Simulative assessments of the IEEE 802.15.4e DSME and TSCH in realistic process automation scenarios

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Abstract

Industrial Wireless Sensor Networks (IWSNs) are found in many application domains that require low latency, robustness, and determinism. The IEEE 802.15.4 standard is not able to cope with the requirements of these applications. For this reason, the IEEE 802.15.4e amendment was introduced, which provides novel MAC-layer profiles that are optimized for a broad range of application domains, including process automation. This paper focuses on two of these profiles, i.e., the Deterministic and Synchronous Multi-channel Extension (DSME) and the Time Slotted Channel Hopping (TSCH). The aim of the paper is twofold. First, assessing their behavior in realistic process automation scenarios. Second, comparing their performance in terms of end-to-end delay, reliability and scalability. The ultimate aim of the work is identifying the limits of those protocols, thus paving the way to further work addressing suitable approaches to tackle them.

1. Introduction and motivation

Industrial Wireless Sensor Networks (IWSN) consist of a number of sensor devices that gather data from the physical environment and send it to controllers. IWSNs are found in many application domains, such as factory automation, distributed process control, real-time monitoring, and so on. Typical requirements for IWSNs are low latency, robustness and determinism for transmission of small-size packets [1], [2]. In recent years, many standard protocols to support IWSNs in different application domains, i.e., WirelessHART [3], ISA100.11a [4], Bluetooth [5], IEEE 802.15.4e [6] appeared and were evaluated in different industrial automation scenarios [7]–[13]. The IEEE 802.15.4 [14] standard proved to be unable to address the typical industrial application requirements. For this reason, in 2012, an amendment was introduced, i.e., the IEEE 802.15.4e standard, which offers new MAC-layer profiles that are optimized for several typical automation domain, including process automation. The IEEE 802.15.4e standard presents three profiles, i.e., the Low Latency Deterministic Network (LLDN), the Deterministic and Synchronous Multi-channel Extension (DSME) and the Time Slotted Channel Hopping (TSCH). In [6] a set of reference application domains is defined for each profile. LLDN targets very low-latency applications, such as those commonly found in robotics, automotive manufacturing and milling machines. DSME is designed for industrial, commercial and healthcare applications, such as process automation, smart metering, and telemedicine. TSCH is intended for process automation applications. Both the DSME and the TSCH are suitable for process automation applications. Unlike other industrial protocols (e.g., WirelessHART and ISA100.11a), the protocols defined in the IEEE 802.15.4e amendment [6] are interoperable with the original IEEE 802.15.4 standard [14], while they provide the real-time behavior required for industrial applications. For this reason, this paper focuses on these two profiles with a twofold aim. First, to assess their behavior in realistic process automation scenarios, highlighting their strong and weak points. Second, to compare their performance in terms of delay, reliability and scalability. One goal of the work is identifying which of the two protocols is the best choice in given operating scenarios based on some parameters such as, the number of nodes, the channel noise, and so on. Moreover, the paper also intends to highlight the limits of those protocols, thus paving the way to the design of novel approaches able to solve them.

The paper is organized as follows. Section 2 presents related work, while Section 3 provides an overview of the profiles defined in the IEEE 802.15.4e amendment. Section 4 describes the realistic application scenarios and presents and discuss the results obtained. Finally, Section 5 gives the conclusions and outlines future work.

