Coordinated Sleeping for Beaconless 802.15.4-Based Multihop Networks

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Abstract. The last few years have seen a wide adoption of the IEEE 802.15.4 MAC/PHY standard for low-power communication between wireless sensor nodes. Within this work we study some fundamental drawbacks of the 802.15.4 specifications for multihop network deployments, which adversely affect efficient node energy consumption. These issues are rectified by investigating a timezone-based scheduling, V-Route, that builds on 802.15.4 beaconless mode to enable both a synchronized sleep scheduling and a bidirectional communication between nodes in the sensor network and the PAN coordinator. The contributions of V-Route are threefold: (1) mitigate collisions, (2) enable packet routing and (3) provide energy saving in a multihop context, while maintaining the full compliancy with the 802.15.4 standard. We present a performance evaluation on energy consumption and latency with real experiments on Philips AquisGrain sensor nodes. Enhancing 802.15.4-based multi-hop networks with V-Route yields energy reduction ranging from 27.3% to 85.3%.

Keywords: Sensor, network, wireless, routing, energy, 802.15.4.

1 Introduction

The advent of sensor-based wireless networks requires standard communication compliancy to allow interoperability among vendors in a multitude of applications. To this objective, IEEE defined in 2003 the 802.15.4-2003 standard [1] that specifies MAC and physical (PHY) layers to enable wireless communication between small battery-operated devices. In particular, the standard targets low data-rate communication in single-hop and multi-hop sensor networks. However, choosing a reliable, energy-efficient, and 802.15.4 compatible routing protocol that can relay packets from the Personal Area Network (PAN) coordinator to the sensor nodes and vice-versa is not part of the standard.

Energy-efficiency in low-power wireless PANs is fundamental, and related work has shown relevant drawbacks for both single-hop and multi-hop -enabled 802.15.4 communication [6,17,19,20]. This paper confirms such prior works and presents experiments on 802.15.4 single-hop and multi-hop networks that exhibited similar issues.

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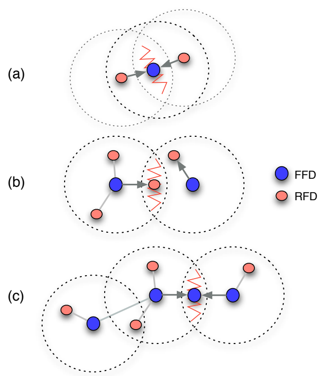

Fig. 1. (a) HTP in single-hop 802.15.4, (b) HTP with nearby independent star networks, and (c) HTP with aggregated star networks in multi-hop deployments

Figure 1 shows three issues with 802.15.4-based single-hop and multi-hop networks: (a) depicts the hidden terminal problem (HTP) in star networks when multiple out-of-range nodes assume a free channel and initiate time-overlapping packet transmissions, resulting in packet collision at the receiver node. The HTP is especially accentuated in the context of nearby independent star networks, as shown in (b); (c) is an example of an 802.15.4 multi-hop network as a form of aggregated star networks. Communication between stars is via Full Functional Devices (FFDs). FFDs carry full 802.15.4 functionality and all features of the standard. 802.15.4 provides no mechanisms for coordinated and energy efficient FFD-to-FFD packet transmission. Therefore, FFDs need to be kept powered on as communication is subsequently realized via CSMA-CA. This constraint reduces significantly the nodes' operative lifetime.

This work rectifies these issues by investigating a timezone-based scheduling that builds on top of 802.15.4 to enable energy-efficient bidirectional communication between nodes in the sensor network and the PAN coordinator. Our approach, named V-route, mitigates packet collisions due to hidden terminals and enables packet routing along with energy-efficient multi-hop communication. V-Route is inspired by and extends the MERLIN architecture which has been studied analytically and through simulations [14]. In contrast, V-Route, which utilizes a scheduling similar to that of MERLIN, is tested on real hardware and intends to experimentally validate the coordinated sleep scheduling and directed broadcast concepts on top of 802.15.4.

A major objective of V-route is 802.15.4 protocol compliancy. Therefore nodes that run our V-route scheduling can still communicate fully in single-hop with nodes that run a beaconless 802.15.4. We present a comprehensive description and empirical experiments of the multi-hop enabling scheduling along with three energy optimizations: transceiver sleep policy, reduced CSMA backoff, and MCU standby mode. Such optimizations yield energy reductions ranging from from 27.3% to 85.3%.

