Beacon Advertising in an IEEE 802.15.4e TSCH Network for Space Launch Vehicles

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Abstract

In space launch vehicles, a NASA study shows that the mass per channel of 0.45 kg for a wiring approach can be reduced to 0.09 kg for a wireless approach.[8] A question arises: which wireless technology is able to meet the requirements of space launch vehicles in terms of latency, throughput and robustness. The IEEE 802.15.4e amendment has been designed to meet such requirements. More specifically, the Time Slotted Channel Hopping (TSCH) mode has been designed for industrial automation, process control and equipment monitoring. It supports multichannel and multihop communications and uses a slotted medium access on several channels. In this paper, we focus on the time needed by a joining node to detect beacons advertising the TSCH network.

An Enhanced beacon is a TSCH frame that contains information on synchronization, channel hopping and timeslot used in the advertised network. However, the advertising policy is left unspecified by the IEEE 802.15.4e standard and is under the responsibility of a layer upper than the MAC one. Since beacons are broadcast, they are lost in case of collisions: the vital information they carry is lost. The main problem is how to avoid collisions between two devices that are not neighbors.

In this paper, we propose a Deterministic Beacon Advertising Algorithm, called DBA. The goal of DBA is to ensure that beacons are transmitted on all frequencies used by the TSCH network, regularly and without collision. With DBA, the exact value for the maximum time for a joining node to detect a beacon can be computed easily. We use the NS3 Simulator to evaluate this time as well as the the number of message losses, considering different network topologies (star or multihop). We compare the performance of DBA with this of two algorithms existing in the state of the art.

1. Context and motivation

Wireless Sensor Networks (WSNs) pave the way to a wide range of applications belonging to as various domains as environment monitoring, factory automation, process control, precision agriculture, e-health, smart city, vehicular communication, etc. The most frequent technologies used by the currently deployed WSNs are based on the IEEE 802.15.4 standard.[13]

1.1 Strengths of IEEE 802.15.4

The physical layer specified by the IEEE 802.15.4 standard[13] operates in the Industrial, Scientific and Medical (ISM) 2.4 GHz short-range radio frequency band. ZigBee,[20] ISA100,[15] WirelessHart[11] and 6LoWPAN[17] chose this physical layer for several reasons. First it is energy-efficient, being of the quality required to maximize network lifetime when some devices are battery-operated. Second, its robustness, evaluated by its bit error rate, is good, a quality required by industrial applications. In addition, the ability to support mesh topologies allows this technology to support link and node failures by means of a dynamic routing. Third, scalability is possible thanks to cluster tree and mesh topologies.

Since the physical layer of the IEEE 802.15.4 standard constitutes a consensus for the development of wireless sensor networks, Freescale, TI, NXP, Microchip, ST Micro and Atmel propose chips and development platforms based on this standard. The availability of Commercial Off The Shelf (COTS) products is also one of the main reasons for the great success of IEEE 802.15.4 WSNs.

With a beacon-enabled network, time-bounded services are provided. They allow any device, one-hop away from the network coordinator, called CPAN, to benefit from a guaranteed transmission both in terms of bandwidth and delays. Notice however that the delay guarantee is not a hard guarantee but depends on the radio propagation conditions. Guaranteed Time Slots (GTS) can be used for that purpose. However, they are limited to 7. We can also notice that there are only a few implementations that provide GTS functionality.

1.2 Weaknesses of the IEEE 802.15.4 MAC protocol

Despite its advantages, the IEEE 802.15.4 standard has been unable to meet the requirements of industrial applications with regard to reliability, delays and energy. The main problems are related to multi-hop topologies for which no delay guarantee can be given. The standard does not specify how beacons could be sent by the different coordinators without collision. The concept of GTS is valid only for one-hop communication (i.e. between a device and its coordinator). The raw throughput offered to applications is limited to 250kb/s. Such a throughput does not allow high rate sampling of sensors (e.g. 1000 samples/s) and small latencies (e.g. less than 50 ms). The communication reliability may be strongly decreased by perturbations of the channel used by the WSN. These perturbations are either internal (i.e. caused by interfering devices in the same network) or external (i.e. caused by an external source like a radar for instance, or by another network sharing the space radio spectrum). In addition, a slotted CSMA/CA may be inefficient because all transmissions are grouped at the beginning of slots instead of being distributed over time. Furthermore, network lifetime may be insufficient, because unless a schedule of medium accesses has been established and installed on all router nodes, the router nodes are not allowed to sleep to save energy: they must always be ready to route any message they might receive.

We observe that ZigBee, ISA100 and WirelessHART each chose different solutions to solve these problems. Another solution, specified in the IEEE 802.15.4e amendment, has emerged. Its explicit goal was to amend the existing IEEE 802.15.4 standard to be able to make it compliant with industrial expectations.

1.3 The IEEE 802.15.4.e standard and TSCH

The IEEE 802.15.4.e standard[14] encompasses the five following protocols, called MAC behavior modes, each of which targets a specific application field. Nevertheless, they share some common concepts such as multi-channel communication, channel hopping and slotted access as we will see in this section. Three of them are well known:

- *Time Slotted Channel Hopping (TSCH)* designed for industrial automation, process control and equipment monitoring. It supports multichannel and multihop communications and uses a slotted medium access on several channels.

- *Deterministic and Synchronous Multichannel Extension (DSM)* targeting industrial and commercial applications that require deterministic delays, high reliability and adaptability to time-varying traffic and environment. Like the 802.15.4 standard, it combines a contention-based access (i.e. CSMA/CA) in shared slots and a collision-free access (i.e. TDMA like with GTS) in dedicated slots. It extends the number of GTS, the number of channels used and introduces the concept of multi-superframe structure for a better adaptivity to a traffic varying over time. It uses either channel hopping or channel adaption (i.e. two neighbor nodes may communicate on any of the free available channels they selected).

- *Low Latency Deterministic Network (LLDN)* supports applications with very low latency like factory automation and logistics. It supports mobile devices (e.g. robots). It provides a fine granularity TDMA access to meet low latency but supports only star topologies and uses a single channel.

