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MEDIUM ACCESS CONTROL FOR WIRELESS NETWORKS WITH DIVERSE REAL-TIME AND RELIABILITY REQUIREMENTS

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I vissa kommunikationsnät räcker det inte att bara leverera data, det är också viktigt att veta exakt när i tiden det kommer fram. Tänk dig till exempel kommunikationen mellan en krockkudde och de sensorer som utlöser den - här är tidskravet helt avgörande! Denna typ av nätverk kallas realtidsnätverk och de förekommer inom många olika områden, inklusive industriell automation, bilindustri, flygsystem, eller robotik. Tidskritisk kommunikation av den typ som krävs av realtidsnätverk är i allmänhet lättare att tillhandahålla i trådbundna installationer. Trådlös kommunikation har dock många fördelar, bland annat ökad mobilitet, minskade kostnader för kablage, samt mer flexibla nätverk. Tyvärr är trådlösa miljöer mer utsatta för störningar och överföringsfel, vilket gör att realtidsfunktioner är mer komplicerade att tillhandahålla. Dessutom behöver fler och fler produkter och föremål koppla upp sig, vilket innebär att system med flera olika sorters tidskrav och krav på tillförlitlighet måste samsas i samma nätverk, och många gånger i nätverk bestående av både trådbundna och trådlösa delar.

Våra vanliga kommunikationsstandarder för trådbundna och trådlösa nätverk (t.ex. IEEE 802.3 “Ethernet” och IEEE 802.11 “WiFi”) har många bra egenskaper i form av hög överföringshastighet och billig hårdvara, men de stödjer inte nödvändigtvis realtidskrav. För att tillhandahålla realtidsgarantier är snabb men framförallt förutsägbar tillgång till mediet helt avgörande. En så kallad medium access control (MAC)-algoritm, som är ansvarig för att kontollera tillgången till överföringsmediet, kan också användas för att minska problem med störningar genom att schemalägga överföringar för att undvika kollisioner, dvs. undvika att flera kommunikationsenheter kolliderar eftersom de försöker sända på samma gång, eller genom att sända om data, som förlorades på grund av störningar.

Denna licentiatuppsats utvecklar och utvärderar flera MAC-algoritmer som lämpar sig för trådlösa realtidsnätverk som används för att kommunicera mellan tillämningar med varierande krav på realtid och tillförlitlighet. MAC-lösningarna är avsedda att användas i den trådlösa delen av ett nätverk bestående av både trådbundna och trådlösa delar. MAC-protokollen utvärderas i termer av "tid att vänta innan tillträde till mediet beviljas", och "overhead som tillkommer pga. protokollet". Vidare utvärderas förmågan hos protokollen att stödja olika typer av datatrafikmönster med olika realtids- och icke-realtidskrav med hjälp av datorsimuleringar. Slutligen föreslår uppsatsen en uppsättning omsändningsscheman som kan användas av MAC-protokollen för att förbättra förmågan att motstå störningar och överföringsfel, och samtidigt kunna tillgodose de givna realtidskraven.

Abstract

Wireless real-time networks are a natural step for deployments in industrial automation, automotive, avionics, or robotics, targeting features such as improved mobility, reduced wiring costs, and easier, more flexible network developments. However, the open transmission medium where wireless networks operate is generally more prone to interference and transmission errors caused by fading. Due to this, real-time communications is in general still provided by wired networks in many of these application fields. At the same time, wired and wireless standards traditionally associated with the consumer electronics application field (e.g., IEEE 802.3 "Ethernet" and IEEE 802.11 "WiFi") are trying to find their way into industrial automation, automotive, avionics, and robotics use cases, since they provide features like high throughput and cheap hardware. Many times, applications with diverse real-time and reliability requirements have to co-exist, and often in hybrid wired-wireless networks to ensure compatibility with existing systems. Given this scenario, it is essential to provide support for data traffic with requirements ranging from real-time time-triggered and event-driven to non-real-time, and enable high reliability with respect to timing constraints, in the context of hybrid wired-wireless networks. This thesis aims at covering the aforementioned requirements by proposing a medium access control (MAC) solution suitable for wireless communications, with support for real-time traffic with diverse time and reliability requirements based on IEEE 802.11. The MAC layer is in charge of providing timely access to the transmission medium, and can be effectively used to increase reliability by means of, e.g., avoiding concurrent transmissions and performing retransmissions. To this end, a set of evaluation criteria is proposed to determine the suitability of a particular MAC method to meet the identified emerging requirements. These criteria include channel access

delay, reliability, protocol overhead, capability to integrate with wired networks, and sensitivity to interference from collocated systems. Next, based on these requirements, a MAC protocol with a set of tunable features is proposed, and evaluated in terms of support for data traffic with different loads and distributions, i.e., emanating from different traffic classes, and from different number of senders. The evaluation is made both analytically, by calculating the worst case delay and, with the help of real-time schedulability analysis, determining the effective load required to guarantee real-time deadlines, as well as by means of computer simulations using the INET framework for OMNeT++ to determine the average delay. Finally, the thesis proposes a set of retransmission schemes to be used together with the proposed MAC protocol in order to improve the resistance against interference and transmission errors. For this, a set of interference patterns with different characteristics is proposed and applied in the simulator. The resulting MAC layer solution is designed to be used at the wireless segment of a hybrid wired-wireless network, and is able to schedule data traffic originating from three different classes: time-triggered, rate-constrained and best-effort. To achieve this, an additional collision domain introducing wireless segments is added to the real-time scheduler, as well as support for real-time retransmissions, to enable high reliability while keeping real-time deadlines.

To my grandmother
Para mi abuela

No hay lección más importante
que la de tu amor incondicional

Acknowledgments

It was a perfect sunny day, lakes and forests were everywhere, and I was about to land in Sweden for the first time. From the beginning, many things looked strange to me, and my days were partly fascinating and at the same time partly unusual. Soon, the days were getting half an hour shorter every week. Winter was coming, and I did not have a cozy apartment to spend it in. However, I had my colleagues at MDH, an amazing group of people from all around the world, who were welcoming and friendly to me from the first day I arrived. Thanks for the time together – without your support nothing would have been the same. I would like to mention at least some names, among the people I had the opportunity to share more time with, so they realize how much I appreciate the time I spent with them. Thanks to Sara Afshar, Mohammad Ashjaei, Matthias Becker, Alessio Bucaioni, Simin Cai, Predrag Filipovikj, Hossein Fotouhi, Mirgita Frasheri, Svetlana Girs, Leo Hatvani, Per Hellström, Ashalatha Kunnappilly, Meng Liu, Nesredin Mahmud, Saad Mubeen, Apala Ray, Mehrdad Saadatmand, Irfan Sljivo, Maryam Vahabi, and others. These people coped with me at work, but a special mention should go to the people who had to stand me at home, i.e., my housemates. Ayhan Mehmed, Guillermo Rodríguez Navas, and Nils Müllner, you were awesome housemates, and Ayhan is triple awesome, because we had to share an apartment not only once but three times! Thanks also to my lovely neighbour in Sweden, Rosario Medina.

* * *

It was a horrible winter day, the snow was everywhere, and I was about to land in Austria for the first time. From the beginning, many things looked strange to me, and my days were partly fascinating and at the same time partly unusual. Soon, the days were getting half an hour longer every week. Winter was leaving, and I did have a cozy apartment to spend it in. It looks like the opposite story to the previous one, but there is one thing that remains, and that is the great group of colleagues that I also have in Vienna. Special thanks to my friends in the project: Marina Gutiérrez, Elena Lisova, Ayhan Mehmed, and Francisco Pozo, and also to the rest of colleagues at TTTech Labs. It is a pleasure to share the time with you every day. Essential is also the support, good guidance, and patience demonstrated by my supervisors Dr. Elisabeth Uhlemann (MDH), Dr. Wilfried Steiner (TTTech), and Prof. Mats Björkman (MDH). I now look back and realize how huge impact it has had on me, with everything I learnt from you. Special thanks also to the people that conceived and administrated the project: Caroline Blomberg, Arjan Geven, Hans Hansson, Christian Reinisch, and Carolina Reyes.

We sometimes do not follow our dreams, because we focus on the difficulties it would require to achieve them. I did not plan to be where I am today, but it is very important to have opportunities come your way, so that you not only achieve your dreams, but you are also able to discover them. I am very thankful to my supervisors, because they trusted me, and thought I was a good candidate to work with this great group of people. However, none of this would have happened without the Marie Skłodowska-Curie actions from the European Union (EU). In today's context, the EU faces many problems, but I hope we do not forget that many of us now have the opportunity to move freely to other EU countries, experience other ways of living, other cultures, meet people, and collaborate in projects like RetNet, which turn into a small, but still a piece of science. I would also like to thank my former and great colleagues at University of Cantabria, and especially my supervisors Mario Aldea Rivas and Michael González Harbour, who helped me take the step that made me end up where I am today.

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Pablo Gutiérrez Peón
Vienna, Austria
October 2016

List of Publications

Papers Included in the Licentiate Thesis[1]

Paper A *Towards a Reliable and High-Speed Wireless Complement to TTEthernet*, Pablo Gutiérrez Peón, Hermann Kopetz, and Wilfried Steiner. In Proceedings of the 19th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Barcelona, Spain, September 2014.

