Real-Time Wireless Communication in Automotive Applications

Rainer Matischek and Thomas Herndl
Infineon Technologies Austria AG
A-8020 Graz, Austria
{rainer.matischek, thomas.herndl}@infineon.com

Christoph Grimm and Jan Haase
Institute of Computer Technology
Vienna University of Technology
A-1040 Vienna, Austria
{grimm, haase}@ict.tuwien.ac.at

***Abstract*—Wireless communication in a car has several advantages, given that demanded safety and real-time requirements are fulfilled. This paper presents a wireless MAC protocol designed for the needs of automotive and industrial applications. The proposed MAC protocol provides special support for network traffic prioritization in order to guarantee worst-case message delays for a set of high-prioritized nodes. The performance is further analyzed with a network simulator and compared with the IEEE 802.15.4 standard CSMA/CA protocol.**

I. Introduction

A modern car integrates hundreds of electronic sensors and actuators, which are connected via cables with an overall length of up to 4 km. Two major drawbacks of these wired systems are a) limited flexibility of deploying sensor devices because of the necessary cable routing, and b) increased weight and costs. For this reason, scientists are now looking for ways to replace some of these cables by wireless communication, particularly for non-safety critical applications, such as the increasing number of passenger comfort sensors.

In contrast to the research activities carried out during the past decade in the field of "Wireless Sensor Networks" (WSN), the underlying optimization targets, network topology and spatial sensor distribution for the considered automotive application field are quite different. Typical "Ad-Hoc" WSN applications (environmental and structural health monitoring, cp. [1]) share the common criteria that nodes are operated with low duty cycles and are optimized for low energy consumption, thereby trading-off message error rates, throughput and latency. However, these design targets fail to meet the requirements for wireless applications in the automotive field.

II. Motivation

A. Wireless Sensor Networks vs. Automotive Applications

The target application of the presented protocol is an in-car wireless network of non-safety critical sensors and actuators. However, in contrast to existing ad-hoc WSN applications, the use of wireless communication techniques in automotive and industrial systems comes along with special requirements on the communication protocols. Today's automotive communication systems are based on various wired fieldbus systems with different properties in terms of data rate, latency, and prioritization. Consequently, the integration of future wireless sensors into such established wired infrastructure will need comparable mechanisms to support a network of devices with different data rates and latency requirements. This is the motivation for this work to design an adapted wireless medium access control (MAC) protocol for automotive and industrial environments with real-time quality of service (QoS) support.

B. Requirements and Design Criteria

To begin with, a list of wireless communication requirements with focus on automotive applications has been derived. One underlying assumption is that all nodes operate in a single channel ISM band below 1 GHz to support various international radio regulations and to avoid mutual interference issues when using the crowded 2.4 GHz band as discussed in [2]. A second assumption is that many nodes are in an overlapping radio transmission range, due to the relatively small area within a car and the resulting reflections and attenuations caused by the vehicle- and surrounding structure. As we want to avoid complex "code division multiple access" schemes, the presented research project is focused on the optimization of the MAC protocol layer. In the following, some important requirements and design criteria are listed:

Network Topology:

- Star topology: Favored topology for automotive applications, because most of the sensors need to communicate with one central unit
- Alternatively, clustered star topology. However, due to the expected overlapping radio transmission areas, all clustered star subnets still need be coordinated with one common MAC protocol

(Soft) Real-Time Requirements:

- Support for high-prioritized ("high-prio") and low-prioritized ("low-prio") nodes
- Guaranteed maximum delays for some of high-prio nodes by using "time division multiple access" (TDMA)
- Further assumption: Some high-prio nodes either operate with high duty cycle, others might sleep for longer periods, but if activated, they need to transmit within their guaranteed delay (fast slot re-reservation)
- Additional random channel access for a larger number of low-prio nodes, such as by "carrier sense multiple access/collision avoidance" (CSMA/CA) protocols

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Complexity and Communication Overhead:

- Implementation requirements intended for devices with even less hardware features as required for the IEEE 802.15.4 "reduced-function devices" [3]. It should be possible to implement the protocol on special energy- and cost-efficient wireless nodes, which are equipped with a dedicated protocol processing unit instead of a full microcontroller, such as described in [4]
- Minimum additional communication overhead compared to plain TDMA MAC protocol variants
- Reduced control overhead as required for the IEEE 802.15.4 and comparable protocols: Neither dynamic slot sizes, nor dynamic length of control packets (such as dynamic beacon packet length)

As a result, this work proposes a hybrid TDMA/CSMA MAC variant with soft real-time support, which will be presented in the subsequent chapters.

