Performance Investigation and Optimization of IEEE802.15.4 for Industrial Wireless Sensor Networks

Mohsin Hameed, Henning Trsek, Olaf Graeser and Juergen Jasperneite
inIT - Institute Industrial IT
OWL University of Applied Sciences
D-32657 Lemgo
{mohsin.hameed, henning.trsek, olaf.graeser, juergen.jasperneite}@hs-owl.de

Abstract

This paper evaluates the performance of IEEE 802.15.4 for industrial wireless sensor networks. The IEEE 802.15.4 protocol has got the ability to provide real time data transmission in wireless sensor networks using guaranteed time slots (GTS) as medium access control mechanism. According to the standard, a maximum of 7 GTSs can be allocated in one superframe. All GTSs are exclusively dedicated to a corresponding node. Hence, the GTS mechanism is rather limited regarding the number of nodes and the needed scalability is missing. In this paper we introduce a new scheduling algorithm called "Earliest Due Date GTS Allocation" which can be implemented at the medium access control layer. Using this scheduling scheme and an appropriate scheduler, the GTS mechanism is enhanced, in order to enable a deployment in large scale networks with real-time requirements.

1. Introduction

The IEEE 802.15.4 protocol [3] has become a communication standard for low data rate, low power consumption and low cost Wireless Personal Area Network (LR-WPAN). The protocol focuses on very low cost communication, which requires very little or no underlying infrastructure. The basic framework supports a communication area of 10 meter or less, commonly known as Personal Operating Space (POS), with a transfer rate of 20, 40, 100 and 250 kbps. The protocol provides flexibility for a wide variety of applications by effectively modifying its parameters. It also provides real time guarantees by using a *Guaranteed Time Slot (GTS)* mechanism for time sensitive applications. Hence, two kinds of network configuration modes are provided in the IEEE 802.15.4 standard [3]:

- **Beacon enabled mode**, a PAN Coordinator periodically generates beacon frames after every Beacon Interval (BI) in order to identify its PAN, to synchronize with associated nodes and to describe the superframe structure.
- **Non beacon enabled mode**, all nodes can send their data by using an unslotted CSMA/CA mechanism which does not provide any time guarantees to deliver data frames.

The IEEE 802.15.4 standard defines both physical (PHY) and medium access control (MAC) layer to construct *Wireless Sensor Networks (WSN)* using either configuration.

The Physical Layer (PHY) is responsible for transmission and reception of data using a selected radio channel according to the defined modulation and spreading techniques. The spreading in all frequency bands is based on Direct Sequence Spread Spectrum (DSSS). The different modulation schemes are binary phase shift keying (BPSK), amplitude phase shift keying (ASK) and offset quadrature phase-shift keying (O-QPSK). The choice of a modulation scheme depends on the desired data rate. The PHY is defined for operation in three different unlicensed ISM frequency bands,

- 868-868.6 MHz: Europe, allows one communication channel with data-rates of 20 kbps (BPSK mandatory), 100 kbps (O-QPSK) and 250 kbps (ASK/O-QPSK).
- 902-928 MHz: North America, allows ten communication channels with data-rates of 40 (BPSK mandatory) and 250 kbps (ASK/O-QPSK).
- 2400-2483.5 MHz: Worldwide, allows sixteen communication channels with a data-rate of 250 kbps (O-QPSK mandatory).

The IEEE 802.15.4 MAC layer provides features like: beacon management, channel access, GTS management, frame validation, acknowledgment frame delivery, association, and disassociation.

