

Average power consumption breakdown of Wireless Sensor Network nodes using IPv6 over LLNs

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Abstract—Achieving low levels of energy consumption is crucial for Wireless Sensor Networks in order to extend battery lifetime. As network protocols become standardized, it becomes mandatory to correctly select the optimal parameters in order to reduce the energy consumption for a certain application.

This paper presents a simple but still powerful approach for the analysis of the average power consumption of a sensor node using the IPv6 over Low power and Lossy Networks (LLN) stack, which is one of the most widely adopted and promising communication stacks. Power consumption is broken down according to the node states (i.e. CPU, IRQ, LPM, Tx, Rx) and according to the network protocols (e.g. CoAP, RPL, 6LoWPAN, ContikiMAC), identifying the relative weight of each protocol in the total energy consumption for several configurations. Results show that the Low Power Listening (LPL) mechanism of the radio duty cycling layer and RPL control messages have the highest impact on the total energy consumption, while the application's report rate has a very low impact for periods over 60 seconds.

I. INTRODUCTION

Wireless sensor networks are becoming a very significant enabling technology in many sectors but they present many challenges due to some of their inherent characteristics. The nodes comprising a wireless sensor network are expected to be small, reliable, low cost, and low power. Since the nodes are usually placed in hard-to-reach areas and in large number, they are powered from batteries or harvest energy from the environment [1]. In both cases reduced levels of power consumption is mandatory, in the former case to avoid frequent batteries or nodes replacement, and in latter case to suit the scarce available energy or to minimize the harvesting system cost and size (e.g. solar panel).

A basic sensor node is composed of the following building blocks: a processing element with radio (RF transceiver), sensors/actuators and a power supply subsystem [2]. Node power consumption results from the sum of the power contributions of its electronic components, which in turn depend on the component state and the actual operation performed. The power profile drain, i.e. the instantaneous power as a function of the time, determines the effective node energy consumption. The hardware together with software and external factors, such as the environment and the interaction with the network, dictates the power profile drain of each node. The hardware defines

the power consumption for each operating mode. The network design and the communication protocols influence the behavior of the nodes. The message exchange within or between the nodes determine the state and actions of the node, particularly the radio operation mode, i.e. receive, transmit or sleep mode, and the microcontroller operation mode. Finally, the application is implemented on top of an operating system which provides services to ease application development, including a communication stack that implements network protocols. The number of user messages injected on the network depends on the application requirements.

Depending on the network characteristics and the application bandwidth requirements, a set of configuration parameters can be chosen trading-off energy consumption with other attributes like latency. Kovasch et al. [3] included the energy consumption in their analysis of the CoAP protocol, but their focus was in the system performance from an application layer perspective and not from the whole network stack. Ali [4] studies the RPL performance including several metrics; however, their energy consumption analysis only considers the time the radio is on without distinguishing between Reception (Rx) and Transmission (Tx) states.

The main contribution of this paper is a deep study of the energy breakdown of one of the most widely adopted communication stacks in LLNs, which is shown on Table I. The effect of varying some parameters, such as ContikiMAC's channel check rate (CCR) and the period of an observable CoAP resource was also studied. The simulations' results were analyzed in order to break down the average power consumption of the node's radio in Tx and Rx states. The results of the simulations show that modifying the default Contiki¹ CCR from 8Hz to 2Hz can achieve energy savings of 30% in the total average power consumption in a typical application. The effect of the application workload in energy consumption was also studied, showing that for an observe period of 60s, the application contribution is almost negligible, suggesting that lower sample rates would not significantly enhance the network lifetime.

The rest of the paper is organized as follows. In Section II we present a background on the network protocols and the software platform and tools used. In Section III we present the study methodology including the description of the simulation

¹www.contiki-os.org

TABLE I. COMMUNICATION PROTOCOL STACK.