III. Related Work

In the past decade, there has been substantial research on MAC protocols for autonomous operation in systems deployed over a large physical area. Most of these projects have focused on reducing signaling overhead and reducing idle listening time. However, an increasing number of research activities are now additionally investigating real-time and QoS issues in WSNs, due to their practical importance. An overview of these research challenges is presented in [5]. Based on this fundamental analysis, some new approaches have followed recently.

An example of an adapted TDMA variant is discussed in [6], which is optimized for dynamic slot sharing. In order to support dynamic network topologies, this protocol is based on various neighbor detection and schedule exchange algorithms and therefore comes with too much overhead for the intended application. Another comparable adaptive TDMA variant is presented in [7], with the drawback that its virtual time slot management needs CSMA based control messages. In contrast, [8], [9] focus on plain hard real-time MAC features and therefore do not support low-prioritized traffic.

Higher flexibility is achieved by hybrid TDMA/CSMA approaches such as presented in [3], [10], [11]. However, the major drawback of these protocols for automotive applications is their dependence on CSMA/CA based slot reservation and their overhead required for dynamic network management.

IV. Design of the SRTST-MAC Protocol

A. Overview

The protocol presented in this work is called "Soft Real-Time Shared Time Slot" (SRTST) MAC to indicate that it provides soft real-time features by using a shared time slot method. In fact, the protocol as such fulfills hard real-time criteria, but since the underlying wireless transmission is prone to failures, the targeted sensor applications are selected so that the failure consequences are not "catastrophic" [12]. Hence, the overall wireless system rather complies with the definition of a soft real-time system.

As concluded in Chapter II, the primary design target of the MAC protocol is to provide basic quality of service (QoS): The integration of high- and low-prioritized nodes into a common network. Therefore, the presented approach combines TDMA and CSMA/CA mechanisms in a special two-step way.

The main difference of the presented approach to existing solutions is the arrangement and purpose of the time slots. Some existing hybrid protocols distinguish between one contention access period (CAP) and one contention free period (CFP) for collision avoidance. However, one major drawback of protocols such as [6], [10], [11] or the widely used IEEE 802.15.4 [3] is that the reservation (or re-reservation) request for a so-called guaranteed time slot (GTS) relies on a message to be transmitted in the CAP via CSMA/CA.

Consequently, the reservation request of such protocols depends on the current channel utilization and might be delayed for an unknown period (as in the nature of CSMA protocols). This is intolerable for the targeted application scenario, where some nodes are inactive over a certain period but then need service within a guaranteed time interval. This major issue will be further discussed and compared with the presented approach in Chapter V.

B. Superframe Structure

The superframe structure of the SRTST-MAC protocol is depicted in Fig. 1. As common in TDMA protocols, the superframe starts with a synchronization "Beacon" message, which is broadcasted by the network coordinator.

The first TDMA step of the protocol is a short "guaranteed reservation period" (GRP) following the beacon. In this period, all high-prio nodes have their "guaranteed reservation slots" (GRS) at permanently dedicated positions, where they can exclusively transmit a very short reservation request message. The coordinator node owns GRS 0, the high-prio node nr 1 owns GRS 1, etc. In other words, this is a plain TDMA period for the high-prio nodes, which is designed to be as short as possible. In the illustrated examples, there are 8 GRS, one for the coordinator and 7 for high-prio nodes.

