Impact of cross-layer interactions between Radio Duty Cycling and routing on the efficiency of a Wireless Sensor Network

A testbed study involving ContikiMAC and RPL

Author1
Department1
Address1
Address1
City1, Country1
email1@email.com

Author2
Department2
Address2
Address2
City2, Country2
email2@email.com

Author3
Department3
Address3
Address3
City3, Country3
email3@email.com

Author4
Department4
Address4
Address4
City4, Country4
email4@email.com

Author5
Department5
Address5
Address5
City5, Country5
email5@email.com

ABSTRACT

The RPL routing protocol and ContikiMAC are respectively two of the most popular routing and Radio Duty Cycling protocols for Wireless Sensor Networks. However, their interactions have not yet been completely understood. In this paper we explore the influence that an often neglected parameter of ContikiMAC (the CCA threshold) has on the performance of a RPL network. Different real-world experiments are presented in this study, proving that the correct parameter tuning is essential in order to have an efficient network. Based on our experience, we provide preliminary guidelines for deploying a functional WSN using these protocols in an interference-poor environment.

CCS Concepts

•**Networks** → **Cross-layer protocols; Network experimentation; Network performance analysis; Network measurement;** *Protocol testing and verification; Link-layer protocols; Routing protocols;*

Keywords

Wireless Sensor Network; ContikiMAC; RPL; Radio Duty Cycling Protocol; Contiki; Zolertia Z1

1. INTRODUCTION

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In battery-operated multihop Wireless Sensor Networks (WSNs), power consumption must be as low as possible in order to increase network lifetime. Such networks are often based on the IEEE 802.15.4 standard, that specifies the Physical and Medium Access Control (MAC) layers for Low-Rate Wireless Personal Area Networks (LR-WPANs) [1].

On one hand, the most power-consuming component in a sensor mote is the radio transceiver. Thus, the radio should be kept off whenever possible. To achieve this, a Radio Duty Cycling (RDC) protocol is added to the MAC layer in the communication stack. Different RDC protocols have been proposed. Among them, one of the most popular is the ContikiMAC RDC protocol [2]. ContikiMAC is the default RDC protocol in the ContikiOS, which is a well-known Operating System specifically designed for running on very constrained devices. On the other hand, to integrate multihop WSNs into the Internet, 6LoWPAN and the Routing Protocol for Low-Power and Lossy networks (RPL) [3] are commonly used.

Subtle implementation issues and unforeseen interactions between protocols are often found in WSNs. However, some of those issues cannot be observed by means of simulations. In this study we analyze how an often neglected parameter of ContikiMAC (the CCA threshold) affects the performance of a Wireless Sensor Network that uses the RPL routing protocol, through real-world measurements. Our goal is to provide guidelines in order to ease the future deployment of WSNs, and show how the performance of the network is harmed when those guidelines are not followed. Some of the findings presented were somewhat surprising and unexpected, proving that a thorough and systematic study of the cross-layer interactions between the different communication protocols is of utmost importance in order to guarantee that the WSN delivers its expected performance.

The RPL and the ContikiMAC implementations available in the ContikiOS are used for this study. Two sets of mea-

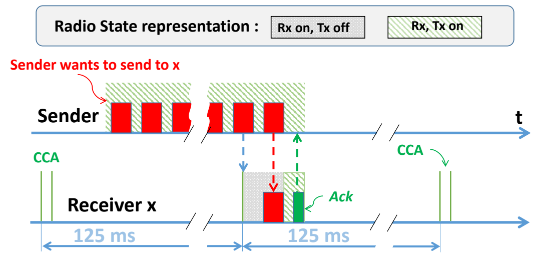

Figure 1: ContikiMAC operation for sending and receiving a unicast packet, with a wake-up rate of 8 Hz.

