Improving robustness of beacon-enabled IEEE 802.15.4 with Round-Robin channel diversity

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Improving Robustness of Beacon-Enabled IEEE 802.15.4 with Round-Robin Channel Diversity

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***Abstract*—Reliable wireless communication even in adverse conditions is the key for building the energy efficient and dependable Internet of Things. In this paper, we explore the benefits of channel diversity for enabling efficient wireless communication: we propose MRR (Multi-channel Round-Robin), a backward-compatible evolution of beacon-enabled IEEE 802.15.4 in which energy constrained nodes take advantage of additional active periods operating on different channels in a round-robin way. Each active period starts with a beacon sent on a cyclically changing channel, which then allows an associated device to transmit data on the channel used for the beacon. MRR schedules the additional active periods at carefully selected instants to avoid direct beacon collisions.**

To motivate our work, we first experimentally corroborate previous findings that channel diversity is an effective way of mitigating variable or poor transmission conditions. Then, we observe that channel diversity improves the quality of transmission even better than expected—it appears that wireless sensor nodes have a radiation pattern that changes significantly from one frequency channel to another, which often results in a considerably improved gain when using the right communication channel. The evaluation of the MRR scheme through measurements on a real indoor multihop testbed shows that the proposed scheme results in significantly improved Packet Reception Ratio even without resorting to *e.g.* channel blacklisting. These results confirm the benefits of multichannel operation and exhibit a fully functional solution that does not add a large overhead compared to using a single channel.

Keywords*—*Wireless Sensor Networks, multi-channel, beacon-enabled 802.15.4, IPv6, auto-configuration

I. Introduction

The IEEE 802.15.4 standard [1] is an efficient and low-power communication technology for wireless sensor networks. In the beacon-enabled mode, time is divided in superframes composed of active and inactive periods (*cf.* Fig. 1). During inactive periods, a node can switch off the radio to save energy. Multihop operation requires a cluster-tree topology that nodes may create based on *Incoming* and *Outgoing* superframes (*cf.* Fig. 2): a node associates with a parent coordinator, uses the *Incoming* active period to send frames to the parent, and acts itself as a coordinator on behalf of child nodes by communicating with them during the active period of its *Outgoing* superframes.

The goal of our work is to improve the communication quality in terms of the packet delivery ratio by exploiting channel diversity in wireless sensor networks based on IEEE 802.15.4. The main issue with taking advantage of channel diversity is to avoid deafness—two nodes that want to communicate in a multi-channel setting, need to agree on the common

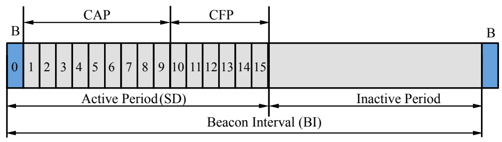


Figure 1: 802.15.4 superframe structure. Our motes only use the Contention Access Period (they do not use the Contention Free Period).

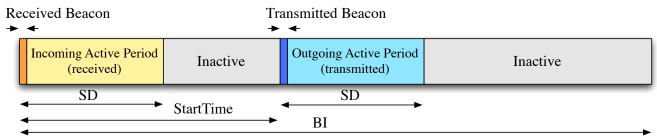
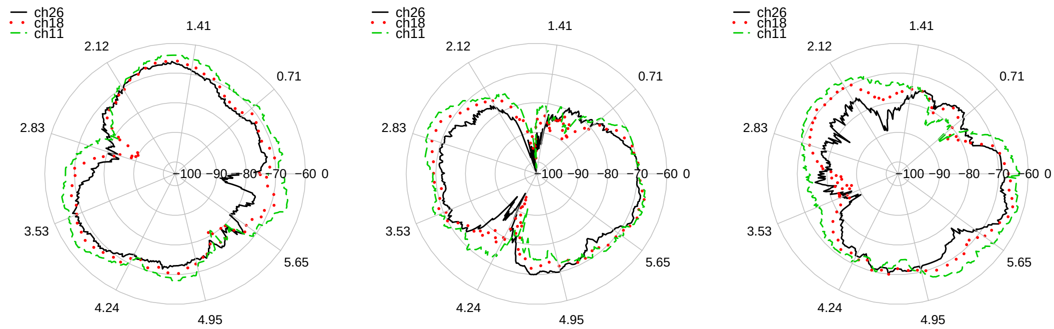


Figure 2: *Incoming* and *Outgoing* superframe structure in IEEE 802.15.4

channel to use. Moreover, nodes need additional mechanisms to discover used channels and assess their quality. They also need to choose channels and beacon transmission times in a way to avoid interference and distribute the load over the channels [2], [3], [4], [5], [6], [7], [8], [9]. Our aim is to minimize the overhead of such operations yet enable an efficient use of multiple channels while remaining backward compatible with the 802.15.4 standard (legacy 802.15.4 devices can still operate in the network comprising nodes with the enhanced multi-channel operation).

