter, there is 100% packet arrival rate.

Regarding power use, then, we see that the leaf node consumes more power than the root node does. This is shown in ??, combined with the current draw for each power state as described in I. Overall, we find that the leaf node has used approximately 4.35 joules of energy whereas that value is only 2.58 joules for the root node. Since each packet carried a data payload of 52 bytes, we find the following power requirements: roughly $89 \frac{mJ}{kbit}$ for the leaf node and $53 \frac{mJ}{kbit}$ for the root node.

2) *5 meters separation:* When we increase the distance to 5 meters, not much changes. As the distance is still very small (and should be easily within range), this is to be expected. The packet delivery ratio is still at 100%, latency is slightly increased to roughly 9.33 slots (but this could be within margin of error - we should look at retransmission rates to verify V).

The energy consumption is essentially the same, they are definitely within margin of error for our current test setup and so will not be discussed further than they have been in IV-B1.

V. FUTURE WORK

- Analyze the TSCH joining process
- Perform the experiments as required for IV
- Further discuss the current results in IV
- Further analyze the found flaws in IV

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