Layer	Protocol	Standard
Application	CoAP	IETF RFC 7252
Transport	UDP	IETF RFC 768
Network	IPv6 / RPL	IETF RFC 6550
Adaptation	6lowpan	IETF RFC 6282
Data link	IEEE 802.15.4 MAC (CSMA)	IEEE 802.15.4
Radio Duty Cycling	ContikiMAC	-
Physical	IEEE 802.15.4 PHY	IEEE 802.15.4

environment and the data analysis methodology. Section IV shows the results of the simulations, including a deep analysis on one node's average power consumption and its variation with the change of some parameters. Finally Section V concludes the paper and states future work.

II. BACKGROUND

In this section we review the main characteristics of the protocols, the software platform and tools used.

A. Network protocols

IEEE 802.15.4 [5] is the de facto standard for low-rate wireless personal area networks (LR-WPANs), which specifies the physical and media access control layers. The Medium Access Control (MAC) layer design is crucial in wireless sensor networks, since it directly controls the radio transceiver, usually the most power-consuming component of the system. Consequently, in the first years of WSN research, the focus was on MAC protocols [6], [7], with the idea of keeping the radio off as much time as possible. The ContikiMAC protocol [8], [9] has integrated the main ideas of previous duty cycling protocols, such as low power listening and phase-lock optimization. In the following years, research headed towards the design of a complete IPv6-based network architecture for wireless sensor networks [10], proposing an adaptation layer to enable the transport of IPv6 packets over IEEE 802.15.4 networks. Finally, the CoAP application-layer protocol was designed specially for WSN. It provides a REST-like interface [11] on top of the UDP transport layer, but with a lower cost than HTTP-based REST interfaces.

Table I shows the analyzed network protocols' stack in this work, which is among the most widely used in WSN. Almost every layer is standardized by the Internet Engineering Task Force (IETF), except the physical and media access control layers which are standardized by IEEE.

1) *CoAP*: The Constrained Application Protocol (CoAP) is a RESTful protocol for use with constrained hardware such as WSN nodes. The REST model works with server nodes that make certain resources available under a URL, and client nodes that access these resources using methods such as GET, PUT, POST, etc. In this work we will use the OBSERVE mechanism, which allows client nodes to retrieve a resource value from a server (GET) and keep it updated over a period of time. From hereon this period will be referred as observe period.

2) *RPL*: The IPv6 Routing Protocol for LLNs, or simply RPL, is a proactive routing protocol based on a tree-oriented strategy, or more specifically a Destination-Oriented Directed Acyclic Graph (DODAG). The distance metric is usually based on some link quality indicator, and one of the most widely used is the Minimum Rank with Hysteresis Objective Function

(MRHOF). The tree topology is automatically built by the nodes exchanging ICMPv6 control packets to find and propagate the routes in the network. RPL enables three operation modes in which different kinds of traffic is supported. This work is restricted to the Storing Mode of Operation with no multicast support, in which each network node stores both the table entries to route packets to all the nodes downwards from the tree and the default route to the root.

There are three types of RPL messages: DODAG Information Solicitation (DIS), DODAG Information Object (DIO) and Destination Advertisement Object (DAO). The former two messages are sent as link-layer broadcast. DIS messages are requests to join a DODAG, whereas DIO messages contain information about the DODAG the sender node belongs to. Essentially, the DIO messages inform the distance to the root node using the DODAG metric. Based on this information received from its neighbors, a node selects its preferred parent for sending messages to the root. The Trickle algorithm [12] is used to control when DIO messages are sent, and it is based on a timer whose duration is doubled each time it is fired, sending fewer messages per unit of time when the network is stable.

3) *6LoWPAN*: 6LoWPAN is an adaptation layer protocol that allows the transport of IPv6 packets over 802.15.4 links. It is in charge of the compression of IPv6 and the upper layer headers and of the fragmentation and reassembly of IPv6 packets. When we refer to 6LoWPAN packets in section IV, we are referring to the packets of the application layer that have been fragmented using this adaptation layer in order to be transmitted.