The remainder of this paper is organized as follows. Section 2 provides an overview of related work and compares our approach against existing architectures. Section 3.3 details the sleep scheduling and routing technique. Section 4 evaluates the proposed technique on Philips AquisGrain nodes. In Section 5 we propose some guidelines to decrease energy consumption for a multihop-enabled 802.15.4 network. Finally, we conclude the paper.

2 Related Work

Literature shows a great number of studies of the different issues intrinsic to the 802.15.4 standard. The problems of high energy cost for idle listening [15], collisions from hidden terminals due to the lack of RTS and CTS mechanisms [18,6], and the risk of frame collisions for nearby coordinators in a multi-hop deployment [19] have been investigated and demonstrated.

Some efforts in adapting energy-efficient mechanisms, such as Low Power Listening (LPL) [13] to 802.15.4, are presented in [10]. Since TI CC2420-like radios do not support long preambles similar to the ones implemented in BMAC, the long preamble is simulated by transmitting a **train of same packet**. However, the LPL/802.15.4 adaptation revealed serious reliability problems due to the interleave between such packet train as studied in [5]. Furthermore, enabling LPL on 802.15.4-based nodes prevents them from communicating with non-enabled LPL nodes, therefore reversing the 802.15.4 compliancy.

A more general approach to reducing energy consumption in the network is to provide a duty-cycle mechanism that regulates the activity of the nodes. However, there is a trade-off between energy efficiency and latency in packet delivery. Studies in [12] demonstrated that latency in packet delivery is heavily affected by the node duty-cycle. Some other experiments, for example in [14], confirmed that forwarding techniques for wireless networks such as [11,7] show a poor performance in delivery rate when deployed in a lossy environment [16] with unreliable nodes.

Besides, although the revised 802.15.4-2006 specifications [2] mention the cluster tree formation where most nodes are FFDs, the standard leaves the resolution of issues related to more complex topologies for higher layers. In particular, ZigBee [3] implements a version of the AODV [11] routing algorithm to automatically construct low-speed ad-hoc networks in the form of mesh or clusters. The current profiles derived from the ZigBee protocols support beaconless and beacon-enabled networks. In beaconless networks, CSMA/CA is used. In this type of network, ZigBee Routers typically have their receivers continuously active, requiring a more robust power supply and subsequently depreciating energy efficiency. In beacon-enabled networks, ZigBee Routers transmit beacons periodically to end-nodes that are able to sleep between beacon receptions, allowing for longer battery life. The usage of the beacon-enabled 802.15.4 is subject to the following issues: (1) ZigBee RFDs can communicate to only one parent FFD, the one responsible for both coordinating RFD sleeping intervals and routing packets from one star to another. However, there is no agreement for a distributed sleeping policy among FFD routers. Therefore, the *FFDs must stay* *awake the whole time* while only RFDs can go to sleep after transmission; (2) The uncoordinated activity of nearby stars especially affects *FFD beacons that are transmitted without checking the channel condition.* Beacons are prone to collide in presence of nearby stars activity. Such issues, confirmed by some of our initial experiments, prevented us from adopting the 802.15.4 beacon-enabled functionality in a multihop network. *Therefore, in the rest of this paper, we will concentrate on studying the 802.15.4 beaconless mode.*

3 Coordinated Sleeping Scheduling over 802.15.4

In order to mitigate packet collisions without affecting the 802.15.4 compliancy and to enable multihop communication we adopt the following 802.15.4 settings:

- **FFD functionality for all nodes:** It allows all nodes to communicate with each other in a peer-to-peer fashion by performing CSMA/CA before transmitting;
- **Beaconless configuration:** 802.15.4 reduces to a plain CSMA/CA with no handshake mechanism in place.

