Towards IEEE 802.15.4e: A Study of Performance Aspects

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***Abstract*—We discuss the applicability of IEEE 802.15.4 for application in industrial automation. Based on the specific requirements in this field, especially w.r.t. real-time operation, we analyzed the weaknesses of the standard protocol and proposed a novel MAC protocol that keeps the original PHY definition in order to work using available IEEE 802.15.4 chipsets. In earlier work, we analytically derived the worst case latency for using the improved protocol version in typical industrial setups. We now also implemented this protocol version in a simulation environment in order to show the typical behavior in the network taking into account typical channel conditions. We performed extensive simulation experiments that show the limitations of the standard protocol and that demonstrate the capabilities of the new protocol in a selected automation scenario. Our protocol variant is going to become the forthcoming IEEE 802.15.4e standard.**

***Keywords*-IEEE 802.15.4, real-time communication, performance evaluation, simulation, analytical evaluation**

I. Introduction

An increasing number of industrial applications are focusing on wireless networks as a core technology. In this context, especially industrial automation is of interest due to the specific requirements w.r.t. transmission latency and reliability. For example, the Siemens Industry Automation Devision is currently evaluating such wireless technologies for use in automation environments. One of the more frequently used technologies to set up Wireless Sensor Networks (WSNs) is IEEE 802.15.4 [1], which is a standard designed for Low-Rate Wireless Personal Area Networkss (LR-WPANs). In contrast to Wireless Local Area Network (WLAN), which is standardized within IEEE 802.11 family, LR-WPANs focus on short-range operation, low-data-rate, energy-efficiency, and low-cost. IEEE 802.15.4 based WSNs are designed for low-rate applications, and they especially focus on energy efficiency.

Meanwhile, the IEEE 802.15.4 standard has become a recognized industry standard and, thus, has been well accepted by industrial users [2]. It provides specifications for both the Physical Layer (PHY) and Medium Access Control (MAC) sublayers. Again, the main design goal has been energy efficient operation, whereas real-time aspects were not a primary concern. Thus, extensions based on IEEE 802.15.4 have been developed closing this gap. A popular approach to use the lower layer definitions of the IEEE 802.15.4 protocol to define more complex network protocols is WirelessHART [3], which has its primary roots in wired industrial networks.

In previous work, we presented a protocol variant that completely incorporated the standard PHY layer and came up with a completely new MAC protocol that allows operation in typical industrial environments [4]. The resulting protocol is currently in the standardization process to become IEEE 802.15.4e [5], and primarily addresses the real-time requirements in such scenarios.

In this paper, we study the performance of this protocol variant in a comprehensive set of simulation experiments in order to show the typical operation of the protocol. In [4], the worst-case delay has been investigated using an analytical model. This is certainly necessary to prove some real-time capabilities. However, for evaluating implementations and to quantitatively study the protocol performance, simulative approaches are needed [6]. Thus, the main contribution of this paper is a simulation model for the new protocol variant IEEE 802.15.4e and the simulative analysis (and comparison to the original standard) in a typical industrial scenario.

The application scenario to be studied in this paper is typical for automation environments. We specifically focus on a well planned industrial environment, which can be considered a typical case. In factory automation, planning tools are used to ensure proper signal distribution between the deployed nodes [7]. We already started integrating such planning tools with our simulation models for more accurately modeling the channel behavior [8]. Thus, reliability is then more an issue w.r.t. stochastic noise and random disturbances. Obviously, this cannot be completely eliminated. In the first part of our evaluation, we therefore consider noise in the radio propagation model in the simulations. We finally also discuss the impact of random disturbances on the transmission time. The selected scenario is similar to the one used in the forthcoming IEEE 802.15.4e standard [5]: We consider a star network of up to 20 nodes collecting sensor readings and transmitting them to a central sink node. Once a certain device detects that sensor readings exceed a predefined threshold, a short alarm message must be sent by the device within a given time frame such as within $10\,\mathrm{ms}$.