In the beacon enabled mode, the PAN Coordinator uses a superframe structure in order to manage the communication between its associated nodes. The superframe structure is defined by means of two parameters: *Beacon Order (BO)* and *Superframe Order (SO)*. Both parameters can be positive integers between 0 and 14 (cf. [3]). A superframe is always bound by two consecutive beacons and includes an active period and an optional inactive period. The values of BO and SO are used to calculate the length of the superframe and its active period. The BO and SO must satisfy the relationship $0 \leq SO \leq BO \leq 14$. According to the 802.15.4 standard, the superframe will not be active anymore if $SO = 15$. Moreover, if $BO = 15$ the superframe shall not exist and the non beacon-enabled mode will be used. As a result, a PAN that wishes to use the superframe structure must use a BO value between 0 and 14 and a SO value between 0 and the value of BO. Using (1) and (2) the length of the superframe and the length of its active period is calculated, also referred to as $BeaconInterval(BI)$ and $SuperframeDuration(SD)$ respectively.

$$SD = aBaseSuperframeDuration \cdot 2^{SO} \quad (1)$$

$$BI = aBaseSuperframeDuration \cdot 2^{BO} \quad (2)$$

where

$$\begin{aligned} &aBaseSuperframeDuration = \\ &aBaseSlotDuration \cdot aNumSuperframeSlots \end{aligned} \quad (3)$$

The constant $aBaseSlotDuration$ describes the number of symbols forming a superframe slot and $aNumSuperframeSlots$ describes the number of slots contained in any superframe.

The active period (SD) is divided into 16 equally sized time slots (TS) for data transmission. Within the active period two medium access coordination functions are defined in IEEE 802.15.4: a mandatory Carrier Sense Multiple Access (CSMA) mechanism for the Contention Access Period (CAP) and an optional Guaranteed Time Slot (GTS) mechanism for the Contention Free Period (CFP). The superframe structure is shown in Figure 1. The CAP shall start immediately after the beacon and complete before the beginning of the CFP on a superframe slot boundary. The CFP shall start on a slot boundary immediately after the CAP and it shall complete before the end of the active period of the superframe. The CFP can be activated by a request sent from a node to the PAN Coordinator.

1. *CSMA:* Two versions of CSMA/CA are defined, the unslotted for the non beaconed-enabled mode and the slotted CSMA/CA for the beaconed-enabled mode. For both versions it is based on backoff periods. A node which needs to transmit data has to sense the medium for a predetermined amount of time, in order to check for any activity on the medium. If the medium is sensed to be "idle" for a specified amount of time, the node is permitted to start a transmission. If the medium is "busy", the node has to defer its transmission.

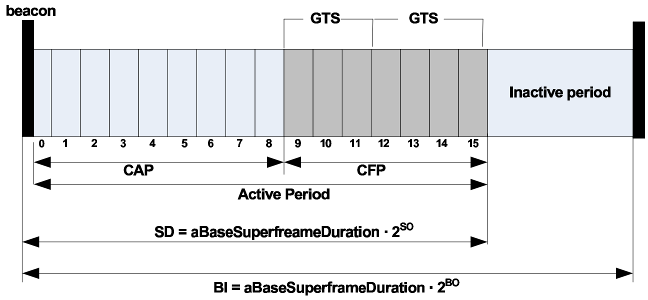

Figure 1. IEEE 802.15.4 Superframe Structure

2. *GTS:* GTS provides real time guarantees for time sensitive applications. GTS can be activated by the request sent from a node to the PAN Coordinator. At the reception of this request, the PAN Coordinator checks whether there are sufficient resources available for the requested node in order to allocate requested time slot. Maximum of 7 GTSs can be allocated in one superframe. The allocation of the GTS cannot reduce the length of the CAP to less then 440 symbols (*aMinCAPLength*) [3].

In this paper only the beacon enabled mode operating at the 2.4 GHz ISM frequency band and at a data rate of 250 kbps is considered. The main purpose of this paper is to evaluate the performance of wireless sensor networks in terms of delay, and propose an optimization technique for industrial specific networks, since the research carried out in the field of industrial sensor networks is very confined.

In section 2 of this paper the state of the art and its short comings are described. Section 3 evaluates the access mechanisms and discusses the feasibility of the best mechanism for industrial automation. The limitations of IEEE 802.15.4 are presented in section 4 while its possible optimization is presented in section 5. Section 6 wraps everything up in order to draw a sufficient conclusion.