The other two have received less interest up to now, they are:

- *Radio Frequency Identification Blink* intended for identification, location and tracking of people or items. A device is allowed to communicate its identifier to nodes without any prior association, using an Aloha-like medium access.

- *Asynchronous MultiChannel Adaptation (AMCA)* targeted to large deployments as in smart utility or infrastructure monitoring. Each device selects its preferred channel that is the channel on which it will receive all its messages. Any sender has to switch to the channel of the receiver.

To summarize, TSCH, DMTS and LLDN use beacons, periodic slotframe/multi superframe/superframe, combine time slotted and CSMA/CA access. TSCH and DMTS use multichannel and channel hopping, they both support star, tree and mesh topologies. More details can be found in .[7]

Since TSCH with its channel hopping and its multichannel TDMA access appears very promising, in this paper, we focus on a TSCH network and evaluate its merits with regard to a standard IEEE 802.15.4 network.

1.4 Motivation and related work

Most of the studies on IEEE 802.15.4e TSCH networks focus on communications in an operational network. Some evaluate the average throughput, the average delays and the average energy consumption either by means of simulations like,[5] or analytical models like Markov models in,[3] or estimators validated on real implementations like[18] and.[19] Others compute upper bounds on the delays for star topologies, using Network Calculus like.[10] In,[5] a TSCH network, for a star topology with a number of nodes ranging from 20 to 120, outperforms a classical 802.15.4 network, both in beacon-enabled and non-beacon-enabled modes, in terms of delivery ratio, energy consumed and delivery delays. In,[3] the authors model the transmission delays obtained with the shared slots of TSCH, for which collisions may occur and point out the differences in collision avoidance used by TSCH and CSMA/CA.

Very few take into account unreliable wireless links unlike,[18] that evaluates the average delivery time and the average energy consumption taking into account the packet error rate on each link visited to reach the sink. In,[19] the energy cost of node synchronization and the use of more links than strictly needed to allow retransmissions is evaluated. The authors of[1] improve the channel hopping mechanism to improve the robustness against interferences created by a WiFi network, for instance. The idea consists in avoiding the channels perturbed by WiFi, that are channels 2, 4, 8 and 16, without regenerating the Frequency Hopping Sequence, that would be energy consuming.

Since on the one hand, the network must be built to allow any data transmission and on the other hand, latency before getting an operational network matters for industrial applications, we focus on the network building phase in this paper. Concerning beacon advertisement, the main difference between 802.15.4 and TSCH networks lies in the multichannel environment used by TSCH. The main problem raised by multichannel is the following: how to ensure that the device that wants to join the network will be both on the same channel and at the same time as one neighbor node already inserted in the network? Some authors like[16] propose to make this phase less time and energy consuming: a fixed and known channel is used to send beacons. Hence, new nodes need to scan only one channel. On the other hand, nodes already inserted in the network should periodically send beacons on this control channel to allow new nodes to detect them. Notice that this solution is not compliant with the IEEE 802.15.4e TSCH standard.

In,[4] the authors propose a Random-based Advertisement (RA) algorithm where each device already in the network advertises its beacon in an advertising slot randomly selected among a given set (i.e. an advertising node sends its beacon in a given advertising slot with a probability equal to the inverse of its number of neighbors simultaneously transmitting their beacon). They show that the time needed by a device to join the network mainly depends on the number of channel offsets used for the advertisement of Enhanced Beacons (EB). However, using many channel offsets is beneficial only if there are more than 4 neighboring advertiser nodes. A reduced joining time is obtained when only a subset of channel frequencies is used for advertisement and this subset is known from the joining nodes.

In,[9] two algorithms are presented: Random Vertical (RV) filling and Random Horizontal (RH) filling. In both algorithms, the CPAN sends its beacons in the first advertisement slot of one slotframe in the multi-slotframe, with channel offset 0. In RV, the other nodes transmit their beacon in the same advertisement slot but with a random channel offset. In RH, the other nodes transmit their beacon with channel offset 0 but in an advertisement slot randomly chosen in the slotframe. These two algorithms exhibit similar performance.

In,[6] the time needed to receive correctly a valid beacon, that we call beacon detection time in this paper, is derived from a Markov model, where the joining node randomly selects one frequency in the set of frequencies used by the TSCH network and stays on this frequency until receiving a valid beacon based on the assumptions that N_c the number of channels available and the number of slots in the slotframe are co-prime (i.e. their greatest common divisor is 1), and the mapping between the pair (Absolute Sequence Number, channelOffset) and the channel frequency is bijective. The optimal beacon schedule is formalized as an optimization problem where the beacon detection time is minimized provided that the sum of the distance between the advertising slots is equal to N_cN_b, where N_b denotes the number of advertising slots. The authors finally propose the Model-based Beacon Scheduling algorithm (MBS), where the CPAN computes the optimal number of links for beacon advertising. This set is broadcast to all network nodes. Each node in the network randomly selects one link among the set of possible links for beacon advertising and transmits its beacon in this link. Simulations show that MBS outperforms RA, RV and RH.

2. Network construction

In this section, we show how an IEEE 802.15.4 network and an IEEE 802.15.4e TSCH network build themselves, highlighting their differences mostly due to the use of multichannel for TSCH. In the following of this paper, an IEEE 802.15.4e TSCH network is called a TSCH network, for the sake of brevity.

Initially, in both a 802.15.4 network and a TSCH network, only the CPAN, the network coordinator, is allowed to send beacons. Each node wanting to join the network performs the following steps successively: 1) Channel scan, 2) Node association, 3) Beacon transmission by the new node, if coordinator. We now study these different steps.

2.1 Beacon transmission

Beacons and more precisely Enhanced Beacons are used to advertise the TSCH network. An Enhanced beacon is a TSCH frame that contains information on synchronization, channel hopping and timeslot used in the advertised network. However, the advertising policy is left unspecified by the IEEE 802.15.4e standard and is under the responsibility of a layer upper than the MAC one.