II. Protocol Performance of IEEE 802.15.4

In this section, we briefly review the standard operation of IEEE 802.15.4. Only those parts that are relevant to

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our performance study are introduced. For a more detailed description of the protocol, the reader is recommended to refer to the protocol standard documents [1] and to [9]. We also recap some typical performance aspects in selected simulation studies.

A. Protocol Overview

In order to synchronize the communication at MAC layer, IEEE 802.15.4 can operate in the so called *beacon-enabled* mode using a well-defined superframe structure. Each *superframe* is bounded by periodically transmitted beacon frames, which allow nodes to synchronize to the coordinator. Each superframe consists of two parts: an active portion and an inactive period. In order to save energy, nodes may enter a low-power (sleep) mode during the inactive portion. The superframe structure is specified by the values of two MAC attributes: the Beacon Order (BO) specified by the parameter *macBeaconOrder* and the Superframe Order (SO) specified by *macSuperframeOrder*. They determine the length of the *beacon interval* (BI) and the length of the active portion of the superframe, Superframe Duration (SD), respectively.

The active portion of the superframe is divided into 16 equally spaced slots, which are called *superframe slots*. The duration of one superframe slot is calculated as $2^{SO} \times$ *aBaseSlotDuration*, where the default value of *aBaseSlotDuration* is 60 symbols. There are three parts in the active portion: a beacon, a Contention Access Period (CAP), and a Contention-Free Period (CFP). In the CAP, all data transmissions rely on a slotted Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) algorithm. For application scenarios requiring real-time operation, so called Guaranteed Time Slots (GTSs) are available in the CFP. A maximum of seven GTSs can be allocated for a single superframe. GTS transfer mode is only applicable in star networks.

B. Protocol Performance

Our simulation model of IEEE 802.15.4 is adapted from a former implementation [10], which was built according to an old version IEEE 802.15.4-2003, using the network simulator ns-2. Our implementation in OMNeT++ conforms with the latest version of the standard IEEE 802.15.4-2006. As a minor addition, we installed an Interface Queue (IFQ)

Table I
MODEL PARAMETERS

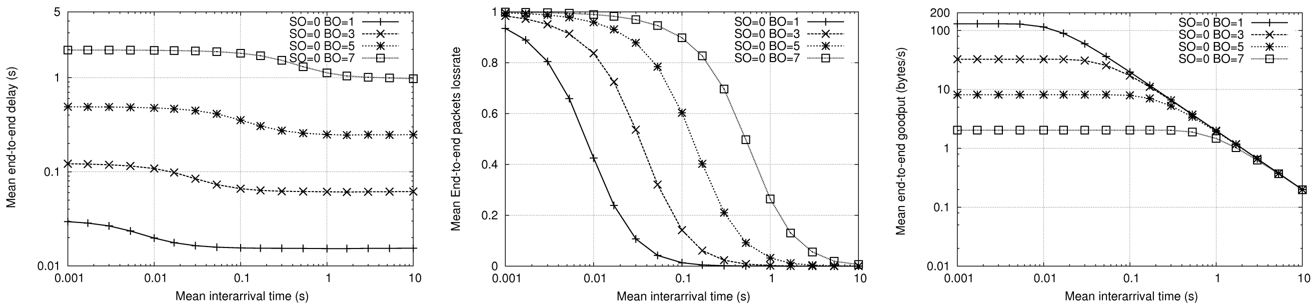
PHY Module Parameters	
Bit rate	$250\,\mathrm{kbit/s}$
Transmitter power	$1\,\mathrm{mW}$
Transmission range	$172\,\mathrm{m}$
Carrier sense sensitivity	$-85\,\mathrm{dB}$
MAC and IFQ Module Parameters	
Synchronization mode	beacon-enabled
Data transfer model	direct with ACK enabled
Traffic Module Parameters	
Traffic type	exponential
Payload size	$1\,\mathrm{byte}$

module that acts as the buffer of the MAC layer [11]. We extensively evaluated the CSMA/CA based operation of the protocol, i.e. the use of the CAP, in [11]. We also implemented and evaluated communications using the GTS-based Time-Division Multiple Access (TDMA) scheme, for which selected results are presented in the following. Table I lists selected model configuration parameters that are fixed in our study. The IFQ size was set to 1. Other internal protocol parameters remain at their default in the IEEE standard.