2. Related work

The research carried out in the field of industrial sensor networks is very limited. In [2] and [4] the performance of IEEE 802.15.4 was measured, but the evaluations are based on security and energy efficiency in wireless sensor networks. In [11] a wireless sensor network based on IEEE 802.15.4 for usage in factory automation was investigated with respect to introduced delays. Koubba in [5] analyzed the GTS allocation and gave an understanding of the behavior of the GTS with respect to delay and throughput using networks calculus. However, the maximum data rate used in his analysis was 120 kbps only. Furthermore, only a single metric is used in his analysis, which is the $superframeorder(SO)$. In case of industrial wireless sensor networks we are always interested in knowing different delays, with different payload sizes and a different number of nodes. The maximum data rate should be 250 kbps and the most appropriate access method should be used.

Issues and challenges of wireless sensor networks for factory automation are discussed in [12] which provides a short survey on the research issues and implementation challenges facing wireless networked control, condition based maintenance and industrial efforts for standardization of communication protocols. It is also limited to the energy efficiency of wireless sensor networks. Delay/Throughput evaluation of the GTS mechanism is done in [7] but the metric used in this analysis is again only the SO. The maximum payload size considered in the analysis is 41 bits, while in industrial automation payload sizes may vary from a few bits up to some bytes. Furthermore, the analysis dealt with low data rates starting from 5 kbps up to 120 kbps. A performance evaluation of the GTS mechanism and its optimization were theoretically measured using network calculus and presented in [6]. Before starting the data transmission, each node selects its desired scheduler from the list of two schedulers, the standard scheduler [3] or an implicit scheduler [6]. Based on the node selection, the coordinator will use the corresponding scheduling scheme to allocate the time slot and to schedule the nodes data. The main drawback of this approach is that nodes have to decide about the scheduling scheme without any additional knowledge about the whole PAN. This leads to the idea that scheduling decisions should always be taken by the PAN Coordinator. The drawback can be identified when some nodes to be scheduled have very soft delay requirements, i.e. can share time slots, but still choose the standard scheduler. In this condition, it will restrict newly arriving nodes. Second drawback is that the implementation of the proposed scheduler [6] is at the network layer, whereas the 802.15.4 standard proposed scheduling at the MAC layer.

3. Engineering aspects of industrial systems

The common engineering cycle for industrial automation systems is always based on a static offline configuration phase. This has a significant impact on the handling of such WSNs. In Figure 2 the basic procedure of the engineering aspect is shown. Sufficient device description (DD) information for the entire wireless network is necessary, which exists in the WSN configuration tool (Engineering Wireless) only. The efforts for the wireless engineering mainly depend on the chosen technology, i.e. IEEE 802.15.4 for this example.

In case of the Industrial Ethernet Standard PROFINET [9, 10] the first step is to use this information to generate a generic station description markup language (GSDML) file (Fig. 2 (1)), e.g. done by a GSDML compiler. After this the generated GSDML file is transfered offline to the PROFINET IO engineering tool (Engineering PROFINET) (Fig. 2 (2)). In this case the efforts for the PROFINET engineering would be comparable to the