Initially, only the CPAN is allowed to send beacons. All other nodes as soon they are powered on, remain silent until they request their association in the network. Hence, the presence of the CPAN is mandatory to initiate the creation of the network. Since beacons are broadcast, they are lost in case of collisions: the vital information they carry is lost. The main problem is how to avoid collisions between two devices that are not neighbors.

As said in Section 1.4, the difficulty with the TSCH networks is to ensure that the joining device is on the same channel and at the same time as its neighbor advertising the network.

2.2 Channel Scan

The IEEE 802.15.4 standard distinguishes two types of scan:

- Scan for energy detection where the goal is to detect which channels are used. These channels may be used by IEEE 802.15.4(e) networks or any other network, like WiFi for instance, that operates in the same radio spectrum.
- Scan of a given set of channels where the goal is here to capture an IEEE 802.15.4(e) beacon to get useful information on the WSN the device wants to join.

To save time, it is usually admitted that any node wanting to join the WSN knows which channels are potentially used by this WSN. Hence, it has only to scan these channels. Each channel scan has a limited duration, upon which the list of beacons heard on this channel is given to the device having requested the scan.

In a TSCH network, the capture of beacons is more complex due to channel hopping. Since the joining node does not know the hopping sequence and the positioning in this sequence, the only possibility for it is to stay on a given channel and wait until it is used by a coordinator to send its beacon.

2.3 Node Association

The IEEE 802.15.4 standard specifies only one-hop associations (i.e. the joining node and the network coordinator are one-hop away). The association step is very important for the joining node, because it receives its short address that is unique in the network. In a network where the Maximum Transmission Unit (MTU) is limited to 127 bytes, the use of a short address on 2 bytes instead of a long address on 8 bytes matters a lot. The problem is how to ensure the uniqueness of the short address in a limited addressing space? Several solutions have been proposed.

Hierarchical addressing where each coordinator node manages some short addresses that have been given by its own coordinator. As a consequence, the short address of a node depends on the coordinator to which it associates. Hierarchical addressing has the advantage of providing a simple routing but is inefficient in case of unbalanced topologies. In addition, node mobility arises problem: the mobile node must obtain another address when it reassociates to another coordinator.

In multihop association, the CPAN is in charge of address management, ensuring the uniqueness of short addresses. The counterpart is that associations have to be known from the CPAN, requiring what is called multihop assocation.[2] The association request of each network node goes upward to the CPAN that allocates a unique and permanent address to the joining node. This short address is contained in the association response that goes downward to the joining node. Intermediate nodes need to forward the association request and the association response.

3. Beacon advertising

We now study beacon advertising in TSCH networks. In the following, we adopt the notations given in Table 1.

Table 1: Notations.

N_s	number of slots in the slotframe
N_c	number of channels in the frequency hopping sequence
N_b	number of advertising slots in the slotframe
BI	beacon interval = period of beacon transmission by a node, expressed as a number of time slots
	for any a and b integers
$gcd(a, b)$	the greatest common divisor of a and b
$lcm(a, b)$	the least common multiple of a and b

Knowing the Absolute Sequence Number (ASN) of a slot, we can deduce its slot offset according to Equation 1.

$$slotOffset = ASN \ modulo \ N_s \tag{1}$$

Knowing the Absolute Sequence Number (ASN) of a slot and its channel offset, Equation 2 allows us to deduce the frequency upon which it is mapped, where F is the bijective mapping of the channelOffsets belonging to the set {0, 1, $\ldots N_c - 1$} on the N_c frequencies used by the TSCH network.

$$frequency = F[(ASN + channelOffset) \ modulo \ N_c] \tag{2}$$

In the following, unless the contrary is explicitly said, we assume that the following assumptions are met:

$A1$) The frequency hopping sequence is a permutation of the N_c frequencies used by the TSCH network.

$A2$) N_s and N_c are coprime: $gcd(N_s, N_c) = 1$.

3.1 General properties

With these notations, we can prove the following properties.

Property 1 *With assumptions $A1$ and $A2$, the same schedule reproduces both in slots and frequencies each $N_c \cdot N_s$ slots. In addition, each slot in the multislotframe of size $N_s \cdot N_c$ has visited each of the N_c frequencies exactly once.*

Proof : See.[6]

Corollary 1 *With assumptions $A1$ and $A2$, if an advertising node transmits its beacon exactly once in each slotframe and always in the same given slot of the slotframe and with the same channel offset, its beacon has been sent over all the N_c frequencies after $N_s \cdot N_c$ slots.*

Since transmitting beacons is bandwidth and energy consuming, the beacon interval is usually kept higher than or equal to the slotframe size N_s. However the beacon detection time should be kept reasonable for joining nodes. Hence, the choice of the beacon interval is a tradeoff between on the one hand, a small number of advertising slots to save resources and maximize protocol efficiency, and on the other hand, a small time between two successive beacons sent by the same node to minimize the joining time.

In all the examples given in this subsection 3.1, we assume that the frequency channel hopping sequence is $0, 1, 2, \ldots 15$, for simplicity reasons. In other words, the F function is the identity. In addition, we assume that the first beacon is sent by the CPAN at slotOffset 0 and channelOffset 0. These assumptions can easily be relaxed but at the cost of a heavier notation.

3.2 BI multiple of N_s

We first focus on the simple case where the beacon interval is a multiple of the slotframe size. *Example* 1 shows that when BI and N_c are not coprime, even if N_s and N_c are coprime, then only a strict subset of the N_c frequencies are visited.

Example 1: Let us consider $N_c = 16$, $N_s = 7$ and $BI = 14$. The beacon schedule is depicted in Table 2. This beacon schedule reproduces in terms of:

- slots, after $lcm(BI, N_s) = BI = 2N_s = 14$ slots.
- frequencies, after $lcm(BI, N_c) = 112$ slots.

- both in slots and frequencies, after $lcm(BI, N_c, N_s) = lcm(BI = 2N_s, N_c) = lcm(14, 16) = 112$ slots, that is strictly less than $BI \cdot N_c = 224$ slots that would be needed to visit each of the N_c frequencies used by the TSCH network.