The performance of IEEE 802.15.4 based star networks for industrial applications is evaluated in terms of three aspects: the end-to-end delay describing the average delay for a single packet from source to sink, the Packet Loss Rate (PLR) summarizing the number of packets dropped by the network (both at the IFQ due to queue overflow and at the MAC due to exceeding the maximum number of retries), and the end-to-end goodput, i.e. the average number of payload bytes received at the sink node per time unit. For each simulation with the same input parameters, we performed at least five independent replications. The simulation time required for each simulation varies drastically with the input traffic and parameter settings, however, it has been chosen long enough to guarantee that more than 5000 packets are received by the sink. In the depicted graphs, the mean value of the selected performance measure is plotted as a single point. Error bars are not shown because the values of the relative standard deviation in the obtained results were always less than $1\,\%$.

Because the original protocol only supports up to 7 GTS slots, we evaluated a simplified scenario to evaluate the standard protocol behavior: one device sending messages to the central sink. In the experiment, the length of the GTS is allocated with a minimal number of superframe slots, which can accommodate at least one complete transaction for transmitting one alarm message with only one byte payload. To study the impact of the protocol configuration, we fixed SO to 0 and explored various BO at 1, 3, 5 and 7. The obtained results are shown in Figure 1.

The measured mean end-to-end delay is shown in Figure 1(a). The saturated value at each curve on the left part of the figure (high network load) represents the maximum delay that the GTS can guarantee for a certain (BO,SO) combination. These maximum delays obtained from the simulations can be easily validated through worst case analysis [4]. Independent of the number of GTSs per superframe, the worst case happens when a message is generated at a device during its own GTS slot, because the device needs to buffer the message until the start of the corresponding GTS in the next superframe. Therefore, the guaranteed maximum delay under the worst case is bounded by the sum of one beacon interval and one transaction duration. For example, for BO=5 the resulting beacon interval (as such the theoretical maximum) is $0.49\,\mathrm{s}$. As shown in Figure 1(a), the saturation area on the curve for BO=5 is at around $0.5\,\mathrm{s}$, is very close to



(a) Mean end-to-end delay (b) Mean end-to-end PLR (c) Mean end-to-end goodput

Figure 1. GTS: end-to-end delay, PLR, and goodput for SO=0 and various values of BO under different traffic loads

this estimated value. Figure 1(b) shows the measured PLR. The curves with larger BO are higher because of the longer inactive period. Since no collision exists in GTS, packets get lost only at the IFQ due to buffer overflow. Furthermore, the goodput is plotted in Figure 1(c). For high traffic load, this is again strongly dependent on the BO, however, for lower traffic load, this metric only depends on the traffic source.

III. Improved Protocol Behavior

In [4], we introduced a more light-weight MAC protocol (which is also the basis for the forthcoming IEEE 802.15.4e standard [5]). In a first step, we removed the restriction to seven GTSs per beacon interval. Additionally, the required minimum CAP and the optional inactive portion have been removed. In this protocol version, BI and SD are no longer determined by (BO,SO) combinations. Since 20 GTSs with a total of $1200\,\mathrm{symbols}$ have contributed the majority of the beacon interval, we further removed the constraint of minimum allocation. Thus, each GTS can be allocated with an exact bandwidth for one complete transaction.

