Hybrid Timeslot Design for IEEE 802.15.4 TSCH to Support Heterogeneous WSNs

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***Abstract*—The IEEE 802.15.4 Time-Slotted Channel Hopping (TSCH) protocol defines two types of timeslots for communications, namely dedicated and shared timeslots. An upper layer in the protocol stack uses these timeslots to design a communication schedule for the network links, based on the required bandwidth for each link. Considering a network with time-varying data traffic generation by each node, the bandwidth requirements are changing over time for each link. This leads to poor efficiency of a predefined schedule when there is no data traffic for the dedicated timeslots, or there is too much data traffic injected to the shared timeslots. In this paper, we propose a new type of timeslot, called hybrid timeslot. A hybrid timeslot acts as a dedicated timeslot for a specific link, when there are packets available to be transmitted on that link. Otherwise, it acts as a shared timeslot that can be accessed by other links, using a contention-based mechanism. The hybrid timeslot has backward compatibility with the TSCH protocol and is functional with a few adaptations in the parameter setup of the TSCH protocol. Experimental and simulation results show that for heterogeneous networks using hybrid timeslots improves communication latency without reliability penalty.**

I. Introduction

Heterogeneity is a native property of many Wireless Sensor Networks (WSNs). It exists in different aspects such as the operation mode of applications, data generation patterns, reliability requirements, and physical layer performance. For instance, in-vehicle WSNs connect several types of sensors in a vehicle to a central entity, each type running a different application. This heterogeneity and dynamics should be properly supported by the network protocol stack. Otherwise, it is not possible to guarantee a level of reliability and Quality-of-Service (QoS) for the network.

Time-Slotted Channel Hopping (TSCH) is one of the MAC operational modes of the IEEE 802.15.4 [1] standard protocol. It aims to improve the reliability of low-power wireless communications through providing guaranteed access to the wireless medium for links in a WSN. In this protocol, time is divided into fixed periods that are called *timeslots*. Each timeslot is enough to transmit a single packet and its acknowledgement. Each link in the network is dedicated to a timeslot in a predefined pattern, named *slotframe*, that repeats over time. Also a timeslot can be shared between multiple links via a slotted CSMA-CA technique. Under fully reliable physical layer communications, TSCH makes the communication behavior of a network almost predictable. This helps the designer of the network to dedicate network resources based on the applications' worst-case requirements. However, time varying behavior of the applications leads to waste of resources when applications are running in non-worst-case modes. The unused resources in this situation could be used for communications of other applications. On the other hand, using shared resources may lead to high contention, when multiple applications are transferring large data volumes.

In this work, we propose a hybrid timeslot that can be used as a dedicated timeslot for communications by one owner node and as a shared timeslot for all other nodes to transmit data to the same destination, if the owner node does not use it for transmission. This is done by performing one or more Clear Channel Assessments (CCA) by the non-owner nodes with a *small delay*; this allows those nodes detect whether or not the owner node skips transmission in that timeslot. The same TSCH CSMA-CA retransmission algorithm that is used for the shared timeslots in the IEEE 802.15.4 [1] protocol is used to manage contention in accessing the hybrid timeslots. The proposed hybrid timeslot imposes very little change to the TSCH protocol and has backward compatibility with it. However, the overhead of this technique, compared to the basic TSCH protocol, is need for a little longer timeslots or shorter maximum size of those packets that are transmitted in the hybrid timeslots by the non-owner nodes. The reason is that transmissions of non-owner nodes in a hybrid timeslot start with a small delay due to the delayed CCAs.

We performed a set of experiments and simulations using the Contiki [2] operating system to evaluate this technique. Results show that using hybrid timeslots in a TSCH schedule leads to lower communication latency compared to only using dedicated or shared timeslots. Moreover, it improves the reliability of the network by reducing the number of packet drops due to buffer overflow. Moreover, the average power consumption of one packet delivery by use of hybrid timeslots is lower than that of shared timeslots.

The paper is organized as follows. An overview of the heterogeneity in WSNs is given in the next section.

Related work about handling traffic heterogeneity in TSCH-based WSNs is surveyed in Section III. The design details of the hybrid timeslots are presented in Section IV. Performance evaluation setups and results are discussed in Section V. Section VI concludes.