We observe in Table 2 that only even frequencies are visited. In such a case, a node that listens on any odd frequency will never detect a beacon advertising the TSCH network and as a consequence, it will never be able to join this network.

Table 2: Slots and frequencies visited by the beacon, $BI = 2 \cdot N_s$.

ASN	Slot	Frequency
0	0	0
14	0	14
28	0	12
42	0	10
56	0	8
70	0	6
84	0	4
98	0	2
112	0	0

Property 2 *With assumptions A*1 *and A*2*, if $BI = k \cdot N_s$, with k an integer ≥ 1, then any given node transmits its beacon each $k \cdot N_s$ slots, always in the same slot of the slotframe. In addition, if BI and N_c are coprime, this beacon is sent over each of the N_c frequencies, exactly once, after $k \cdot N_s \cdot N_c$ slots.*

Proof : Let us consider any node that transmits its beacon at ASN $i \geq 0$ in the slot $s \in [0, N_s)$ of the slotframe. Since it transmits its beacon every BI slots and BI is a multiple of N_s, this node will transmit its beacon at ASN $i + m \cdot k \cdot N_s$, with m integer ≥ 0. This ASN occupies the slot $[(i \text{ modulo } N_s) + (m \cdot k \cdot N_s \text{ modulo } N_s)] \text{modulo } N_s$. That is the slot s. If the beacon sent at ASN i is sent on frequency $f \in [0, N_c)$, this beacon will be sent again in slot s and frequency f after $lcm(BI, N_s, N_c)$. Since $BI = k \cdot N_s$ and N_c are coprime, $lcm(BI, N_s, N_c) = k \cdot N_s \cdot N_c$ is the first time where the frequency f is reproduced for slot s. Since $lcm(BI, N_s, N_c) = BI \cdot N_c$, $BI \cdot N_c$ slots enable the transmission of N_c beacons, we get the property.

3.3 *BI* greater than N_s

We now consider the general case where $BI > N_s$, without being a multiple of N_s. Let us focus on *Example* 2.
Example 2: With $N_c = 16$, $N_s = 5$ and $BI = 7$, the beacon schedule is depicted in Table 3. After $lcm(BI, N_s) = 35$ slots, the schedule reproduces in terms of time slots. It reproduces in terms of frequencies after $lcm(BI, N_c) = 112$ time slots. We observe that when BI and N_s are coprime, each slot of the slotframe becomes at some time in the schedule an advertising slot where a beacon is transmitted.

Table 3: Slots and channels visited by the beacon, BI and N_s coprime.

ASN	Slot	Frequency
0	0	0
7	2	7
14	4	14
21	1	5
28	3	12
35	0	3
42	2	10
49	4	1
56	1	8
63	3	15
70	0	6
77	2	13
84	4	14
91	1	11
98	3	2
105	0	9
112	2	0
etc.		

Property 3 *If N_s and BI are coprime, then each slot in the slotframe becomes, at some time in the schedule, an advertising slot.*

Proof : The beacon schedule reproduces in terms of slots after $lcm(BI, N_s)$ slots. Since N_s and BI are coprime, $lcm(BI, N_s) = BI \cdot N_s$. Hence, considering any slot $s \in [0, N_s]$, the next beacon sent in s is sent $BI \cdot N_s$ time slots later. During this time interval, exactly N_s beacons have been sent. Hence, the property.

To avoid that any slot in the slotframe is an advertising slot, we propose to fix the number of advertising slots in the slotframe. This number is equal to N_b. Notice that if all the advertising slots are grouped together in the slotframe, the time interval between two successive beacons sent by the same advertising node may reach $BI + N_s$ which may be unacceptable by the application. That is why, we introduce the following rule that spaces the advertising slots "regularly" in the slotframe.

Definition 1 *The N_b advertising beacons are said regularly spaced when then occupy the slots $k_1 \cdot \lceil \frac{N_s}{N_b} \rceil$, with $0 \leq k_1 \leq u$, as well as the slots $u \cdot \lceil \frac{N_s}{N_b} \rceil + k_2 \cdot \lfloor \frac{N_s}{N_b} \rfloor$, with $0 < k_2 < \lfloor \frac{N_s - u}{N_b} \rfloor$ and $u = N_s$ modulo N_b.*

This is illustrated by *Example* 3.
Example 3 : With $N_s = 13$ and $N_b = 5$, the advertising slots occupy the slots 0, 3, 6, 9 and 11 in the slotframe of size 13.

Definition 2 *A beacon is said to be sent at the right time if and only if it has been sent at a time equal to $k \cdot BI$ with k integer ≥ 0.*

Example 4: With $N_s = 5$, $N_c = 16$ and $BI = 7$ and two advertising slots that are 0 and 3, the beacon schedule that reproduces exactly the same sequence of slots every $N_s \cdot BI$ slots and uses only the two advertising slots 0 and 3 is depicted in Table 4. The column 'ASN req' represents the different multiples of BI, whereas the column 'ASN real' represents the ASN in which the beacon is really advertised to be mapped in one of the slots 0 or 3. The term in this column appears in bold when it differs from the ASN requested. For instance, at ASN 7, a beacon should be sent to meet the BI period, however it is postponed to ASN 8 to be sent in slot 3 that is an advertising slot. In this beacon schedule, two beacons are sent at the right time in each cycle of $BI \cdot N_s$ consecutive slots (see for instance the first cycle delimited by ASN 0 and 35, we have $N_f = 2$). At ASN 148, each of the N_c frequencies has been visited at least once.

Table 4: Slots and channels visited by the beacon, $BI = 7 > N_s = 5$ and $N_b = 2$

ASN req.	ASN real	Slot	Frequency
0	0	0	0
7	**8**	3	8
14	**15**	0	15
21	**23**	3	7
28	28	3	12
35	35	0	3
42	**43**	3	11
49	**50**	0	2
56	**58**	3	10
63	63	3	15
70	70	0	6
77	**78**	3	14
84	**85**	0	5
91	**93**	3	13
98	98	3	2
105	105	0	9
112	**113**	3	1
119	**120**	0	8
126	**128**	3	0
133	133	3	5
140	140	0	12
147	**148**	3	4
...	...	...	...