A. Towards IEEE 802.15.4e

In order to achieve better comparability in hardwares, the IEEE 802.15.4 PHY layer is completely preserved. Each superframe consists of an IEEE 802.15.4 compliant beacon, n GTSs and $n+1$ Short Interframe Spaces (SIFSs). All GTSs need to be preallocated to each of the n devices. The frame structure is shown in Figure 2. In the application scenario, only uplink transmissions is assumed. Therefore, an Extra Short Interframe Space (XSIFS) with a shorter length is defined for the interframe space between neighboring GTSs.

In the used star topology, the communication is initiated by the coordinator through broadcasting a beacon frame,

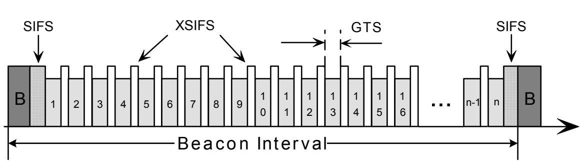


Figure 2. TDMA-based superframe structure

which carries the information of the deployed superframe structure including the beacon interval and the position of the GTS preallocated to each device. Upon reception of the first beacon, each device knows all the settings of the superframe as well as its own GTS and has the following two options:

- *Beacon tracking enabled* – The device keeps in sync with the coordinator through tracking the periodically transmitted beacons. For this purpose, the device has to stay awake a short period of time before the scheduled arrival of each beacon. Upon successful reception of the beacon, it can go back to a sleeping state and wake up again only in its own GTS if it has a message to send.
- *Beacon tracking disabled* – In order to save as much energy as possible, the device can go to sleep immediately after receiving the first beacon. It will wake up again only when a new message is generated. To transmit the message, the device needs first to resynchronize to the coordinator by tracking the next coming beacon. Upon reception of one beacon, the node can locate its own GTS and send the message within this GTS. Afterwards, the node can go back to sleep again.

In all cases, the coordinator has to stay awake all the time to transmit beacons and to receive data from the devices. In industrial applications, such a coordinator is assumed to be sufficiently powered.

Furthermore, the MAC format has been updated in a way to keep the original IEEE 802.15.4 PHY layer for hardware compatibility. Thus, the PHY header with length of $6\,\mathrm{octets}$ needs to be preserved. In addition, the original beaconing mechanism and beacon frame structure remain unchanged in the new protocol version. Instead, we remove the security field, the sequence number, the address information, and the frame control field. The new protocol relies on unacknowledged transmissions and we consider carefully planned industrial environments. Furthermore, all GTSs are preallocated to each device, thus, we can use an implicit addressing mode exploiting the relative position of the GTS in the superframe. The frame control field contains information defining the frame type, addressing

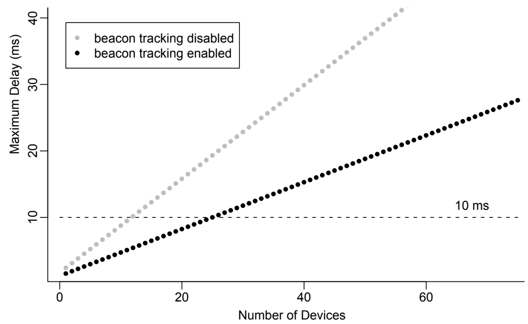


Figure 3. Worst case delays for a varying number of devices

mode control flags, and other control flags, which are no longer required for the simplified mode of operation.

B. Performance Analysis

We evaluated the protocol performance analytically in [4]. Based on these findings, we were able to determine the worst case delay for both beacon tracking enabled and disabled mode. These theoretical bounds are depicted in Figure 3. As can be seen, some certain delay threshold, e.g. $10\,\mathrm{ms}$ can be guaranteed for a maximum number of about 12 nodes for beacon tracking disabled, i.e. energy efficient communication. For beacon tracking enabled mode, about 24 nodes can be supported.

In order to evaluate the average behavior of the protocol, we implemented the new protocol variant in our simulation framework. Thus, we prepared a new set of simulations using the OMNeT++ simulation engine with exactly the same setup. The major difference is the number of simulated nodes. According to the requirements, we are still focusing on a simple star topology, however, we allowed for 20 nodes to be deployed in the field. All the nodes were randomly distributed and, again, we performed at least 5 simulation runs for each individual experiment.