3.1 Traffic Patterns

The performance of a multihop routing algorithm and transmission scheduling can vary greatly according to the traffic patterns. In contrast to applications for mesh networks that might have any node exchanging packets with any other node, most sensor network applications requires many-to-one (towards the sink) or one-to-many (from the sink to the other nodes) multihop communication, referred to as *upstream* and *downstream* communication, respectively. Therefore, a cooperation between a routing algorithm and a sequential scheduling of transmission is advantageous. **In other words, it is beneficial if a packet retransmission is scheduled immediately after a node receives a packet traveling upstream or downstream.** Furthermore, theoretical studies in [8] demonstrate that an address-less forwarding policy merely based on directed broadcast towards nodes with higher or lower hop count relative to the sink node achieves greater energy saving and reliability than an address-based approach. **V-route adopts this communication trend by *transmitting all the upstream or downstream packets without specifying a particular forwarder* with smaller or higher hop count respectively.** This minimalist communication approach is named **timezone-based directed broadcast** as nodes with different hop count are defined to be in a different timezone. This approach generates packet duplication which is appropriately reduced by allowing nodes to overhear packets being transmitted by neighbours and delete the ones successfully transmitted, in what amounts to a **packet overhearing mechanism**. Optimizing transmission allocation to forward packets consecutively to nodes with lower or higher hop count (i.e. to a lower or to a higher timezone) reduces the packet latency that can effectively be traded-off for energy savings. Within this work we apply and demonstrate that directed broadcast

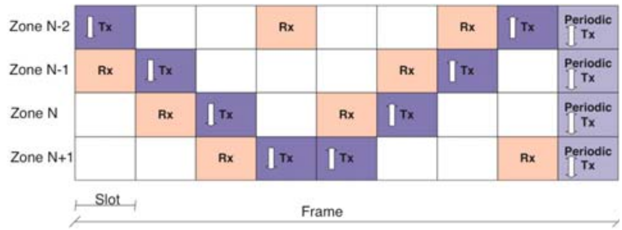

Fig. 2. The table of scheduling with periodic local broadcast

with overhearing is beneficial for 802.15.4 networks. In general, a certain number of consecutive upstream transmissions should also be followed by a number of downstream consecutive transmissions. This can be represented as an upstream/downstream V-shaped scheduling as shown in Figure 2. The next two sections highlight the division in zones of the 802.15.4 network and how the scheduling table of V-Route is implemented.

3.2 Setup and Maintenance Phases

802.15.4 beacons are used only during the association phase to form the network. Once completed, CSMA-CA is used for all communication. At the beginning of network formation, 802.15.4 nodes broadcast periodically a 802.15.4 Association Request (AR) in order to find a coordinator in the vicinity. When the PAN coordinator receives a AR, it starts associating neighboring nodes by an Association Response (AR) that contains the 802.15.4 PAN specifications. At this point the V-Route procedure begins. Following a subsequent Data Request from the node, the PAN coordinator issues a $2 - byte$ short address to the node together with timing information for synchronization. The node is now associated to the network. Using V-Route, the node can become a FFD in timezone 1 and therefore act as coordinator delegate for further nodes. Newly associated nodes will then be in timezone 2; the process is repeated recursively until all nodes are associated. *The timezone is provided in an extra byte field in each packet transmitted.* At the end of the association process the network is divided in timezones as shown in Figure 3. The timezone of a node is the minimum number of hops required for its packets to reach the PAN coordinator. For instance, the packets of nodes within the 3^{rd} timezone need to be forwarded at least three times to get to the PAN coordinator. Nodes are now ready to adopt a coordinated sleeping policy provided by the scheduling table as described in Section 3.3.

In order to cope with network changes such as battery depletion, replacement and mobility, a node's timezone has a *preset expiration time*. A node's timezone expires if the node does not receive a zone update message, which all nodes send periodically, within a certain timeout period. In case of zone expiration due to a parent node failure or a link break, the node follows a zone re-establishment process.The node start broadcasting upstream and then downstream a Timezone

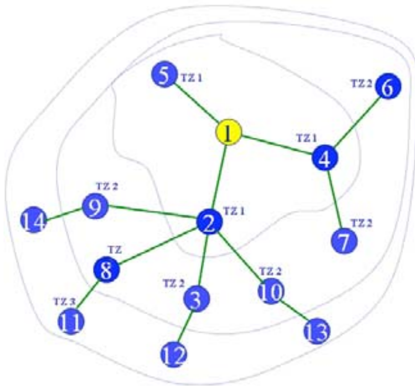

Fig. 3. The initial timezone setup by flooding and different path generation

Update Request (TUR). In case of no response, the node disregards the sleeping scheduling policy until it listens to any packet being transmitted to acquire the timezone and then restore the scheduling.