Paper B *A Wireless MAC Method with Support for Heterogeneous Data Traffic*, Pablo Gutiérrez Peón, Elisabeth Uhlemann, Wilfried Steiner, and Mats Björkman. In Proceedings of the 41st Annual Conference of the IEEE Industrial Electronics Society (IECON), Yokohama, Japan, November 2015.

Paper C *Medium Access Control for Wireless Networks with Diverse Time and Safety Real-Time Requirements*, Pablo Gutiérrez Peón, Elisabeth Uhlemann, Wilfried Steiner, and Mats Björkman. To appear in Proceedings of the 42nd Annual Conference of the IEEE Industrial Electronics Society (IECON), Florence, Italy, October 2016.

[1]The included articles have been reformatted to comply with the licentiate thesis layout.

Paper D *Applying Time Diversity for Improved Reliability in a Real-Time Wireless MAC Protocol*, Pablo Gutiérrez Peón, Elisabeth Uhlemann, Wilfried Steiner, and Mats Björkman. MRTC report, ISRN MDH-MRTC-311/2016-1-SE, Mälardalen Real-Time Research Centre, Mälardalen University, September 2016. Submitted to the IEEE 85th Vehicular Technology Conference (VTC-Spring), Sydney, Australia, June 2017.

Additional Papers, Not Included in the Licentiate Thesis

Next Generation Real-Time Networks Based on IT Technologies, Wilfried Steiner, Pablo Gutiérrez Peón, Marina Gutiérrez, Ayhan Mehmed, Guillermo Rodríguez-Navas, Elena Lisova, and Francisco Pozo. In Proceedings of the 21st IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Berlin, Germany, September 2016.

Contents

I

Thesis

Chapter 1

Introduction

It is not easy to imagine today's world without the connectivity provided by well-known technologies like Ethernet and WiFi, for wired and wireless local area networks (LAN) respectively. Data communication networks are found everywhere around us, covering a vast amount of different applications. This deployment has greatly benefited from the development of digital alternatives to previous analogue-only based solutions. Examples of this can be found in, e.g., the transition from analogue to digital phones, and in the replacement of the traditional mechanical control systems with drive by wire systems in cars and airplanes. The use of data communication networks is sometimes the only way to achieve the functionality of a system that consists of several components that are not placed together (e.g., a sensor and an actuator). In other cases, the exchange of digital information is not strictly required, but can provide additional and relevant functionality if compared to the stand-alone system operation (e.g., exchanging traffic information when driving a car). In some scenarios, data communication networks should not only fulfil the basic requirement of exchanging data, but the data also needs to be delivered in time. Networks that have to fulfil time requirements are known as real-time networks.

We find real-time networks in fields like industrial automation [1], automotive [2], avionics [3] or robotics [4], usually included under the umbrella of the operational technology (OT) field. Communications in the OT field is usually characterized by real-time requirements, which are imposed by the need to react to physical world processes that evolve over time. The first attempts to provide real-time capabilities with data communication networks was based on wired technologies, since at that moment the use of cables provided faster speeds, less interference problems, and more security. PROFIBUS [5], for the factory field level, and CAN [6], coming from the automotive industry, are important examples of wired real-time communication technologies still in use. The real-time requirements have also evolved over the years, from supporting only strict time and safety requirements, towards the support of applications also containing traffic with more relaxed requirements using the same communication infrastructure. In the past years, the interest to support wireless connectivity has notably increased, since it comes with a set of distinctive features and advantages. When compared to wired networks, wireless networks are generally easier to deploy and to modify, enable increased mobility, and reduce cost by avoiding the use of wires. In many cases, the adoption of wireless communications has been made by extensions to existing wired technologies [1] [7], creating hybrid wired-wireless networks that take advantage of the best characteristics of both approaches. Unfortunately, some drawbacks still prevent wireless networks from being widely used in real-time environments [8][9], despite the advance in research performed to overcome these issues. Wireless networks suffer from shadowing and multipath fading in a much more severe way than wired networks do. Pathloss is also considerable, and interference can completely destroy the wireless signal. Additionally to the advantages provided by wireless deployments, advantages from using communication technologies in the information technology (IT) field (e.g., Ethernet and WiFi) are also emerging, since these networks are generally capable of providing high transmission rates, and feature low cost hardware. Unfortunately, these communication technologies coming from the IT field commonly lack real-time support. At the same time, communication standards in the OT field are in general not characterized by high transmission rates, support only one specific traffic class (e.g., the WirelessHART protocol [1] for time-triggered real-time communications), and usually target specific deployments, with custom-made expensive solutions. The desired technology combines the best from OT and IT, providing high transmission rates and real-time support with diverse time and reliability requirements.

In communication systems, the medium access control (MAC) layer is in charge of granting access to the transmission medium. In real-time communication systems, the MAC protocol has the additional requirement to provide access to the medium within a bounded amount of time. To maximize reliability when the medium is shared between several potential senders, transmissions should not happen at the same time. A way to guarantee that such concurrent transmissions do not take place is to use real-time schedulers, that allocate the transmissions while keeping the required timing constraints. Once access is granted, the transmission must also reach the receiver with a certain probability to fulfil the timing requirements. Lamentably, the latter is not easy to achieve in wireless networks due to the presence of interference resulting in transmission errors.

1.1 Scope of the Thesis

This thesis presents the design of a MAC protocol intended for wireless communications with support for traffic with diverse time and reliability requirements, i.e., both real-time and non-real-time. The MAC protocol is able to work in the context of a hybrid wired-wireless network. To guarantee real-time deadlines, traffic must gain access to the wireless medium in a predictable way. The thesis proposes to use a traffic scheduler, that guarantees that the management of real-time traffic is possible not only in the wireless segment, but also with traffic to and from the wired segment. Further, the thesis proposes several different ways of handling data traffic, which in turn results in three different MAC protocols with tunable parameters, each one targeting a different set of application requirements varying from completely predictable access to flexible access for traffic with diverse requirements. Once timely access to the wireless medium is achieved, the problem of interference and transmission errors is addressed by proposing measures to increase the reliability of the communication at the MAC level, so that it is suitable for real-time traffic with high requirements on reliability. The proposed MAC schemes together with the associated reliability enhancements have been evaluated using real-time schedulability analysis and computer simulations in INET for the OMNeT++ simulator [10], for different conditions including different traffic loads, different distributions of the load, different types of traffic, and different interference scenarios. The simulations provide valuable information about the performance of the described solutions and the protocol settings with best fit to different scenarios.

1.2 Thesis Outline

This thesis is written as a compilation of papers, and consists of two parts: an overview of the complete thesis (Part I), and the included papers (Part II). The remainder of Part I is structured as follows. Chapter 2 covers the background concepts of the thesis. Chapter 3 provides a review of the related works. Chapter 4 addresses the problem formulation. Chapter 5 presents the thesis contributions and provides an overview of the included papers. Chapter 6 finalizes Part I with the thesis conclusions and future work. The included papers are collected in Part II, from Chapter 7 to 10.

Chapter 2

Background

2.1 Traffic with Diverse Time and Reliability Requirements

The support to traffic with diverse time and reliability requirements using the same network infrastructure implies coping with applications having different levels of timeliness and reliability needs, that must coexist together in the network without compromising the quality provided. Diverse time requirements leads to the classification of traffic according to their need for real-time and non-real-time service. Real-time communication must be present in any application where it is not only necessary that data is delivered, but the instant when it is delivered is equally important. In many cases, this relevance is clearly tied to safety, since safety can be compromised in case the timeliness is not observed. When talking about real-time traffic, two main paradigms are normally considered: time-triggered and event-driven. In the time-triggered paradigm [11], traffic is ruled by the time, so transmissions happen at pre-defined instants, often periodic, in a schedule that is followed by the network devices. This makes the behaviour of the protocol predictable and very easy to verify. In the event-driven paradigm, traffic is ruled by events, and transmissions happen in response to these events. The predictable properties of event-driven networks are more complex to prove, and usually depend on the scheduling policy, that is, the way events interact when using the network resources. Generally, the time-triggered paradigm fits better with applications requiring periodic transmissions, like between sensors and actuators. In turn, the event-driven paradigm is better for applications with sporadic data transmissions, like communication between an airbag and the sensors that trigger it. This event has high priority because it is an emergency, and the amount of time to respond to this event must be upper bounded. Providing networking services to this application under the time-triggered paradigm would generally require the allocation of frequent periodic transmission opportunities, that are not used most of the times since triggering an airbag is a rare event, with resulting bandwidth waste. Real-time traffic has been the traditional focus of OT, while in the IT field, timeliness is not so relevant but more and more often desired. Indeed, flexibility, throughput, and scalability are among the featured characteristics in the IT domain. Merging the OT and IT worlds under a single communication infrastructure is therefore desired. One way to implement different levels of timeliness and reliability is by the definition of traffic classes. With the time-triggered (TT) traffic class, highly predictable communications with low jitter can be provided. Periodic traffic flows characterize this traffic class, that fits better to applications that need to transmit periodically. Note that non-periodic applications can also make use of this traffic class. In the worst case, a non-periodic message arrives at the MAC layer just after a periodic transmission opportunity, so it has to wait until the next opportunity which implies a duration of the period of the TT flow. The rate-constrained (RC) traffic class also supports real-time traffic, but for event-driven data. RC targets real-time applications having an average bandwidth that is not strictly periodic, e.g., video streaming. Finally, the best-effort (BE) traffic class coming from the IT world, does not provide any real-time guarantee for the traffic flows. A proper schedule is the key to allow the different traffic classes to share the same physical transmission medium.