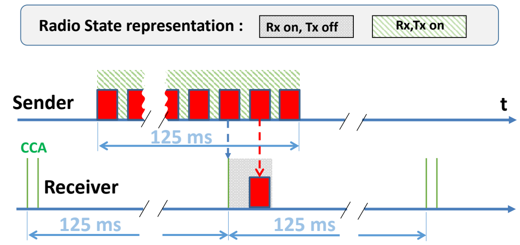

Figure 2: ContikiMAC operation for sending and receiving a broadcast packet, with a wake-up rate of 8 Hz.

surements are presented. The first one consists on a simple set-up with two motes, deployed in an office environment. For this experiment, the performance of ContikiMAC is measured in terms of PDR when one of the nodes is sending unicast packets to the other. The second one consists on a RPL network with 20 motes installed in a remote location, far from any external radio interference (such as WiFi). In this experiment, the nodes are running the RPL routing protocol together with ContikiMAC.

The rest of the paper is organized as follows. Sections 2 and 3 introduce ContikiMAC and the RPL routing protocol. Section 4 looks at the related research work. Section 5 shows the set-up for the experiments made. Section 6 presents and discusses the obtained results. Some guidelines for future deployments are provided in 7 and concludes in Section 8.

2. CONTIKIMAC

Radio Duty Cycling (RDC) protocols keep the radio off as much as possible. ContikiOS includes different asynchronous RDC protocols which do not require any clock synchronization mechanism. They all base their operation on periodic radio wake-ups (typically, 8 times per second). The elapsed time between two successive wake-ups is called the wake-up interval (typically, 125 ms).

For this study we focus on the operation of ContikiMAC, the default RDC protocol in the ContikiOS.

ContikiMAC [2] periodically wakes up the radio to check for channel activity, by performing two consecutive Clear Channel Assessments (CCAs). These CCAs are checks for radio activity in the channel, through a measurement of the RSSI (Received Signal Strength Indicator). If the strength of the radio signal is higher than a certain threshold, called "CCA threshold", the receiver keeps its radio on. Two consecutive CCAs are performed in order to ensure that at least one of them will detect the presence of a possible packet. Once the packet has been received, an ACK is sent. Therefore, the CCA threshold parameter is pivotal for the correct functioning of the network, since it determines the value of RSSI below which packets are not detected.

To transmit a unicast packet, the node's RDC layer repeatedly sends the packet until the receiver wakes up, receives it and acknowledges it. This is illustrated in figure 1.

If the RSSI of the signal at the receiver is below the CCA threshold, the sender will continue transmitting the packet for a full wake-up period. If no ACK is received, CSMA will schedule a retransmission. This process will be repeated until the maximum number of CSMA retransmissions is reached. In that case, the packet will be dropped.

To transmit a broadcast packet, the mote sends the packet repeatedly during a full wake-up interval. This way, it is ensured that every possible receiver will have woken up to receive the broadcast. Broadcast packets are not acknowledged. The operation of ContikiMAC for broadcasting a packet can be seen in figure 2.

ContikiMAC's performance can be improved by activating an option called "phase optimization". This will monitor wake up times of every known neighbor. This way, when a mote has a packet to send to another with which it has already exchanged packets before, it will not start sending repetitions of the frame immediately, but wait until close to the moment at which the receiver will wake up.

3. RPL ROUTING PROTOCOL

3.1 General concepts

The IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) is defined in RFC 6550 [3]. RPL is the protocol in charge of finding multi-hop routes to reach every destination within a WSN, which is, in the Internet terminology, an IP subnet. Figure 3 shows the typical protocol stack for a Wireless Sensor Network using RPL and 6LoWPAN.

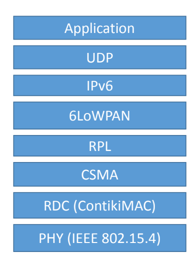

Figure 3: Protocol stack for a WSN.

RPL is designed to meet the requirements of Low-Power and Lossy Networks (LLNs), or in our particular case, of Wireless Sensor Networks (WSNs). Such networks consist of resource-constrained nodes (limited processing capabilities, limited memory and usually battery-powered) that are connected by lossy links with low data rates.