II. Motivation: Heterogeneous WSNs

Heterogeneity may exist in different layers of the protocol stack of WSNs, from application layer down to the physical layer. This can be caused by different capabilities of wireless nodes or different running applications on them. Heterogeneity in each layer may affect the functionality and performance of other layers as well. Furthermore, nodes' behavior may change over time due to the changes in the operational mode of the nodes. For instance, an application that is running on a wireless node may change the data generation rate due to some events received from the attached sensor or changes in power source conditions. Also, different nodes may be attached to different types of sensors and generate different traffic patterns. Intra-vehicle WSNs are an example of heterogeneous WSNs. These networks typically include several types of sensor nodes with different data generation patterns, modes of operation, and power conditions.

Considering the application heterogeneity, dedicating TSCH communication resources to links in a WSN may lead to waste or lack of resources. On the other hand, sharing TSCH communication resources between multiple nodes may lead to poor performance of connections and unsatisfied reliability and latency requirements in some cases. This makes TSCH scheduling of such WSNs complex and it may make it difficult to meet the reliability requirements.

III. Related Work

The IEEE 802.15.4 [1] TSCH protocol defines two generic types of timeslots, namely dedicated and shared timeslots. Dedicated timeslots are defined to be assigned to a specific [transmitter, receiver] couple, called a link. This guarantees that only one node is transmitting on a specific [timeslot, channel] and there is no interference from nodes in the network for that communication. Shared timeslots are defined to share the medium between multiple source-destination nodes through a slotted CSMA-CA mechanism. These timeslots are usually used for communications with low bandwidth and low reliability requirements. The IEEE 802.15.4 [1] standard leaves the assignment of timeslots to the links (scheduling) to the upper layers in the protocol stack (i.e., a sublayer between network and MAC layers). Such a scheduler decides on the number of dedicated and shared timeslots for each link, based on the application data rate and its QoS requirements.

Heterogeneity of applications in a WSN makes the scheduling task very challenging. This is because every change in the application data rate and its requirements may need changes in the TSCH schedule. On the other hand, changes in the channel quality can affect the effective allocated TSCH bandwidth to a link, and require the TSCH schedule to be adapted accordingly. [3] presents a scheduling algorithm that uses shared timeslots for retransmission of different flows in order to satisfy required reliability. This shortens the slotframe size and forwarding delay by reducing the number of required dedicated timeslots in each slotframe. Besides using shared timeslots next to the dedicated timeslots for a link, [4] introduces slot reuse for the forwarding nodes, by which dedicated timeslots to each node's indirect children may be used by the node for upstream data forwarding. Results shows better reliability than simple timeslot sharing in multihop topologies. However, these techniques may lead to waste of MAC bandwidth if the data generation rate of an application becomes less than the dedicated bandwidth allocated to it.

On-the-fly bandwidth reservation [5] is a dynamic scheduling technique that aims at adapting the TSCH schedule of a node to its actual bandwidth requirements. This technique constantly monitors the amount of data being sent towards each of the node's neighbors. Then if the data rate changes, it asks the upper sub-layer (i.e., 6top [6]) to add or delete dedicated timeslots to the schedule. This technique requires continuous monitoring of application data traffic and negotiation between neighbor nodes, which results in transmission overhead. It imposes continuous changes to the TSCH schedule and has a delay of few slotframe periods to apply required changes to the TSCH schedule. Furthermore, authors use a constant slotframe length for this setup that may not satisfy the latency requirements of some applications.

The available dynamic scheduling techniques (e.g., [3], [4], and [5]) dedicate an initial bandwidth to each link and use different techniques to adapt it over time based on the changes in the application and/or channel behavior. However, these scheduling techniques can only use dedicated and shared timeslots that are either available to only one link or to all links. If a dedicated timeslot in a schedule is not used for transmissions by the assigned link, no other link is allowed to use it until it is removed from the schedule by the scheduler. The slot reuse technique that is introduced in [4] is only operational for links under the same routing hierarchy. On the other hand, a shared timeslot can be potentially used by all links. If more than one link in a neighborhood uses it for transmissions, all communications fail with a high chance. These restrictions inspired us to design hybrid timeslots for the IEEE 802.15.4 [1] TSCH MAC to be used by different schedulers to control the dynamism of the bandwidth requirements at the timeslot level. Using this new type of timeslot, a scheduler can only consider an average amount of bandwidth to be allocated for each link and there is no need to add or remove timeslots at runtime to handle variations in the links' bandwidth requirements. In other words, hybrid timeslots take care of dynamic bandwidth requirements in a heterogeneous WSN.