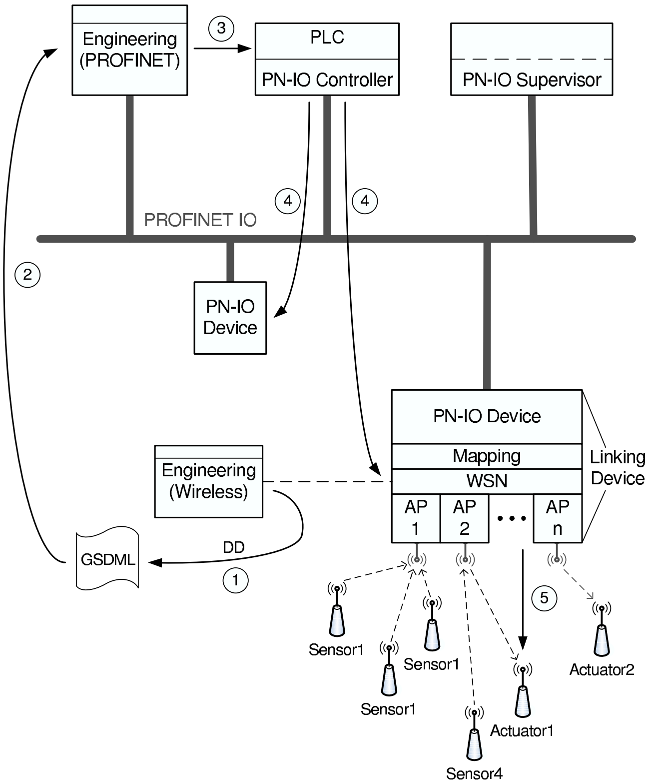

Figure 2. Engineering of an Industrial Automation System

engineering of a wired modular field device. The GSDML file is then used to create a project with configuration and parameterization, which is passed to the PROFINET IO controller (Fig. 2 (3)). The PROFINET IO controller configures all PROFINET IO devices (Fig. 2 (4)) in the start-up phase of the system along with the mapper inside the linking device. The necessary mapping information depends on the WSN configuration and is usually contained in the generated GSDML file. The last task is to start-up the wireless network by the wireless engineering tool (Fig. 2 (5)). This could have also been done in the beginning of the procedure. Depending on the wireless technology used, the WSN can also be up and running before the system starts. Whenever a new type of wireless device is added the whole procedure has to be repeated, starting with step 1. It might also be required, if a mobile wireless sensor leaves or enters a certain cell of the WSN.

Due to the previously described procedure, dynamic behavior of an industrial wireless sensor network is always a problem and not desired, leading to a static network configuration. Therefore the scheduling has to be done once during the startup phase of the system and can be kept as computed in this stage. This is a major difference compared to wireless sensor networks for other application areas.

4. Performance evaluation of IEEE 802.15.4

In order to evaluate the performance of the IEEE 802.15.4 access mechanisms, we used an OPNET simulation model developed and described in [8].

The Medium Access Delay is used as main metric in this work. It has been defined as the time interval between frame generation and the actual medium access of that frame. In Figure 3 the definition of the medium access delay t_{MA} is shown. In wireless sensor networks, if the node is using the CSMA based mechanism, will depend strongly on the nodes backoff time. In case of using the GTS mechanism, the medium access delay t_{MA} will depend on the GTS length, the SO and the payload size.

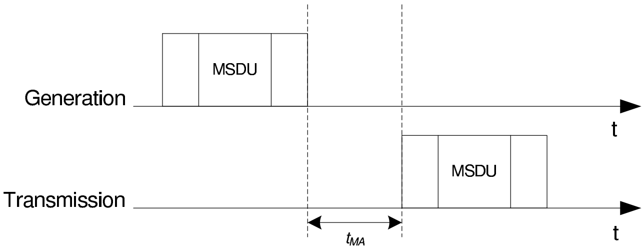

Figure 3. Definition of the Medium Access Delay

In the first scenario, two to seven nodes are considered using either CSMA or GTS in order to evaluate the best feasibility for industrial automation systems. The GTS mechanism can allocate a maximum of seven GTS in one superframe. In the scenario all nodes are transmitting cyclic traffic to the coordinator, using an interarrival time of $1s$ and $SO = BO = 1$. This means no inactive period is present in this superframe structure. The MAC service data unit (MSDU) size is 128 bits, which is the maximum possible payload size with $SO = 1$. It can be seen in Figure 4 that GTS outperformed CSMA when having more than four nodes. The GTS maintained its parameterized bounds whereas the CSMA only fulfills the requirements in setups with a few number of nodes. With an increased number of nodes it can be observed that the CSMA delay also increases while the delays for GTS mechanism remain almost constant. For instance, seven nodes lead to a GTS delay maximum of $30.5ms$ in comparison to a maximum CSMA delay of $60.16ms$.