An important aspect of V-Route maintenance phase is the node synchronization. In order to synchronize the clocks of the AquisGrain sensor nodes in our testbed, we implemented an improved version of the FTSP protocol [9] enhanced with efficient linear regression and Kalman filtering as detailed in [4]. Network-wide time synchronization, relative to a unique time master node, is achieved. The adopted MAC-layer time-stamping, explained further on, effectively minimizes nondeterministic delay components that affect the time synchronization performance [9]. Clock drift rate estimation is used to estimate the difference in counting rate between nodes. It is used to decrease the sending rate of time synchronization messages and thus the energy consumption needed to achieve time synchronization, by estimating the time offset progress behavior in between synchronization instances.

3.3 V-Route Communication Scheduling

Following the setup phases described in section 3.2, the node can avail of the scheduling table shown in Figure 2 to regulate sleeping and activity periods of nodes. Although 802.15.4 does not support multicast, V-route can practically achieve it by broadcasting when either nodes with a lower or higher hop count are sleeping i.e. upstream or downstream broadcast. The V-Table is important as it regulates the cyclic sleeping of nodes within a frame so to reduce the chances of running into a HTP. We present the scheduling for 802.15.4 and its performance through experiments on real hardware. Following are the 3 types of transmissions supported by the V-table:

– **Upstream transmission** in which a node can transmit to nodes located 1 hop closer to PAN coordinator, i.e. to nodes in a lower timezone;

– **Downstream transmission** in which a node can transmit to nodes located 1 hop at a longer distance from the PAN coordinator, i.e. to nodes in a higher timezone;
– **Local broadcast** in which a node transmits simultaneously to all the neighboring nodes, i.e. those that are in the directly higher timezone, those from the directly lower timezone and those in the same timezone as the transmitting node.

While nodes within the same timezone contend the channel for transmission, the adjacent zone owns the slot for reception and nodes in further timezones are in sleep mode, to prevent possibilities of packet collisions due to HTPs. Packets traveling in each of the above directions are respectively enqueued separately in 3 small FIFO buffers. Packets are then dequeued according to the current slot time in the V-table. The total length of the V-table is equal to the length of a single frame while each small rectangle depicted in Figure 2 represents a time slot. It supports consecutive transmission of 4 timezones and therefore it consists of $4 \times 2 + 1$ timeslots: 4 timeslots for upstream transmission, 4 timeslots for downstream transmission, and 1 timeslot for local broadcast. Replicating the same table allows scheduling packet transmission for nodes located more than 4 hops away from the PAN coordinator. In general, the allocation of upstream, downstream, and local broadcast transmissions in a symmetric network of N zones requires $N \times 2 + 1$ timeslots per frame. We refer to [14] for more information about the V scheduling table, the optimal number of slots in a table an how to access it.

4 Optimization Techniques

This section describes three energy saving V-route based optimization techniques for beaconless 802.15.4. The techniques are presented in an incremental manner: *Each optimization uses the previous optimization in addition to a new energy saving technique.*

1. **Transceiver Sleep Policy:** This optimization regards the powering down of the transceiver at the transmitter and receiver sides. Recall that in V-route, packets of upstream, downstream and local broadcast communication are enqueued in 3 distinctive FIFO buffers. At the transmitter side, rather than waiting for the end of the allocated transmission slot before powering down the radio, we allow the transmitter's radio to be turned off right after the last packet transmission from the appropriate queue is acknowledged successfully. In addition, we provide each packet with a check-bit that is set to one if the packet being transmitted is the last in the sender buffer. This allows the receiver to turn off the radio immediately after the last packet in the queue is received correctly and the acknowledgment is sent. Enabling the transceiver sleep policy optmises the activity time both at transmitter and receiver sides according to the node data traffic.
2. **V-Route Short CSMA:** This optimization regards the 802.15.4 idle listening. With the CSMA-CA used by 802.15.4, a node with a packet to transmit