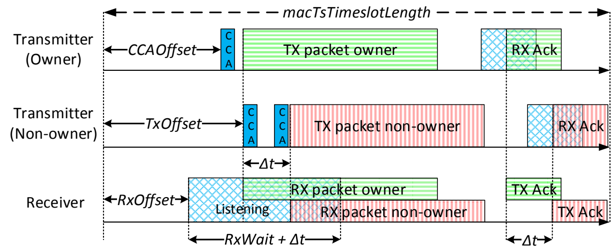

Fig. 1. Timeslot diagram for a hybrid timeslot. An owner transmitter follows the default timeslot diagram, while a non-owner transmitter uses a Δt delay for communication offsets.

IV. Hybrid Timeslot Design

A. Background

Our proposed idea of using hybrid timeslots that act as both dedicated and shared timeslots is inspired by the Z-MAC [7] protocol. Z-MAC assigns two types of transmitters to a communication slot, namely owner and non-owner transmitters. Based on the type of the transmitter in each slot, Z-MAC performs a random back-off within a first (for owner) or second (for non-owners) contention window. After the back-off period, it runs CCA and if the channel is clear, then it starts transmission. This gives higher priority to the owner transmitter of a timeslot compared to the non-owner transmitters. Z-MAC uses CSMA-CA in each slot and thus, the slot size must be larger than the sum of the two contention windows, the CCA period and one packet propagation time. However, the IEEE 802.15.4 [1] TSCH protocol considers no contention period within a timeslot in order to reduce the timeslot size and increase the bandwidth utilization. Instead, TSCH uses back-off on timeslots to handle contentions on accessing shared timeslots.

While Z-MAC uses message exchanges to negotiate on the owner transmitter of a timeslot, we add hybrid timeslots to the TSCH protocol as a new type of timeslots that a TSCH scheduler can use for scheduling. We design a diagram for hybrid TSCH timeslots that follows the basic TSCH timeslot diagram. This diagram enables defining owner and non-owner access to a timeslot. Only one owner node can be assigned to a hybrid timeslot to have guaranteed access to it. We dedicate a part of hybrid timeslots for performing CCAs by the non-owners to check if the owner is active. Thus, the non-owner nodes can use that timeslot for shared transmissions (as defined in the TSCH protocol), whenever the owner skips packet transmission in that timeslot.

B. Design

Fig. 1 shows the proposed diagram for the hybrid timeslots. It has the same timeslot timeline as the one defined in the IEEE 802.15.4 TSCH [1] standard for the owner node, whereas it has a different timeline defined for communications of non-owner nodes in the hybrid timeslots. In this timeline, a non-owner transmitter wakes up at *TxOffset* offset from the beginning of the timeslot. Then, instead of transmission, it listens to the medium for a Δt period. This listening period is to detect if the owner of the timeslot starts a transmission in this timeslot. We use Clear Channel Assessments (CCAs) with mode 3 to do this. This CCA mode reports a busy medium if it detects a signal with the IEEE 802.15.4 modulation and spreading characteristics or signal energy above a threshold. Using only one CCA in a very short Δt period may lead to missing the owner transmission due to synchronization error between timeslots of the owner and non-owner nodes. We propose to perform two CCAs, one at the beginning of the Δt period, and one at the end of it. The first CCA guarantees that if the timeslot of the non-owner starts later than the owner node and the owner transmits a very short packet, the non-owner still will be able to detect that packet transmission. Otherwise, the non-owner transmission might then clash with the acknowledgment of the owner packet. Placing the second CCA at the end of the Δt period helps a non-owner to detect transmissions of the owner even if the timeslot of the non-owner is ahead of the timeslot of the owner. If both CCAs show a clear channel, a non-owner considers this as skipped transmission by the owner and starts packet transmission at *TxOffset*+Δt offset. Accordingly, the acknowledgment process is delayed by Δt.

The Δt duration should be defined based on the timeslot synchronization error margins. As defined in the IEEE 802.15.4 TSCH [1] standard, a receiver node wakes up earlier than the *TxOffset* for a *guardtime* (typical value of $1ms$, considering preamble transmission time [8]). This is done to compensate synchronization errors when the timeslot of the transmitter is ahead of that of the receiver. Also, the receiver continues listening for a *guardtime* after the *TxOffset*, to compensate backward synchronization error. Therefore, a *guardtime* is defined to be the maximum synchronization loss between two nodes in the network. Accordingly, an owner and non-owner of a hybrid timeslot may lose synchronization for a *guardtime*. To enable a non-owner node to detect packet transmissions by the owner, even in the case that it starts its timeslot ahead of the owner, we need to set $\Delta t \geq$ *guardtime*. This enables the second CCA in the Δt period to still detect transmission by the owner, if the non-owner timeslot is ahead. We choose the $\Delta t =$ *guardtime* to impose the least overhead to the TSCH timeslots.