The steep increase of the CSMA delay for an increasing number of nodes is caused by more collisions on the channel due to the rising network load. The previous analysis yields that only the GTS mechanism fulfills the requirement of deterministic delays, which is very important in industrial automation. As a consequence the subsequent evaluations are based only on the GTS mechanism using different parameters.

Figure 5 presents the maximum values of the medium access delays of nodes using GTS mechanism. It also evaluates the effect of different payload sizes on the

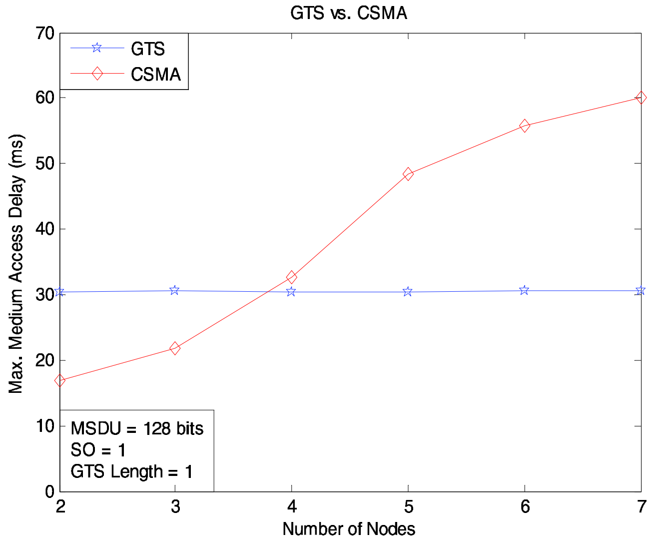

Figure 4. CSMA vs. GTS Medium Access Delay

medium access delay, since the standard defines a small inter-frame space (SIFS) for a $MSDUsize \leq 40bits$ and a long inter-frame space (LIFS) for the remaining sizes. In this scenario, similar to the previous scenario, cyclic traffic with an interarrival time of $1s$ and $SO = BO = 1$ is considered. It can be seen that for the payload size less than or equal to 40 bits, the delay value is smaller than $30ms$. For more then 40 bits payload size, the delay value lies between 30 to $31ms$.

The overall analysis of Figure 5 shows that different payload sizes have no significant influence on the medium access delay.

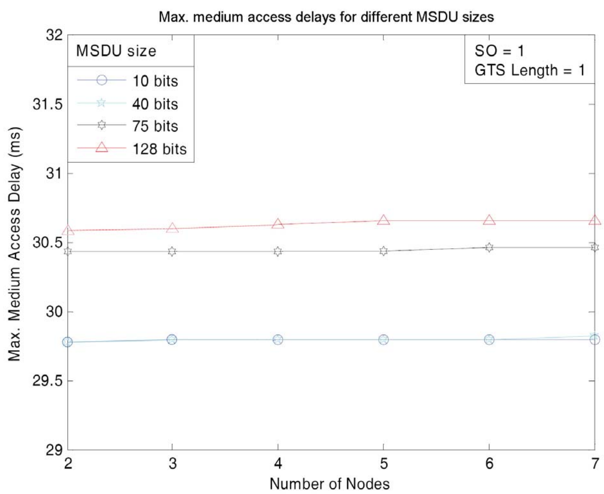

Figure 5. Effect of different MSDU sizes

In Figure 6, two nodes are considered to show the effect of different GTS lengths on the maximum delay. The GTS length is variable depending on the nodes requirements and its GTS request. In this scenario, the parameters $SO = BO = 1$ and a payload size of 128 bits is used. It can be seen that increasing the GTS length causes a significant reduction of the delay. However, an increased GTS length causes a decreased number of nodes.