Based on an experimental evaluation of channel performance in outdoor and indoor conditions, we propose MRR (Multi-channel Round-Robin), a scheme for using multiple channels in a round-robin way by extending the standard operation of beacon-enabled 802.15.4. In the scheme, a node schedules additional active periods operating on different channels during the inactive period of the standard beacon interval. Each active period starts with a beacon sent on a cyclically changing channel so that associated devices may send their packets on the channel used for the beacon. MRR schedules the additional active periods at random instants to avoid beacon collisions. The scheme keeps backward compatibility with nodes that do not support multi-channel operation.

We start the paper with an experimental study of 802.15.4 motes in real radio conditions. The study shows that transmissions on different channels exhibit significantly different performance both in outdoor and indoor environments. This first insight corroborates the previous research results and we posit that the observed differences come from antenna radiation patterns variations whereas multipath fading is in general the



(a) receiver placed flat (horizontal antenna)

(b) receiver placed vertically (horizontal antenna)

(c) receiver placed horizontally (vertical antenna)

Figure 3: Reception patterns for an 802.15.4 device

sole invoked reason. We then introduce the proposed scheme and evaluate its performance through measurements on a real-world multihop testbed deployed indoor. The measurements show that the scheme results in a significantly improved PRR (Packet Reception Ratio) without having to resort to complex schemes to adapt to channel quality variations.

II. Experiments with Multi-Channel Transmissions

Much recent research pointed out the benefits of multi-channel transmissions [10], [11], [12], [13], [14]. In this section, we corroborate their finding on our specific hardware with experimental measurements and provide a new possible explanation for the improved gain from channel diversity that is not usually put forward in the literature. In the measurements, we use sensor motes with a Cortex-M3 clocked at 12 MHz with 32KB RAM and 256KB flash as well as a 802.15.4 2.4GHz radio transceiver. They run a fully operational IP protocol stack based on Contiki [15] that integrates the IEEE 802.15.4 beacon-enabled mode and supports IP routing over 6LoWPAN adaptation.

A. Outdoor Radiation Pattern

The first experiment takes place outdoors on a large empty parking lot with the receiver node in the middle, one meter above the ground and the sender on a robot that circles around the receiver. The constant distance between the two nodes is maintained using a string between the center of the circle and the robot. Fig. 3 shows the average RSSI (Received Signal Strength Indicator) at each robot position at which, the sender transmits three trains of 20 packets on three different channels. We perform measurements one after the other so the atmospheric conditions remain constant during the experiment. We can observe that the signal strength notably varies with the aspect angle. For instance, the pattern in Figure 3b is expected—it corresponds to a typical dipole radiation pattern. What is less expected, though, is the difference of up to 10dB from one channel to another in many directions. Furthermore, channel 11 has a higher signal reception strength in many, but not all directions.

This observation for the outdoor case, in which there is a single path between the sender and the receiver, sheds light on the more complex case with multiple paths, *i.e.* indoor [10]. The power fractions of the signal sent on each of the multiple paths between the sender and the receiver change when the sender uses different channels. At the receiver, the reception gain for each of the path will also vary. So, the signal that results from the combination of the incident radio waves will strongly depend on the channel used. The antenna radiation pattern variations have a significant effect at any distance between the sender and the receiver and it adds up to the radio channel multipath fading sensitivity to the wavelength, which is usually rather limited at a short distance (for path lengths differing by 1m, the coherence band is as large as the entire 2.4GHz ISM band [10]). In essence, both effects combine and add up to each other [16].

B. Indoor Measurements

Indoor conditions are different from those observed outdoors with multiple paths even when a sender and a receiver are in the same room. Our experiment involves a fixed transmitting node and a mobile receiver that moves away from the sender by steps of 1.5 cm, which is well below the wavelength. In each position, the sender transmits three bursts of 20 packets on different channels, then the receiver moves to the next position.

Fig. 4 presents the number of received packets at each position. The position of the receiver has a major impact on the signal strength and consequently on PRR. We performed several runs to assess the stability of the results, even though only one is presented here due to space constraints. We note that, in general, channel 11 gives better results than other channels, which reflects the overall better gain observed for this channel outdoor. Nevertheless, there are positions, *e.g.* around step 700 where other channels give much better results.

Figure 5 represents the histograms of the RSSI variation when changing channel over one third of the ISM band at various positions at a distance of 8 to 10 meters. RSSI changes of 10dB or more are routinely witnessed, which confirms the previous findings.

The results show that we can greatly benefit from better transmission performance by taking advantage of channel diversity, both in indoor and outdoor cases. However, we still need to organize the operation of nodes, since they already have their place in a cluster-tree topology. Actually, we have chosen to enhance the 802.15.4 beacon-enabled mode with the MRR (Multi-channel Round-Robin) proposal to notify other nodes with what channel to use and when.