If the owner skips transmission in a hybrid timeslot, the receiver should keep listening for a longer time to receive a packet from one of the non-owner nodes. As the *TxOffset* is delayed for a Δt in the timeline of non-owner transmitters, the listening phase at the receiver node should be extended for a Δt period to compensate that delay. The default listening duration is defined as *RxWait* in the protocol, which is twice the synchronization loss *guardtime*. Thus, the receiver in a hybrid timeslot shall listen for the start of an incoming packet for a longer time equal to $3 \times$ *guardtime*.

Since multiple non-owner nodes may try to use a hybrid timeslot for their transmissions, collisions may happen. This is the same situation that happens in the shared timeslots. Thus, we treat transmissions by the non-owner nodes in a hybrid timeslot the same as the shared transmissions and use the same CSMA-CA algorithm specified by the IEEE 802.15.4 [1] TSCH protocol for shared timeslots.

All the dedicated timeslots in a TSCH schedule can be replaced by hybrid timeslots, considering the dedicated transmitter as the owner of the timeslot. This can share the unused bandwidth that is dedicated to each node with other nodes. This reduces long packet delivery delays due to packet buffering at the source nodes, caused by the limited allocated bandwidth to nodes. This also reduces the need for shared timeslots, that are normally used in a TSCH schedule for retransmission of un-acknowledged packets, resulting in shorter slotframes.

Adding hybrid timeslots to a TSCH MAC imposes no special adaptation to the IEEE 802.15.4 [1] TSCH standard and is backward compatible. This means that the nodes with hybrid timeslots enabled and nodes without ability to use hybrid timeslots can communicate without problems within the same network. This only requires increase of the *RxWait* duration by Δt.

C. Design Trade-offs

A non-owner transmitter in a hybrid timeslot may aim at sending the packet to either the same destination as the owner, or a different one. If a non-owner node aims to transmit its data packet to a different node, that receiver should be aware of this decision and listen in that timeslot. As multiple non-owners may share the same hybrid timeslot, multiple receivers should be listening in each hybrid timeslot to receive packets from multiple possible sources. For each transmission by the owner or non-owner nodes, all the receivers should receive that packet and then check if the packet is for them. This imposes a considerable idle listening and overhearing energy wastage. Furthermore, coordinating transmitters and receivers on using a hybrid timeslot in the non-owner mode adds overhead to the TSCH scheduler. Accordingly, we recommend that in a hybrid timeslot, a non-owner transmitter only uses the timeslot if it has data towards the same destination as the owner. This fits well with the tree topology structure that is used by known routing protocols for WSNs such as RPL [9]. This also prevents cumulative clock drifts, as the primary and secondary users are synchronized to the same parent.

The delayed communications of non-owner nodes in hybrid timeslots require a Δt extra time within a timeslot. This can be reached either by increasing the length of all timeslots by Δt, or reducing the maximum size of the packets that get transmitted in a hybrid timeslot by the non-owner nodes. Using longer timeslots leads to an overhead for ordinary timeslots, while the second technique does not have such an overhead. By using the second technique, a non-owner node can only use a hybrid timeslot for transmission if the size of its packet is short enough to be transmitted within the timeslot bounds. A maximum size packet in the standard (133 bytes in the physical layer) takes $4256\mu s$. This time should be reduced to $(4256\mu s - \Delta t)$ for non-owner transmissions in hybrid timeslots. Accordingly, the maximum length of the packet can be calculated in bytes (one byte per $32\mu s$). In typical industrial applications in which a WSN is used for monitoring, application data is usually only a few bytes. This gives the opportunity to all data packets to be transmitted in hybrid timeslots. However, nodes are still able to transmit the maximum size packets in the ordinary and owner hybrid timeslots. Transmission of the maximum size packets is necessary to handle protocol-defined packets (e.g., enhanced beacon packets). If the network is required to support the maximum packet size that is defined in the protocol for all packets, the timeslot size needs to be increased by Δt.