RPL builds a Destination Oriented Directed Acyclic Graph (DODAG). It is a network topology in which nodes are organized in a hierarchical way, forming a configuration that converges in the root node. RPL provides routing paths in both directions, upwards (from the nodes to the sink) and downwards (from the sink to the nodes). To create the

DODAG, RPL uses ICMPv6 control messages. The three basic types of RPL control messages are:

- DODAG Information Object (DIO): It contains the information that allows a node to discover a RPL Instance, learn its configuration parameters , select a DODAG parent set, build and maintain upward routes. The interval of time between DIOs transmitted by the same node follows the Trickle algorithm as described in [4].
- DODAG Information Solicitation (DIS): This type of message may be used to solicit a DODAG Information Object from a RPL node.
- Destination Advertisement Object (DAO): These messages are necessary in order to build and maintain downward routes.

3.2 RPL routing metrics

The RPL routing protocol is basically a generic Distance Vector protocol, that leaves the process of route selection to an external mechanism called Objective Function (OF). An Objective Function defines how nodes select parents and how they translate one or more metrics and constraints into a value called Rank. The Rank indicates how close to the root a node is: the higher the rank, the further away the node is from the DODAG root. A single DODAG must use a common OF.

Only two OFs have been standardized in two RFCs. RFC 6552 [5] defines the Objective Function Zero (OF0), which minimizes hop count to sink. RFC 6719 [6] defines the Minimum Rank with Hysteresis Objective Function (MRHOF). MRHOF is used to minimize a certain metric (e.g. latency or Expected Number of Retransmissions), while using hysteresis to avoid route changes in response to small metric changes. According to [6], each node obtains its path cost by summing up the selected link metric to the path cost advertised by the parent. The node can then convert the path cost through a parent to a Rank value as specified in table 1:

Node/link Metric	Rank
Hop-count	Cost
Latency	Cost/65536
ETX	Cost

Table 1: Conversion of Path cost to Rank.

For this study, we consider MRHOF using the Expected Number of Retransmissions (ETX) as a routing metric. ETX is the average number of retransmissions of a packet at the CSMA level.

In every node, the ETX value is computed for each neighbor as a moving average by the following formula:

$$NewETX = \frac{RecordedETX \times 90 + NumTX \times 10}{100} \quad (1)$$

Where NumTX is the maximum number of retransmissions at the CSMA layer.

By minimizing ETX, power consumption and packet end-to-end latency are implicitly minimized by reducing the number of retransmissions necessary to transmit a data packet successfully.

4. RELATED WORK

To the best of our knowledge, the effect of the interaction between RPL and the ContikiMAC protocol on the perfomance of WSNs had not been intensely studied. Most research work has mainly focused on simulation experiments. However, the authors in [7] have found important differences in the behavior of RPL networks with different link estimation algorithms, demonstrating that real-world measurements are necessary to understand the functioning of the different communication protocols, and their interactions. The authors in [8] and in [9] made a simulation study of the performance of RPL in different scenarios, using the ContikiMAC protocol with its default settings. In [8] a study of the impact of using different OFs in a RPL network, varying the network densities by adding more nodes into the network was presented.

ContikiMAC is a well-known RDC protocol. Some research efforts have been made on solving some timing issues and incompatibilities existing in the ContikiMAC RDC protocol, as presented in [10] or in [11]. The authors in [12] show how the CCA mechanism in which ContikiMAC is based may originate unnecessary wake-ups in noisy environments, affecting energy efficiency and link performance and propose a modified ContikiMAC protocol to overcome these issues. In [13] an enhancement for ContikiMAC is proposed by using adaptive radio duty cycling.

Interactions between RPL and ContikiMAC should be well understood. A lack of understanding of the cross-layer interaction between those protocols may lead to network malfunctioning and protocol incompatibilities, as the authors of [9] suggest in their paper.

5. EVALUATION SET-UP

The implementation of the ContikiMAC RDC protocol included in the Contiki OS was used. For all the experiments presented in this paper, the Contiki OS was running on the Zolertia Z1 [14] nodes. The Zolertia Z1 nodes feature the popular Texas Instruments' CC2420 radio chip [15].