4) *CSMA*: The IEEE 802.15.4 standard defines the use of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in the MAC layer. This mechanism does carrier sensing before transmitting every packet to check whether the channel is idle or not. Once the channel is detected idle for transmission, the packet is transmitted. In Contiki N carrier senses are performed before transmitting, where N is a configurable integer with a default value of 6.

5) *ContikiMAC*: ContikiMAC is a radio duty cycling (RDC) protocol based on the Low Power Listening (LPL) mechanism, that uses periodic wake-ups (Clear Channel Assessment or CCA) to listen for packet transmissions from neighbor nodes. This enables the radio transceiver to achieve duty cycles below 1% [13], making an important reduction on the energy consumption in comparison with the systems that do not manage the RDC layer. LPL determines a baseline energy consumption that can be calculated from the CCR. If during a periodic wake-up a transmission is detected, the radio transceiver is kept on in order to receive the packet. After the packet is successfully received, a link-layer acknowledgement is sent.

For the transmission of packets, the phase lock mechanism is used. Every time a node sends a packet to a neighbor, it records the time at which the neighbor replied with an acknowledgment, learning its phase. Using the phase information, the sender does not start to send its strobes until the neighbor is awake. If the sender misses the awake period of the neighbor, the sender will simply continue to send strobes for an entire period. Broadcast transmissions do not receive

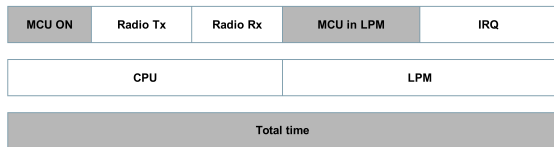


Fig. 1. Sensor node states estimated by Energest. Boxes in gray represent calculated times using Energest estimations.

link layer acknowledgements and they are a bit different from unicast transmissions. Broadcasts are intended to be received by every neighbour node, so the sender needs to repeatedly send the packet during the full wake-up period. The CSMA/CA mechanism described in Section II-A4 only senses the channel N times for the first packet of the transmission burst to avoid collisions. From hereon the wakeup interval will be referred as CCR.

B. Software platform and tools

1) *Contiki OS*: Contiki OS is an open source, event-driven operating system oriented to WSN applications using constrained hardware. This OS manages the hardware resources and includes different libraries such as network stacks and a file system. Contiki OS's scheduler manages sleep modes powering down the microprocessor when there is neither processing needed nor events scheduled in the event queue.

2) *Energest Module*: Energest is a software-based on-line energy estimation mechanism implemented as a Contiki module, that measures the accumulated time the sensor node is in different states such as CPU, LPM, IRQ, Tx and Rx. The mechanism runs directly on the sensor nodes and provides real-time estimates of the current energy consumption. The different states are represented in Figure 1. LPM state is activated when the sensor node goes to LPM but is not deactivated in the interrupt requests handling, so the actual time the sensor node is in LPM is $LPM - IRQ$. CPU state is activated whenever the node is active, including radio transmissions, so the real time the CPU is active without using the radio transceiver is $CPU - Tx - Rx$.

Taking this into account, we can calculate the average power as stated on equation 1.

$$P_{avg}^{state} = DC_{state} \times I_{state} \times V = \frac{t_{state}}{t_{total}} \times I_{state} \times V \quad (1)$$

where I_{state} is current consumption at a certain state and V is the operating voltage.

The current consumptions of each state were taken from the MSP430F5438 [14] and CC2420 [15] datasheets, and the operating voltage was 3V. Note that for Tx and Rx states, CPU current consumption is taken into account.

3) *Cooja Network Simulator*: For the analysis of the network and the hardware emulation we used the Cooja Network Simulator [16]. Cooja is a Java-based network simulator capable of emulating several platforms with radio communication.