2.2 Networks in the Operational Technology Field

The use of data communication networks in industrial automation, automotive, avionics or robotic environments has from its origin relied on wired technologies [12]. The interest from industry for these networks grew as a result of the transition from analogue-based hardware to digital. Once devices like sensors, actuators or servo drives were able to manage information in digital format, the adoption of data networks to interconnect components was purely a matter of time. Many of the early data communication protocols in the OT field were part of the fieldbus family of standards that includes widely used protocols like PROFIBUS and CAN, which remain very popular today. Real-time guarantees are provided by these protocols ensuring predictable medium access, and highly reliable communications. Although the fieldbus technologies have been able to cover the requirements of OT field applications, they are generally limited by low transmission speeds and lack of flexibility to support traffic with diverse time and reliability requirements. Efforts to improve this have been made through protocol evolutions and developments of completely new protocols like FlexRay, envisioned to be the successor of CAN. On the other hand, technologies coming from the IT domain, with Ethernet being the most relevant example [13], are able to provide high-speed transfer rates but they lack real-time support. The trend is to merge the best of both the OT and IT worlds by providing real-time guarantees at high-speed transfer rates. Examples of this merge are Internet of Things, intelligent transportation systems, and smart cities [14]. To this end, several attempts have been made towards a real-time version of Ethernet [15]. One of them is the Flexible Time-Triggered Ethernet (FTT-E) [16], that supports real-time and non-real-time traffic by dividing time into elementary cycles with synchronous and asynchronous windows. In the synchronous window, real-time traffic is transmitted following the time-triggered communication paradigm. A schedule is used to define the points in time for the transmissions. In FTT-E, the schedule is created by a master node and known by all the participants in the network. Further, the schedule can change at every elementary cycle, if needed. The asynchronous window is dedicated to event-driven real-time traffic, and is sent after being requested by the master node (polling-based mechanism). The Avionics Full-Duplex Switched Ethernet (AFDX) [17] technology comes from the aircraft industry and is based on the use of virtual links (VL) that have a certain amount of bandwidth allocated. The use of traffic shapers guarantees that this bandwidth is not exceeded. Another Ethernet-based technology, Time-Triggered Ethernet (TTE) [18], applies the time-triggered paradigm to provide real-time traffic guarantees, but with additional support for event-triggered real-time traffic. TTE also conveys standard Ethernet traffic without any real-time guarantees. Finally, the more recent Time-Sensitive Networking (TSN) [19] is a set of IEEE technical standards that provides specifications for real-time communication over IEEE 802.3 and IEEE 802.11. This set of standards includes aspects like traffic shaping and stream reservation, that enable real-time communication over Ethernet. The traffic shaper is based on a time-triggered schedule to guarantee that the bandwidth is not exceeded, while the stream reservation protocol is in charge of assuring that transmission paths are reserved along the network.

Although wired networks are able to provide real-time guarantees at high-speed, a remaining step is the use of wireless communications. In OT environments, the adoption of wireless networks can be very beneficial [20]. Wireless networks involve reduced wiring, and this translates into some benefits like reduced costs, easier deployment, and better adaptation for systems with moving components. Interestingly, wireless networks are expected to complement existing wired networks, instead of replacing them [7]. In this context, an approach to adopt wireless access in OT deployments is to use them as extensions to existing wired technologies [8], as done with the HART protocol for sensor networks [1], which was extended with wireless capabilities in the so-called WirelessHART standard. Although WirelessHART provides wireless real-time communication capabilities, the rate is fairly low, and basically only TT traffic is supported.

2.3 Wireless Medium Access Control Protocols

The medium access control protocol is the network component in charge of providing access to the transmission medium. In real-time communication systems, this access must be provided within strict time boundaries. Once access is granted, the transmission must be reliable enough to convey the real-time data with sufficient reliability guarantees. The need to cover these two requirements puts wired technologies well ahead from their wireless counterparts. Mechanisms like the arbitration phase to decide who has the right to transmit, that is the key to provide predictable access medium access in the CAN protocol, can in general not be implemented in wireless protocols because it requires the communication interface to be able to transmit and receive at the same time. Also, wireless channels usually experience higher error rates than wired ones, due to e.g, a higher attenuation than in wires. Shadowing and multipath fading can be prominent in wireless channels, to the point that the signal can be altered or completely destroyed. On the whole, a very important limitation of the link capacity is caused by interference, that can be classified into two groups. First, interference produced by transmissions from other wireless communication devices that can be part of the network or be external. Second, interference produced by unintentional sources of interference like electrical systems (e.g., electrical sparks or microwave ovens), and natural sources of interference (e.g., electrical storms). Given the likely presence of interference, and errors due to shadowing and fading, some of the transmissions can end up in failure. To what extent these failures can compromise the communication is crucial in real-time systems. The use of feedback mechanisms can help the sender to take appropriate measures in case of transmission failures. For example, the automated repeat request (ARQ) mechanisms perform retransmissions based on the received feedback resulting in an increased reliability. However, in real-time systems, care must be taken to limit the number of retransmissions with respect to real-time deadlines.

A very popular MAC protocol both in wired and wireless settings is carrier sense multiple access (CSMA). CSMA is based on sensing the medium, for a time called interframe space (IFS) before transmitting. If the medium is or becomes occupied during the sensing time, the node defers its access until it becomes free again. An additional backoff time calculated from a contention window (CW) is added to avoid that several nodes try to send at the same time when the medium becomes free. This protocol is based on contention and provides a random medium access time. As a consequence, it cannot be used for real-time traffic. Token passing-based MAC protocols can provide predictable access to the medium. Access is granted after reception of a unique token that circulates between the network participants, normally in a round robin fashion. The token approach has important drawbacks, including the overhead caused by the token circulation and the lack of flexibility of the round robin assignment. In polling-based protocols, a message is sent to inform each node when it is allowed to transmit. A centralized controller is generally in charge of sending the polling messages and thereby constitutes a single point of failure. The main drawback of this mechanism lies in the overhead introduced by the polling messages. With time division multiple access (TDMA) protocols, it is possible to provide predictable medium access with generally little overhead. In

TDMA, time is divided into time-slots that are assigned to the nodes following a schedule. The schedule can be created offline and periodically repeated during network operation, or online via a central controller or some mechanism to update the schedule at runtime. To inform the potential transmitters about the possibility to transmit, the schedule can either be handed in advance to them, or a centralized coordinator assigns a periodically reoccurring designated time-slot. A requirement of using TDMA is that nodes need to share the same notion of time, so that the boundaries of the time-slots match between the different nodes. This is normally achieved by a clock synchronization protocol that introduces some overhead.

2.3.1 IEEE Standards for Wireless Local and Personal Area Networks

The wireless standards IEEE 802.11 for LAN and IEEE 802.15.4 for personal area networks (PAN) are behind most of the wireless communication solutions in the OT field [12][21]. Both standards define the physical and MAC layer, with IEEE 802.11 targeting applications that require high throughput, and IEEE 802.15.4 targeting energy-efficient wireless sensor networks (WSN). The success of these technologies is the key to providing cheaper and interoperable hardware. However, in most of the cases, the MAC protocols offered by these standards cannot provide real-time guarantees [8].

The basic MAC defined in IEEE 802.11 is called distributed coordination function (DCF). It is based on CSMA, hence no predictable channel access can be provided. The standard provides an extension to enable predictable channel access by means of a polling mechanism called the point coordination function (PCF), but this architecture has been proved to be very limited to support real-time traffic [22], e.g., polled stations can transmit messages[1] of arbitrary length that will delay subsequent traffic. As a consequence, the IEEE 802.11e standard modification targeting quality of service was developed. This standard version defines the enhanced distributed channel access (EDCA) and the hybrid coordination function coordinated channel access (HCCA) mechanism. EDCA provides traffic prioritization by assigning different values of IFS and CW. Traffic with higher priority will have lower values of IFS

[1] Frames in IEEE 802.11.

and CW than lower priority traffic. Even though EDCA can improve the transmission latency for higher priority messages, predictable access is not ensured, collisions can still occur, and real-time traffic requirements are not supported [23]. In HCCA, transmissions are triggered by polling messages (CF-Poll) sent from a central coordinator. Short interframe space (SIFS) is used to protect transmissions from nodes using the regular value of IFS. In HCCA, the time between two beacon frames is called superframe, and is divided into a contention free period (CFP), in which HCCA is used, and a contention period (CP), in which EDCA is used. The polling phase is over when the coordinator sends a CF-End message. In Figure 2.1, the data exchange between the so-called quality of service stations (QSTA) and a quality of service access point (QAP) is depicted. In the contention period, it is possible that the coordinator initiates controlled access phases (CAP) based on HCCA. With HCCA, predictable medium access can be provided, but the polling mechanism introduces a significant overhead [24]. As for feedback mechanisms in IEEE 802.11, the receiver transmits an acknowledgement (ACK) message after a successful data message reception. If the sender does not receive the ACK, the message is retransmitted, with an upper limit in the number of times this can be done. Therefore, with the ACK mechanism, the probability of a successful delivery of messages is increased, but a guarantee is not given in terms of time boundaries due to the uncertain number of retransmissions. Additionally, the ACK mechanism only applies to unicast frames, so in practise broadcast and multicast frames are less likely to be delivered.