The simulation results are shown in Figure 4. As can be seen from the graphs, there is a bend in all the curves at the packet interval of about 0.01 s. This can be clearly seen in Figure 4(c). This bend is related to the maximum channel utilization.

In Figure 4(a), the end-to-end delay is shown. As expected, the delay for the beacon tracking enabled mode ranges at slightly more than $4\,\mathrm{ms}$ on average, which is clearly below the worst case measure of roughly $8\,\mathrm{ms}$. Even through in real-time environments the average does not count as a basis measure, this observation shows that the channel clearly provides capacities that can be used for non-real-time traffic. For a higher traffic load (the packet interval shorter than 0.01 s), the end-to-end delay drastically increases due to buffering effects. The same trend can be observed for the beacon tracking disabled mode.

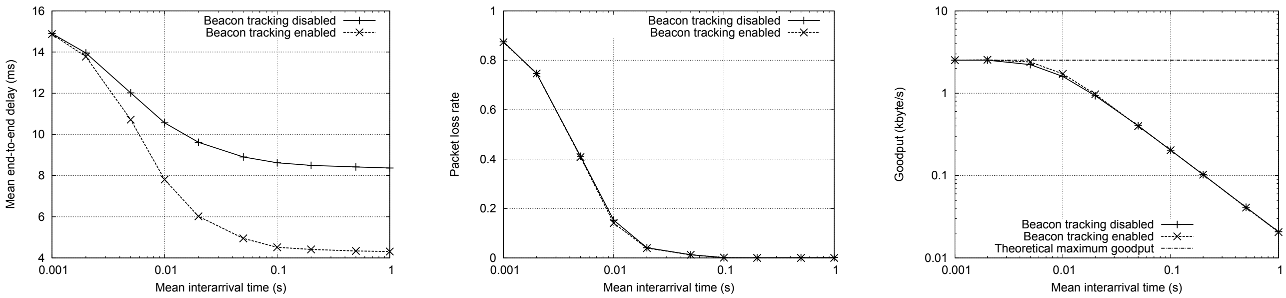
Equally important is the evaluation of the PLR. As shown in Figure 4(b), the PLR is negligible unless the throughput approaches the channel capacity. Therefore, the measures at the packet interval shorter than 0.01 s have to be carefully weighted also for the end-to-end delay measures.

IV. Related Work

Focusing mainly on the performance evaluation of the IEEE 802.15.4 protocol, there have been a number of research activities that utilized evaluation techniques such as experimental lab measurements, analytical calculations, and simulation experiments. An early experiment based on a realistic hardware environment was presented by Lee [12], who investigated the throughput, delivery ratio, and Received Signal Strength Indicator (RSSI) as the primary performance metrics. Using off-the shelf IEEE 802.15.4 radios, Petrova et al. [13] measured the Packet Error Rate (PER) and RSSI both in indoor and outdoor environments. The authors also used the measurement results to calibrate the error model for subsequent simulation experiments.

In contrast, the majority of recently published articles in the context of performance evaluation of IEEE 802.15.4 were based on analytical modeling or simulation based approaches. One of the earliest analytical evaluations of the energy efficiency of IEEE 802.15.4 was performed by Timmons et al. [14] for medical sensors in a body area networking. Concentrated on dense deployment scenarios as studied in the WSN community, Bougard et al. [15] developed a compact analytical model to calculate the average power consumption in a star network of 1600 nodes. Tao et al. [16] proposed a Markov chain model for IEEE 802.15.4 MAC to analyze the saturation throughput. In [17], the performance of the IEEE 802.15.4 GTS allocations has been evaluated for real-time WSNs. Using the analytical *network calculus* formalism, the authors analyzed the delay bounds as guaranteed by one GTS allocation. Kohvakka et al. [18] analyzed a large-scale cluster-tree network in terms of power consumption and goodput analytically. Ramachandran et al. [19] developed a Markov model to analyze the CAP of the IEEE 802.15.4 superframe in terms of throughput and energy consumption.