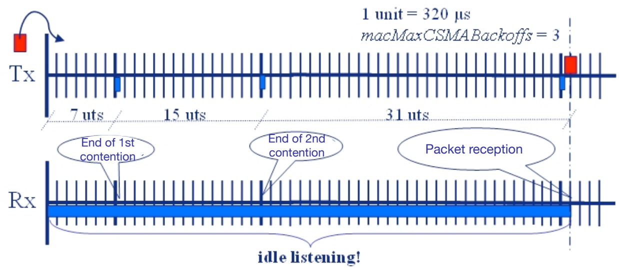

Fig. 4. Receiver idle listening of the CSMA period in 802.15.4

at time t picks up a time between t and $t + 2^{BE-1} units(1unit = 320\mu sec)$ where BE is the backoff exponent. The protocol provides a variable, namely $macMaxCSMABackoffs$, that regulates the number of packet retransmissions, which the standard 802.15.4 configuration sets to 3. This means that a transmitter can assess the channel 3 times consecutively after which it declares access failure and the packet is dropped. Although the backoff period is effectively used to increase the data rate in protocols such as IEEE 802.11, it is known to cause long period of idle listening at the receiver. On the other hand, decreasing the backoff period would adversely affect the reliability. To explain the CSMA idle listening of 802.15.4, Figure 4 shows how nodes in receiving zones would need to keep listening on the channel for at least 53.5 units (*53 units for CSMA and 1/2 units for CCA*), in order to catch a possibly late packet transmission and even if no packet is being transmitted.

Notifying V-route to re-schedule the packet in the next frame if a channel access failure occurs can solve this issue. Figure 5 shows how adding a function call, namely *V-Route Handle*, into the 802.15.4 code allows notifying V-Route of a channel access failure. Subsequently V-Route will be responsible for rescheduling the packet transmission in the next frame. This optimization allows the number of backoffs, $macMaxCSMABackoffs$, to be set to 0, hence reducing the receiver idle listening from 53 to 8 units of time (7 for CSMA and 1 for CCA). This translates in a reduction of receiver idle listening from $17.2ms$ to $2.56ms$. The number of packet retransmissions before transmission failure is now handled by V-route therefore allowing adaptation for example depending on the relevance of the packet itself.

3. **MCU Stand-by Mode:** This optimization regards putting the MCU in standby mode by availing of the V-Route zone activity coordination. As shown in Figure 7, some of our initial measurements at the oscilloscope of the beaconless 802.15.4 demonstrate that the current needed to power on the MCU can be greater than the current needed for the radio in transmitting mode. These measurements highlight the importance to implement coordinated duty-cycled activities also for the MCU, which is often overlooked when developing energy-efficient communication architectures.Using

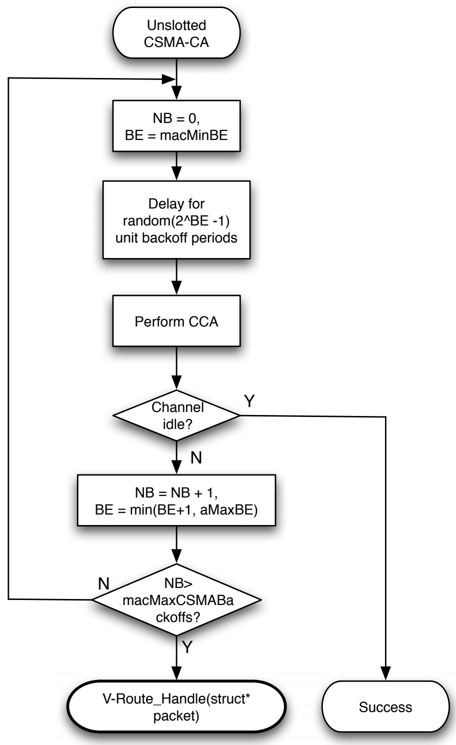

Fig. 5. The V-Route packet handling mechanism included in the unslotted CSMA of 802.15.4

CC2420 - Current consumption (mA)	
Listening	18.8
Transmit -25 dBm	8.5
Transmit -15 dBm	9.9
Transmit -10 dBm	11
Transmit -5 dBm	14
Transmit 0 dBm	17.4
Sleep mode 0	1
Sleep mode 1	0.02
Sleep mode 2	0.001
Data rate (Kbps)	250

ATMega 128 - Current consumption (mA)	
Normal	12
Stand-by	4.1
Power down	0.25

Fig. 6. The electrical node specifications measured at the oscilloscope

Low data rate: Energy per second (1 packet/m = 30 B/m)					
TxPower (dBm)	**Etot (mJ/s)**	**Etx %**	**Elisten %**	**Eswitch %**	**Emmcu %**
0	106.8393	0.0110	66.2767	0.0004	33.711
-10	106.8349	0.0070	66.2794	0.0004	33.7132
-25	106.8332	0.0054	66.2804	0.0004	33.7137