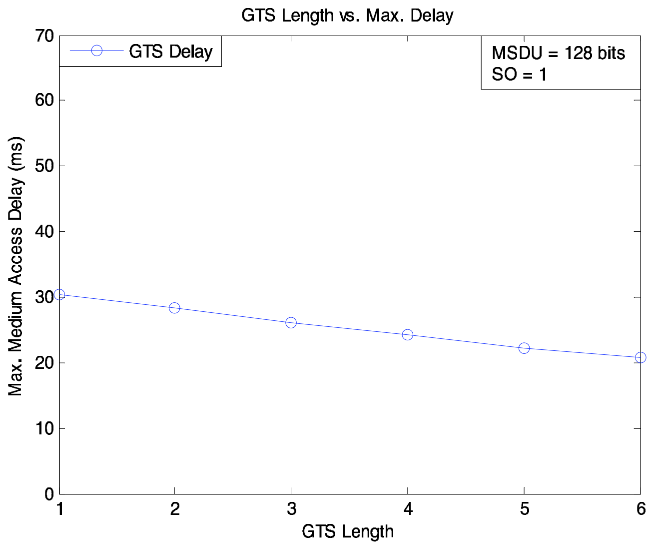

Figure 6. Effect of a different GTS length on the max. delay

5. Limitation of IEEE 802.15.4 and GTS scheduling

IEEE 802.15.4 defines the contention free period (CFP) as an optional part within a superframe. During the CFP nodes can transmit using the GTS mechanism. It is activated by a request sent from a node to the PAN Coordinator. The GTS request frame contains the requested GTS length and its start/stop timing. On receiving this request, the PAN Coordinator checks whether there are sufficient resources available or not. If the requested time slots are available, the PAN Coordinator will allocate them and if not, the nodes request will be denied. The GTS mechanism, as proposed in the standard [3], has some limitations in terms of its deployment in large scale networks. This is due to the maximum of 7 GTSs in one superframe and the exclusive dedication of every GTS to its respective node. As a result, a maximum number of 7 nodes at a time are currently supported [6] by the standard.

However, industrial applications for wireless sensor networks require not only real-time guarantees, a large number of nodes must also be facilitated. This can not be obtained with the current GTS scheduling scheme. Therefore, section 6 proposes an optimization and enhancement of the current GTS scheduling with the ability of facilitating more than 7 nodes at a time.

6. Optimization of GTS with the Earliest Due Date GTS allocation algorithm

In order to solve the above mentioned problem, a new scheduling scheme called *Earliest Due Date GTS Allocation (EDDGTSA)* is proposed. The pseudocode of EDDGTSA is shown in Algorithm 1. The basic concept of EDDGTSA is to schedule nodes depending on their maximum allowed delays using the principles of the EDD algorithm [1].

Table 1. Input of the EDDGTSA algorithm

Name	*Description*
listOfNodes	List of currently accepted nodes
newNode	New node (with normDelay and reqTS)
normDelay	Normalized delay for newNode
reqTS	Required time slots for newNode

The algorithm is based on the input information provided in Table 1. According to the new scheduling scheme, all nodes will send their maximum allowed delays to the PAN Coordinator. For the sake of simplicity the maximum allowed delay ($maxDelay$) of a node is normalized with (4). Hence, it is always a multiple of BI and the superframe cycle time respectively.