D. Hidden Terminal Problem

The hidden terminal problem may affect the functionality of hybrid timeslots. This happens when two-hop neighbors of an owner of a hybrid timeslot try to send packets on that timeslot as non-owners. In this case, they cannot detect the transmission by the owner and thus, they use the timeslot for transmission. This may cause packet reception failure at the receiving node. However, for small networks such as in-vehicle networks, this situation never happens, as all wireless nodes are in the range of each other. For larger networks, there are multiple options to prevent this problem. One option is to consider this hidden terminal problem during TSCH scheduling. This can be done by assigning non-owner transmitters to a hybrid timeslot only if they are a direct neighbor of the owner. Another solution is that the scheduler only takes care of assigning owner transmitters to the hybrid timeslots in the same way as for dedicated timeslots. In this case, at runtime each node can broadcast a message to all of its one-hop neighbors, specifying the hybrid timeslots that it owns. By receiving this message, a node can add those hybrid timeslots to its schedule, as non-owner timeslots. Thus, only the one-hop neighbors of the owner node that are able to detect whether or not the owner node skips transmission on a hybrid timeslot can use it as non-owner nodes. This prevents the hidden terminal problem.

V. Performance Evaluation

A. Setup

To evaluate the functionality and performance of hybrid timeslots within a TSCH schedule, we added it to the TSCH protocol implementation on top of the Contiki [2] operating system. We perform a set of lab experiments using 10 NXP JN5168 dongles [10]. These dongles include a wireless microcontroller which integrates a 32-bit RISC processor and a 2.4GHz IEEE 802.15.4 compliant transceiver. We deploy a network with one coordinator (node 1) and nine sensor nodes that send packets towards the coordinator. Each node is the owner of one hybrid TX timeslot in a slotframe of size 10 timeslots, with the coordinator as destination. The first timeslot of the slotframe is used for the network advertisement by the coordinator. Other nodes can use hybrid timeslots as non-owner transmitters, if they have waiting packets to transfer.

Considering a *guardtime* of $1ms$ for the TSCH timeslots, hybrid timeslots are required to be $1ms$ longer or have about 32 bytes shorter maximum size of packets. Accordingly, we define two types of schedules for hybrid timeslot evaluations. One, the Hybrid schedule, contains hybrid timeslots with length $15ms$ and physical frame size up to 101 bytes. The other schedule type is called L-Hybrid and uses hybrid timeslots that are Δt = *guardtime* longer in length ($16ms$) and can handle the default maximum size frames.

Hybrid timeslots can be used by any type of TSCH scheduler or bandwidth control mechanism. Thus, for performance evaluations, we compare the performance of this new type of timeslot with the dedicated and shared timeslots. Accordingly, we define two other TSCH schedules. The first schedule consists of a slotframe of size 10 timeslots in which each timeslot is dedicated to one node to send its packet to the coordinator. The other schedule has only one timeslot that is shared between all nodes for transmission and reception.

In our experiments, we extract the performance of each schedule under different data generation scenarios, namely periodic, dynamic-periodic, event-based, and heterogeneous. In the periodic scenario, each node uses a fixed period for data generation (multiplication of the node id and half of the length of one slotframe). For the dynamic-periodic scenario, every two seconds a random data generation period between 0.5 and 8 slotframe lengths is selected for each node. In the event-based data generation pattern, each node sends 10 packets in a burst after a random time between 2 to 4 seconds. We use a combination of the three data generation scenarios as the high-rate heterogeneous scenario (Het.-high rate), in which every three transmitter nodes use one of the data generation patterns. Furthermore, we define a low-rate heterogeneous scenario (Het.-low rate) by reducing the data generation rate of each node to 10% of the high-rate heterogeneous scenario.

To have a clean comparison between different timeslot types, we place all the sensor nodes in an interference-free environment and with a short distance of each other. This provides fully reliable links for all the experiments. The maximum retransmission count of the MAC layer is set to 6. The size of the MAC outgoing buffer towards each neighbor is set to 16 packets.

To better investigate the performance of the hybrid timeslots in comparison with other types of timeslots, we also perform a set of simulations using COOJA [11]. We use the same network setup as the one used for the lab experiments, using Sky motes that emulate the behavior of the TelosB/Tmote Sky platform [12]. In our simulations, we study the effect of physical layer reliability on the performance of different schedule types. We consider the high-rate heterogeneous data generation scenario for this set of evaluations.

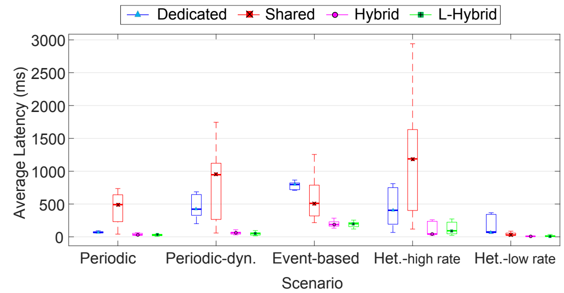

Fig. 2. Distribution of links' average packet delivery latency for different schedule types and different data generation patterns.