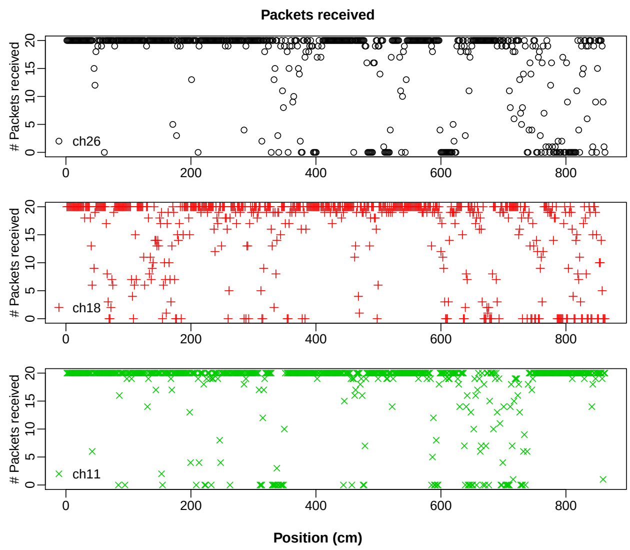


Figure 4: Number of received packets on different channels when the receiver moving away from the sender.

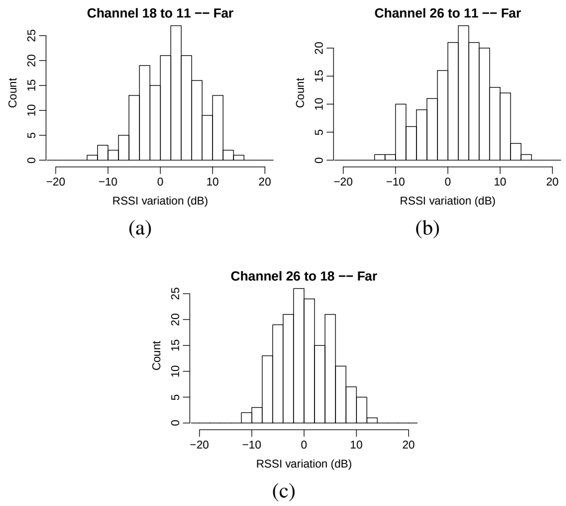


Figure 5: Histogram of the RSSI difference

III. MULTI-CHANNEL ROUND-ROBIN

In the standard beacon-enabled 802.15.4 mode, beacons sent by a coordinator node on a given main channel delimit the beacon interval that begins with an active period for communication between child nodes and the coordinator. The proposed MRR scheme consists of scheduling additional active periods during the standard beacon interval. Each active period starts with a beacon sent on a cyclically changing channel (the channels are different from the main channel). In this way, associated devices can transmit data on the channel used for the beacon, in the immediately following active period.

Fig. 6 illustrates the principle of the MRR scheme: Node 1 sends 3 additional beacons on 3 different channels during the standard beacon interval (the Beacon Order BO of 6 on a single channel is equivalent to BO=4 on all 4 channels). The choice of channels allows covering the entire frequency band of 802.15.4 with four channels: 11, 16, 21, 26. An adaptive mechanism can be implemented, like blacklisting a channel when a low PRR is experienced.

We define a *superframe slot* as an active period of SD duration placed at integer multiples of SD (SD is the superframe duration, *cf.* Fig. 1). Beaconing nodes can choose any slot and any channel for their additional beacons—Section III-A proposes a simple algorithm for choosing the slots and channels.

Note that MRR is backward compatible with the 802.15.4 standard: a device that does not implement MRR can still associate with a coordinator and communicate with other nodes on a single channel. In other words, we replicate the superframe on several channels to improve PRR while remaining standard compliant on each individual channel.

As our solution is based on the beacon-enabled 802.15.4 mode, each coordinator will have several associated devices. We recall that if two or more nodes have frames to send in the same superframe, they use the standard slotted CSMA/CA method to avoid colliding repeatedly.

A. Determining StartTimes on Multiple Channels

In the standard, the StartTime parameter is the time offset between the *Incoming* and the *Outgoing* superframes. In MRR, there is one StartTime per channel and several *Incoming* superframes.

To avoid beacon collisions, we propose to start with a random choice of slots for the additional beacon transmission times—the choice comes from a uniform distribution of available slots (*cf.* 6). After an initial selection of slots, a joining node first listens during those slots to check if they are used by other nodes. If any activity is detected, this particular slot is marked as not available and another one is considered (*cf.* Fig. 7). The slots of the parent node are marked not available from the start. Such a distributed solution is suitable for networks with sub-cluster trees having different parameters of superframe durations and beacon intervals, giving a high degree of flexibility to schedule the instants of sending beacons.

A node includes the information on the number of additional beacons to send, their slots, and their channels in beacon frames. We need one byte to represent the current slot and another one for the total number of slots used. Then, for each extra slot, we need two bytes for the slot and the corresponding channel (see Figure8). The payload of a single beacon is thus enough for a node that tries to join the network to get the necessary information to synchronize with other nodes. This mechanism allows for great flexibility in choosing beacon slots. The same slots can be used for different channels, but also on the same channel in different regions of the network, if two nodes do not hear each other. The mechanism does not guarantee that beacons do not collide with a third node, but beacon collisions are generally not harmful, since IEEE 802.15.4 transmissions are effectively quite robust [17].