High data rate: Energy per second (10 packet/s = 300 B/s)					
TxPower (dBm)	**Etot (mJ/s)**	**Etx %**	**Elisten %**	**Eswitch %**	**Emmcu %**
0	107.5825	0.5890	65.9264	0.01738	33.4672
-10	107.3491	0.3732	66.0695	0.01742	33.5398
-25	107.2580	0.2886	66.1256	0.01744	33.5683

Fig. 7. Initial results of transmitter energy in single-hop 802.15.4

the scheduling of V-route, the MCU can go into stand-by mode in each time slot where the node is not scheduled to transmit or receive.

The next section highlights the performance evaluation of V-route along with the three energy optimization techniques for V-route-enhanced 802.15.4 presented in this section.

5 Performance Evaluation

This section presents the energy results obtained through experimentations on a network of Philips AquisGrain sensor nodes. Firstly, we specify the experiment configuration and related performance metrics. We then present the comprehensive results for V-route over 802.15.4 and plain 802.15.4 for both star network and multihop network environments.

5.1 Metrics and Setup

V-route is validated by the **node energy consumption per second** metric considering both CPU and transceiver consumptions. In order to include diverse application scenarios, we set 3 different data rates: (1) a low data rate of 1 *pkt per min*, (2) a medium data rate of 1 *pkt per sec*, and (3) a high data rate of 10 *pkt per sec*. Each packet transmission from zone to zone was acknowledged by the receiver. The length of the packet payload was fixed to 30 *bytes* while the length of each experiment was slightly more than 10 *minutes*. All the experiments were conducted in an office environment consisting of few rooms, corridors and people on their usual business activity.

The Philips AquisGrain sensor module includes a CC2420 radio transceiver (2400-2483 Mhz, 250 kbps, output power ranging from -25 to 0 dBm) and an ATMega128L microcontroller (4K RAM, 128K program memory). To improve the accuracy of the experiment we measured the node's consumption at the oscilloscope. The relevant electrical specifications are detailed in Figure 6. It is interesting to note that such values, which have been obtained by direct measurements at the oscilloscope in a Philips laboratory, differ slightly from the standard data sheet values though they do not affect the final energy consumption trend of the protocol.

The final energy was obtained by considering both transceiver and microprocessor consumption as they proved to be the two most consuming components on our nodes as shown in Figure 6. The energy calculation was achieved by timestamping each time the transceiver changed a state and then by incrementing 4 variables that held sleeping, receiving, transmitting and switching times. Such times were then periodically transmitted to the PAN coordinator, which was connected to a PC, that estimates the energy by using the values in Figure 6. Rather than calculating the energy directly at the sensor, this method proved to be largely more accurate due to difficulty of handling 64-bit variables at the node.

An important setup aspect is to calculate the minimum slot length to allow accommodating at least one packet transmission. In 802.15.4, the packet length varies depending on the data carried, with a payload that may vary from 0 to 127 *bytes*, always prefixed with 6 *bytes* of preamble and header. This makes a maximum packet length of 135 *bytes* which are transmitted in 4.256 ms at 250 *kbps* on 2400 MHz frequency band. Each packet is then transmitted with a prior CSMA-CA period of maximum 17.120 ms as described in section 6. This lead to a minimum possible V-route slot length of 21.376 ms plus a short time for packet ACK. In the experiments we tested 3 different slot times of 50 ms, 100 ms and 250 ms that allow transmitting 2, 4 and 6 packets respectively within the same slot.

5.2 802.15.4 Transmitter Measurements

The transmitter measurements are carried out in a single-hop environment consisting of a receiving node connected to the PC through serial port and 10 transmitter nodes. We set a high data rate scenario of *10 pkt per sec*. The experiment is repeated for 3 different transmission powers that correspond to the highest, the medium and the lowest possible transmitting power with a $CC2420$ chip. The goal is to identify the significant components that regulate the transmitter energy consumption in a high contention scenario. The results shown in Figure 7 are obtained by averaging the consumption of all the transmitters. The main interesting implications are summarized as follow:

- In contrast to common expectations, increasing the transmission power has an almost insignificant effect on the overall energy consumed by the 802.15.4 transmitter, as the percentage of time the transceiver is transmitting is very low. However, the transmission power to choose might be pondered taking into account that an excess of transmission power notably increases the chances of packet collisions and reduces the number of simultaneous transmissions in a multihop environment. This aspect may be a point for further studies.