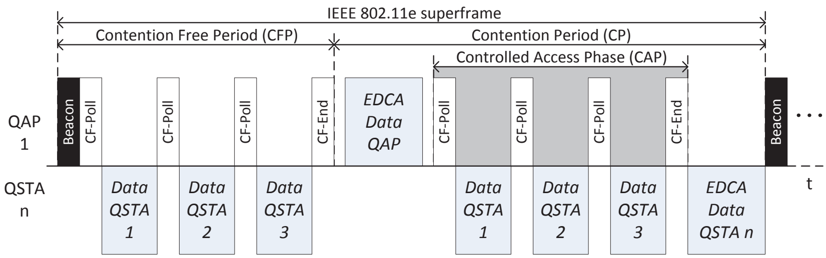

Figure 2.1: HCCA superframe.

The IEEE 802.15.4 standard is also based on CSMA, but comes with a non-mandatory feature called Guaranteed Time-Slots (GTS) as an attempt to provide predictable medium access. The GTSs are transmission slots granted to the nodes, based on the requests sent by the nodes to a coordinator. To notify the specific assignment of GTS, the beacon frame is used. However, since the GTS requests are performed via messages sent using CSMA, it is not sure that the requests will be successful, so access to the channel is not always guaranteed. The GTS mechanism is a contention free period, that is used in conjunction with the controlled access period (CAP) (Figure 2.2). In the CAP, nodes use CSMA. Given that energy efficiency is a key issue in WSN, the IEEE 802.15.4 standard also provides an optional inactive period, in which nodes sleep and do not perform any transmission or reception.

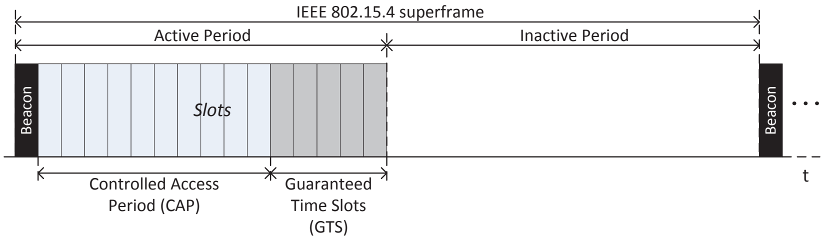

Figure 2.2: IEEE 802.15.4 superframe.

Chapter 3

Related Work

3.1 Predictable Wireless Medium Access Protocols

Extensive research has been performed to provide guaranteed access, i.e., access is predictable and granted within a bounded time to the wireless medium, using IEEE 802.11 hardware. The most common approach is to add an additional MAC protocol on top of the standard CSMA. Moraes et al. [25] present a token passing approach for IEEE 802.11. To protect the traffic from external CSMA transmissions, the highest priority EDCA is used, while external nodes are expected to use the regular priority level. However, token-passing protocols have important drawbacks, including the token circulation overhead, and the need to run a procedure to restore the token every time it gets lost. Son et al. [26] present a polling MAC with a dynamic adaptation mechanism that adjusts the number of polling messages sent to each node depending on the history of previous data and empty messages sent by the node. Unfortunately, the polling messages introduce a noticeable overhead. Cicconetti et al. [27] focus on improving the admission and scheduling algorithms of HCCA, proving that better performance can be achieved, when the admission and scheduling algorithms are designed to fit specific use cases. Trsek et al. [28] present the IsoMac TDMA approach (Figure 3.1). In IsoMAC, the time between two beacon frames is divided into a scheduled and a contention phase. The scheduled phase is in turn divided into time-slots, that are assigned based on the requests sent by the nodes to a coordinator. The schedule defines a downlink (DL) and an uplink (UL) phase, and is conveyed using the beacon frame. Prioritization with respect to legacy DCF traffic is achieved by means of separating the frames with SIFS instead of DIFS. The feedback is based on ACK messages, as in IEEE 802.11. However, these are not sent in the same way as in the standard, but the acknowledgement of downlink messages is postponed until the uplink phase. Regarding the uplink messages, these are not acknowledged, but the coordinator uses the information contained in the schedule to detect failed messages. IsoMAC outperforms standard IEEE 802.11, specially regarding communication jitter. Unfortunately, the schedule is created after feedback provided via contention, with best-effort (BE) and management (M) messages, which implies that the chance to use time-slots is not guaranteed.

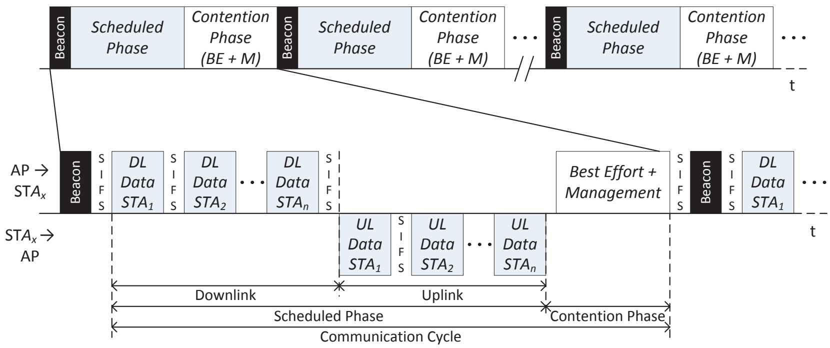

Figure 3.1: IsoMAC channel access [28].

Wei et al. [29] present a TDMA protocol with online allocation of time-slots based on the requirements specified by the nodes when joining the network. The schedule is conveyed using the beacon frame, with the specific scheduling policy left open to be chosen by the user. Feedback about the success of a transmission is sent inside the time-slot. Retransmissions can be set to happen inside the slot, or in a different slot if there is a free one. Latencies are decreased with respect to the standard DCF, and the packet loss ratio is improved for real-time traffic in the studied office scenario, where interference can be considerable. Another TDMA protocol is presented by Costa et al. [30]. In this paper, the time dedicated for high priority traffic is divided into time-slots, in which access is performed using a higher priority class from EDCA than legacy traffic. A feature of this protocol is that it allows direct transmissions between the nodes, avoiding to make them through the access point. However, predictable access is not guaranteed due to the use of EDCA. The work from Jonsson et al. [31] presents a MAC protocol for IEEE 802.11 based on keeping a control channel where the nodes exchange information about their requirements. Based on this requirements, all nodes build an earliest deadline first (EDF) schedule for the data exchange.

Several other MAC protocols have been proposed for WSN following similar approaches, but with the additional focus on energy efficiency. However, targeting energy efficiency generally implies the drawback of having low transmission rates. One of the most relevant protocols is WirelessHART [1], originated after extending the wired HART fieldbus protocol with wireless capabilities. WirelessHART is a multi-vendor, inter-operable wireless standard for secure and reliable industrial communications, that is based on IEEE 802.15.4. WirelessHART follows a TDMA scheme, in which part of the time-slots are pre-assigned following the time-triggered paradigm, and a subset of the slots can be accessed dynamically though contention. However, as mentioned above, WirelessHART mainly targets TT traffic and the transfer rate is rather low. The work by Kim et al. [32] presents RRMAC, a TDMA protocol that executes a superframe structure between beacon frames, with contention-free and contention access periods. Similarly to other MAC protocols in wireless sensor networks, there is an additional inactive period where nodes do not communicate in order to save energy. Time-slots are assigned to every node during the contention phase, and therefore access is not guaranteed as contention may prevent a node from getting access to a time-slot. In the work from Afonso et al. [33], the authors present another example of a TDMA protocol with contention and contention-free phases, and a beacon to convey the schedule. In this protocol, retransmissions are used to increase the reliability which take place in the contention-free period. The dual-mode real-time MAC protocol by Watteyne et al. [34] presents an approach that avoids collisions and involves relaying, but requires the nodes to know their position to decide when to relay. In WSN, it is also common to adopt certain strategies to collect data in a more efficient way. In the specific case of RRMAC, the communication between nodes follows a tree structure, in where the nodes aggregate the data sent by their connected branches.

3.2 Reliability at Medium Access Control Level

Several papers have shown the relevance of increasing the reliability in IEEE 802.11 and IEEE 802.15.4. Apart from the fact that errors due to fading is a major reason for reduced reliability in wireless communications, the operation of several different wireless technologies in the license-free industrial, scientific, and medical (ISM) radio band is a major source of interference. This problem of interference is not restricted to overlapping channels, but it can also be relevant in the case of collocated channels, as found in the work from Lo Bello et al. [35] regarding the IEEE 802.15.4 standard. Also, unintentional interference is present in wireless channels, sometimes to the extent that transmissions are compromised [36][37]. Nevertheless, the use of contention-based MAC protocols is a substantial cause, as shown by Anastasi et al. [38]. In this paper, the authors show that better delivery ratios can be achieved by carefully selecting the MAC parameters settings in IEEE 802.15.4, i.e., the contention window, the backoff values, or the number of retries. Similar conclusions can be derived for IEEE 802.11, as shown in the article by Seno et al. [39]. In this paper, the authors explain that the backoff procedures and the retransmission mechanism of IEEE 802.11 are the main reasons for the lack of support for real-time deadlines.