2. Related Work

The IEEE 802.15.4e [6] amendment provides support to apply the IEEE 802.15.4 standard to application domains that require specific properties, such as reliability, low latency and scalability. Several works in the literature deal with the IEEE 802.15.4e, but most of them focus on only one of the three profiles provided in the amendment [6]. In [1] the performance of the LLDN protocol are evaluated in a simple scenario and an extension of the standard retransmission mode is also presented. The work considers the LLDN protocol only. In [15] a simulative assessment of an improved version of the IEEE 802.15.4 standard is presented. Although in the paper such an extension is called IEEE 802.15.4e protocol, it is just an early version of the LLDN protocol. The works in [16] and [17] propose some improvements to the LLDN protocol. The first one suggests to use redundant transmissions in IEEE 802.15.4e network to reduce the effect of packet loss. The second provides a two-level network in which several sub-networks operate at the same time on different channels, thus enhancing the LLDN scalability. In [18] the performance, in terms of packet delivery ratio and delay, of the DSME are evaluated through simulations for a wireless hospital room scenario. As in the amendment [6] e-health and patient monitoring are mentioned as reference applications for the DSME protocol, such scenarios are not suitable for a comparative evaluation between the DSME and the other two profiles described in the standard [6]. In [19] the performance of the DSME protocol in the presence of IEEE 802.11 interference are assessed. The outcome is that the DSME protocol is more reliable, under WLAN interference, than the IEEE 802.15.4. In [20] and [21] the performance of DSME are compared, through simulations, to those of the IEEE 802.15.4 protocol, in terms of energy consumption and throughput, respectively. In [20] a novel energy efficient implementation of the DSME protocol (called ELPIDA) is presented and compared with the native DSME approach and the IEEE 802.15.4 protocol. The results proved that the power consumption of DSME or ELPIDA is always lower than that of the IEEE 802.15.4 protocol. Although the chosen simulation scenario of [20] and [21] is typical of a process automation applications, and so also TSCH protocol would have been a suitable candidate, both works do not address comparative assessment with the TSCH. The focus of the work in [22] is the formation process of TSCH networks, especially as far as the joining time (i.e., the total time taken by a new node to join the network) is concerned, but nothing is said about the DSME and LLDN. In the work it is proved that using more channel offsets significantly reduces the joining time, but may be beneficial only when the network density is extremely high. In [23] the advantages offered by the TSCH protocol are compared to the features provided by the WirelessHART standard, while in [24] the performance of coordinated sampled listening (CSL), which is a feature presented in [6] that foresees that a transmitter node sends wakeup frames before sending a data, are investigated and compared to that of TSCH.

Comparing with related works, this paper provides a twofold contribution. First, a performance evaluation of the DSME and TSCH protocols under a realistic process automation scenario based on [2] and [25], with the aim of addressing both scalability and reliability. In particular, we assessed the effect of retransmissions on the end-to-end delay of the two protocols and their reliability under different channel propagation parameters. Moreover, scalability was assessed evaluating the impact on the end-to-end delay of increasing the number of network nodes. Second, a comparative evaluation of the two protocols to highlight the strengths and the weaknesses of each of them. To the best of our knowledge there is no previous work that presents a comparative assessments of the DSME and the TSCH protocols in a realistic process automation scenario. The LLDN is not addressed in this work because, as specified in [6], it is not designed for process automation applications.

3. Overview of the 802.15.4e standard

In this Section an overview of the IEEE 802.15.4e amendment is presented. About the LLDN protocol just a brief introduction is provided, as this work focuses in on the TSCH and DSME protocols only.

3.1. Low Latency Deterministc Network (LLDN)

The IEEE 802.15.4e-LLDN protocol is specifically devised for industrial applications requiring low latency, such as those found in manufacturing, in robotics, etc. According to the LLDN profile, time is divided in superframes (SFs), that repeat one after the other in a regular way. A SF consists of several timeslots and each node has assigned one or multiple timeslots in which it is allowed to transmit. Each timeslot is large enough to accommodate the transmission of one packet. The LLDN protocol provides a star topology in which nodes transmit using a Time Division Multiple Access (TDMA) mechanism. According to the LLDN protocol the network is managed by the PAN coordinator, which is responsible for the network configuration and node synchronization.

3.2. Deterministic and Synchronous Multi-channel Extension (DSME) protocol

The IEEE 802.15.4e-DSME protocol [6] is designed for meshed networks and allows for a very efficient allocation of the available resources by exploiting both time and frequency multiplexing. The DSME extends to 15 the number of Guaranteed Time Slots (GTS) per superframe that was provided by the IEEE 802.15.4. One additional slot is used for sending the beacon frame.

The medium access is based on a specific time structure, called multi-superframe (multi-SF). Each multi-SF consists of a set of SFs and each SF consists of several consecutive timeslots. Each SF is composed of three parts: a) An Enhanced Beacon (EB); b) The Contention Access Period (CAP), c) The Contention-Free Period (CFP). During the CAP, that is made up of at most 8 timeslots in which monitoring periodic data, urgent or non-periodic data can be sent, the network devices compete for channel access using a slotted CSMA/CA. The CAP is mandatory just for the first SF in a multi-SF. In fact, the *CAP reduction* flag can be enabled to allow all the superframes (but the first one) to skip the CAP. A beacon timeslot is scheduled at the beginning of each SF. Such a timeslot is used by the PAN coordinator to send the beacon frame in the first SF only. The other beacon timeslots are used by the other nodes that expect to receive packets, i.e., *coordinator nodes*.