III. METHODOLOGY

A. Simulation environment

We chose to emulate in the Cooja Network Simulator the EXP-5438 platform, which consists of an MSP430F5438 [14]

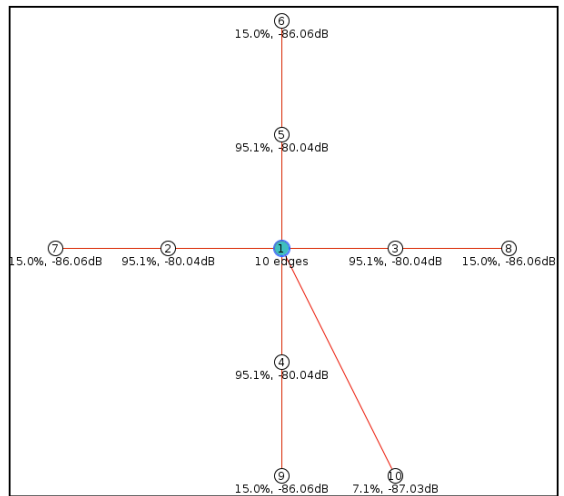


Fig. 2. Network topology

MCU and a CC2420 [15] radio. We selected this platform because it is very similar to the well-known Tmote-Sky [17] that is used as reference in many research works, but it has more ROM memory that has allowed us to compile more complex applications. As radio medium, we used Multi-path Ray-tracer Medium (MRM) [18] and configured its parameters in order to obtain a link quality of 95% between neighbor nodes. This value was chosen in order to obtain a good link [19]. The network topology is shown in Figure 2 and was comprised by 10 EXP-5438 nodes that used the network protocols described in Section II.

The node with ID 1 is a border router and also the RPL network sink. This node is the only one that has the RDC protocol disabled and it observes a CoAP resource on each of the other nine nodes. Nodes with IDs 2 to 10 are CoAP servers with observable resources. Between simulations, CCR and the observe period of the resources was changed in order to analyze their influence on the average power consumption.

In order to select the simulation time, a long-term simulation was executed (24 hours) and the variation of the duty cycle of each node state was analyzed. As it is shown on Figure 3, after around 4 hours of simulation the duty cycle of each state remains steady, so this length of time is enough for our analysis. Figure 3 shows the first 12 hours of simulation because the rest did not contain relevant information.

During the simulation, each network packet was captured and recorded using the Cooja Radio Logger for later analysis.

B. Data analysis

The main objective of the data analysis was to break down the average power consumption of a node according to the different network protocols. In order to accomplish this task, we analyzed the node with ID 2 as it is representative of our network. We chose to study the variations in average power consumption in order to detach from the simulation time variable.

To break down the average power consumption of the radio in Tx and Rx states according to the different network protocols, we had to create an empirical model to relate the