Retransmissions are a common approach to improve reliability. The way to perform these retransmissions has been well covered in literature, but with major differences in aspects like how to schedule retransmissions or the actual number of retransmissions needed. The first factor greatly depends on the scheduling policy used for regular traffic, while the latter is tied to the specific scenario, and its corresponding interference pattern. In the IEEE 802.11 standard, retransmissions are just enqueued to happen as soon as the medium is free to transmit. The number of retransmissions required to achieve a certain reliability level is a very important parameter, since it can also provide bounds on the time required to convey messages. The work by Dominguez et al. [40] is focused on characterizing the behaviour of retransmissions in IEEE 802.11, showing that in most of the cases just one retransmission attempt is enough in the factory floor scenario they study. The authors also show that small frames, which are the ones usually found in industrial networks, result in fewer retransmissions. The effect of retransmissions under different real-time scheduling policies is also a common problem in literature. Jonsson et al. [41] develop a real-time schedulability analysis for the EDF scheduling policy that takes retransmissions into account. Seno et al. [39] also propose to use EDF scheduling policy. The scheduler is run by a centralized coordinator that polls the nodes when they are allowed to transmit. The authors also investigate the IEEE 802.11 mechanism called multi-rate support, that allows the nodes to tune the transmission rate to the signal-to-noise ratio (SNR). A reduced transmission rate is generally preferable when the SNR is low. However, changing the transmission rate depending on the SNR can compromise the real-time behaviour. Retransmissions can also be applied to TDMA protocols. Willig et al. [42] extend this problem to include retransmissions from relaying nodes, by proposing various heuristics that solve the scheduling problem within computational and memory constraints. The article by Berger et al. [43] targets reliability in WSN by proposing a TDMA protocol with two variants. In the first one, several samples are sent in one packet. If the packet is lost, it is enqueued to be retransmitted later. A packet is also lost when the retransmission queue is full and has to leave room for new packets. Therefore, the instant when to perform a retransmission is random, and the protocol is not suitable for real-time settings. To overcome this, the second alternative is based on bounding retransmissions to happen inside a longer time-slot. In the work presented by Demarch et al. [44], the HCCA mechanism from IEEE 802.11 is used. This work introduces a new mechanism, the Integrated Scheduling and Retransmission Approach (ISRA). Reliability is targeted by a probabilistic estimation of the number of retransmissions that each node needs. Transmissions and retransmissions use HCCA to get protection against CSMA-based traffic. Retransmissions can happen in two ways: immediately after the transmission, or deferred to happen later. The approach for increased reliability in WirelessHART is to schedule two time-slots for every transmission, and a third time-slot where a transmission using an alternate route is required. ACK is used, but only to save energy, so the slot remains empty.

The use of feedback to trigger retransmissions is also a common practise, but it is not always available. This is the case of some WSN devices with a simplex (only capable of sending) transmission interface. In the absence of feedback, retransmissions can be scheduled to always happen. In the work by Parsch et al. [45] a novel MAC protocol for WSN with simplex transmissions is presented, where ACKs cannot be sent. The authors estimate the number of retransmissions needed, based on the probability of interference and the desired reliability level.

Chapter 4

Problem Formulation

4.1 Research Problem

The adoption of wireless real-time communication systems in the OT field will bring the advantages of reduced wiring, flexible and easier deployment, as well as mobility capabilities. Wireless hardware standardized by IEEE 802.11 is successfully used in IT environments for reasons like its flexibility, high throughput, and low cost. However, WiFi standards cannot be used as they are for applications with real-time requirements due to the unpredictable MAC scheme. As a consequence, the support for real-time and non real-time traffic under the same wireless communication infrastructure is not possible with regular IEEE 802.11. Also, emerging applications demand traffic with diverse time and reliability requirements, expressed in the form of traffic classes ranging from time-triggered and event-driven real-time traffic, to non-real-time traffic. Additionally, this support is required to happen over hybrid networks with wired and wireless segments, in which traffic is able to be transmitted on any of the segments to reach the destination. The fundamental key to solve this problem resides on the link layer, since it contains the MAC protocol which gives access to the transmission medium, and can provide solutions to the problem of reliability, e.g., by the support of retransmissions that should co-exist with the original traffic without compromising deadlines.

The aforementioned requirements are only partially covered by the technologies described in Section 3. Some of the MAC protocols are based on token passing or polling, and are inefficient due to the significant overhead. Other protocols are able to build a schedule for predictable medium access, but the schedule is built by using contention-based MAC. Similarly, the protocols based on EDCA are not able to provide predictable medium access. Further, WSN protocols are not suitable to fulfil high throughput demands, due to their requirement of low power consumption. Finally, most of the protocols that exist today do not provide support to traffic with diverse time and reliability requirements, and cannot co-exist with a wired protocol.

4.2 Research Hypothesis

The work in this thesis is built on the following hypothesis: It is possible to develop a wireless medium access control protocol using IEEE 802.11 hardware that provides access to the transmission medium within time boundaries for both time-triggered as well as event-driven real-time traffic, and with support also to non-real-time traffic, all in the context of a hybrid wired-wireless network. It is possible to provide solutions for increased reliability based on this protocol, so that the network can still comply with the real-time requirements even in interference and error-prone environments.

4.3 Research Questions

From the presented research hypothesis, the following research questions are derived and need to be addressed to deal with the stated problem.

- RQ1. How can we provide support to high rate transmission of traffic with diverse real-time and reliability requirements under the same network infrastructure, so that they are able to co-exist, also in the context of a hybrid wired-wireless network?
- RQ2. How to provide sufficient reliability level, while keeping real-time deadlines in interference and error-prone scenarios?
- RQ3. What criteria must be used to evaluate the validity of the targeted solution with respect to the requirements? What scenarios (i.e., traffic load, interference level, etc.) are suitable to test the requirements?

4.4 Research Method

In order to formulate the research problem, the deductive research methodology was adopted. The deductive approach formulates the hypothesis based on the existing theories. For that, the literature related to predictable wireless medium access protocols was reviewed. This literature included scientific papers, as well as communication standards that serve as ground for many of the studied protocols. Later, the MAC protocol solution was formulated as a solution to the problem.

The solution was validated though calculations, using the schedulability and worst-case analysis techniques for communications with timing constraints. Additionally, the solution was tested using a simulation tool that was chosen after reviewing several of the commonly applied simulation tools for wireless MAC protocols. The selection of the scenarios to simulate was founded based on the combination of other examples found in literature, discarding scenarios that did not result in anything interesting i.e., no notable difference between scenarios, and talking to experts in communication networks both at the Mälardalen University and at the company TTTech, where the industrial PhD studies are held. To validate the results from the simulation of the MAC protocols, they were compared to the worst-case analysis, by artificially forcing the specific conditions at which the worst-case happens (e.g., messages from all sources that have to be sent all at the same time in the simulator). Additionally, the compliance of the simulation results with the protocols operation was checked. For this, the simulation logged all relevant events (e.g., channel sensing, transmission start and end), and a tool was developed to verify the correctness of the events in terms of applicability (is channel sensing valid in TT slots?), timing (is this transmission time according to the transmission rate?), and order (receive only after the transmission is done). More information about the developed simulation can be found in [46]. When the solution did not fulfil the requirements, or when new requirements appear, it was modified and tested again. Results were published and peer-reviewed by experts in the area.

Chapter 5

Thesis Contributions and Overview of Included Papers

The thesis presents three main contributions that address the research questions formulated in Section 4.3. The thesis contributions are outlined in Section 5.1, in the same order they were developed, given that each contribution builds upon the previous one. The contributions are distributed along four papers, from which an overview is given in Section 5.2. For mapping between papers, thesis contributions, and research questions, refer to Table 5.1.

5.1 Thesis Contributions

5.1.1 Contribution 1: Identification of the Need for a Wireless Complement to Time-Triggered Ethernet

The first thesis contribution is an outcome of the state of the art overview, performed with the objective of finding a high-speed wireless complement to TTE. It presents the introduction to the general problem, that is, the support for TT, RC and BE in wireless networks, coexisting with wired ones. The problem is narrowed down to the definition of collision domains, both in wired and wireless networks, in which concurrent transmissions should not take place to enable real-time guarantees. It is proposed to use IEEE 802.11, due to its high throughput and compatibility with Ethernet. Given that standard IEEE 802.11 does not provide real-time guarantees, or when provided it is done so with a considerable overhead, possible solutions are investigated, resulting in proposing to use a MAC scheme based on TDMA over CSMA that satisfies the requirements of predictable channel access, and fits with the time-triggered communication paradigm employed by TTE. This contribution is presented in Paper A, and partially answers RQ1.