After the GRP, the coordinator broadcasts a so-called "reservation bitmap" (RBM) to notify all active nodes within the network, which slots are reserved in this superframe cycle and which of them are free. This mechanism is necessary

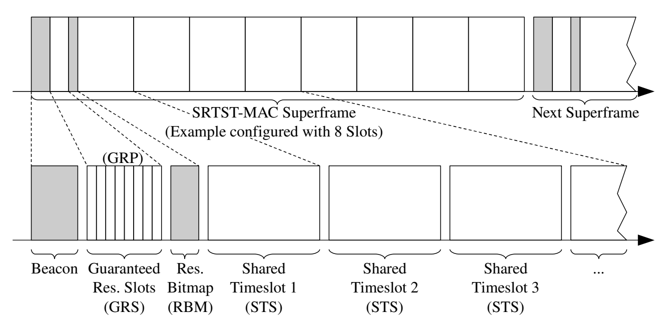

Fig. 1. Superframe Structure of the SRTST-MAC Protocol

because of the asymmetric transmission ranges between the nodes (which would lead to the "hidden node problem"). Not all nodes are within the radio reception range of each other, but it is assumed (and ensured) that all nodes will receive the RBM from the coordinator.

After the RBM period the second and final TDMA step follows, which is called "shared time slot" (STS) period. Each of the successive STS corresponds to a GRS, which means that there is the same number of STS as GRS. Depending on the reservation in the current superframe (received in the RBM), an STS is either exclusively used by a high-prio node for data transmission (TDMA mode) or free for any low-prio node using CSMA/CA mode. For this reason, it is called a shared time slot, because it is shared by TDMA and CSMA transmission nodes.

It is important to note that the superframe additionally includes configurable guard times in between all of the above-mentioned time slots (even between each GRS), in order to tolerate minor time deviations due to clock drift.

C. MAC Algorithm and General Conditions

1) Beacon Frame: In order to reduce the complexity and overhead of the protocol, the length of the beacon packet is constant and as short as possible. In contrast to IEEE 802.15.4, the length is not dynamically growing because of reservation or acknowledgment messages for individual nodes. Since the number of high-prio nodes (number of GRS and STS) is fixed at runtime, the required number of bits for control overhead can be kept constant as well. This limitation is also useful for deterministic worst-case delay analysis.

2) Acknowledgment Mechanism: The acknowledgment information for high-prio nodes is included in the beacon packet, since it is only a bitmap of constant length corresponding to the number of GRS. With only one bit of overhead per high-prio node, this protocol provides a very fast and efficient acknowledgment mechanism, compared to the transmission of separate acknowledgment messages (with additional PHY layer overhead) as used in some related protocols.

Additionally, if the protocol is configured in a way, that only one low-prio CSMA transmission is allowed per STS, then the same bitmap can also be used for the acknowledgment of low-prio nodes. Otherwise, if the configuration allows more than one low-prio transmission per STS, the corresponding low-prio acknowledgment messages are transmitted as a dynamic list in the "downlink" data slot of the coordinator (STS 0).

3) Guaranteed Reservation Slots (GRS): The GRS period directly follows the beacon frame in order to guarantee the least possible time deviation due to clock frequency variations of the nodes, which is important because of the required short slot duration. In fact, the advantage and efficiency of the SRTST-MAC protocol is primarily based on the condition that the duration of the GRS for the reservation is kept as short as possible in relation to the time reserved for the actual data transmission in the STS.

Basically, the transmission of only a preamble (minimum requirement by the transceiver) within the right dedicated GRS would suffice to identify the requesting high-prio node. However, in order to allow for integrity checks, the protocol adds 1–2 data fields to the preamble: A subnet/group-address (not needed for isolated networks) and a binary value which corresponds to the GRS slot number (for 8 slots, 3 bits are sufficient). With this additional information, the coordinator is able to check, if the request is received in the correct GRS and from the correct node before confirming the reservation. It is worth mentioning that the performance of the GRS reservation method can be increased, if the used RF-transceiver device (physical layer) is optimized for fast start-up and frame synchronization, such as described in [13].

4) Reservation Bitmap (RBM): In order to minimize the communication overhead, the RBM frame transmitted by the coordinator only contains the optional subnet/group-address, the actual slot reservation bitmap (the bit length corresponds to the number of GRS), and an integrity check code.