The CFP is made up of a set of multi-channel GTS (called DSME-GTSs), which are used for communication between two devices and are characterized by pair-wise assignments of channels and time slots. The CFP follows immediately after the CAP and extends to the end of the superframe. A device in a DSME network can play one of the roles of PAN coordinator, coordinator or end node.

- The PAN coordinator usually is the sink node of the network and sends EB every beacon interval (BI). There is one PAN coordinator for each network. The EB sent by the PAN coordinator contains a specific DSME PAN descriptor, which includes information about time (to synchronize the network nodes), channel hopping and timeslots.
- The coordinator is the sink node for some of the network nodes. A coordinator sends a beacon at least once per multi-SF, in the beacon slot, in order to declare its presence in the network. It acts as a relay for the nodes that cannot reach the PAN coordinator directly. In the same network multiple coordinators nodes are allowed.
- End nodes produce data and send it to the relevant coordinator (or to the PAN coordinator, if it is close enough). After receiving a beacon, an end node can compete for transmitting the data during the CAP or ask for a DSME-GTS.

The duration of the SFs and the structure of the multi-SF depends on the following parameters:

- The MultiSuperframe Order (MO), which describes the multi-SF length.
- The Beacon Order (BO), which indicates the number of SFs any coordinator has to wait to transmit a beacon.
- The Superframe Order (SO), which represents the length of the active portion of the superframe, which is equal to the superframe length as the standard [6] does not foresee an inactive portion in the SF.
- Beacon Interval (BI), which is the time interval between two consecutive Enhanced Beacon frames sent by the PAN coordinator.

The number of superframes in a multi-SF is given by formula (1):

$$numberOfsuperframes = 2^{(MO-SO)}. \quad (1)$$

The number of multi-superframes in a beacon interval can be obtained as in formula (2):

$$numberOfMultisuperframes = 2^{(BO-MO)}. \quad (2)$$

The superframe duration (SD), in symbols (in the 2.45GHz PHY Layer the standard specifies that 62500 QPSK-symbols per second are transmitted), is given in formula (3):

$$SD = aBaseSuperframeDuration * 2^{SO} \quad (3)$$

where $aBaseSuperframeDuration$ is the number of symbols forming a superframe when SO is equal to 0. The multi-superframe duration (MD), in symbols, is given in formula (4):

$$MD = aBaseSuperframeDuration * 2^{MO}. \quad (4)$$

The BI duration, in symbols, is shown in formula (5):

$$BI = aBaseSuperframeDuration * 2^{BO}. \quad (5)$$

The value of MO, SO, and superframe duration, SD, are related as in formula (6):

$$0 \leq SO \leq BO \leq 14. \quad (6)$$

In Figure 1 the structure of two consecutive multi-SFs, seen from the perspective of two generic coordinator devices, named Device 1 and Device2, is shown. The Device2 receives the EB during the beacon timeslot in the first SF and then is able to send an EB itself during the beacon timeslot in the third SF. During a BI, multiple multi-SFs can be scheduled. The multi-SF structure is defined by the coordinators, which periodically transmit an EB with the DSME PAN descriptor.

The DSME implements channel hopping. The series of channels used at each slot is referred as the hopping sequence. The transmitter switches to the channel used by the receiver in order to send a data frame. If the receiver successfully receives the data frame, it sends an acknowledgement frame (ACK) to the transmitter on the same channel. Group ACK are also foreseen by the standard, as follows. A coordinator allocates two timeslots for acknowledgement purposes. The first, here called TACK1, is used to acknowledge all the data frames received from the first GTS in the superframe to the TACK1 timeslot, while the second, called TACK2, is used to acknowledge all the data frames received after the TACK1 frame, but before the transmission of the TACK2 frame.

The maximum number of devices that can act as a receiver, including the PAN coordinator, is given by the total number of SFs in the Beacon Interval (BI), corresponding to the number of available beacon slots.

3.3.Time Slotted Channel Hopping (TSCH)

The IEEE 802.15.4e-TSCH is suitable for multi-hop networks where multi-channel communication allows for an efficient use of the available resources [22]. Nodes synchronize periodically, on a periodic SF that consists of a sequence of contiguous timeslots. In each timeslot a node is allowed to send a maximum-size data frame and receives the relevant acknowledgement (ACK). In order for the PAN coordinator to advertise the presence of the network, an Enhanced Beacon (EB) is sent. The kind of information contained in the EB is the same as the one in the EB of the DSME, described in the previous subsection.