5.1.2 Contribution 2: A MAC Protocol for Wireless Communications with Support for Traffic with Diverse Time Requirements

This thesis contribution first develops a set of evaluation criteria to determine the suitability of a particular MAC method to meet the requirements outlined in Contribution 1. These criteria include protocol overhead in terms of time left for BE, channel access delay, reliability, hardware requirements, integration with the wired network, and resistance to different types of interference. Then, a set of TDMA MAC protocols is developed intended for wireless access, able to support traffic with diverse time and reliability requirements by means of the three traffic classes of TTE: TT, RC and BE. The allocation of real-time traffic (TT and RC) is performed by the TTE scheduler, updated with additional constraints to model the wireless broadcast domain. The remaining time after allocation of real-time traffic is left for non-real-time traffic (BE). The MAC protocols are evaluated in terms of the identified criteria. Also, schedulability analysis is used to find protocol overhead in terms of time left for BE, and worst case channel access delay. The results proved that the protocols are able to provide predictable access to all scheduled traffic.

This contribution also includes a simulation of the MAC protocols in INET for OMNeT++. For this, the concept of collision domains in the TTE scheduler is formally introduced, and the scheduler is adapted to cover the requirements of the wireless broadcast domain. The simulation tests the protocol alternatives under different traffic scenarios, that include varying the total traffic load, the ratio of each type of traffic in the total load, and traffic emanating from only one node, or from all. The simulation provides results on the channel access delay and the number of collisions. This contribution is presented in Paper B (analytical study) and Paper C (simulation), and answers RQ1 and partially RQ3.

5.1.3 Contribution 3: A MAC Protocol for Wireless Communications with Support for Traffic with Diverse Time and Reliability Requirements

This thesis contribution takes the work from Contribution 2 and explores its limitations with regards to providing real-time guarantees under interference scenarios. For this, the MAC protocols developed in Contribution 2 are revisited, and their performance with respect to real-time deadline miss ratio is measured by simulations. The suggestion of a set of relevant interference scenarios, including CSMA and jamming, and different durations and intensity of interference, is also part of the contribution. In addition, a mechanism for improved reliability through retransmissions, which are scheduled using an updated version of the TTE scheduler, is proposed. The simulation results account for the percentage of failed packets, time left for BE traffic, and MAC to MAC delay. An outcome of this contribution is the proper selection of a reliability mechanism valid against different types of interference. This contribution is presented in Paper D, and answers RQ2 and partially RQ3.

Table 5.1: Mapping between papers, thesis contributions, and research questions.

Paper	**Thesis Contribution**	**Research Question**
A	TC1	RQ1
B	TC2	RQ1, RQ3
C	TC2	RQ1, RQ3
D	TC3	RQ2, RQ3

5.2 Overview of Included Papers

5.2.1 Paper A: Towards a Reliable and High-Speed Wireless Complement to TTEthernet

Authors:

Pablo Gutiérrez Peón, Hermann Kopetz, and Wilfried Steiner.

Summary:

In this paper, the state of the art in deterministic wireless communication approaches is reviewed. The paper presents quality criteria for wireless networks taken from industrial use cases, and outlines candidates for a wireless complement to wired TTEthernet.

Contributions:

TC1.

Research questions:

RQ1.

Author's contribution:

The author was the main driver of the paper and wrote most of the text. Furthermore, the author performed the state of the art review, and proposed the use of IEEE 802.11 hardware for a wireless extension to TTEthernet, outlining possible MAC protocol candidates.

Status:

Published in Proceedings of 19th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Barcelona, Spain, September 2014.

5.2.2 Paper B: A Wireless MAC Method with Support for Heterogeneous Data Traffic

Authors:

Pablo Gutiérrez Peón, Elisabeth Uhlemann, Wilfried Steiner, and Mats Björkman.

Summary:

Three MAC protocols, named 1, 2, and 3, are proposed, each one able to deal with three different traffic classes: TT, RC and BE. In particular, the three protocols differ in the way they handle the time left for BE traffic, but still with the objective of eliminating or reducing collisions, and maximizing the amount of traffic supported. Protocol 1 divides the remaining time into time-slots that are assigned in a round-robin fashion. This allows predictable access also for BE traffic, but with a potentially long minimum delay. Protocol 2 also assigns slots offline in a round-robin fashion, but in case the slots are not used by the assigned prioritized node at runtime, the rest of the nodes having BE traffic to transmit can try to get it through contention. This allows predictable access, with a chance for low delay, but each slot has to be made longer to account for contention. Protocol 3 does not strictly use slots for BE, but merges all consecutive BE slots into phases that are accessed through contention. This does not allow predictable access for BE but is good when the data traffic is unevenly distributed between the senders, or changes rapidly. The protocols are evaluated with a set of evaluation criteria, including e.g., channel access delay, required hardware, protocol overhead and resistance to interference.

Contributions:

TC2.

Research questions:

RQ1, RQ3.

Author's contribution:

The author was the main driver of the paper and wrote most of the text. Furthermore, the author proposed the three MAC protocols, and the set of criteria that was later used to evaluate the protocols.

Status:

Published in Proceedings of 41st Annual Conference of the IEEE Industrial Electronics Society (IECON), Yokohama, Japan, November 2015.

5.2.3 Paper C: Medium Access Control for Wireless Networks with Diverse Time and Safety Real-Time Requirements

Authors:

Pablo Gutiérrez Peón, Elisabeth Uhlemann, Wilfried Steiner, and Mats Björkman.

Summary:

The protocols presented in Paper B are further refined, so that protocols 2 and 3 are offered in two versions. In Protocol 2, different contention windows sizes are used, one that only allows a backoff value of 0 (Protocol 2A), and one that allows a larger value (Protocol 2B). As for

Protocol 3, the alternatives are related to storing of the backoff value between phases. Protocol 3A stores the backoff, while Protocol 3B does not. A simulator in INET for OMNeT++ is developed, and provides results in terms of average access delay and packet collisions as a function of different protocol settings and traffic patterns. As for BE traffic, it is shown that Protocol 1 is predictable, whereas Protocol 3 is more flexible dealing with different types of traffic. When no characteristics about BE are known, Protocol 2 stands out as the best possible option.

Contributions:

TC2.

Research questions:

RQ1, RQ3.

Author's contribution:

The author was the main driver of the paper and wrote most of the text. Furthermore, the author was the main contributor in the proposal of the refined MAC protocol alternatives. The author also developed the simulator, and introduced the different traffic patterns that defined the simulation scenarios from which the results were obtained.

Status:

To appear in Proceedings of the 42nd Annual Conference of the IEEE Industrial Electronics Society (IECON), Florence, Italy, October 2016.

5.2.4 Paper D: Applying Time Diversity for Improved Reliability in a Real-Time Wireless MAC Protocol

Authors:

Pablo Gutiérrez Peón, Elisabeth Uhlemann, Wilfried Steiner, and Mats Björkman.

Summary:

In this paper, two retransmission schemes for improved reliability for MAC protocols supporting traffic with diverse time requirements are presented and simulated. Protocol 1 does not use feedback and thus have shorter slots implying less overhead, while in Protocol 2 slots include time for feedback and contention. The two protocol versions are offered both with retransmissions located consecutively after the original transmission, or delayed towards the deadline. The protocols are simulated for a set of relevant interference scenarios, and evaluated in terms of failed message transmissions, time left to be used by BE traffic, and average MAC to MAC delay.

Contributions:

TC3.

Research questions:

RQ2, RQ3.

Author's contribution:

The author was the main driver of the paper and wrote most of the text. Furthermore, the author proposed the development of the retransmission schemes, and implemented them in the simulator. The author also suggested a set of relevant interference scenarios that serve to test the retransmission schemes. The results show that different protocol settings can be successfully applied to combat different kinds of interference to improve transmission reliability and timeliness.

Status:

MRTC report, ISRN MDH-MRTC-311/2016-1-SE, Mälardalen Real-Time Research Centre, Mälardalen University, September 2016. Submitted to the IEEE 85th Vehicular Technology Conference (VTC-Spring), Sydney, Australia, June 2017.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The real-time communication requirements of OT applications have originally been covered by wired technologies. The advantages provided by wireless communications could not be exploited in these scenarios, due to lack of reliability and timely access to the transmission medium. To overcome this, the approach used in this thesis was to take advantage of the successful combination of Ethernet and IEEE 802.11 in the IT field, and proposing the extension of a real-time wired technology based on Ethernet, TTE, with IEEE 802.11 hardware. To perform this extension, the MAC protocol is crucial, since it is in charge of providing access to the transmission medium. Given the lack of real-time guarantees of the standard IEEE 802.11 MAC, a new MAC protocol was presented in this thesis work. This MAC protocol adopts the traffic classes of TTE, enabling support for both time-triggered and event-driven real-time traffic, coexisting with non-real-time traffic. A scheduler is in charge of guaranteeing real-time characteristics to time-triggered and event-driven traffic in TTE. In this thesis, the TTE scheduler was extended to provide predictable medium access also in wireless segments. As for the non-real-time traffic, three MAC protocol versions were proposed, that provide different levels of determinism versus flexibility to this kind of traffic.