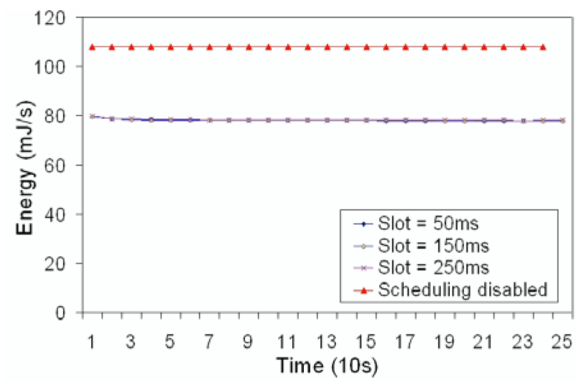

Fig. 8. Comparison between the energy consumption of a plain multihop-enabled 802.15.4 and 802.15.4 enhanced with V-route

- In spite of a high traffic condition per node, the transmission energy spent is almost insignificant with respect to the node's overall consumption. In fact the node spends a great amount of time in sensing the channel prior to transmission;
- Idle listening when no packets are sent and CPU energy consumption dominate the node energy utilizations. This confirms the 802.15.4 idle listening issue.

These transmitter measurements presented some relevant 802.15.4 drawbacks that will be addressed by V-Route and its optimization techniques, as detailed in the next section.

5.3 Energy Results

This section presents energy consumption results in a V-Route enhanced single-hop 802.15.4 network. These single-hop experiments compare a plain beaconless 802.15.4 to V-Route enhanced 802.15.4, providing us with energy gains achieved with the V-Table sleep scheduling. As shown in Figure 8, the node's energy consumption is reduced from an average of 108 mJ/s for a plain 802.15.4 to 78 mJ/s for a V-route-enhanced 802.15.4. This yields to about 27.3% energy savings.

In contrast to what we initially expected, figure 8 also shows that varying the slot time has no significant effect on the node's energy consumption. Clearly, by increasing the slot length we are in fact modifying both the active and sleeping slots and therefore the node duty cycle remains unchanged. Optimizations 1 rectifies this situation while Optimizations 2 and 3 focus on the 802.1.5.4 CSMA-CA backoff and microcontroller activity, respectively.

Figure 9 shows the improvements achieved with turning off the transceiver immediately after transmission of the last packet to a receiving zone (Transceiver

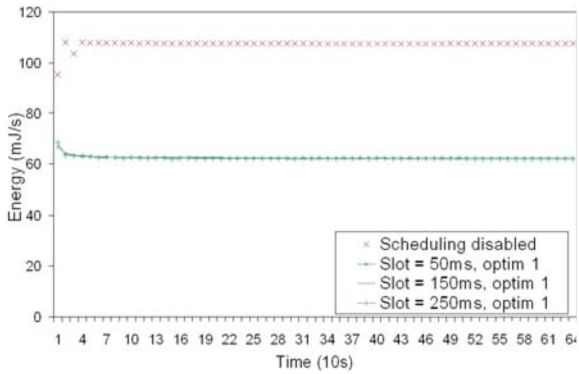

Fig. 9. Optimization 1: energy consumption results at transmitter side

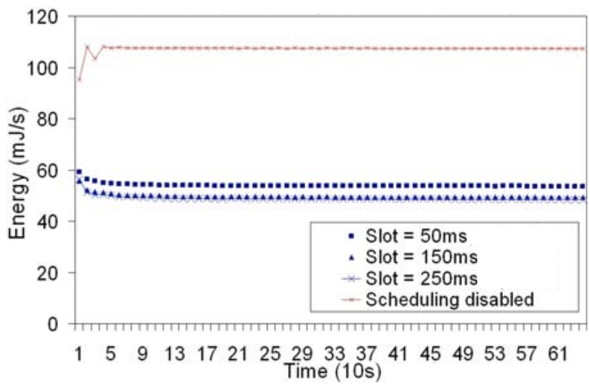

Fig. 10. Comparison of optimization 1 against beaconless 802.15.4

Sleep Policy at the transmitter side), as described in Section 4. The simple but effective optimization yields up to 42.9% energy consumption decrease with respect to having devices always on as shown in figure 9. This corresponds to additional energy saving of 15.6% with respect to the non-optimized V-route (when transceivers are kept on until the end of the allocated slot).