The only overhead of the solution is the extra information included in beacons. If we target a specific duty cycle, the multichannel solution will not consume more energy than the standard beacon-enabled mode. However, it is clear that if certain nodes do not support MRR communication, their potential data rate will be reduced as they will have to wait more between two slots on the same channel.

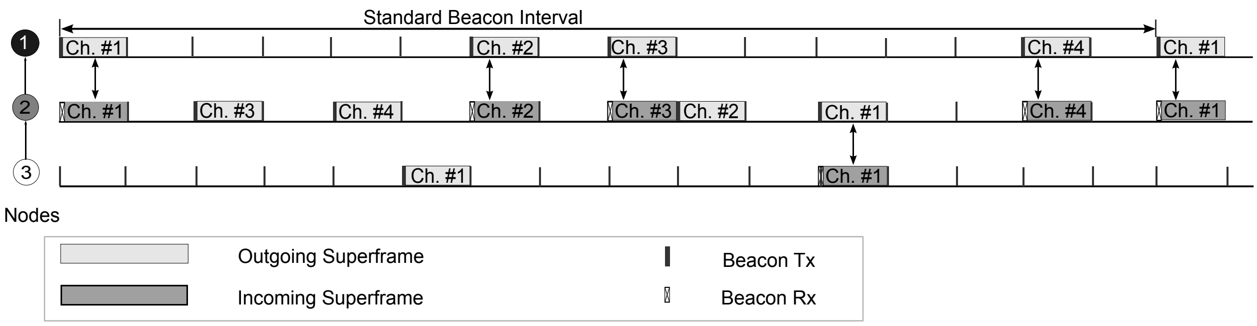


Figure 6: Principle of MRR. During the standard beacon interval delimited by two beacons on the same channel (Channel #1), a node sends additional beacons on different channels (Channels #2, #3, #4) to take advantage of channel diversity. The beaconing slots are delimited by the black vertical lines.

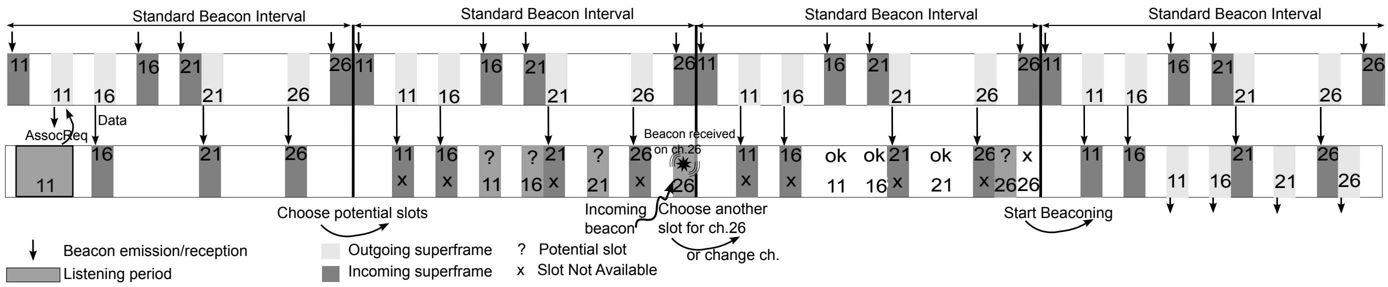


Figure 7: Distributed slot selection for nodes joining the network. Random selection of beaconing slots and avoidance of overlapping active periods.

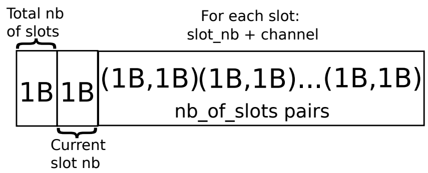


Figure 8: Extra information included in the beacon payload.

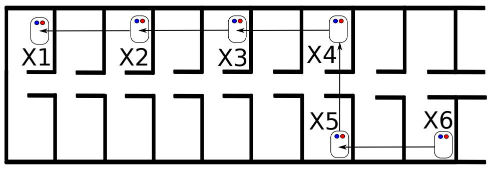


Figure 9: Node placement in the experiments.

B. *Dealing with Multicast Frames*

Multicast frames need special handling if legacy nodes are present as they only listen to beacons on a single channel. In this case, if we send a multicast frame on a different channel than the one on which a single-channel node operates, it will be received by all other nodes, but not by the legacy one. To overcome this issue, we propose to change multicast frames into a series of unicast frames for the associated devices, which guarantees that the frame will be received by all the nodes, even when they wake up for a subset of beacons. When the single-channel node wakes up, it will retrieve the multicast frame using the usual unicast transmission procedure: it gets notified that it has a pending frame in the beacon and requests its transmission.