In a TSCH network, the superframe concept is replaced with that of slotframe. The slotframe contains either contention-based or contention-free timeslots. The main difference between the slotframe and the superframe is that the network nodes are supposed to share a common notion of time, so the slotframe automatically repeats without requiring beacon frames to initiate communications. The timeslots assignment to the devices within the slotframe may initially be communicated through a beacon, but usually they are configured by the higher network layers when the device joins the network. In Fig. 2 an example of TSCH slotframe structure is shown. In this example, among the five timeslots of each slotframe, only three are assigned, to node A, B and C respectively, while the remaining two timeslots are empty.

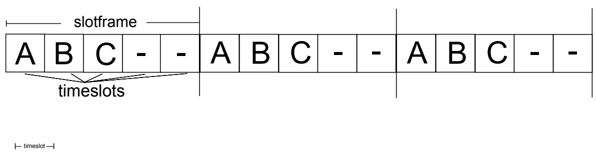

Figure 2. The TSCH slotframe structure.

In TSCH all the transmissions are direct. If a single transmission attempt fails or the ACK is not received within a predefined time-out, the data frame is deferred to the next time slot assigned to the same <*sender, destination*> pair of nodes. The device can retry data transmission and waits for the ACK up to a given maximum number of times.

The TSCH combines time slotted access with multi-channel transmission and channel hopping capabilities. The hopping sequence is defined by an ID, the sequence length and an ordered list of channels. This default sequence is a pseudo-random list of all the channels available at the physical layer. A link

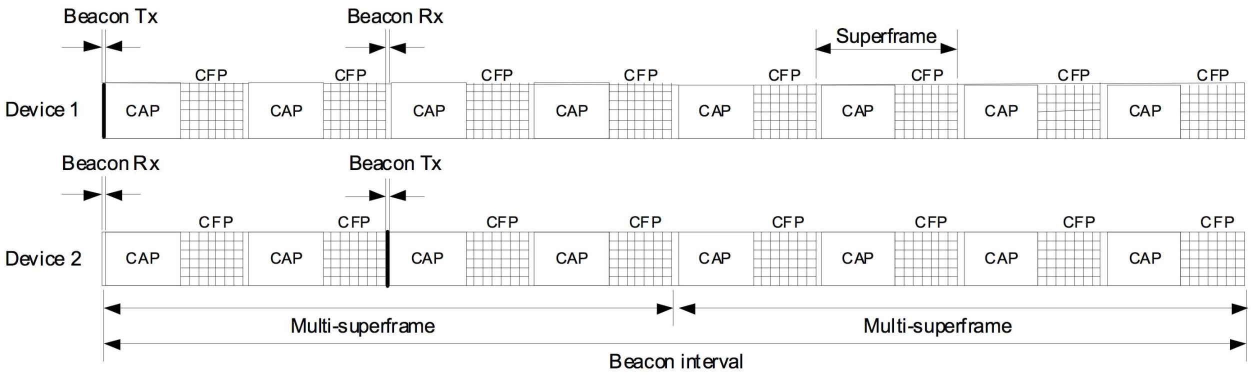

Figure 1. The DSME multi-SF structure shown in the IEEE 802.15.4e [6].

between communicating devices is represented by a pair <*timeslot, channel offset*>. Shared links are intentionally assigned to multiple devices for transmission. This can lead to collisions and result in a transmission failure detected by a missing ACK. In order to reduce the probability of repeated collisions, a retransmission backoff algorithm is implemented for shared links. This backoff algorithm has the following properties:

- The wait for a retransmission backoff applies only to the transmission on shared links, there is no wait for transmission on dedicated links.
- In case of transmission failure on a shared link, a device initializes the backoff exponent (BE)(which is a parameter used for determining the backoff delay) to a given minimum, called $macMinBE$.
- The retransmission backoff is calculated in terms of the number of shared transmission links. The device shall delay for a random number of shared link in the range 0 to $2^{BE}-1$ before attempting a retransmission on a shared link.
- For each successive failure on a shared link, the device should increase BE, up to a given maximum value, i.e., $macMaxBE$. According to [6], the value of $macMaxBE$ for TSCH is chosen in the range 3 to 8.
- A successful transmission in a shared link resets the backoff window to the minimum value.
- In dedicated links, Clear Channel Assessment (CCA) may be used to promote coexistence with other users of the radio channel. In this case, backoff delay is not foreseen.