5) Shared Time Slot (STS): A detailed description of the STS structure is depicted in Fig. 2. The slot is shared by high-prio and low-prio nodes and accessed in two ways: High-prio nodes use TDMA transmission and low-prio nodes need to perform a CSMA/CA algorithm. Compared to other hybrid protocols, the STS period can be seen as an interleaved mode of CFP and CAP, instead of dynamically changing the period lengths with the need for re-ordering of time slots (along with increased communication overhead and complexity).

a) High-Prio Transmission: Having the "send-request" received by the upper protocol layer, the node first waits for the next superframe and re-synchronizes via the beacon message. Having its reservation request transmitted in its dedicated GRS, the node waits for the reception of the RBM. Only if the RBM confirms that the coordinator has received the request, the node schedules a wake-up at the time of its reserved STS. Finally, the node treats the reserved slot as a plain TDMA slot and starts the transmission without any clear channel assessment. Fig. 2.a shows the composition of the data frame. It consists of a preamble, the payload length, and a special header field (which also includes the node-address) to indicate the high-prio TDMA message. The integrity of the whole

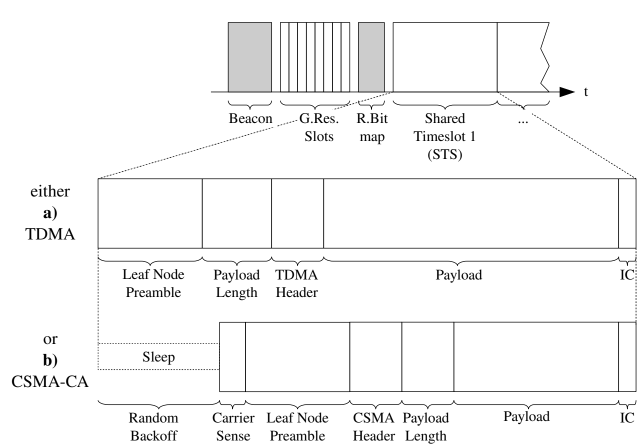

Fig. 2. Structure of the Shared Time Slot (STS)

message including the payload is ensured by an integrity check (IC) field (e.g. a CRC checksum).

b) Low-Prio Transmission: Since all nodes (including the low-prio nodes) are required to transmit in synchronized slots, only a standard CSMA backoff within the short STS period does not suffice to avoid radio collisions efficiently. Therefore, this protocol proposes an alternative 3-step backoff algorithm in order to spread the transmission probability over several time slots, which acts as an analogy to the Non- or P-Persistent CSMA mode (cp. [14]):

- Step1: Superframe selection: Right after the “send-request” of the upper protocol layer (can be at any time within the superframe), the node checks the currently valid RBM if there are still remaining free slots within this superframe. If yes, the first random value decides if the transmission attempt starts in this superframe or in the next one. This mechanism can be compared to a P-Persistent CSMA decision.
- Step 2: STS selection: Depending on step 1, the node either directly uses the current RBM or waits for the RBM of the next superframe. Among the free slots listed in the RBM (“0”), the node selects a random slot number and returns to sleep mode.
- Step 3: Finally, at the start of the selected STS, the node performs a slotted CSMA/CA algorithm in Non-Persistent mode (e.g. IEEE 802.15.4 standard), and transmits the CSMA frame (see Fig. 2.b). The frame format only differs from the TDMA frame in the header information hence the two priority types can be distinguished.

D. Communication Example

An example of the SRTST-MAC network communication is shown in Fig. 3. The example assumes 8 time slots, at which high-prio node 1 owns GRS (and STS) number 1, high-prio node 3 owns GRS (and STS) number 3, etc. All nodes with a number >8 are defined as low-prio nodes.

In the illustrated superframe cycle, nodes 1 and 3 perform a reservation for data transmission and all other high-prio nodes are currently inactive. Consequently, the coordinator broadcasts the RBM with the value “10100000” (1=reserved, 0=free) and both high-prio nodes transmit in their reserved STS 1 and 3.