A schedulability analysis, together with a comparative study of aspects such as delay, reliability, and efficiency was performed. Additionally, a simulation using the well-known network simulation tool INET for OMNeT++ was developed, in order to demonstrate the ability of the MAC protocols to handle different types of traffic with different patterns and protocol settings, and evaluate the average channel access delay, and the provided reliability. It was shown that depending on the application needs, a protocol version providing either predictability or flexibility can be used. Once medium access is granted, the transmission may suffer interference and other errors, that can compromise the reliability. To this end, the simulation was extended in order to test the proposed MAC schemes under different interference scenarios. It became clear that countermeasures were needed in order to increase reliability, and to this end two alternative mechanisms based on retransmissions were proposed. For this, the TTE scheduler was adapted so that it was able to schedule retransmissions following the two possible mechanisms. The resulting MAC layer solution is designed to be used on top of IEEE 802.11 at the wireless segment of a hybrid wired-wireless network, and is able to provide high reliability while keeping real-time deadlines of data traffic originating from three different classes: time-triggered, rate-constrained and best-effort.

6.2 Future Work

The work presented in this thesis is the starting point for a set of many ideas that are interesting to explore in the future. Since the developed protocol was designed to be compatible with TTE, the simulator can be extended so that hybrid wired-wireless networks are simulated jointly, to ensure that traffic reaches any point in the network, no matter which segment. To this end, it would be desirable to simulate hybrid networks with different topologies and sizes, specially to verify how the different scenarios have an impact on the task of scheduling, and determine the limits from which it is no longer possible to meet the real-time requirements. Additionally, it can be interesting to obtain performance measures related to the task of scheduling, e.g., check whether a scenario is schedulable within time and memory computational constraints.

New ideas to extend this research work are also concerned with the mechanisms to improve reliability. So far, this thesis showed that under interference and error scenarios, it is possible to improve reliability. It would be desirable to explore the limits of the mechanism based on time diversity, and work towards using other ideas that can improve both the reliability and timing aspects, e.g. by means of spatial diversity and cognitive radio. Spatial diversity, as standardized in IEEE 802.11n, can also help to increase reliability by retransmissions that happen in parallel, in the so-called spatial streams. On the other hand, the novel concept of cognitive radio, based on retrieving and exchanging information about the channel conditions to detect the channels that are free before transmitting, is also promising. The implementation of both mechanisms, together with the challenge of scheduling them, should be foreseen.

Last but not least, it is desired to port the aforementioned concepts to a hardware implementation, so that the capabilities and limitations of the proposed ideas are verified also by real-world experiments.

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II

Included Papers

Chapter 7

Paper A: Towards a Reliable and High-Speed Wireless Complement to TTEthernet

Pablo Gutiérrez Peón, Hermann Kopetz, and Wilfried Steiner.

In Proceedings of the 19th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Barcelona, Spain, September 2014.

Abstract

TTEthernet is a general purpose communication infrastructure for applications with real-time and/or fault-tolerance requirements. It is based on Ethernet as standardized by the IEEE and allows the integration of mixed-criticality applications in a single physical network. However, currently TTEthernet only operates in wired network settings. With growing industrial demand of the design freedom that comes with wireless communication solutions we are interested in extending TTEthernet to a wireless communication paradigm.

In this paper we review the state of the art in deterministic wireless communication approaches. We deduce quality criteria for wireless networks from industrial use cases and outline candidates for a wireless complement to wired TTEthernet.

7.1 Introduction

TTEthernet [1] is a communication platform for mixed-criticality systems, which are systems capable of hosting applications with differing time- and safety-criticality requirements. As of today TTEthernet is a wired Ethernet communication solution operating on OSI layer 2 and independent on the underlying physical layer.

Providing a deterministic wireless complement to TTEthernet will increase the application fields of this technology; covering the increasing demand of wireless communication solutions in the industrial field. That demand comes from their great advantages as compared to wired fieldbuses, specially when addressing systems that require some degree of mobility and flexibility. Besides, reduced wiring is another benefit that helps to decrease installation costs. These advantages are not new to industry, as wireless control and monitoring systems have been applied successfully in many application domains like industrial process control and automation [2] or robotic systems [3]. While current research is focused on improving reliability and real-time properties of a wireless communication and/or on the interconnection of wireless and wired networks, our approach is different. For our research, we consider a given wired communication platform (i.e., TTEthernet) and explore possibilities on how to change any number of wired links to a wireless solution.

The survey we conducted to find wireless technologies suitable for this TTEthernet-extension stated that most of the research works and applications in industrial systems are based on IEEE 802.15 and IEEE 802.11 [4][5][6][7]. However, while the energy-efficient IEEE 802.15 provides with 802.15.4e "time-slotted channel-hopping" (TSCH) a communication paradigm similar to time-triggered communication, we focus on IEEE 802.11 in this work due to its superior data rates, that for us are more important than preserving energy and better fit an Ethernet-based communication network like TTEthernet.

The rest of the paper is structured as follows: in the following section we define requirements on a wireless extension to TTEthernet. Section 7.3 addresses IEEE 802.11 MAC layer, its deterministic features and presents existing real-time solutions based on that MAC layer. Taking the existing solutions into account we present candidate solutions for wireless TTEthernet extension in Section 7.4. Finally, we conclude in Section 7.5.

7.2 Quality Criteria and Trade-Offs

When opting for wireless media as a mean of data transmission, an unprotected media is being used and many drawbacks compared to wired media are introduced. In general, lower transfer rates are achieved using wireless. Besides, that rate is not constant due to changes on the strength of the signal that are caused by variations on the relative position of the antenna with respect to its surrounding objects.

There are three main factors that cause signal changes in wireless communication: multipath fading, shadowing and interference from other wireless devices [8]. While multipath fading and shadowing can be a relevant problem, interferences caused by competing signals in overlapping frequency bands can distort or completely remove a signal, and are of special concern when devices want to exchange information at the same time. Facing this scenario, determinism (with respect to channel access) cannot be assured. Therefore, any approach trying to provide determinism to a wireless medium must consider the following:

- all devices that want to exchange information with a bounded medium access delay shall be under the same coordination mechanism (centralized access to the medium), and
- wireless equipment, which can cause interference, shall be kept out of the operation area or controllable by some other higher-level entity (i.e. defining a restricted wireless area, which generally is not a problem on factory environments).

Taking this as a base concept, the time-triggered communication paradigm appears highly suitable for deterministic wireless communication: the nodes in the network are synchronized to each other and assigned predefined communication slots. During these slots, the nodes are guaranteed exclusivity of transmission in a given frequency band and spatial area.

The problem of extending a real-time Ethernet-based network with wireless nodes has been addressed before, as presented in [9] and [10].

A short selection of wireless technologies that can provide some degree of determinism is made in [2], [4], [5], [6] and [7]. These papers address IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (Low rate WPAN) and IEEE 802.11 (WiFi) as standards that include some deterministic features in their Media Access Control (MAC) layer. However, only IEEE 802.11 will be considered in this paper for the following reasons:

- Seamless integration into IEEE 802.1 standards: TTEthernet is based on standard Ethernet and its wireless complement needs to work well with the IEEE 802.1 bridging standards.
- High throughput: data rates achievable by IEEE 802.15 are quite low (in the order of kbps or few Mbps) compared to IEEE 802.11 (near to Gb order). Our requirement is to work at least at 10 Mbps.
- Large number of nodes: while the number of nodes in IEEE 802.15 (with regards to the number of Guaranteed Timeslots) is quite limited [11] TTEthernet networks are targeting thousands or even tens of thousands of nodes.

Additionally, TTEthernet looks for a technology with a communication latency of a few μs per communication hop. Bounded latency is also a key element to assure reliability, which is a core parameter in our research that we target as good as it can possibly get. For this we are willing to trade the quality of other properties in favour of reliability.

7.3 Wireless Communication Based on IEEE 802.11

7.3.1 IEEE 802.11 Original MAC

The basic MAC defined in the standard is the *Distributed Coordination Function* (DCF). As it is based on CSMA/CA, no determinism is provided when accessing the medium. Furthermore, the standard also defines an extension to improve the transmission quality: the so called *Point Coordination Function* (PCF). On this approach, the access point uses a polling mechanism to give the stations the right to transmit data. Unfortunately, it has been found that this architecture has many limitations for transmitting real-time traffic [12].

7.3.2 IEEE 802.11e MAC (Quality of Service Amendment)

The IEEE 802.11e amendment defines new mechanisms working over DCF: EDCA (Enhanced Distributed Channel Access) and HCCA (HCF Coordinated Channel Access).

As the underlying MAC in IEEE 802.11 is based on CSMA/CA, every station will start transmission only if it detects the medium to be idle. The duration of the idle detection is called the Arbitration InterFrame Space (AIFS) and it differs for different types of traffic. In particular, EDCA is based on the use of different AIFS: higher priority traffic has shorter AIFS than lower priority traffic and, thus, it is more likely to be sent first (no guarantee is given). The same mechanism is used for assigning different backoff times (i.e., the duration a station needs to wait after collision) for different priorities. On EDCA, the amount of time a station has to transmit frames is called Transmission Opportunity (TXOP). During this period, a station has the right to transmit as many frames as it can, free of contention. Although EDCA improves the transmission latency for high priority frames, due to its MAC mechanism, collisions of traffic with either the same or different priority will occur and the resulting latency and reliability is insufficient for many use cases.