4. Simulative Assessment

In this section the simulative and comparative assessment between TSCH and DSME is described. The assessment focuses on the process automation domain. The used simulator is developed using the OMNet++ simulation environment. The INETMANET framework was adopted for the wireless channel and the IEEE 802.15.4 physical layer, while the MAC layers were developed from scratch. The simulation models were validated analytically by comparing the simulation timing with those analytically calculated. Following the findings in [2], in a process automation context the network contains a maximum of 50 nodes. The purpose of this assessment is to compare the two protocols in order to evaluate reliability, scalability and maximum delay. Note that processing delays are excluded from the simulations as they are implementation-dependent.

Two scenarios are considered, called Scenario A and B, respectively. Scenario A is adopted to assess the reliability and delay performance of the two protocols, while Scenario B is used to evaluate their scalability.

4.1.Reliability and delay assessment

To assess both the reliability of the two protocols under study and the impact of retransmissions on the end-to-end delay, a network with 10 sensor nodes and a PAN coordinator that acts as sink node for all the data frame sent from the sensors was simulated. Different kinds of sensors, taken from realistic scenarios, are considered. For monitoring applications, there are pressure (PS) and temperature sensors (TS). For closed-loop control, there are torque sensors (TqS) and for interlocking and control there are flow (FS) and proximity sensors (PxS). In both protocols, two sensor nodes have a twofold role: they act as sensor nodes, sending data to the PAN coordinator, and as coordinator nodes, collecting data from other sensors that cannot reach the PAN coordinator directly and forwarding them to the PAN coordinator in a multihop way. In both simulations a single possible retransmission for each message is assumed. Nodes are placed in a sensing area of 50 x 50 meters. Both the PAN coordinator and the relay nodes are placed in the sensing area to be in the range of the sensor nodes that are directly connected to them, while the sensor nodes are randomly placed following a uniform distribution. The network data rate is 250 Kbps.

Table 1 shows the traffic characterization. The first column shows the sensor name, which includes the sensor type, so the PS-1 node is the first pressure sensor, the TS-1 is the first temperature sensor and so on. The second column shows the payload at the application layer in bytes, while in the third column the period at which the data are sent by the relevant sensor node is shown. The last column shows the magnitude order of the maximum delay allowed by the relevant application.

Table 1. Traffic characterization

Sensor Nodes	Payload	Period	Delay
Monitoring and supervision			
PS-1	50 bytes	1 s	*ms*
TS-1	40 bytes	5 s	*s*
Closed loop control			
TqS-1	50 bytes	200 ms	*ms*
TqS-2	50 bytes	200 ms	*ms*
TqS-3	50 bytes	500 ms	*ms*
Interlocking and control			
FS-1	50 bytes	250 ms	*ms*
FS-2	50 bytes	250 ms	*ms*
FS-3	50 bytes	500 ms	*ms*
PxS-1	25 bytes	150 ms	*ms*
PxS-2	25 bytes	250 ms	*ms*

In this simulation the Packet Loss Ratio (PLR) and the End-to-End Delay (E2ED) are assessed.

The PLR is defined as the number of lost or corrupted messages over the overall number of messages transmitted by the sensors nodes (at the application layer). The PLR is calculated as in Formula (7)

$$PLR = \left(1 - \frac{NumRxMessages}{NumTxMessages}\right) \times 100 \qquad (7)$$

where *NumRxMessages* is the number of messages correctly received, while *NumTxMessages* is the overall number of messages transmitted by the sensor nodes.

The E2ED is the time a messages takes from its generation in the source application to its arrival in the sink application. It is calculated as in Formula (8)

$$E2ED = ArrivalTime - GenTime. \qquad (8)$$

In this scenario the Log-normal Shadowing propagation model is adopted. The assessment was performed with different propagation parameters measured in the industrial environment in [26]. The adopted parameters are shown in Table 2, where

Table 2. Propagation Parameters

Run no.	d_0	$PL(d_0)[dB]$	n	$\sigma[dB]$
0	15m	63.57	2.40	4.97
1	15m	63.57	2.77	5.42
2	15m	63.57	3.44	8.63

$PL(d_0)$ is the path loss measured over the reference distance d_0, n is the path-loss exponent and σ is the standard deviation.