Finally, we get the following property:

Property 4 *With assumptions A1 and A2, if $BI > N_s$, BI is coprime with both N_s and N_c, and the N_b advertising slots are regularly spaced, and the beacons are advertised according to a sequence of slots that reproduces every $N_s \cdot BI$ slots, then at least one beacon has been sent on each N_c frequencies after at most $BI \cdot N_s \cdot N_c$ slots.*

Proof : Let us denote by T the number of consecutive slots after which the beacon schedule reproduces in time slots. Since BI and N_s are coprime, $T = BI \cdot N_s$. Since the first beacon sent in slot 0 is advertised at the right time, we have by construction at least one beacon sent at the right time per cycle T. Let us show that this beacon is sent on a new frequency in each cycle T during the first N_c cycles. By contradiction, we assume that there exists two integers k_1 and k_2 with $0 \leq k_1 < k_2 < N_c$ such that they are mapped on the same physical frequency: $k_1 \cdot BI \cdot N_s - \lfloor \frac{k_1 \cdot BI \cdot N_s}{N_c} \rfloor \cdot N_c = k_2 \cdot BI \cdot N_s - \lfloor \frac{k_2 \cdot BI \cdot N_s}{N_c} \rfloor \cdot N_c$. We obtain: $(k_2 - k_1) \cdot N_s \cdot BI = (\lfloor \frac{k_2 \cdot BI \cdot N_s}{N_c} \rfloor - \lfloor \frac{k_1 \cdot BI \cdot N_s}{N_c} \rfloor) \cdot N_c$. Since N_c divides the right member of this equation, it also divides the left member. Since N_c and BI are coprime, N_c divides $k_2 - k_1$. By definition, $k_2 - k_1 < N_c$. Hence, a contradiction. It follows that $k_1 = k_2$. Hence, the property showing that after N_c cycles, the beacon has been sent on each of the N_c frequencies.

4. The Deterministic Beacon Advertising (DBA) algorithm

Taking into account the properties proved in Section 3.1, we are now able to specify a new algorithm, called DBA for Deterministic Beacon Advertising. The goal of DBA is to ensure that beacons are transmitted on all frequencies used by the TSCH network, regularly and without collision.

4.1 General principles of DBA

The principles of DBA are the following:

- Any beacon is transmitted in one of the N_b advertising slots of the slotframe. These N_b advertising slots are regularly spaced in the slotframe.
- The CPAN is in charge of initiating the beacon transmission in an advertising slot.
- Any advertising node, that is not the CPAN, repeats the beacon received from its association parent in an advertising beacon whose relative position with regard to the beacon received has been computed during node association. The channel offset has also been computed during node association to ensure the uniqueness of transmitters in this slot and over this channel offset. The computation of N_b is detailed in subsection 4.2.

The functioning of DBA is depicted in Figure 1 for a topology of four nodes with $N_s = 11$, $N_c = 16$ and $N_b = 3$ and $BI = N_s$. The CPAN transmits its beacon in ASN 0 with slotOffset 0 and channelOffset 0 mapped on frequency 0. Node 1 that is listening frequency 0 receives this beacon and then transmits its beacon in the next advertising slot (ASN3, with slotOffset 3 and channelOffset 0). Node 2 receives the beacon of node 1 and sends its beacon in the next advertising slot (ASN 7, slotOffset 7, channelOffset 0). In ASN 11, the CPAN sends its beacon that is received by nodes 1 and 3. Node 1 transmits in ASN 14, slotOffset 3, channel0ffset 0, whereas node 3 sends its beacon in the same slot as node 1 but with channelOffset 1.

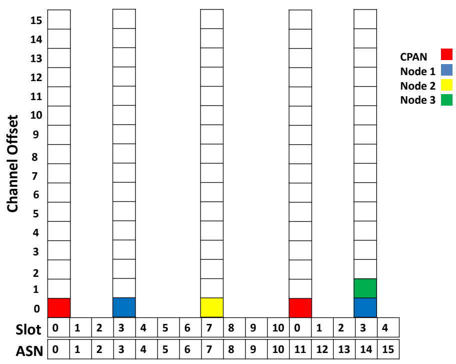


Figure 1: Transmission of beacons in DBA.

With these principles, DBA meets the following property:

Property 5 *Knowing N_s, N_c, BI and N_b and provided that N_s and N_c are coprime, and BI is coprime with both N_s and N_c, the exact value for the maximum joining time can be computed for DBA. It is equal to the time upon which all the N_c frequencies have been visited by the beacon schedule and is obtained from the beacon schedule.*

4.2 Computation of N_b

The value of N_b should meet the following two requirements:

$R1$) it should enable a quasi regular transmission of beacons close to BI.

$R2$) it should allow each advertising node (including the CPAN) to transmit its beacon without collision.

Requirement $R1$ is met by spacing regularly the N_b advertising slots in the slotframe. Requirement $R2$ is met by giving to each advertising node n a unique pair (slot, channelOffset) ensuring that n is the only node transmitting in this pair. This is done by the CPAN during the node association. Any joining node receives the smallest beacon advertising slotOffset that is strictly higher than the slotOffset of its parent with a channelOffset unused up to now. Hence, assuming that the first beacon is sent by the CPAN in ASN 0 with slotOffset 0 and channelOffset 0, the minimum possible value of N_b is given by Equation 3 for a star topology and by Equation 4 for a multihop topology, respectively:

$$N_b \geq 1 + \lceil \frac{N-1}{N_c} \rceil \tag{3}$$

$$N_b \geq 1 + \sum_{h=0}^{maxhop} \sum_{i \in h} \lceil \frac{Nchildren(i)}{N_c} \rceil \tag{4}$$

where $maxhop$ denotes the maximum number of hops between a node and the CPAN, $i \in h$ denotes any node i that is h hops away from the CPAN in the association and $Nchildren(i)$ is the number of children of node i in the association tree.