Most frequently, simulation based approaches have been used, either in the simulation-based performance study of IEEE 802.15.4 or as a validation tool for analytical approaches. Zheng et al. [10] developed a simulation model of IEEE 802.15.4 for ns-2, which they used for a comprehensive performance study. Relying on a simulation model of IEEE 802.15.4 in OPNET, Koubaa et al. [20] analyzed the performance of the IEEE 802.15.4 slotted CSMA/CA mechanism in terms of throughput, delay, and success probability. As an extension to the previous work, Jurcik et al. [21] implemented GTS functions in the OPNET model and investigated the performance of the GTS mechanism in terms of throughput and delay. In our previous work presented in [6], [11], we extended the performance measurements of the protocol to analyze typical communication parameters



(a) Mean end-to-end delay (b) Mean end-to-end PLR (c) Mean end-to-end goodput

Figure 4. New protocol variant: end-to-end delay, PLR, and goodput for beacon tracking enabled / disabled mode

such as the PLR, the end-to-end delay, and the goodput with special focus on the energy consumption for specific scenarios relevant to industrial sensor network applications.

Nevertheless, most of the previously described performance studies focus on typical WSN applications rather than industrial automation domains. Thus, broad performance measures that do not apply to low-latency applications in hard real-time environments are obtained (either analytically or by means of simulation). Similar studies have been conducted for delay-sensitive sensor and actor networks [22].

We now briefly describe and compare those existing simulation models of IEEE 802.15.4 that have been used for the mentioned simulation experiments. The ns-2 model implements most of the functions defined in the specifications, however, according to an obsolete standard version IEEE Std 802.15.4-2003. Furthermore, GTS simulations are not supported in the ns-2 model. The OPNET model was developed within the framework of open-ZB project [23] that aims to provide open source toolset for IEEE 802.15.4 and ZigBee, developed for the OPNET Modeler, which is a commercial network modeling and simulation environment. The OPNET model supports slotted CSMA/CA and GTS in beaconed-enabled star networks. Our new IEEE 802.15.4 model has been developed for OMNeT++ [24], which is a public-source, component-based and discrete event simulation environment and is becoming increasingly popular in the networking community. In contrast to the existing two simulation models in ns-2 and OPNET, our model has been built conforming to the latest version of the standard IEEE 802.15.4-2006 in an open-architecture simulation environment.

V. Conclusion

The main advantage of the improved version of the IEEE 802.15.4 is that the MAC layer keeps the original PHY layer for best hardware compatibility with existing devices. The improvements include a modified superframe structure supporting only GTS allocations and a new data frame format. We studied the protocol performance of this new IEEE 802.15.4 variant that will become available as IEEE 802.15.4e [4], [5]. In order to estimate the protocol behavior, we previously analyzed the worst case delay using an analytical model. In this work, we extended the performance evaluation by studying the protocol behavior in selected simulation experiments. We primarily focused on the analysis of the real-time capabilities of both the standard protocol and the new protocol variant. Additionally, we investigated the packet loss rate and the possible goodput depending on the traffic load. As can be seen from the presented results, the simulation experiments clearly confirm the analytical evaluation. Depending on the traffic load, the delay bounds are clearly kept and no packet loss occurs. However, at some throughput threshold at about 0.01 s for the packet interval, the channel becomes saturated and the delay increases due to buffering effects.

We are currently investigating the communication reliability, which needs to be considered as a similarly important aspect in industrial networks [2], [25]. Reliability is especially of interest w.r.t. signal distribution and channel properties [7]. We are just completing the interconnection of our simulations with more realistic physical layer models based on frequency planning and measurement tools such as SINEMA E [8].

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