In order to study the impact of the CCA threshold parameter on the network performance, we first made some measurements with a simple unicast link for different values of the CCA threshold. Some of these experiments were later extended to a 20-node RPL network, and different performance parameters were measured. All the presented results were obtained through real-network experiments.

5.1 Unicast Link

The experimental set-up for the unicast measurements, is shown in Figure 4. It consists of two Z1 motes. One is sending 59-bytes unicast packets transmitted at a Packet Generation Rate (PGR) of one packet per second. The other mote is receiving packets, connected to a laptop running Linux.

A second PC running Windows is used to monitor the radio traffic by means of a Texas Instruments sniffer cc2531 and the associated free sniffer software SmartRF. This monitoring proves very helpful to quickly detect errors in the choice of communication parameters and/or detect mote malfunctioning.

Table 2 shows the experiment settings for the unicast measurements. We used for all our experiments CSMA as MAC protocol allowing for a maximum of three packet retransmissions. The nodes are programmed to wake up 8 times per

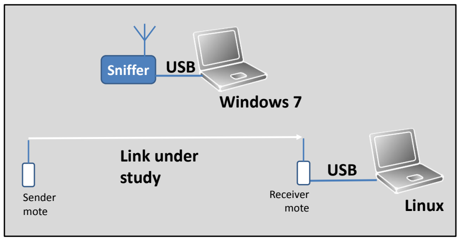

Figure 4: Set-up for the unicast measurements in an office environment.

second. The applications running on the nodes are based on the unicast Rime example provided with Contiki, slightly modified in order to be able to measure the RSSI of the signal in the receiver node.

Setting	Value
Contiki version	2.6 [1]
MAC protocol	CSMA
Max. Number of RTX	3
RDC protocol	ContikiMAC
Channel Check Rate	8 Hz
Phase Optimization	ON
Application	Based on Rime Unicast example

1. The results also apply for other Contiki versions.

Table 2: Network settings for the unicast experiments in an office environment.

As explained earlier, the CCA threshold sets the value of RSSI below which packets are not detected. In order to evaluate the effect of this parameter on the Packet Delivery Ratio (PDR) of a unicast transmission, different experiments were made varying this threshold: -90 dBm (sensitivity of the cc2420 radio), -85dBm, -77dBm (default value in the ContikiMAC implementation), and finally -65dBm. For all those CCA threshold values, we modified the RSSI on the receiver side by increasing the physical distance between motes.

5.2 RPL Network

The implementation of the RPL routing protocol and the ContikiMAC RDC protocol included in the Contiki OS were used. Three performance parameters were measured, being: Packet Delivery Ratio (PDR), packet end-to-end latency, and node power consumption.

Measurements in the real RPL network were made by using the Dual Network system, presented in [16], which allows to measure all the mentioned parameters. The testbed consists of 20 motes. One of them acts as the RPL root node. The measurements were made in the countryside, far from external radio sources. Each sender node has an average PGR of one packet per minute. The nodes use the built-in ceramic antenna featured by the Zolertia Z1 nodes, and the transmission power is set to -5 dBm. Each experiment ran for at least one hour, in order to get statistically significant results.

Figure 5 shows the physical position of the nodes deployed in the testbed.

Table 3 shows the experiment settings for the testbed mea-

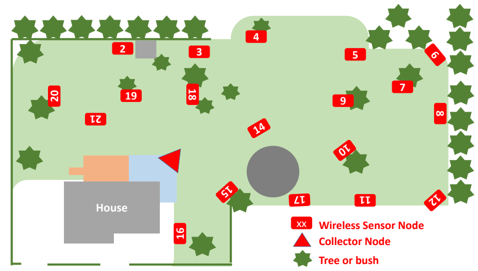

Figure 5: Testbed map in an environment without external interference.

surements. We used for all our experiments CSMA as MAC protocol allowing for a maximum of three packet retransmissions. The nodes are programmed to wake up 8 times per second using ContikiMAC as RDC protocol. The applications running on the nodes are based on the RPL-collect applications provided with Contiki, slightly modified in order to be able to measure the metrics under study for each experiment through the dual-network measurement technique.