4.3 Example

We run the DBA algorithm on the following example: $N_s = 5$, $N_c = 16$, $BI = 7$ and $N_b = 2$. The advertising slots in the slotframe are computed according to Definition 1, they are the slots 0 and 3. Table 4 in *Example* 4 provides the schedule in slots and frequencies for beacon advertising. The maximum time given by Property 5 is equal to 147 slots. After this number of slots, all the N_c frequencies have been visited, whereas Property 4 gives an upper bound of 560 slots.

5. Performance evaluation

In this section, we compare the performance of DBA with those of RV and RH.[9] More precisely, our goal is to evaluate the time needed to build the network, the number of messages exchanged and the number of message losses, considering different network topologies (star or multihop).

The performance evaluation is conducted using the NS3 simulator.[12] We first implemented the NS3 modules needed to build a 802.15.4 network and then the NS3 modules for a TSCH network. To allow a fair comparison between the different algorithms used to transmit beacons, namely RV, RH and our algorithm DBA, we consider a multi-slotframe of size $N_c \cdot N_s$. In this multi-slotframe, we have N_b advertising slots. Simulation parameters are given in Table 5. Simulation results are averaged over 30 runs.

Table 5: Simulation parameters.

Parameter	Value
N_s	1511
N_c	16
N_b	15
BI	1511
slot size	10 ms

5.1 Star network

In the star topology, we consider a number of nodes different from the CPAN ranging from 1 to 40. All these nodes are one-hop away from the CPAN.

5.1.1 Joining time

We evaluate the time needed by one node to detect a beacon on the frequency it has randomly chosen among the N_c frequencies used by the TSCH network. All the nodes already inserted in the network advertise the TSCH network by transmitting a beacon. Results are depicted in Figure 2. As expected, the joining time decreases when the number of advertising nodes increases. This can be explained by the fact that the probability of detecting a beacon on the frequency randomly chosen by the joining node increases with the number of its neighboring nodes. We observe that the decrease in the joining time is large up to 10 nodes, then it becomes moderate up to 20 nodes. The RV algorithm provides the worst results. This is due to the fact that collisions may occur between two network nodes having selected the same channelOffset to transmit their beacon. RH is better than RV for any TSCH network with more than 2 nodes. The DBA algorithm outperforms RV and RH providing joining times that are up to 3 times less than RV.

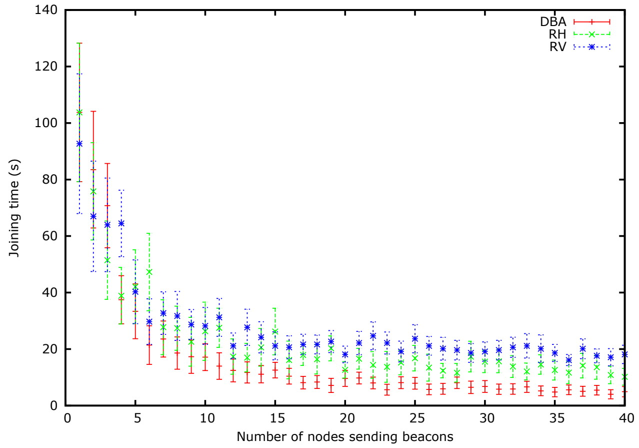


Figure 2: Joining time.

5.1.2 Number of beacons exchanged during joining time

We evaluate the number of beacons transmitted from the time when the joining node is powered on up to the time it receives its first beacon. Among these beacons, some of them collide. We also evaluate the number of beacons dropped because of a collision. Results are depicted in Figure 3 for DBA, Figure 4 for RH, and Figure 5 for RV, respectively.

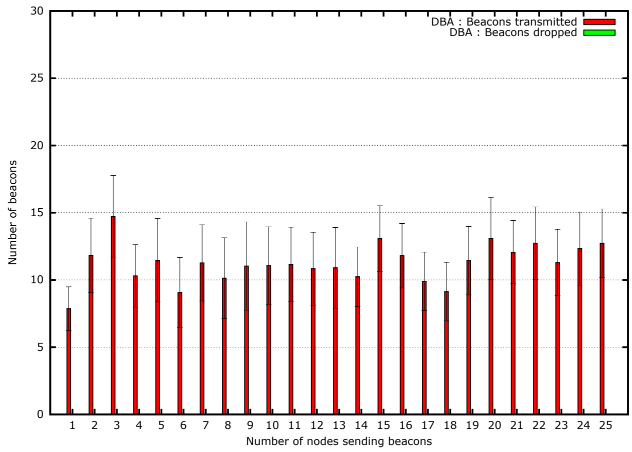


Figure 3: DBA: Transmitted vs dropped beacons.

For DBA, the number of transmitted beacons is almost constant around 11, it is not impacted by the number of advertising nodes. Since DBA is deterministic, there is no beacon dropped after a collision, as illustrated in Figure 3.

For RH, the number of transmitted beacons is around 10 for a network consisting of up to 5 nodes, and around 15 for a number of nodes in $[5, 16)$. The number of dropped messages is higher than 1 for a number of nodes ≥ 5, it reaches 6 for 25 nodes, as illustrated in Figure 4.

For RV, the number of transmitted beacons is the highest reaching 15 transmissions for a network with a number of nodes in $[5, 15]$ and 19 transmissions for 25 nodes. The number of dropped beacons is around 1 for a network with 3 nodes and increases quickly with the number of nodes in the network to reach 19 for 25 nodes. This explains the large joining times obtained with RV. This is a weakness of the RV algorithm that can be observed as soon as the number of nodes in the network is higher than or equal to 3.