IV. Evaluation and Performance Results

We have implemented MRR on the previously described motes running Contiki and set up an indoor testbed for validating the performance of MRR:

6 nodes arranged in a line separated by a distance of typically 2 office rooms (or 10m to 15m, *cf.* Fig. 9). Even though the setup is of a limited size, the environment allows for obtaining realistic results in a deployed operational network: all kinds of interference are taken into account (interference from WLANs, humans, obstacles, etc.). In this set up, even though we use the maximum transmission power (6 dBm), many packets are lost. However, by using 4 channels (11, 16, 21, 26) evenly spread along the whole ISM 2.4GHz band, at least one of them always leads to a PRR over 50%.

Recall that beacons are broadcast frames, they do not use neither retransmission nor clear channel assessment. Hence, to ease the comparison with unicast frames, we have configured no retransmissions for unicast frames when the acknowledgment is not received, so nodes attempt to transmit each frame only once.

Each run lasts long enough for the transmission of 15,000 beacons on each channel. As for unicast frames, depending on the node placement in the chain topology and the channel number, the number of acknowledged frames or missed ones varies from 200 to 15,000 (except for two cases in which there were only about 20 frames on a particular channel between two nodes). The unicast frame size is 22 bytes and the beacon frame size is 61 bytes.

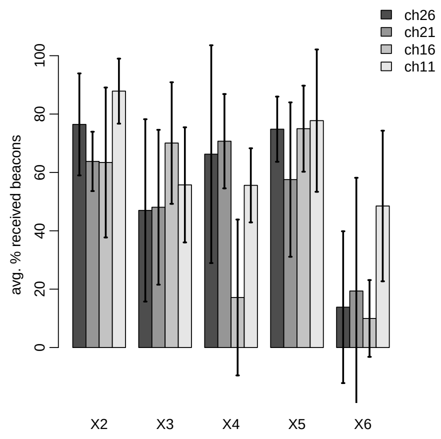


Figure 10: Mean and standard deviation of Beacon Reception Ratio at each node.

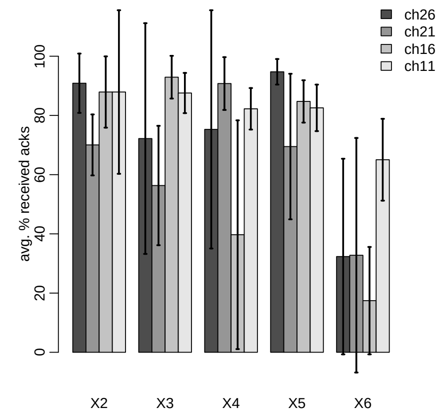


Figure 11: Mean and standard deviation of Unicast Reception Ratio at each node.

Figs. 10 and 11 represent the percentage of received beacons and acknowledgments averaged over 10 runs. The performance of some channels is highly variable, so it readily appears that choosing a channel and sticking to is not a viable strategy.

Continuously using multiple channels for packet transmission is a double-edge sword, though: packets are transmitted alternatively on good and bad channels, so we need to estimate the real gain of spreading transmissions on several channels with a metric that reflects the transmission quality on a given channel. For this purpose, we have chosen the familiar Expected Transmission Count (ETX) metric [18] that captures the average number of attempts required to transmit a frame. ETX is inversely proportional to PRR:

$$\mathit{ETX} = 1/\mathit{PRR}.$$

We extend this metric to communication on several channels by defining Multichannel ETX (METX): Eq. 1 represents the probability of missing a transmission on one or several channels until the frame is received. We first define $F(l)$, the probability that a frame is successfully received after l attempts (or maybe dropped after the k-*th* attempt):

$$F(1) = \frac{1}{n}\sum_{i=0}^{n-1} P_i \qquad F(2) = \frac{1}{n}\sum_{i=0}^{n-1}(1-P_i)P_{(i+1) \bmod n}$$

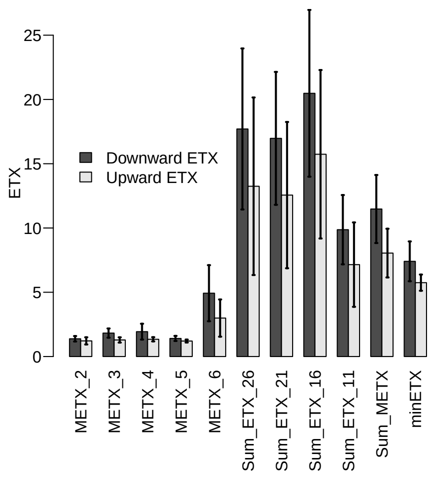


Figure 12: Mean and standard deviation for the METX metric at each node, sum of ETX when using the same channel along the chain of node, METX for multi-channel operation and ETX if each hop used the best available channel

$$F(k-1) = \frac{1}{n}\sum_{i=0}^{n-1}\left(\prod_{j=0}^{k-3}(1-P_{(i+j) \bmod n})\right)P_{(i+k-2) \bmod n}$$

$$F(k) = \frac{1}{n}\sum_{i=0}^{n-1}\prod_{j=0}^{k-2}(1-P_{(i+j) \bmod n})$$

and

$$\mathit{METX} = \sum_{j=1}^{k} jF_j, \tag{1}$$

where P_i is the probability of a successfully reception on channel i (equal to 1-PRR), n is the number of channels ($n = 4$ in our example), and k the maximum number of retransmissions. In a nutshell, METX represents how many retransmissions are needed to send a packet, taking into account different transmission probabilities on each channel.