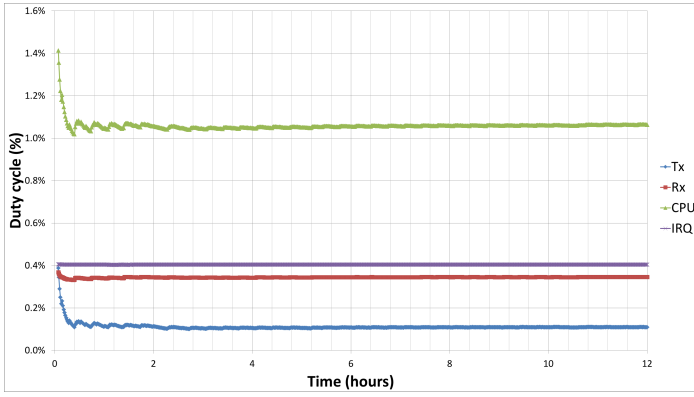


Fig. 3. Variation of different state's duty cycle in time

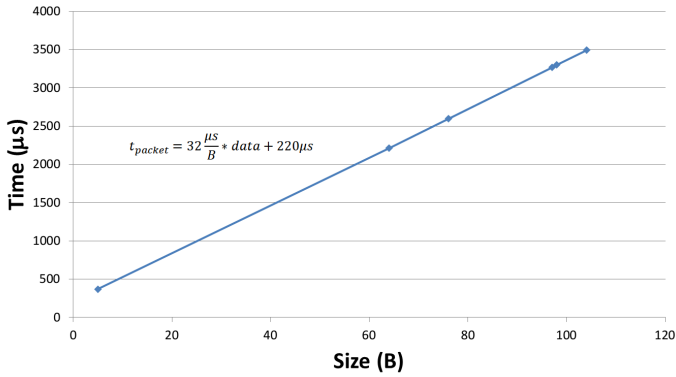


Fig. 4. Time spent sending or receiving a packet as a function of the size

size of the packets (information we obtain from the packet) with the radio time spent transmitting and receiving them. For this purpose we analyzed the Cooja timeline and recorded the time spent transmitting and receiving several packets of different sizes. We found out that they have a linear relation with an offset as shown in Figure 4. The curve slope is $32\mu s/B$ which is in correspondence with the nominal IEEE 802.15.4 data rate [5]. After obtaining this model, we proceeded to estimate the elapsed time to transmit and receive every packet and then calculated the average power consumption related to each network protocol as shown on Section IV. To analyze the impact of broadcast traffic, we also broke down the ICMPv6 average power consumption according to the different RPL control packets (DIO, DIS and DAO). Besides the packet times, we also had to take into account the time the radio is in Rx state due to the LPL and CSMA as described on section II. These times were calculated following [8].

The LPL time is calculated as:

$$t_{LPL} = N \times t_{ON} = \frac{t_{sim}}{2 \times t_r + t_c + t_{CCA}} \times 2 \times t_r \quad (2)$$

where t_{sim} is the simulation time, t_{CCA} is the inverse of the CCR, $2 \times t_r$ is the time elapsed performing two consecutive CCAs and t_c is the time between consecutive CCAs.

The CSMA time is calculated as:

$$t_{CSMA} = 6 \times t_r \times (N_{unicast} + N_{broadcast}) \quad (3)$$

where $N_{broadcast}$ is the number of broadcast transmissions and $N_{unicast}$ is the number of unicast transmissions.

This analysis was repeated for different CCRs (2, 4 and 8Hz) and different observe periods of the CoAP resources (6 and 60s). We then validated our model comparing the estimated total time for Tx and Rx as described before with the Energest Tx and Rx reported times. An error minor than 1,5% was achieved in every case.

IV. RESULTS

In this section we present the results of the simulations and data analysis described in Section III.

A. Average power consumption breakdown

As a case of study, we made a deep analysis of the average power consumption with a configuration of CCR at 4Hz and an observe period of 60s. In Section IV-B we will compare these results with the ones obtained with other configurations.

Table II shows the results of the Energest module, where it can be observed that the radio Rx state has the higher average power consumption, followed by the LPM, CPU, radio Tx and IRQ states.

TABLE II. ENERGEST RESULTS WITH CCR AT 4Hz AND AN OBSERVE PERIOD OF 60s

Node state	DC(%)	$P_{avg}(\mu W)$
CPU	0.61	114.51
TX	0.11	64.35
RX	0.35	227.4
LPM	98.53	163.5
IRQ	0.40	75.6

Using the methodology described in Section III-B the average power of radio Tx and RX states given by Energest can be decomposed in the different network protocols as stated on Table III. The application layer traffic is the one under the CoAP row summed up to the one under 6LoWPAN row. This is because when CoAP messages are fragmented, the first fragment is identified as a 6LoWPAN packet. When the final fragment arrives, the packet is reassembled and recognized as CoAP. The only fragmented packets in our network are CoAP messages, as RPL control packets do not have the size to be fragmented.