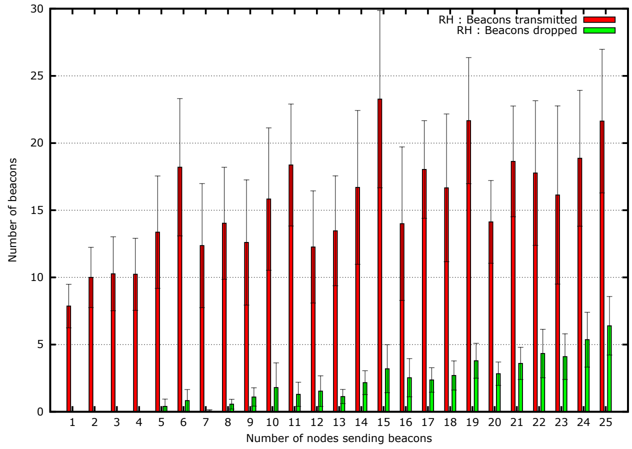


Figure 4: RH: Transmitted vs dropped beacons.

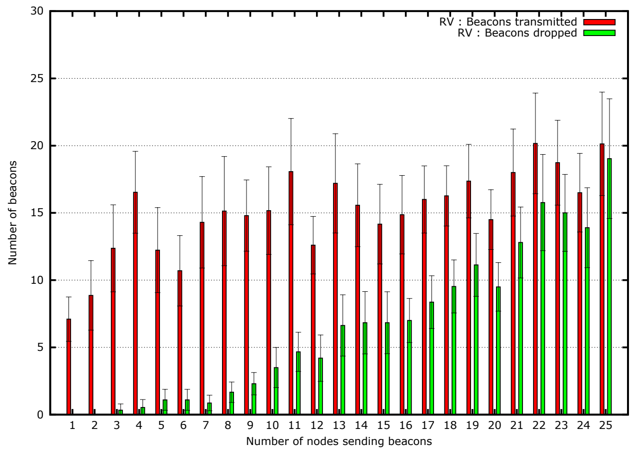


Figure 5: RV: Transmitted vs dropped beacons.

5.1.3 Impact of the beacon period on the joining time

To study the impact of the beacon period on the joining time, we consider a network of 20 nodes with a star topology. Each of them advertises the network by sending beacons with the beacon interval BI. Figure 6 depicts the time needed for a node to join this network while varying the beacon interval in the set $\{N_s,\ 3 \cdot N_s,\ 5 \cdot N_s\}$.

As expected, the joining time increases with the beacon interval. When the beacon interval is small $BI = N_s = 15$ seconds, the joining time is small for all the algorithms tested: it is equal to 10 seconds for DBA and 12 seconds for RH, whereas it reaches 18 seconds for RV. However, when the beacon interval increases ($BI = 3 \cdot N_s$ and $BI = 5 \cdot N_s$), the joining time increases considerably especially for the RH algorithm. In contrast, it remains small for the DBA algorithm, even for $BI = 5 \cdot N_s = 75$ seconds, where it reaches only 33 seconds, compared with 42 and 71 seconds for the RV and RH algorithms, respectively.

The DBA algorithm provides a satisfying joining time even when the beacon interval is great and this is due to its determinism.

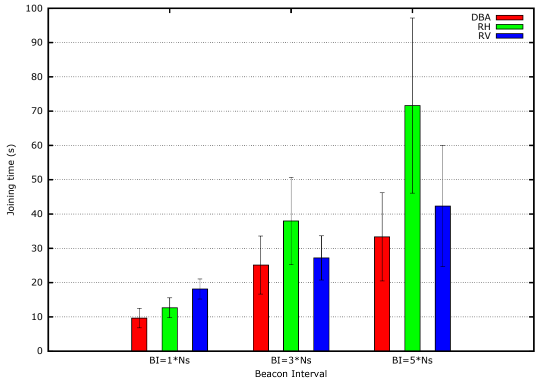


Figure 6: Joining time in a network of 20 nodes.

5.2 Multihop network

Now, we focus on a random topology where 20 nodes are randomly deployed in an area of dimensions 400mx300m. The CPAN is located in the center of this area. Unlike the star topology, the 20 nodes are not one-hop away from the CPAN. Figure 7 depicts the random topology adopted. Nodes 10, 12, 13, 15 and 20 are two-hop away from the CPAN, whereas the other nodes are one-hop away. After having checked network connectivity, we evaluate the joining time and the number of beacons exchanged in this multihop network.

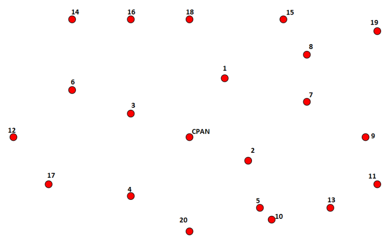


Figure 7: Random topology of 20 nodes and one CPAN.

5.2.1 Joining time

In a multihop network, the location and the number of neighbors have a big impact on the joining time. Even if the total number of nodes in the network is great, the number of one-hop nodes for a given node may be small (e.g. ≤ 3). Hence, the joining time may not decrease when the number of nodes sending beacons increases, as illustrated in Figure 8.

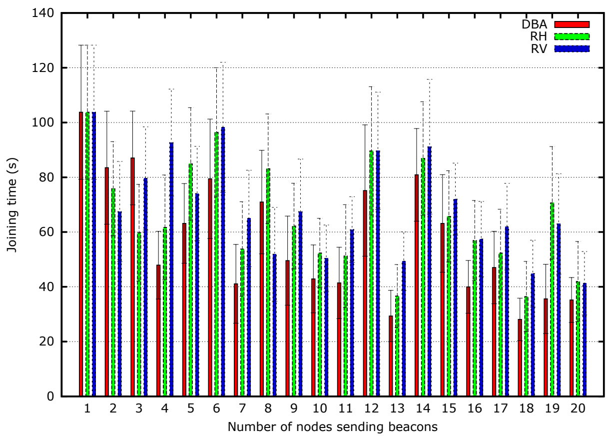


Figure 8: Joining time.

A more interesting way to interpret Figure 8 is to consider that a value of i on the x-axis represents the identifier of the node joining the network depicted in Figure 7. During this time, the CPAN and all nodes with an identifier smaller than i send beacons. This interpretation takes into account the number of one-hop nodes of the joining node and shows that the joining time decreases when the number of one-hop nodes advertising beacons increases. In addition, we can observe that when the number of nodes sending beacons is higher than 4, the DBA algorithm provides the smallest joining time.