We investigated various metrics to evaluate the performance of our proposed technique. Packet Reception Ratio (PRR) is the percentage of packets that are successfully received at the receiver node over the total number of data packets generated by the sender node. The communication latency is the time between data sample generation by the application on the source node and its reception at the coordinator node. We also investigate the average number of transmissions at the MAC layer to successfully deliver a packet. This parameter gives an estimation of the average power that is consumed to deliver one packet on a link.

B. Experimental Results

In our lab experiments, we investigate the performance of different schedule types under different data generation scenarios. Fig. 2 uses boxplots to show the distribution of the average packet delivery latency of the nine available links, for all the schedules and scenarios. This figure shows the expected result that longer timeslots of the L-Hybrid schedule lead to a little higher latencies compared to the Hybrid schedule. However, both Hybrid and L-Hybrid schedules provide lower latency for all links compared to the other two schedules, under all data generation patterns. This is because each node can use the first unused hybrid timeslot to deliver its packet and reach low latencies, while at the worst case if there is no free non-owner hybrid timeslot available, it uses the hybrid timeslot that it owns. The Dedicated schedule performs well for all the links under the periodic scenario, in which the packet generation period is longer than the slotframe size and packets are not queued in the MAC buffers. For the Periodic-dyn. and Event-based scenarios in which the application data generation rate may go temporarily higher than the supported bandwidth by the dedicated schedule, this schedule shows higher data delivery latencies due to packet buffering. Because of the contention-based communications in the Shared schedule, this schedule performs poor under all scenarios, except in the Het.-low rate scenario in which it performs better than the Dedicated schedule. This is because when the application data rate is low, the contention on accessing a shared timeslot is also low. Thus, with a high probability, a packet can be successfully transmitted on the first shared timeslot right after its generation. On the other hand, high data generation rates lead to more

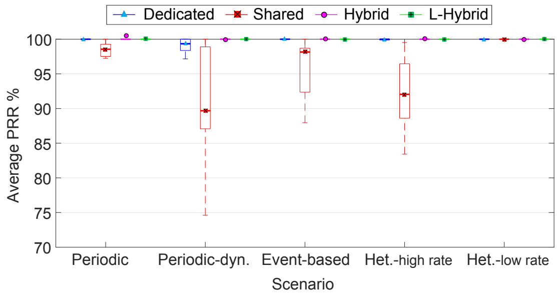

Fig. 3. Distribution of links' average PRR for different schedule types and different data generation patterns.

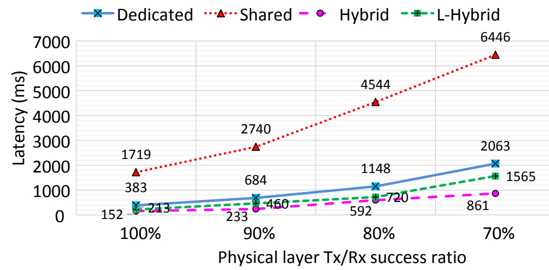

Fig. 4. Average end-to-end latency (packet generation to receiving acknowledgment) for heterogeneous data generation scenario under different physical layer Tx/Rx success ratios.

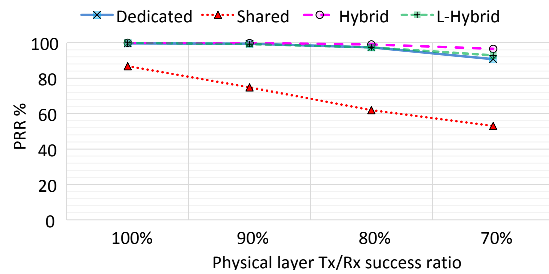

Fig. 5. Average application PRR for heterogeneous data generation under different physical layer Tx/Rx success ratios.

contention and use of long back-off windows, causing long latencies for the Shared schedule. This shows that shared timeslots are more suitable for low data rates.

Fig. 3 shows the distribution of links' average PRR for different schedules and scenarios. The Dedicated, Hybrid, and L-Hybrid schedules can handle the data traffic and deliver almost all packets. This is because all these schedules dedicate an amount of bandwidth to each link and guarantee transmission of a basic data rate for the application. However, the Shared schedule cannot guarantee a bandwidth for each link and the provided bandwidth is highly depending on the data rate of other links. Therefore, the Shared schedule only provides good communication reliability when data generation rate is low (e.g., Het.-low rate scenario).