TABLE III. AVERAGE POWER CONSUMPTION BREAKDOWN WITH CCR AT 4Hz AND AN OBSERVE PERIOD OF 60s

	Protocol	DC(%)	$P_{avg}(\mu W)$
Tx	CoAP	0.0097	5.70
	ICMPv6	0.0945	55.29
	6LoWPAN	0.00554	3.24
	IEEE 802.15.4	0.00153	0.90
Rx	CoAP	0.0058	3.81
	ICMPv6	0.0092	6.03
	6LoWPAN	0.0011	0.75
	LPL	0.30	195.18
	CSMA	0.026	16.95
	IEEE 802.15.4	0.0023	1.50

It can be observed that the CoAP application packets have a very low weighting over the total average power (around 15% for Tx and negligible for Rx), so increasing the CoAP resources observe period would not have great impact on reducing the average power consumption. It can also be

observed that in this case the CoAP Tx average power is 50% higher than Rx since the node with ID 2 transmits its own CoAP messages and also routes the packets from node with ID 7. The radio Rx average current is dominated by the LPL, and packet traffic weighs less than 5%. Since the ICMPv6 RPL messages represent over 85% of the Tx average power consumption, it is worth analysing them carefully. Table IV shows the consumption breakdown of ICMPv6 RPL messages. DIO and DIS are broadcast packets and they represent over 95% of the total RPL packets.

TABLE IV. RPL TX AVERAGE POWER BREAKDOWN FROM TABLE III

Control Packet	DC(%)	$P_{avg}(\mu W)$
DIO	0.0911%	53.30
DAO	0.0032%	1.87
DIS	0.0002%	0.11

B. Comparison of results changing CCR and observe period

When analysing the average power consumption calculated from the results of the Energest module varying the CCR and observe period, we obtain the results shown on table V. It can be observed that the total average power consumption reduces around 30% when lowering CCR from 8Hz to 2Hz. Also if we reduce the observe period from 60s to 6s, the total average power consumption increases around 60%.

If we consider for example a platform using a Power Amplifier/Low Noise Amplifier (PA/LNA) like the TI CC2592 [20], the transmit power is seven times higher, so the increase in the Tx average power due to the decrease of the CCR could make the total average consumption to increase.

TABLE V. ENERGEST RESULTS VARYING CCR AND OBSERVE PERIOD

	8Hz, 60s	4Hz, 60s	2Hz, 60s	4Hz, 6s
	$P_{avg}(\mu W)$	$P_{avg}(\mu W)$	$P_{avg}(\mu W)$	$P_{avg}(\mu W)$
CPU	51,61	114,51	141,29	237,42
TX	38,69	64,34	109,85	166,72
RX	418,25	227,41	130,61	388,46
LPM	160,62	163,50	161,28	159,34
IRQ	146,47	75,59	40,23	74,63
Total	815,64	645,34	583,26	1026,57

According to the protocols described in Section II and the presented model, we expect to observe the following effects on the average power consumption when the CCR is reduced from 4Hz to 2Hz: a) Tx times increase as broadcast times double, b) Rx times decrease as LPL times reduce to half, c) CPU times increase according to the increase of processing times due to the handling of more radio packets and d) IRQ time reduces due to the decrease of radio interruptions for the CCA.

These effects are reflected on the simulation results obtained with a configuration of CCR at 2Hz and an observe period of 60s as shown on Table VI. *Diff* column shows the variation with the simulation at 4Hz and an observe period of 60s. It is interesting to remark that in Tx the ICMPv6 packets traffic (mostly broadcast) increases by 80%, while CoAP, 6LoWPAN and 802.15.4 packets traffic change less than 20%.

In order to examine how the observe period influences the average power consumption, we performed a simulation

TABLE VI. AVERAGE POWER CONSUMPTION BREAKDOWN WITH CCR AT 2Hz AND AN OBSERVE PERIOD OF 60s

	Protocol	DC(%)	$P_{avg}(\mu W)$	Diff(%)
Tx	CoAP	0.010	5.94	4.55
	ICMPv6	0.17	99.75	80.45
	6LoWPAN	0.0065	3.84	18.78
	IEEE 802.15.4	0.0015	0.87	-2.77
Rx	CoAP	0.0059	3.84	1.56
	ICMPv6	0.0049	3.24	-40.35
	6LoWPAN	0.0011	0.72	-4.08
	LPL	0.15	97.86	-49.87
	CSMA	0.027	17.46	3.05
	IEEE 802.15.4	0.0019	1.23	-17.71

maintaining the CCR at 4Hz but decreasing 10 times the observe period to 6s. We expected to see several effects on the average power consumption such as: a) LPL times remain equal, b) the RPL traffic increases, c) CoAP, 6LoWPAN and 802.15.4 packet traffic increases 10 times, d) CSMA times increase 10 times, e) CPU times increase according to the increase of processing times due to the handling of more radio packets and f) IRQ times remain equal because most of the interruptions belong to the radio's LPL which remains constant.