5.2.2 Number of beacons exchanged during network building time

We now evaluate the number of beacons transmitted and the number of beacons dropped due to a collision while a node is trying to join this multihop network. Simulation results are depicted in Figures 9, 10 and 11 for the DBA, RH and RV algorithms, respectively. With RV, the number of transmitted beacons remains less than 60, whereas it reaches 78 for RH and DBA. With regard to the number of beacons dropped due to a collision, this number is null with DBA that is deterministic. It remains less than 17 with RH and climbs up to 37 with RV.

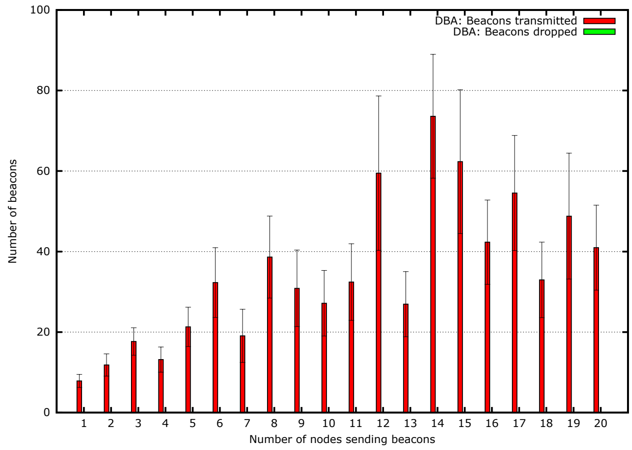


Figure 9: DBA: Transmitted vs dropped beacons.

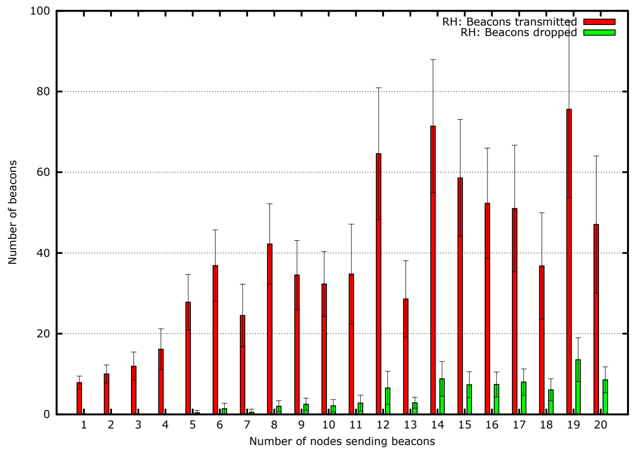


Figure 10: RH: Transmitted vs dropped beacons.

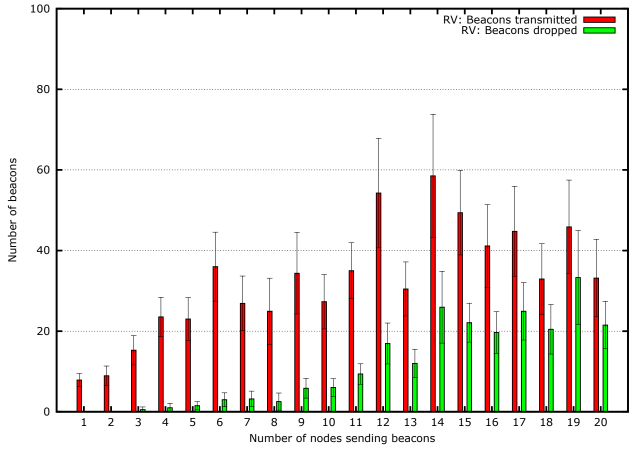
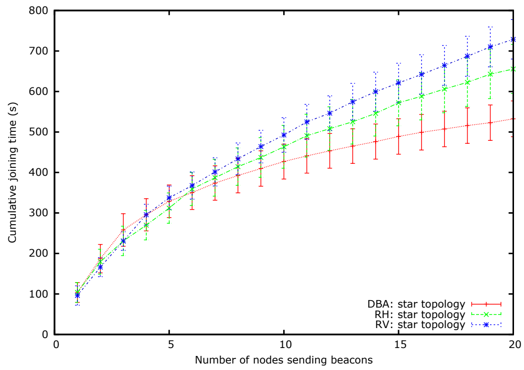
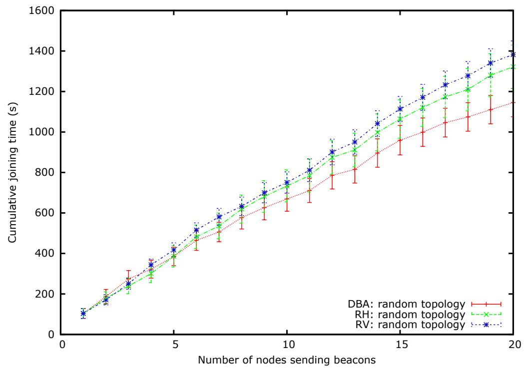


Figure 11: RV: Transmitted vs dropped beacons.



(a) Star topology.



(b) Random topology.

Figure 12: Cumulative joining time.

6. Conclusion

The IEEE 802.15.4e amendment has been designed to meet the requirements of industrial applications with regard to the wireless sensor networks supporting them. Because of its scheduled medium access and multichannel transmissions, the TSCH mode has received much attention. In this paper, we focus on the time needed by a node to detect a beacon sent by a TSCH network, as well as on the time needed to build a TSCH network. These times are important for industrial applications where new nodes are inserted progressively, or when failed nodes are replaced. Both times highly depend on the beacon advertisement policy, policy that is not specified in the standard. That is why we propose DBA, a Deterministic Beacon Advertisement algorithm that ensures a regular transmission of beacons without collisions. The performance evaluation made with the NS3 simulation tool shows that DBA clearly outperforms existing solutions such as RV and RH. In addition, DBA is able to provide the exact value of the maximum joining time.

Acknowledgment

Study co-funded by CNES and Inria in the framework of the CNES Launchers Research and Technology program.

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