To better understand the trade-offs of multi-channel communication, Figure 12 shows the average (along with the standard deviation) METX for each hop (indexed by the node number) and the sum of ETX or METX for different combinations: i) Sum_ETX_26, Sum_ETX_21, Sum_ETX_16, Sum_ETX_11 are the sums of ETX_n when channel n is used for all hops, ii) Sum_METX, the sum of METX over all hops (we take into consideration all channels and the number of expected transmissions based on the performance of each channel), and iii) minETX, the ideal ETX metric, which corresponds to the one we got on the best performing channel for each hop (*a posteriori*).

The sum of METX comes often close to minETX, which is notable because METX corresponds to a systematic frame transmission on all channels in a round-robin way without any evaluation of the channel quality, whereas implementing minETX would require at least a periodical channel probing mechanism and a significant signaling traffic. METX is a poor metrics for node 6 because the only usable channel is 11. This effect would call for some channel blacklisting mechanism and it is also the reason why Sum_METX is larger than Sum_ETX_11.

The fact that upward frames are always transmitted after a beacon reception effectively increases the probability of a successful transmission: the upward ETX does not grow as notably as in the downward direction, when the conditions worsen (Fig. 12).

Our multi-channel scheme contributes to the good performance of the network. The main drawback of using a single channel is probably the fact that a joining node might not be able to receive beacons on a specific channel (or just a few). Consequently, it cannot associate and join the network. The Multi-channel Round-Robin scheme overcomes this problem by enabling the use of other channels.

Another important aspect to point out is that although the nodes did not move at all between the experiments, in one case, channel 26, at the end of the spectrum band, performed the best. In the other case, it was channel 11 at the other end of the spectrum band. As the environment is dynamic (for example, people moving around), the quality of a WSN can be drastically impacted. In a real deployment of a WSN, the distance between nodes could be in the range of 5 to 10 meters. Hence, channel diversity becomes necessary to attain good performance.

V. Related Work

The IEEE 802.15.4e amendment [19] updated the previous standard [1] to accommodate new functionalities such as channel hopping: Time-Slotted Channel Hopping (TSCH) and Deterministic and Synchronous Multi-Channel Extension (DSME). TSCH mode [20] basically defines a couple of timeslots and channel frequencies for each communication link between two devices. The major challenge in this mode is node synchronization as well as allocating slots between two synchronized devices. At the same time, TSCH has the advantage of the fact that once it has a well established schedule of slots allocated to nodes, there is no need of CSMA/CA as in most cases, only two nodes will communicate during the same slot on any single channel.

The DSME variant uses periodical standard beacons and enables multiple-channel communications only during the contention-free period (CFP): it assigns one or more slots to any associated device that asks for a Guaranteed Time Slot (GTS). The main drawback of this variant is that if the beacon is not received, there will not be any communication afterwards (no CFP), so the channel on which beacons are sent must be carefully chosen.

Watteyne *et al.* showed that multipath fading can cause destructive interference, which results in no signal seen at the receiver [10]. To overcome the deep fading, the first solution is to move the node by a few centimeters (it can cope with fading at the node, but it may also decrease the quality of a link to another node) or by changing the channel. The authors explained that a change of 5 MHz (the difference between two adjacent channels) is enough to overcome adverse multipath fading.

Srinivasan *et al.* observed that Telos and MicaZ sensors exhibit link asymmetry, a "grey region" of reception, and temporal variations in packet loss [11]. Packet losses are highly correlated over short time periods, but they are independent over longer periods. They also underlined that long-term asymmetries are rare.

Many authors proposed to take advantage of multiple channels in cluster-tree sensor networks. MC-LMAC (Multi-Channel Lightweight Medium Access Control) [9] is based on a scheduled access: each node controls a timeslot to transmit on a particular channel. Nodes use a common channel to exchange control information. TMCP (Tree Based Multi-channel Protocol) is a centralized solution proposed to minimize the interference within the tree by creating several subtrees rooted at the PAN coordinator: each subtree operates on an orthogonal channel [8]. However, nodes in the same subtree keep on colliding mainly because TMCP only reduces collisions among the 1-hop neighborhood of the PAN coordinator. Several other papers had similar objectives [2], [3], [4], [5], [6], [7], but their proposals all involve non-backward compatibility with the standard 802.15.4 protocol.