The low-prio node 9 (see Fig. 3) initially waits for the RBM to check for available slots and in this example, randomly selects to perform a transmission attempt in the STS number 2. In this STS, it starts the transmission attempt by selecting a random backoff time, then performing carrier sensing (CS), and finally starting the transmission (TX) if no collision is detected.

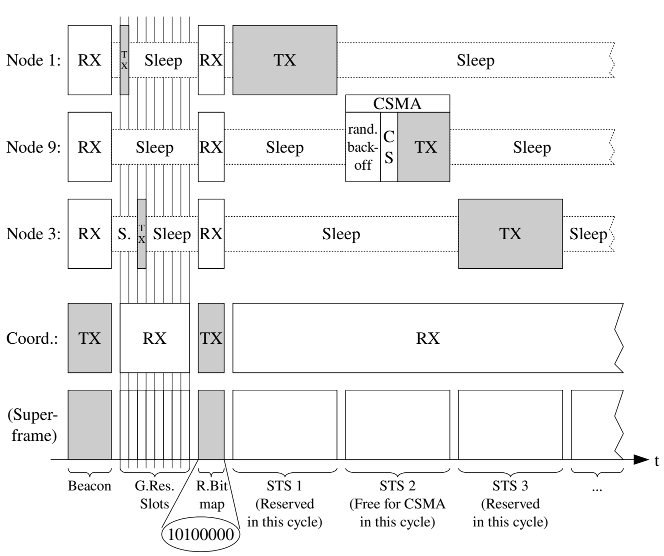

Fig. 3. Communication Example: Nodes 1, 2 (High-Prio), Node 9 (Low-Prio)

V. Implementation and Evaluation

A. Implementation and Simulation Environment

In order to simulate and evaluate the performance of the SRTST-MAC protocol, an appropriate network simulator is required. In the course of this work, the “Power Aware Simulation Framework for Wireless Sensor Networks” (PAWiS) has been selected, as further described in [15]. It is based on the discrete event simulator “OMNeT++” (cp. [16]) with additional features in order to simulate power consumption, wireless communication, noise, and interferences. Particularly the support for dynamically moving or temporarily interfering nodes is important to simulate automotive or industrial environments and therefore was a criterion to select this simulation framework.

B. MAC Configuration and Simulation Scenarios

The simulation scenario is setup with the following target application in mind: In-car wireless network of non-safety critical sensors and actuators with heterogeneous duty cycles and communication requirements. For a few special nodes (single devices or compound sensor arrays), a guaranteed maximum message delay is required (real-time requirement). In the simulation scenario an upper limit of 100 ms is assumed to suffice various high duty cycle applications such as for example servo control (e.g. for the seats or exterior mirror) or parking sensors. Accordingly, the superframe duration of 100 ms has been selected. In order to allow for either low data rates (better robustness against noise) or larger data packets, 8 STS with a duration of 10 ms have been selected.

The corresponding SRTST-MAC superframe configuration is presented in Table I. It has to be noted that the setup assumes

TABLE I
SELECTED SRTST-MAC SUPERFRAME CONFIGURATION

Beacon Duration	6 ms
8 * GRS Duration	1 ms
RBM Duration	2 ms
8 * STS Duration	10 ms
App-Task Duration	4 ms
SuperFrame Duration	100 ms

larger beacon duration in order to reserve additional space for future control fields if needed. Furthermore, an optional "App-Task" period is reserved in which the MAC layer can safely communicate with the application or perform application tasks without interfering or delaying the scheduled MAC time slots (if only a single microcontroller or protocol processor is used).

As a reference for the performance evaluation, another widely used standard protocol has been implemented: The IEEE 802.15.4 MAC [3] protocol in the non-beacon-enabled CSMA/CA mode. This mode has been selected, in order to evaluate the worst-case delays for the dynamic slot reservation, which is located in the contention access period. This comparison is also considered as representative for other related hybrid protocols that rely on plain CSMA/CA for the slot reservation (as mentioned in Chapter IV-A), as this is a critical issue for automotive and industrial applications.