TABLE VII. AVERAGE POWER CONSUMPTION BREAKDOWN WITH CCR AT 4Hz AND AN OBSERVE PERIOD OF 6s

	Protocol	DC(%)	$P_{avg}(\mu W)$	Diff(%)
Tx	CoAP	0.088	51.69	807.68
	ICMPv6	0.14	82.5	49.23
	6LoWPAN	0.057	33.12	921.02
	IEEE 802.15.4	0.0080	4.74	429.42
Rx	CoAP	0.062	40.68	969.28
	ICMPv6	0.014	9.36	55.19
	6LoWPAN	0.0010	0.93	24.85
	LPL	0.30	195.18	-0.01
	CSMA	0.19	126.03	644.11
	IEEE 802.15.4	0.019	12.66	737.26

The obtained simulation results are shown on Table VII, and even though the effects are not exactly identical to the ones described in the previous paragraph, they are very similar. *Diff* column also shows the variation with the simulation at 4Hz and an observe period of 60s. Variations in CPU and IRQ average power consumption can be observed on table V.

C. Results analysis

The results confirm that using protocols that achieve very low radio duty cycles is a great advantage as the system is in Low Power Mode over 98% of the time. Nevertheless, the Radio's Rx and Tx states consume a considerably high share of the overall power. Modifying the CCR has a great impact on the radio's Rx and Tx states average power consumption. Reducing the CCR decreases the radio's Rx average power consumption while it also increases the radio's Tx average power consumption. If we consider for example a platform using a power amplifier, the Tx average power consumption would increase considerably. In this case if we reduce the CCR, even though the Rx average power would decrease, the total average power consumption could increase. Also if we consider very lossy networks, the radio's Tx duty cycle could increase due to the increase in RPL DIOs, so the convenience of reducing the CCR should be carefully analyzed. The presented approach shows an efficient way to perform this analysis.

V. CONCLUSIONS AND FUTURE WORK

The average power consumption of a sensor node using the IPv6 over LLNs was deeply analyzed, breaking it down according to the different network protocols. We observed that the Rx state of the radio has the highest average power consumption in almost every configuration due to the LPL mechanism. The Tx state of the radio also has a considerable contribution to the total average power consumption and most of the Tx traffic is due to broadcast RPL control messages. Reducing the CCR decreases the Rx average power consumption, while it increases the Tx one. Convenience of modifying it should be carefully analyzed taking into account the amount of broadcast messages transmitted and the absolute values of the Tx and Rx average power. Dynamically changing the CCR could be a good solution for reducing the energy consumption in unstable networks (e.g. due to time-varying propagation conditions or mobile nodes).

The impact of the application report rate was also analyzed. If an observe period of 60s is used, the average power consumed to transmit and receive the application layer packets is negligible compared to the average power consumed by RPL control messages in Tx and LPL in Rx, meaning that increasing the observe period would not impact on the total average power consumption. If we reduce the observe period to 6s the average power consumed to transmit and receive the application layer packets dramatically increases and becomes comparable to the average power consumed to transmit the RPL control messages.

Future work should include further analysis considering: a) different packet error rates between neighbor nodes, b) different topologies (i.g. linear, grid, random), and c) higher network size. When changing the network's topology or size, nodes at different positions should be analyzed (i.g. nodes near to the root, leaf nodes, intermediate nodes), since the application traffic and RPL messages (DAO) depend on the number of nodes downwards. Finally, measurements on real sensor nodes would give information to confirm the simulation results.

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