$$normDelay = \left\lfloor \frac{maxDelay}{BI} \right\rfloor \qquad (4)$$

Algorithm 1 EDDGTSA algorithm

procedure EDDGTSA($listOfNodes, newNode$)
  $listOfAllNodes$.add($newNode$)
    ▷ newNode contains normDelay and reqTS
  $table$:=createTableNodeDelay($listOfNodes$)
    ▷ rows: normDelay, columns: nodes
  $superframes$:=createArrayOfSuperframes()
  sf_number :=1
  while $table \neq \emptyset$ **do**
    $sf := superframes[sf\_number]$
    while sf. hasUnassignedSlots() **do**
      sf.assignNodeMinAllowedDelay($table$)
      $table$.removeNodeMinAllowedDelay()
    $superframes$.add(sf)
    for all $row_i \in table$ **do**
      if $sf\_number \mod i = 0$ **then**
        if $row_i \neq \emptyset$ **then**
          ▷ Time requirements not fulfilled
          return DENIED
    if $table = \emptyset$ **then**
      return $superframes$ ▷ SUCCESS
    for all $row_i \in table$ **do**
      if $sf\_number \mod i = 0$ **then**
        $table$.fillRow($i, listOfNodes$)
    $sf\_number := sf\_number + 1$
  return b ▷ The gcd is b

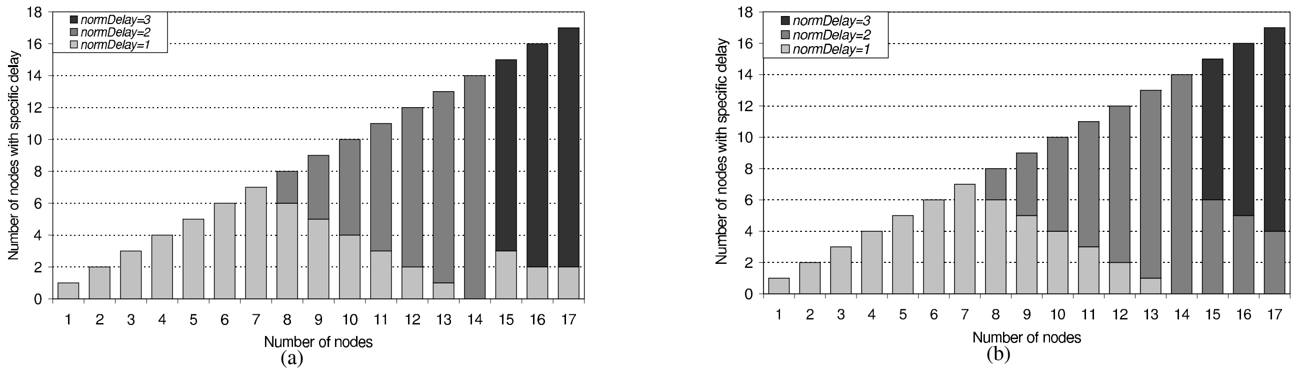

Figure 7. Number of nodes with respect to their requested maximum delays

Unfortunately, the amount of GTS in one superframe is too small to handle a sorted list of nodes as needed for the EDD algorithm. For this reason the EDDGTSA algorithm requests a list of all nodes as an argument. With this list a table of nodes based on their requirements is created. Hence, each row of the table consists of nodes with the same normalized delay $normDelay$, e.g. the first row contains all nodes with $normDelay = 1$, the second row contains all nodes with $normDelay = 2$, etc.

Using this table the algorithm creates a chain of superframes. The first seven slots of the first superframe will be assigned to nodes having the smallest $normDelay$. Nodes that have been assigned to a slot will be removed from the table. After the first superframe is occupied, the algorithm checks whether the first row r_1 of the table is completely empty. If not, the scheduler can not guarantee the maximum allowed delay for the nodes that are still in the first row and stops. When the complete table is empty the algorithm also stops, because the scheduling task is finished.

Supposing there are still pending nodes in other rows, the scheduler proceeds with the second superframe. For this reason the table is again filled with nodes having a $normDelay = 1$, because these nodes must be part of every superframe. Then the remaining nodes with the smallest $normDelay$ values are placed in the superframe and removed from the table. To assure that the schedule still complies with the allowed delays, the first and second row of the table must be empty now. Afterwards, the rows are again refilled and the scheduler moves to the third superframe. The steps of filling a superframe, deleting nodes from the table and refilling the specific rows of the table is repeated until the table is completely empty before refilling or else the allowed delays can not be preserved.

The rows r_i that must be empty after assembling the superframe SF_j are determined following (5). Furthermore, it is necessary to refill these rows before the scheduler is allowed to continue.