All relevant common simulation settings, which have been used for the protocol implementation, are listed in Table II. Especially the physical layer overhead and the CSMA/CA settings are configured exactly as defined in the IEEE 802.15.4 specification for 100 kbps at 868 MHz. This makes the protocol simulations comparable with each other. The only special setting used in both protocols is an infinite number of retries or backoffs respectively, in order to suppress transmission abort.

C. Simulation Results and Interpretation

The presented SRTST-MAC and the IEEE 802.15.4 standard CSMA/CA MAC have been individually simulated in a network of 20–60 nodes. In both cases, the application layer is identically configured to initiate a MAC-transmission in order to simulate two assumed application scenarios. In order to generate sufficient data for statistical evaluation, the message delays and transmission failures of 60 seconds real-time communication have been logged, whereas the random initialization value (identical for both protocols) has been changed in each simulation run (a feature provided by the OMNeT++ [16] framework).

TABLE II
COMMON SIMULATION PARAMETERS

Physical Layer and Bit Overhead	
Frequency Band	868 MHz
Data Rate	100 kbps
PHY Overhead (Preamble, CRC, etc.)	64 bits
MAC Overhead (16 bit Addresses, etc.)	56 bits
CSMA/CA Configuration	
Random Backoff Exponent	3–8
Backoff Unit Duration	200 μs
Carrier Sense Duration	80 μs
Application Configuration (e.g. in Alarm Mode)	
Payload Length	64 bytes
Transmission Interval of 7 High-Prio Nodes	0.1–0.5 s
Transmission Interval of all Low-Prio Nodes	1.0–2.0 s

The most important comparison criterion is the maximum message delay of high-prioritized nodes (or slot reservation delay in case of IEEE 802.15.4), which in no case should exceed the defined 100 ms. Furthermore, the message delays for the remaining low-prioritized nodes are compared in order to evaluate potential trade-off.

1) Alarm Mode Scenario (Increased Duty Cycle): The first scenario is intended to simulate either an alarm condition in automotive applications (e.g. in case of bad road condition) or any industrial applications with an increased duty cycle (see Table II). Fig. 4 shows a histogram of the message delays in a network of 60 nodes. In all cases the delay of the SRTST-MAC high-prio nodes are below 100 ms and therefore meet the real-time requirements. Although a huge number of CSMA/CA transmissions are below 100 ms, there are already a few outliers with a delay up to 200 ms. The dependency of such outliers on the network density is depicted in the "99.9% quantile plot", shown in Fig. 5. Taken a probability of 1‰ (1000 ppm), the CSMA/CA delays exceed 100 ms at 30 nodes and increasing further on. That means, for example, that a transmission of a sensor in 5-s intervals would fail each

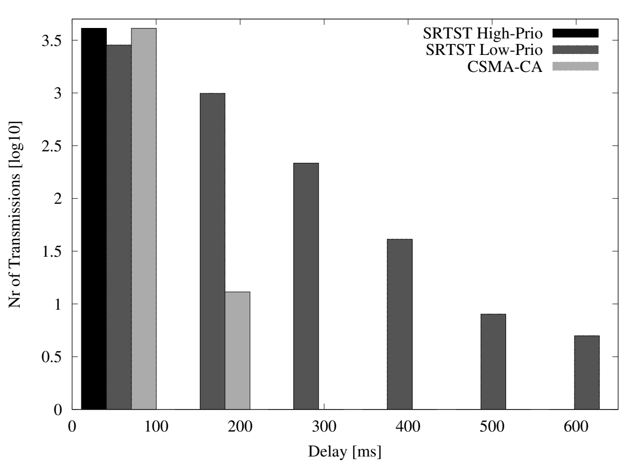

Fig. 4. Histogram of Message Delays, 60 Nodes (7 High-Prio)