Figure 10 shows results of the Transceiver Sleep Policy at the receiver side, described in Section 4. The optimization allows 55.1% energy decrease with respect to having devices always on. This corresponds to an additional energy saving up to 12.2% for 250 ms slot time. It is interesting to note that by introducing the **Transceiver Sleep Policy**, we can now affect the node duty-cycle by varying the slot time. A longer slot time results in a smaller node's duty-cycle and therefore appreciable energy saving.

Figure 11 shows results from the second optimization, **V-Route Short CSMA** that reduced the 802.15.4 idle listening from 17.2ms to 2.56ms. This

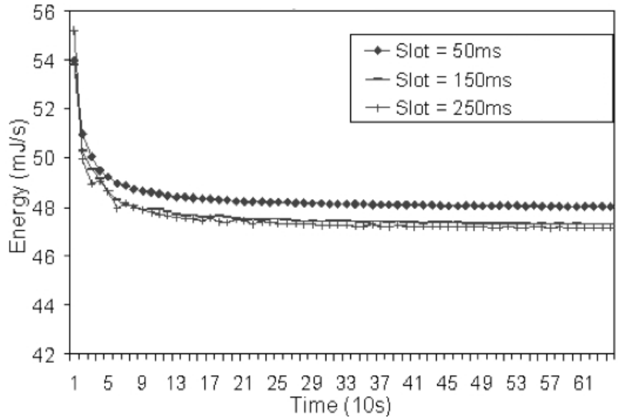

Fig. 11. Optimization 2 energy consumption results

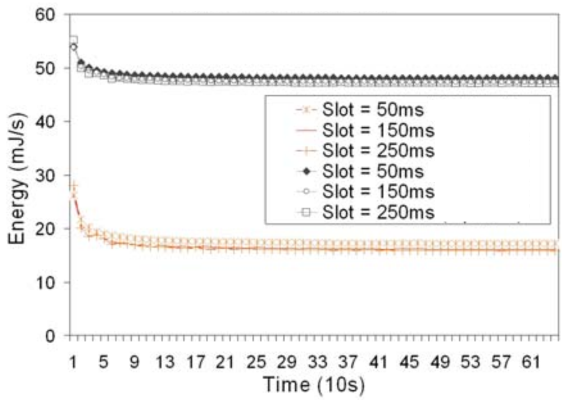

Fig. 12. Optimization 3 energy consumption results

allowed an significant increase of the 802.15.4 packet delivery rate. In contrast, the subsequent rescheduling of packets by V-Route generated an increase of packet overhearing. However, the optimization allowed further 1.3% energy reduction with respect to the previous optimization, therefore leading to 56.4% overall energy reduction.

Figure 12 shows results from the MCU Stand-by Mode optimization that allows coordinated **MCU stand-by mode**. The ATMega128 processor allows a 250 μA standby current that is restored to activity by clocking an external 32 KHz crystal. This optimization yields 15.9 mJ/s of energy which results to an extreme 85.3% overall energy saving. This is a further 28.9% energy saving with respect to the V-Route Short CSMA optimization.

6 Conclusion

802.15.4 intends to offer MAC and Phy layer capabilities for WPAN and wireless sensor networks. Therefore, it is key to understand the real performance of the protocol on typical multihop WSN scenarios. Furthermore, a major goal of this work is to build a routing architecture over 802.15.4 that preserves fully the protocol compliance. Initially this paper highlighted some key issues of 802.15.4 beacon-enabled mode for multihop networks. This imposes the usage of beaconless mode and a subsequent implementation of activity coordination among nodes. The paper proposes V-route as an 802.15.4 compliant packet scheduling and routing policy to enable energy-efficiency and high reliability in both single-hop and multihop environments. V-Route is allows enhancing the 802.15.4 with three energy optimization techniques. Experimentations of V-route yielded high data delivery rate and energy reduction ranging from 27.3% to 85.3% against a beaconless 802.15.4.

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