Setting	Value
Contiki version	2.6 [2]
MAC protocol	CSMA
Max. Number of RTX	3
RDC protocol	ContikiMAC
Channel Check Rate	8 Hz
Phase Optimization	ON
RPL OF	MRHOF
RPL routing metric	ETX
Application	Based on RPL-Collect

2. The results also apply for other Contiki versions.

Table 3: Network settings for the RPL experiments in an environment without external interference.

6. RESULTS

6.1 Unicast Link

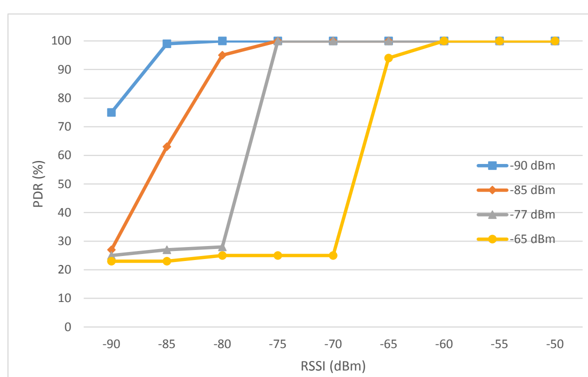

Figure 6: Packet Delivery Ratio for different CCA threshold values and different RSSIs in a unicast link.

Figure 7: Example of packet burst received below the CCA threshold (-77 dBm).

The results of the PDR measurements for the unicast link are shown in figure 6.

As expected, for RSSI values above the CCA threshold the PDR is always 100%. Below this threshold, the PDR drops dramatically. This behavior is coherent with the functioning of ContikiMAC, since signals below the CCA threshold do not wake up the receiver. In the case of a CCA threshold of -90 dBm, the PDR at this value drops down to 75%, since we are operating at the sensitivity limit of the CC2420 transceiver.

However, one can observe that below the CCA threshold the PDR is not 0%, even for RSSIs as low as the sensitivity of the radio (-90 dBm). With the help of the TI sniffer, we observed that due to external interference (the link was deployed in an office environment), the RSSI detected by the receiver was at certain moments above the threshold. As a consequence, the radio of the receiver was kept on waiting for an incoming packet. Once a packet had been received and acknowledged, the sender would then start sending all the queued packets while the radio of the receiver is still awake. Figure 7 shows an example of a burst of packets that were acknowledged, with an RSSI (-81 dBm) below the CCA threshold (-77 dBm in this example).

Therefore, it is advisable to set this threshold with a value higher than -90dBm (or the sensitivity of the radio), in order to have a predictable network PDR for values equal or above the threshold. The behavior of the network below the CCA threshold depends on the level of interference.

6.2 RPL Network

Figures 8, 9 and 10 show the performance of the network in terms of Packet Delivery Ratio (PDR), average packet end-to-end latency and average power usage respectively, vs. average hopcount and per node. All the 19 sender nodes transmit on average one packet per second. Each marker in the presented graphs represents a node in the network.

PDR (see figure 8) improved significantly for a CCA threshold of -84 dBm. This is due to the fact that most of the links in the network had an RSSI below the default CCA threshold (-77dBm). This behavior is coherent with the results presented in 6.1. As can be observed, not only the overall PDR improved when lowering the CCA threshold, but also the nodes that were located further away from the sink (in terms of hopcount) showed better PDR than those nodes located on the first hop in the case of a CCA threshold of -77 dBm.

In terms of latency (see figure 9), one can observe that the further away the node is from the sink, the higher the latency becomes. When comparing the performance in terms of latency of nodes in the same position in the DODAG (e.g. nodes on the first or second hop) the experiment with a CCA threshold of -84 seems to show a slight improvement. However, and since multihop communications were preferred for the case of a CCA threshold of -84 dBm, network average latency did not show a clear improvement with respect to the network with a CCA threshold of -77 dBm.

The results depicted in figure 10 show that the network with a CCA threshold of -84 dBm is more power-efficient. Subsequently, by lowering the CCA threshold in the presented network, network lifetime also improved.