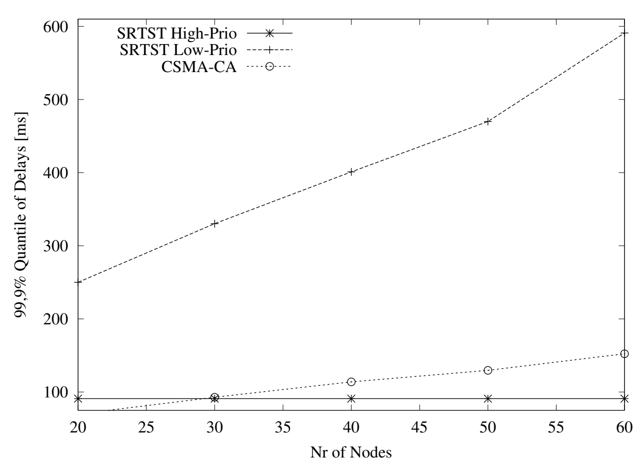

Fig. 5. 99.9% Quantile of Message Delays

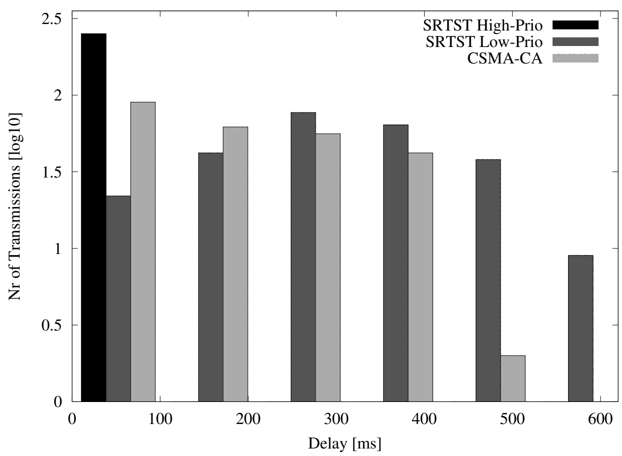

Fig. 6. Worst-Case Comparison, Histogram of Message Delays, 60 Nodes

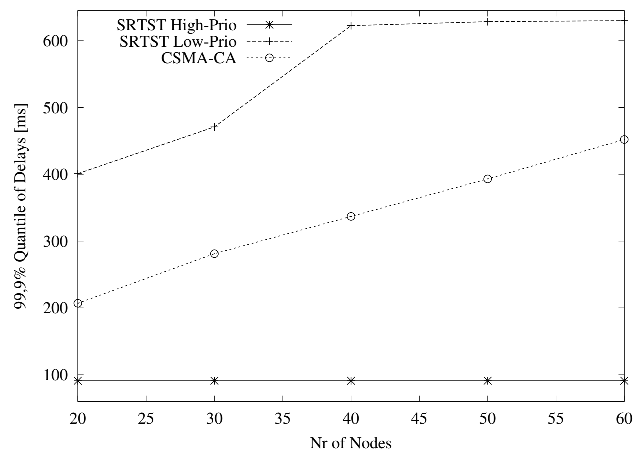

Fig. 7. Worst-Case Comparison, 99.9% Quantile of Message Delays

1.5 hours (just because of the internal network traffic), which is unacceptable for the most targeted automotive applications.

Although the delays of the SRTST-MAC low-prio nodes are significantly higher than the CSMA/CA delays, this is considered as an acceptable trade-off for the 100% guaranteed high-prio delays.

2) Worst-Case Scenario: The second simulation scenario assumes the worst-case: All nodes try to transmit at the same time. Such rare cases could happen, if the nodes were "virtually synchronized" by an external event (e.g. if all vibration sensors react on the same shock) and then start to transmit in the same alarm interval. Fig. 6 and 7 clearly show, that even in this worst-case all high-prio nodes match their real-time limit, whereas the CSMA/CA performance decreases significantly and even approaches to the delays of the low-prio nodes.

It has to be added, that another very recent publication [17], which is dedicated to the performance analysis of IEEE 802.15.4 [3], also concludes that such CSMA/CA approaches are inappropriate for (industrial) applications with stringent real-time requirements.

VI. Conclusion

This work introduces a novel real-time wireless MAC protocol with basic QoS support for high- and low-prioritized traffic in a common network. It ensures a guaranteed worst-case delay for high-prioritized nodes, which is an improvement to existing related hybrid TDMA/CSMA variants. Simulation results for an automotive application scenario have been analyzed and compared with the IEEE 802.15.4 MAC.

Acknowledgment

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