The worst case scenario for the *while* loop beginning in line 8 is when each of the n nodes requires 7 slots and has a maximum allowed delay of n or more cycles. In that case n superframes are needed. The *while* loop is executed n times.

The worst cases for the *for all* loops in lines 14 and 21 is when each node has a different maximum allowed delay. In that case the $table$ consists of n rows. The *for all* loops are also executed n times. As a result the upper bound for this algorithm is given by $O(n^2)$.

$$r_i = \begin{cases} \text{must be checked for} & if \;\; j \mod i = 0 \\ \text{emptiness and refilled} & \\ \text{must neither be checked} & otherwise \\ \text{nor refilled} & \end{cases} \tag{5}$$

As the usage of the GTS mechanism provides a contention free period, it can be assumed that no collisions occur. Hence, the effects of collisions were disregarded for our analytical calculations. Furthermore it was assumed that no packets were lost during transmission.

The enhancements of the aforementioned algorithm can be seen in Figure 7. It shows the total number of nodes connected to the coordinator and requirements which could be guaranteed for different scenarios. For example, it can be seen in (a) when having a total number of 11 nodes, 3 nodes require a maximum delay guarantee of $normDelay = 1$ and the rest of the nodes have a maximum delay guarantee of $normDelay = 2$. Figure 8

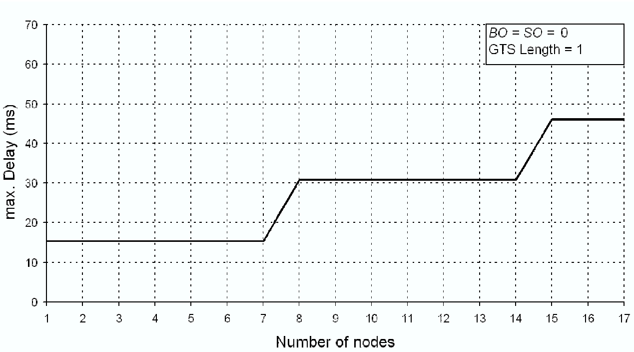

Figure 8. Maximum allowed delay vs. Number of nodes

shows the maximum allowed delays in terms of the number of nodes. It has been calculated under the condition that the requirement of every node is identical.

7. Conclusion

Finally, it can be concluded that the GTS outperformed the CSMA and maintained its parameterized bounds, whereas the CSMA only fulfills the requirements in setups with very few number of nodes. However, the GTS mechanism has some limitations in terms of its deployment in large scale wireless networks which can be overcome by using the proposed EDDGTSA algorithm. EDDGTSA is a new approach to allocate the GTS in IEEE 802.15.4 based WSNs. This proposal is motivated by the limitation of GTS allocation in the standard. EDDGTSA solves the problem by allowing multiple nodes to share the same GTS time slot in different superframes on the basis of their maximum allowed delays. The results in section 6 provide the upper bound of the EDDGTSA complexity and is given by $O(n^2)$.

The performance in terms of number of nodes which have a maximum delay guarantee has been significantly improved as compared to the standard GTS scheduling mechanism. Due to the static behavior of industrial system, as described in section 3, the deployment of EDDGTSA scheduling algorithm in industrial wireless sensor networks is reasonable and should be used. Furthermore, the EDDGTSA scheduling scheme can easily be implemented, because only a slight modification of the existing scheduling scheme is necessary. Application scenarios including acyclic traffic with real-time requirements, for instance alarms, are not covered yet. However, a possible solution would be to either use the next available time slot within the CFP or to use the standard CSMA/CA mechanism during the subsequent CAP to transmit the message. Whether the CAP or the CFP is used, depends on the acyclic message and its time of occurence.

Future work in this area includes a detailed simulation study and investigation of the proposed algorithm which might result in a further refinement. Moreover, it is planned to implement the newly proposed EDDGTSA scheduling algorithm on an evaluation platform.

Acknowledgements

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