In general, our lab experiments prove the functionality of the hybrid timeslots as a new type of timeslot for the TSCH protocol. The results show the positive effect of this new type of timeslot on reducing the end-to-end communication latency in a TSCH network. Moreover, this latency reduction does not affect reliability of the communications.

C. Simulation Results

We use the same source code that is used for our lab experiments to perform simulations in the COOJA simulator. Here we investigate the performance of different schedules under different physical layer reliability levels (Tx/Rx success ratios) for the Het.-high rate scenario. Fig. 4 shows the average link latency for different schedules. The Hybrid schedule reduces the latency about half the average latency of the Dedicated schedule, as every node can use the first free hybrid timeslot for packet transmission. While the same back-off mechanism is used in the hybrid and shared timeslots for non-owner access, the average latency of the Hybrid schedule is about one tenth of the latency of the Shared schedule. This is because, in the worst case, data of a node is transmitted in the dedicated timeslot to that node with a latency equal to the latency of the Dedicated schedule. However, if there is a timeslot closer to the packet generation time of which the owner skips transmission, the node has the chance to transmit the packet, leading to a lower average latency.

Since most of the traffic in the Hybrid schedule is transferred in owner timeslots, only a part of the traffic is transmitted in the non-owner timeslots. This leads to less contention on accessing non-owner timeslots and use of shorter back-off windows compared to the Shared schedule, leading to lower latencies for Hybrid schedule. Furthermore, due to the heterogeneity of the data generation, different nodes may have different data rates at any point of time. Using hybrid timeslots, a node that has a high data generation rate in a period of time can steal the bandwidth allocated to another node with a lower data rate in that period. This leads to less packet queuing of Hybrid and L-Hybrid schedules compared to the Dedicated schedule and lower communication latency for them. As the L-Hybrid schedule uses longer timeslots, it provides higher communication latencies compared to the Hybrid schedule. For the same reason, the L-Hybrid schedule reduces the TSCH MAC bandwidth that results in more contention on the access to non-owner timeslots, which again increases the average communication latency. However, the provided average communication latency by the L-Hybrid schedule is still much lower compared to the Dedicated and Shared schedules.

Fig. 5 shows that using both Hybrid and L-Hybrid schedules provides higher PRR compared to the Shared schedule, for different physical layer transmission success ratios. This is because each link in a Hybrid schedule is the owner of one timeslot and has a minimum guaranteed bandwidth (minimum PRR is equal to the Dedicated schedule), while in a Shared schedule no bandwidth is guaranteed meaning that the contention probability determines the PRR. More contention on accessing shared timeslots leads to more retransmissions and more waiting packets in the MAC buffer that causes buffer overflow and packet drops. For lower physical layer transmission success ratios, both schedules with hybrid timeslots even performs better than the dedicated

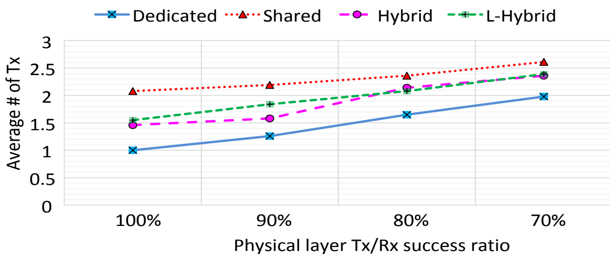

Fig. 6. Average number of transmissions for heterogeneous data generation under different physical layer Tx/Rx success ratios.

schedule. This is because when nodes experience more transmission failures, they need to keep the packet in the MAC buffer and retransmit it for the maximum retransmission count. For the Dedicated schedule, each retransmission leads to a delay of one slotframe for all the packets in the buffer. As this buffer has a limited size, it may get full some times and newly generated packets can be dropped. However, a schedule with hybrid timeslots shares the unused allocated bandwidth to a node with other nodes that may have packets waiting in the buffer. This reduces the probability of packet drops that may be caused by MAC buffer overflow.

Fig. 6 shows the average number of transmissions that is made to successfully deliver each packet over the available links for different physical layer transmission success ratios. When the physical links are 100% reliable, as there is no disturbance for the dedicated communications, all packets can be delivered by only one transmission. However, for the Shared schedule that uses contention-based communications in all timeslots, on average more than one transmission is needed to successfully deliver each packet. As hybrid timeslots inherit the specifications of both dedicated and shared timeslots and a node may use these timeslots either as dedicated or shared, the average number of transmissions of hybrid timeslots sits between those of the Dedicated and Shared schedules. The retransmission cost is actually for reaching lower communication latencies (in line with observations made in [13]). However, the average transmission count of the Hybrid and L-Hybrid schedules is increasing with the same slope as for the Dedicated schedule, when physical layer transmission success ratio decreases. This shows that the ratio between power consumption of these two schedules is getting closer for lower communication reliabilities. For the Shared schedule, although less packets are successfully delivered for lower physical layer reliability, the average number of transmissions is also increasing for the delivered packets. This shows that under high data generation rates, the Shared schedule performs poor in term of power consumption, as well as reliability and latency. However, both hybrid schedules provide better reliability and latency compared to the Dedicated schedule, at the cost of more power consumption.