Abdeddaim *et al.* proposed MCCT (Multi-Channel Cluster Tree), a cluster-tree construction protocol for nodes in IEEE 802.15.4 beacon-enabled mode [21]. By using several orthogonal channels throughout the network, it reduces collisions between control and data frames, which leads to better packet delivery ratio and improved fairness. MCCT includes a method to build a cluster-tree suitable to minimize beacon collisions: the neighbor discovery procedure uses a dedicated control channel in parallel to the superframe structure of IEEE 802.15.4. This control channel is used for channel assignment and superframe scheduling with channel diversity. Romaniello *et al.* designed a Multi-Channel Beacon Train (MCBT) protocol [22] that accelerates the process of joining the network, which is critical for energy harvesting nodes. They can indeed scan the channel continuously for much shorter periods than non-rechargeable battery operated nodes. Nevertheless, in both discussed schemes, the association and further communication between any given device-coordinator pair takes place on a single channel, so that, in a cluster, communications do not benefit from any channel diversity.

Discussion

Compared to MCCT or MCBT, the scheme proposed in this paper brings a significant improvement of the Packet Delivery Ratio by enabling communication on several channels between device-coordinator pairs. We do not compare it experimentally with TSCH or DSME, because implementing the variants requires a major additional effort while the main point of the paper is to confirm experimentally the benefits of multi-channel transmissions and propose a simple backward compatible scheme that shows the improved performance over the standard. Competing with the variants was not the primary goal of the paper, however, we plan to port OpenWSN that includes TSCH on our motes and compare its performance with MRR on a larger testbed.

Nevertheless, compared to TSCH, MRR is a fully operational solution that includes the routing mechanism and requires no additional signaling. There is no doubt that TSCH could lead to a more efficient operation, because the communication channels between each two nodes can be fine tuned and completely avoid channel interferences when several nodes communicate in the same time. But MRR has also a room for improvement, like banning those channels that do no work well for a majority of nodes.

One notable difference between MRR and DSME is that in MRR, beacon transmission benefits from channel diversity, which can notably increase the effective coverage of each coordinator, as well as frame reception reliability. DSME restricts the use of several channels to contention-free transmissions after an explicit reservation handshake, which may only happen on a given fixed channel.

VI. Conclusions

Our experimental results show that taking advantage of multiple channels is paramount to improve the quality of communications that use publicly available radio bands. Indoor environments often vary (people move around, doors open/close etc.) so the radio channel quality changes in a unpredictable way. The best way to fight fading and interference is to use multiple channels that span the whole available frequency band.

In this paper, we have proposed MRR (Multi-channel Round-Robin), a scheme that uses multiple channels in a round-robin way. A node schedules additional active periods operating on different channels during the inactive period of the standard beacon interval. Active periods start with beacons sent on different channels. A joining node can transmit a data packet on the same channel as the received beacon. We have also proposed a random allocation scheme to choose the instants of the additional active periods to avoid beacon collisions. MRR integrates perfectly well with beacon-enabled 802.14.5 by using beacons on multiple channels to invite nodes to use a given channel for communication.

The evaluation of the proposal through measurements on a real-world multihop testbed deployed indoors shows that the scheme results in significantly improved PRR.

A simple and efficient extension to MRR would be to to avoid using the channel on which beacon transmission results in poor performance. The change needs to be done with caution though, as not all associated devices perceive the same link conditions, so the change requires an explicit feedback from all nodes. A device can simply just skip beacons sent on a channel that exhibits poor performance. Along the similar lines, a node may avoid sending unicast packets on particular channels if their PRR is low. Nodes that do not have any associated devices can save energy by only sending beacons once in a while or on a single channel until they receive a request for association, as it has been proposed elsewhere [23].

References

[1] "IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)," *IEEE Std 802.15.4-2011 (Revision of IEEE Std 802.15.4-2006)*, pp. 1–314, Sept 2011.

[2] G. Zhou, C. Huang, T. Yan, T. He, J. A. Stankovic, and T. F. Abdelzaher, "MMSN: Multi-Frequency Media Access Control for Wireless Sensor Networks," in *INFOCOM*, april 2006.

[3] K. Chowdhury, N. Nandiraju, D. Cavalcanti, and D. Agrawal, "CMAC - A multi-channel energy efficient MAC for wireless sensor networks," in *WCNC*. IEEE, april 2006.

[4] X. Chen, P. Han, Q.-S. He, S. liang Tu, and Z. long Chen, "A Multi-Channel MAC Protocol for Wireless Sensor Networks," in *CIT*. IEEE, 2006.

[5] M. Jovanovic and G. Djordjevic, "TFMAC: Multi-channel MAC Protocol for Wireless Sensor Networks," in *TELSIKS*. IEEE, sept. 2007.