In both the DSME and TSCH networks each node is assigned one slot for the message transmission and one for the retransmission. Hence, the configuration parameters were heuristically chosen in order to obtain the lowest superframe period, while taking into account the above assumption. The slot position does not influence the results, as simulations are repeated with different random message generation start times of the nodes and the application which generates messages is not synchronized with the superframe slots. The radio transmission power was set to 1 mW, sensitivity is set to -85 dBm. The simulation parameters for the DSME and TSCH networks are shown in Table 3

Each simulation run has a duration of 600s to collect a significant number of data. Moreover simulations are repeated three times varying the seed for the random number generation, which influences the nodes position, the application start times of the nodes and the log-normal pathloss model.

The PLR results, presented in Table 4, show that with the three different propagation parameters the packet loss ratio is always lower than 0.01%. Such a

Table 3. Simulation parameters

Parameter	Value/Range
DSME Network	
Beacon Order (BO)	4
Multisuperframe Order (MO)	3
Superframe Order (SO)	2
Group Ack	enabled
CAP Reduction	enabled
Slot duration	3.84 ms
TSCH Network	
Num. of slot in a Superframe	20
Slot duration	10 ms

result demonstrates that the protocols behave similarly as far as reliability is concerned.

Table 4. Packet Loss Ratio results

Run no.	PLR DSME	PLR TSCH
0	0%	0%
1	0.005%	0%
2	0.01%	0.005%

Fig 3 shows the Cumulative Percentage Distribution (CPD) of the end-to-end delay, defined as the percentage of messages with the delay lower than a given value (i.e., the relevant x-axis value), for the run no. 2. The results of the other runs are quite similar to these ones.

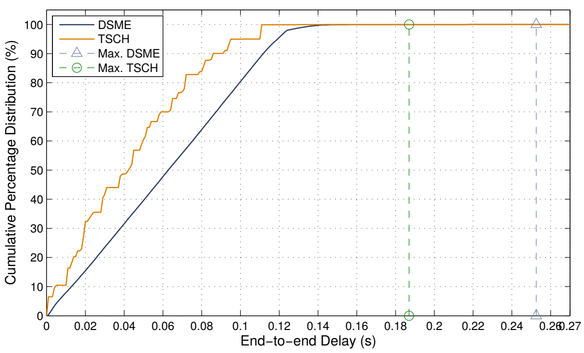

Figure 3. End-to-end delay for the run no. 2 in Table 2.

The results in Fig. 3 show that in this scenario the TSCH protocol provides significantly lower delays than the DSME protocol. In fact, 70% of messages in the TSCH simulation obtain delays lower than 61ms, while the same percentage of nodes in the DSME simulation has end-to-end delay values close to 90ms.

The maximum end-to-end delay (the vertical dashed lines in Fig. 3) is 187ms in the TSCH simulation and 253ms in the DSME one. The difference between the two maximum end-to-end delays is mainly due to the fixed and static multi-superframe structure of DSME, which presents more GTSs than those required, hence introducing a higher delay.

The order of magnitude of these values is the same, or lower, than the order of magnitude of the maximum delay allowed by the application (Table 1). This confirms that both DSME and TSCH are suitable for process automation, although TSCH provides lower end-to-end delays.

Note that the stepped trend of the TSCH distribution is due to the long timeslot duration (i.e., 10 ms).

4.2 Scalability Assessment

To assess the scalability of the two protocols, a network in which each sensor node periodically transmits a 70-byte message with period equal to 500ms was deployed. The aim of this simulation is to evaluate and compare the delays when increasing the number of nodes in the network.

In both protocols four sensor nodes have a twofold role. They act as sensor nodes, sending data to the PAN coordinator, and as coordinator nodes, collecting data from the sensors that cannot reach the PAN coordinator directly and forwarding them to the PAN coordinator. The messages with an end-to-end delay higher than their period are here called late messages.

For both the protocols, the configurations were designed tuning the relevant parameters (BO, SO, MO, etc.) so as to avoid that the message end-to-end delay is higher than the message generation period.