VI. Conclusion

This paper introduces a new type of timeslots for the IEEE 802.15.4 Time-Slotted Channel Hopping (TSCH) protocol, called hybrid timeslots. Hybrid timeslots are proposed to support heterogeneity and time-varying behavior in the data generation in wireless senor networks. Each hybrid timeslot has an owner transmitter that uses the timeslot as a normal dedicated timeslot. If the owner skips transmission in a hybrid timeslot, that timeslot can be used as a shared timeslot by all the other nodes that have a packet towards the same destination as the owner transmitter. Experimental and simulation results show that using hybrid timeslots instead of dedicated timeslots in a TSCH schedule reduces the communication delay by half on average, while keeping the communications reliable. This comes with small increase in power consumption that is still lower than the power consumption of a schedule with only shared timeslots.

Acknowledgment

This work was partially supported by the SCOTT and ENABLE-S3 European projects, that have received funding from the ECSEL Joint Undertaking under grant agreements no. 737422 and 692455-2, respectively.

References

[1] "IEEE Standard for Low-Rate Wireless Networks," *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, pp. 1–709, April 2016.

[2] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki- a lightweight and flexible operating system for tiny networked sensors," in *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*. IEEE, 2004, pp. 455–462.

[3] M. Hashimoto, N. Wakamiya, M. Murata *et al.*, "End-to-end reliability- and delay-aware scheduling with slot sharing for wireless sensor networks," in *8th International Conference on Communication Systems and Networks (COMSNETS)*, Jan 2016, pp. 1–8.

[4] A. Elsts, X. Fafoutis, J. Pope, G. Oikonomou, R. Piechocki, and I. Craddock, "Scheduling High-Rate Unpredictable Traffic in IEEE 802.15.4 TSCH Networks," in *2017 13th International Conference on Distributed Computing in Sensor Systems (DCOSS)*, June 2017, pp. 3–10.

[5] M. R. Palattella, T. Watteyne, Q. Wang *et al.*, "On-the-Fly Bandwidth Reservation for 6TiSCH Wireless Industrial Networks," *IEEE Sensors Journal*, vol. 16, no. 2, pp. 550–560, Jan 2016.

[6] Q. Wang, X. Vilajosana, and T. Watteyne, "6top Protocol (6P)," Internet Engineering Task Force, Internet-Draft draft-ietf-6tisch-6top-protocol-07, Jun. 2017, work in Progress. [Online]. Available: https://datatracker.ietf.org/doc/html/draft-ietf-6tisch-6top-protocol-07

[7] I. Rhee, A. Warrier, M. Aia, J. Min, and M. L. Sichitiu, "Z-MAC: A Hybrid MAC for Wireless Sensor Networks," *IEEE/ACM Trans. Netw.*, vol. 16, no. 3, pp. 511–524, Jun. 2008.

[8] R. Tavakoli, M. Nabi, T. Basten, and K. Goossens, "Guard-Time Design for Symmetric Synchronization in IEEE 802.15.4 Time-Slotted Channel Hopping," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, June 2018.

[9] T. Winter and RPL Author Team, "RPL: IPv6 routing protocol for low-power and lossy networks," 2012.

[10] NXP Semiconductors, "JN516x IEEE802.15.4 Wireless Microcontroller," accessed: Sept. 2017. [Online]. Available: http://www.nxp.com/docs/en/data-sheet/JN516X.pdf

[11] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, "Cross-Level Sensor Network Simulation with COOJA," in *Proceedings. 31st IEEE Conference on Local Computer Networks*, Nov 2006, pp. 641–648.

[12] MEMSIC Inc., "TelosB mote platform," accessed: March. 2018. [Online]. Available: http://www.memsic.com/userfiles/files/Datasheets/WSN/telosb_datasheet.pdf

[13] T. Watteyne, J. Weiss, L. Doherty, and J. Simon, "Industrial IEEE802.15.4e networks: Performance and trade-offs," in *2015 IEEE International Conference on Communications (ICC)*, June 2015, pp. 604–609.