[6] Y. Kim, H. Shin, and H. Cha, "Y-MAC: An Energy-Efficient Multi-channel MAC Protocol for Dense Wireless Sensor Networks," in *IPSN*. IEEE/ACM, 2008, pp. 53–63. [Online]. Available: http://dx.doi.org/10.1109/IPSN.2008.27

[7] J. Borms, K. Steenhaut, and B. Lemmens, "Low-Overhead Dynamic Multi-channel MAC for Wireless Sensor Networks," in *EWSN*, Coimbra, Portugal, 2010.

[8] Y. Wu, J. A. Stankovic, T. He, and S. Lin, "Realistic and Efficient Multi-Channel Communications in Wireless Sensor Networks," in *INFOCOM*. IEEE, 2008, pp. 1193–1201.

[9] O. D. Incel, L. van Hoesel, P. Jansen, and P. Havinga, "MC-LMAC: A multi-channel MAC protocol for wireless sensor networks," *Ad Hoc Netw.*, vol. 9, no. 1, pp. 73–94, Jan. 2011. [Online]. Available: http://dx.doi.org/10.1016/j.adhoc.2010.05.003

[10] T. Watteyne, S. Lanzisera, A. Mehta, and K. Pister, "Mitigating Multipath Fading through Channel Hopping in Wireless Sensor Networks," in *Communications (ICC), 2010 IEEE International Conference on*, May 2010, pp. 1–5.

[11] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis, "Understanding the Causes of Packet Delivery Success and Failure in Dense Wireless Sensor Networks," in *Proceedings of the 4th International Conference on Embedded Networked Sensor Systems*, ser. SenSys '06. New York, NY, USA: ACM, 2006, pp. 419–420. [Online]. Available: http://doi.acm.org/10.1145/1182807.1182885

[12] A. Bardella, N. Bui, A. Zanella, and M. Zorzi, "An experimental study on IEEE 802.15.4 multichannel transmission to improve RSSI–based service performance," in *Real-World Wireless Sensor Networks*. Springer, 2010, pp. 154–161.

[13] Y. Wu, J. A. Stankovic, T. He, and S. Lin, "Realistic and Efficient Multi-Channel Communications in Wireless Sensor Networks," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*. IEEE, 2008.

[14] A.-W. Chen, B. Shih, C. Chang, and C. Chen, "Enhanced MAC channel selection to improve performance of IEEE 802.15.4," *International Journal of Innovative Computing, Information and Control*, vol. 6, no. 12, pp. 5511–5526, 2010.

[15] M. Durvy, J. Abeillé, P. Wetterwald, C. O'Flynn, B. Leverett, E. Gnoske, M. Vidales, G. Mulligan, N. Tsiftes, N. Finne, and A. Dunkels, "Making Sensor Networks IPv6 Ready," in *sensys*, Raleigh, North Carolina, USA, Nov. 2008.

[16] L. O. Varga, M. Heusse, R. Guizzetti, and A. Duda, "Why is frequency channel diversity so beneficial in wireless sensor networks?" in *2016 Wireless Days (WD)*, March 2016, pp. 1–3.

[17] L.-O. Varga, G. Romaniello, M. Vučinić, M. Favre, A. Banciu, R. Guizzetti, C. Planat, P. Urard, M. Heusse, F. Rousseau, O. Alphand, E. Dublé, and A. Duda, "GreenNet: an Energy Harvesting IP-enabled Wireless Sensor Network," *to appear in IEEE Internet of Things Journal*, 2015.

[18] D. S. De Couto, D. Aguayo, J. Bicket, and R. Morris, "A High-Throughput Path Metric for Multi-Hop Wireless Routing," *Wireless Networks*, vol. 11, no. 4, pp. 419–434, 2005.

[19] "IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer," *IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1–225, April 2012.

[20] P. Thubert, T. Watteyne, M. R. Palattella, X. Vilajosana, and Q. Wang, "IETF 6TSCH: Combining IPv6 Connectivity with Industrial Performance," in *Proceedings of the 2013 Seventh International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, ser. IMIS '13. Washington, DC, USA: IEEE Computer Society, 2013, pp. 541–546. [Online]. Available: http://dx.doi.org/10.1109/IMIS.2013.96

[21] N. Abdeddaim, F. Theoleyre, F. Rousseau, and A. Duda, "Multi-Channel Cluster Tree for 802.15.4 Wireless Sensor Networks," in *Proceedings of the 23rd IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'12)*, Sydney, Australia, Sep. 2012.

[22] G. Romaniello, E. Potetsianakis, O. Alphand, R. Guizzetti, and A. Duda, "Fast and energy-efficient topology construction in multi-hop multi-channel 802.15.4 networks," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2013 IEEE 9th International Conference on*. IEEE, 2013, pp. 382–387.

[23] C.-A. La, L.-O. Varga, M. Heusse, and A. Duda, "Energy-Efficient Multi-Hop Broadcasting in Low Power and Lossy Networks," in *Proceedings of the 17th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems*. ACM, 2014, pp. 41–50.