The simulation parameters for the DSME protocol are shown in Table 5. The last column of the Table shows the multi-superframe duration, which depends on the number of superframes in a multi-superframe and on the superframe length. In all the simulations, the DSME-GTS duration is equal to 3.84 ms. The number of superframes in the multi-superframe can be increased as a power of two (Formula (1)). This, in turn, entails that the number of slots increases as a multiple of 16. In the DSME simulations one GTS for data transmission is required for each sensor node and retransmissions are handled in dedicated slots (DSME-GTSR). Hence, each single node requires from one to two slots, so the higher the number of nodes in the network, the higher the number of DSME-GTS required, that in turn entails a higher multi-superframe duration. Such a value is important to understand the timings of messages. In fact, in this scenario a message is multi-hop, i.e., it is first transmitted from the sensor node to a coordinator node and then to the PAN coordinator. As a result, if the multi-superframe duration is higher than half of the message period (i.e. 500ms), the message delay may be higher than the message generation period. In the simulation with 50 nodes this value is close to half of the message period. As all the DSME-GTS are assigned, there is no room for retransmissions. In the other cases (i.e., with 10 and 30 nodes), the choice to enable the group ACK is mandatory, as the messages have to be transmitted within the multi-superframe, otherwise they would arrive to the PAN coordinator too late.

Table 5. Simulation parameters for DSME

# of nodes	BO	MO	SO	GroupACK	MultiSF Period
10	4	3	2	enabled	122.88ms
30	4	3	2	enabled	122.88ms
50	5	4	2	disabled	245.76ms

The configuration for the TSCH protocol is shown in Table 6. Even in this configuration a slot is assigned to each node, therefore the superframe period is equal to the number of nodes multiplied by the slot size (i.e., 10ms). Looking at Table 6, in the networks with 10 and 30 nodes the superframe periods are lower than the sampling periods in Table 1. This allows message retransmissions, as a message has a chance to be retransmitted once without being late. On the contrary, in the 50-nodes configuration, if a message is retransmitted it will interfere with the transmission of the next messages, as in this configuration all the slots are used. For this reason in the 50-node configuration retransmissions are not allowed.

Table 6. Simulation parameters for TSCH

#. of Nodes	#. of Slots	Superframe Period
10	10	100ms
30	30	300ms
50	50	500ms

The end-to-end delay results for the network with 10 nodes, 30 nodes and 50 nodes are shown in Fig. 4, in Fig. 5, and in Fig. 6, respectively.

In Fig. 4, the case of a network with 10 nodes shows that the TSCH protocol performs better than the DSME. In fact 99% of messages present delays lower than 100ms, while the DSME approaches 150ms. The

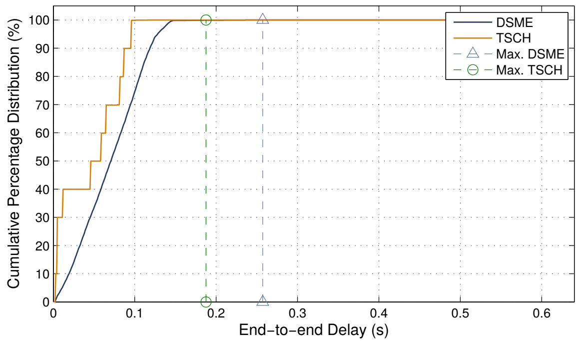

Figure 4. End-to-end delay: 10 nodes.

maximum delay for the TSCH is lower than 200 ms, while for the DSME is close to 260ms.

In fact, the DSME superframe fixed structure entails a higher delay for messages to be transmitted, as the multi-superframe grows exponentially with the number of superframes.

Increasing the number of nodes in the network, results start changing. In Fig. 5, that refers to 30 nodes, while the delay distribution is in favor of the TSCH protocol, the maximum delays, represented by the vertical dashed lines, show that the TSCH presents a higher maximum delay than the DSME. This is because the TSCH does not have slots dedicated to retransmissions, thus retransmitted messages interfere with the regular transmissions. In the case of the DSME, the message lateness is due to the number of retransmission slots assigned to a coordinator, which is chosen lower than the number of nodes connected with each coordinator (as a higher number of retransmission slots would entail adding more superframes in the multi-superframe thus introducing delays higher than the message periods). Hence, the messages that need to be retransmitted will wait for the next DSME-GTSR in the next multi-superframe.

In the simulation with 50 nodes (in Fig. 6) the delays of the DSME are lower than the TSCH ones. In particular with the DSME, 80% of messages experience a delay lower than 313ms, while with the TSCH delays are lower than 418ms.