As explained earlier, when lowering the CCA threshold nodes are woken up when detecting weaker signals. In our network, this meant that links with a lower RSSI required less CSMA retransmissions, reducing latency and node power consumption. By reducing the number of CSMA retransmissions, we are also reducing the level of internal interference, diminishing the probability of packet collision.

Surprisingly, we observed that lowering the CCA threshold had an important impact in the network topology. For a CCA threshold of -84dBm, multihop communications were preferred. Figures 11 and 12 depict the topology of the network (RPL DODAG) obtained at the end of the measurement (1 hour). One can observe that in figure 11 some of the nodes did not join the network, since the CCA threshold value by default in ContikiMAC was not fitting the characteristics of the network. Once the CCA threshold was lowered, all the nodes could join the DODAG.

Figure 13 shows the average path cost (ETX value from the node to the DODAG sink) vs. average hopcount per node. For nodes on the first hop, path costs for both CCA threshold values are comparable. However, with a CCA threshold of -84 dBm nodes that were located further away

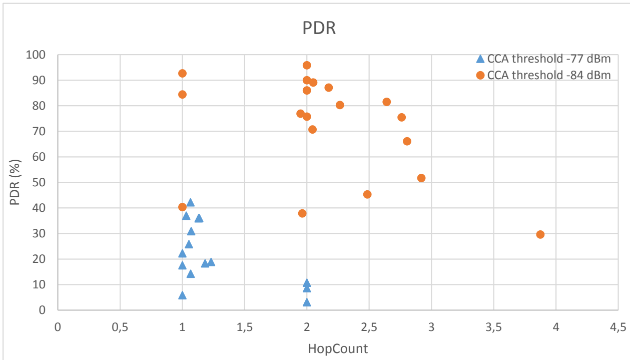

Figure 8: Packet Delivery Ratio for two different CCA threshold values.

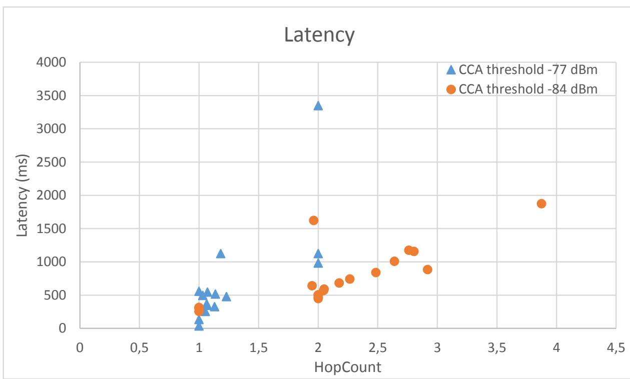

Figure 9: Average packet end-to-end latency for two different CCA threshold values.

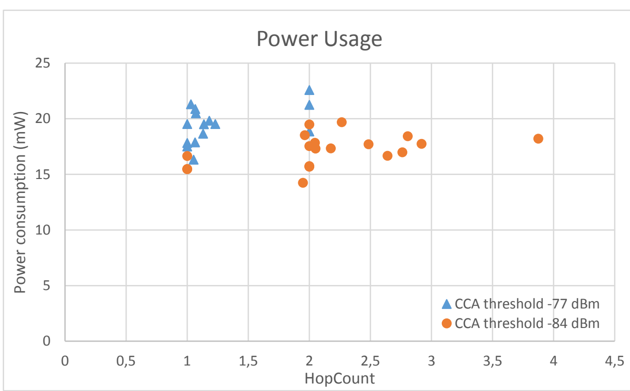

Figure 10: Average node power usage for two different CCA threshold values.

from the sink in the DODAG presented lower path cost than when using a CCA threshold of -77 dBm. These results confirm what we deduced earlier: by lowering the CCA threshold, the number of expected retransmissions (ETX) was reduced, and so were power usage and latency implicitly.