Scalability results show that the fixed-structure of DSME penalizes the networks in which the number of nodes is lower than 30. In fact, using the group ACK, retransmissions occur in dedicated DSME-GTSR located at the end of the superframe (this entails a high number of slots and a long waiting period for regular

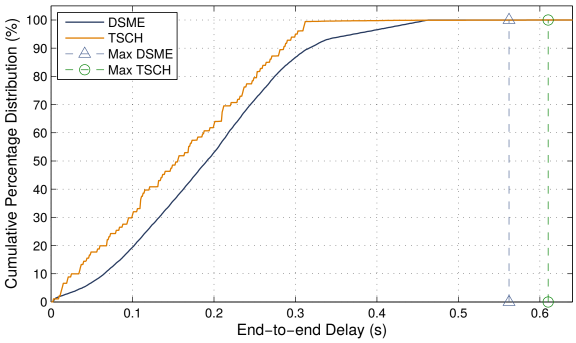

Figure 5. End-to-end delay: 30 nodes.

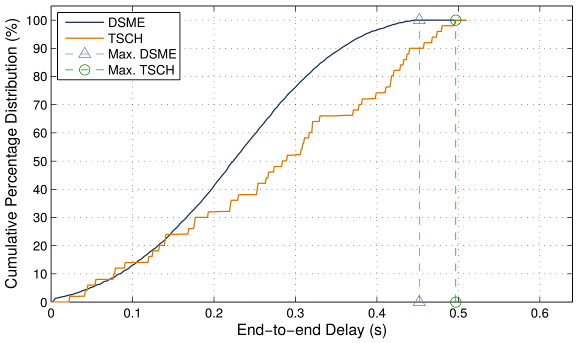

Figure 6. End-to-end delay: 50 nodes

message transmissions) and this will entail high delays. The adoption of the classical ACK mechanism of the IEEE 802.15.4 is allowed, but it is not suitable for these scenarios, as retransmissions cannot be accommodated in the same multi-superframe (as specified in the standard [6]).

On the contrary, if the number of nodes is higher than 30, the DSME performs better compared to the TSCH, as the latter provides a longer superframe period than the DSME multi-superframe duration.

As far as scalability is concerned, TSCH performs better than DSME when the number of nodes is lower than 30, as there are no dedicated retransmission slots, so a lost message will be retransmitted in the next available slot for the same node that failed the transmission. However, this entails that retransmitted messages will interfere with the regular message transmission, as in the case of retransmission, the regular message transmission will be delayed to make room for the retransmission. This is an advantage when the number of nodes is low, as the superframe period is low too and there is time left for retransmissions. When the number of nodes is higher than 30, the superframe period increases, thus decreasing the possibility of retransmissions.

5. Conclusions and future works

This work presented a performance assessment of two of the three IEEE 802.15.4e profiles, i.e., the DSME and TSCH. According to the IEEE 802.15.4e amendment [6], process automation represents the reference application domain for both the profiles. The evaluation is performed in a realistic process automation scenario and the performance metrics are reliability, delay and scalability. As far as reliability is concerned, both protocols proved to be robust towards channel noise. In general, TSCH offers better end-to-end delays than DSME. In particular, simulation results show that DSME perform better than TSCH in terms of end-to-end latency only when the number of nodes is higher than 30. This result derives from the rigid structure of the DSME multi-superframes, in which the number of superframes in multi-superframes grows as a power of 2 and the number of slots in a superframe is equal to 16. When the number of nodes is low, such a structure leads to an overprovisioning of DSME-GTS that not only affects the bandwidth efficiency, as more slots than those actually needed are used, but also determines long delays for the messages to be transmitted. On the contrary, when the number of nodes grows, all the DSME-GTS in the multi-superframe are used, thus improving the bandwidth efficiency, and the DSME delay values are better than those of TSCH, thanks to the smaller size of the DSME slots compared to the TSCH ones.

Conversely, the TSCH has a more flexible slotframe structure than DSME, as a single timeslot can be inserted in or removed from the superframe. However, timeslots have to be larger than in DSME, in order to accommodate the ACK. This means that in networks with a high number of nodes, the superframe period grows faster in TSCH than in DSME. Moreover, another limitation is that the IEEE 802.15.4e standard does not provide group ACK methods for the TSCH.

Ongoing work extends this study to address possible approaches to overcome the limits of DSME or TSCH previously mentioned. Moreover, the support provided by the two protocols to event-driven traffic will be investigated. A timing analysis of the two protocols is also in progress.

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