In a nutshell, the CCA threshold value chosen by default in ContikiMAC was the cause of the poor performance of the RPL network. Since ETX is computed based on the number of CSMA retransmissions, the CCA threshold has a direct impact on the computed ETX. Not only the nodes

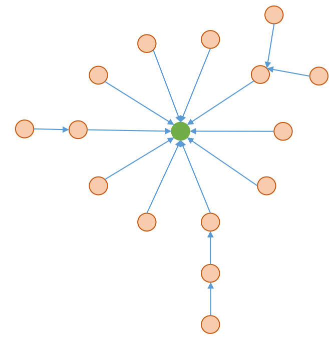

Figure 11: DODAG obtained at the end of the experiment (one hour) for a CCA threshold of -77 dBm, showing only the preferred parent for each node.

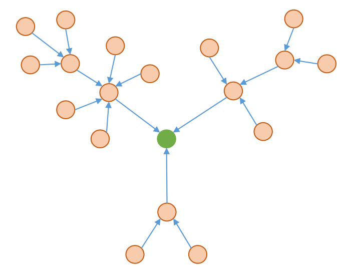

Figure 12: DODAG obtained at the end of the experiment (one hour) for a CCA threshold of -84 dBm, showing only the preferred parent for each node.

in the DODAG performed poorly, but some nodes could not join the DODAG. Hence, the CCA threshold must be low enough in order to allow all the nodes to join the network. This proves that before deploying any WSN using RPL together with the ContikiMAC RDC protocol, a study of the RSSI of the links becomes necessary, in order to choose the appropriate CCA threshold value.

Note that in the network under study, only internal interference exists, since it was deployed in an interference-poor environment. However, as shown in 6.1, the presence of external interference will have an impact on the performance of the network.

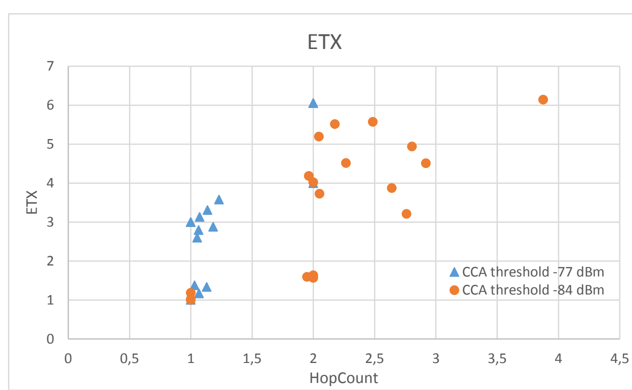

Figure 13: Average ETX per node for two different CCA threshold values.

7. GUIDELINES FOR FUTURE DEPLOYMENTS

The optimal CCA threshold value will vary depending on the level of external interference, the physical disposition of the nodes and the link RSSI for the different links in the network. For future WSN deployments using these protocols, the following points should be taken into account:

1. The performance of the network below the CCA threshold becomes random and dependent on the presence of interference.

2. In the presence of external interference, the CCA threshold should be high enough to avoid unnecessary wake-ups.

3. The CCA threshold should be higher than the sensitivity of the radio chip used in the sensor motes.

4. In a RPL network using MRHOF and ETX, the CCA threshold must be low enough to allow all the nodes to join the DODAG.

As the presented experiments show, networks with different CCA thresholds will result in very different network topologies (DODAGs). By choosing the optimal CCA threshold value for a certain network deployment, we might favor multihop communications, but the overall performance of the network will improve. If these guidelines are not followed, several CSMA retransmissions may be needed to receive data from a node or, in the worst case, some nodes may never join the network. This would obviously hamper very seriously the efficiency of the network.

8. CONCLUSIONS

In this paper we have studied the impact that the CCA threshold in ContikiMAC has on the performance and topology of a RPL Wireless Sensor Network, when using MRHOF and ETX as a routing metric, in an environment with no external interference. These measurements can only be made my means of real-world deployments. We have shown how a lack of understanding of the cross-layer interactions can lead to network malfunctioning, affecting the main QoS parameters in a WSN: Packet Delivery Ratio, packet end-to-end latency and power usage. Based on our experience, we have extracted some guidelines to ease future network deployments based on RPL and Contikimac.

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