HCCA, on the other hand, manages channel access by treating the TXOPs of the stations as time slots. A dedicated protocol defines how time slots are assigned to stations and, after assignment, the time slots are executed one after the other as polled by the access point (see Figure 7.1). To guarantee that the polling frames and TXOPs are respected, the AIFS mechanism is again used, i.e., polled traffic has shorter AIFS than than legacy traffic.

The detailed timing of EDCA and HCCA is depicted in Figure 7.1. Time is divided in the so called *superframes*. A superframe is the time between two consecutive beacons. That time is, again, subdivided into two periods: Contention Free Period (CFP) in which HCCA is used and Contention Period (CP) in which EDCA is used. During the CP, the access point can also initiate Controlled Access Phases (CAP) using HCCA at any time, whenever a transmission of real-time critical data is necessary.

Admission of traffic and scheduling of TXOPs on HCCA is not addressed in the standard. Both components are left opened to the implementer and can be designed with respect to the specific application.

HCCA can provide deterministic data transmission. However, its polling mechanism results in a significant communication overhead when transmitting frames with small payload [13]. Currently Commercial Of-The-Shelf (COTS) devices do not implement HCCA (its features have only been simulated) and it is unclear if and when the industry will adopt

HCCA in the future.

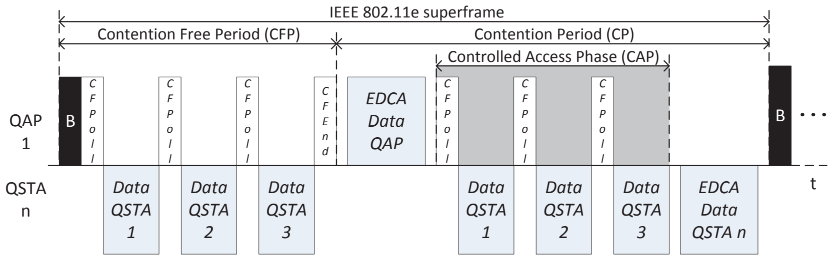

Figure 7.1: IEEE 802.11e MAC superframe

7.3.3 IsoMAC

Several proposals have been made to overcome the limitations of 802.11 MAC in regards to deterministic data transmission. In [14], a token-based coordination mechanism was proposed. Some others are focused on improving the admission control and scheduling algorithms of HCCA (i.e. [15] and [16]). One of the most promising solutions is IsoMAC [12]: a TDMA approach based on 802.11e MAC (without HCCA), that provides a way to satisfy soft real-time flows.

IsoMAC is based on a centralized channel manager, the so called *flexWARE Controller*, which is the scheduler and resource manager for the whole system. It gives the stations the right to use timeslots based on their requirements, which are communicated via *resource request frames* from the station to the Controller. These frames include a detailed traffic specification (latency, jitter, update time and payload size). The admission control of the coordinator uses this traffic specification to decide whether a new node can be accepted or not, depending on the already admitted traffic flows and the available resources. This scheduling is dynamic: a station can ask for resources at any time.

The scheduling is made through *communication cycles*, which consist of two parts (see Figure 7.2):

- Scheduled phase (SP). Real-time traffic is transmitted within assigned timeslots. This phase is further divided in timeslots for downlink and uplink. As seen on Figure 7.2, IsoMAC uses SIFS

(Short IFS) between frames during the SP. As legacy stations use DIFS (DCF IFS), that guarantees a higher priority when accessing the medium (SIFS<DIFS).

- Contention phase (CP). Best-effort and management traffic is transmitted during this phase. The ordinary DCF and EDCA are used. As this is the phase that stations use to ask the flexWARE Controller for resources, its duration guarantees that at least one data frame can be transmitted.

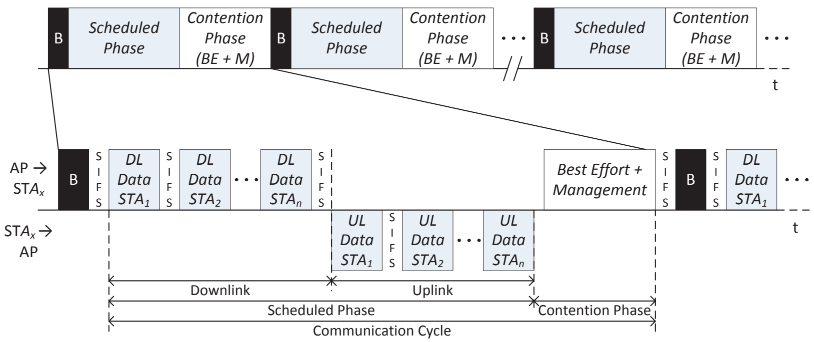

Figure 7.2: IsoMAC channel access [12]

The scheduling information is delivered to the nodes using the beacon frame *vendor specific* field. This field is also used to deliver timing information from the master clock at the flexWARE Controller to the nodes based on the IEEE 1588 Precision Time Protocol (PTP).

IsoMAC also specifies error recovery mechanisms based on acknowledgements and provisions for scheduled re-transmissions. IsoMAC is currently implemented [17] and tested on industrial environments. Results show an improved bandwidth utilization (as no acknowledgement is needed for every message) compared to HCCA and 1 μs jitter clock synchronization.

7.4 Candidate Solutions for TTEthernet

An example of a wired TTEthernet network is depicted in Figure 7.3. It consists of six switches (A-F) and seven end stations (1-7). End stations can be connected to the switches with single or several communication links with consequently differing reliability properties for their communication. Figure 7.3 also depicts a traffic scenario of time-triggered traffic (TT1, TT2) integrated with best-effort traffic (BE1, BE2, BE3) and rate-constrained traffic (RC1, RC2). The end stations send TT1 and TT2 when their respective slots in the synchronized time are reached, i.e., at times t.1 to t.9. BE and RC traffic is sent in an unsynchronized way.

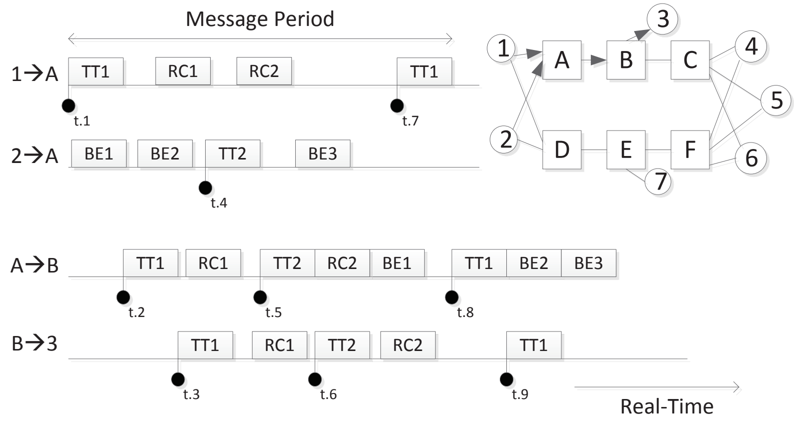

Figure 7.3: Example scenario of integrated time-triggered and non-time-triggered communication

The envisioned wireless complement to TTEthernet allows to replace any one (or any number) of wired with wireless communication links. Consequently, the wireless complement also allows to transport TT traffic as well as RC and BE traffic. An example of such a combined wired/wireless communication in TTEthernet is depicted in Figure 7.4. As shown, TTEthernet (sub-)networks N1 and N2 are connected to Access Points (AP1-AP3) and slave nodes (STAtions). In this example, N1 and N2 communicate TT traffic over a wireless link using access point AP2. Other slave nodes communicate with AP1 and AP3 without being attached to a wired network. Such slave nodes may be sensory equipment. It is essential that we consider wireless communication not only at the edges, but at any point of the network.

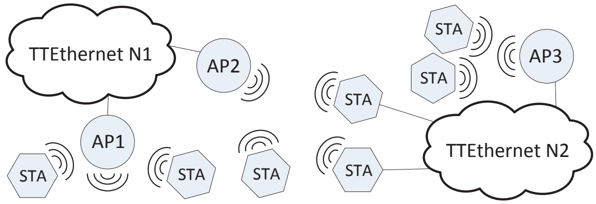

Figure 7.4: Combined wired/wireless TTEthernet use case

For some use cases IEEE 802.11e HCCA and IsoMAC are certainly candidate solutions for a wireless complement to TTEthernet. Ideally, these protocols can be integrated as wireless variants for the TT traffic class. There are, however, some shortcomings that need to be addressed by a more generic solution. Some of the additional functionality required is as follows.

- TTEtherent networks sometimes become spatial large with a requirement of coordinated wireless communication on remote locations. Hence, multiple access points need to be synchronized to each other.
- To improve the communication efficiency, the wireless components should be able communicate without being polled by a master station.
- For reliability reasons, fault-tolerance and robustness mechanisms need to be implemented. E.g., the wireless communication needs to tolerate the temporary or permanent loss of wireless components, like access points.

The synchronized timebase of the nodes in the network is a core element to satisfy this additional functionality. However, the establishment of an overall synchronized time is non-trivial. For example, TTEthernet implements the fault-tolerant clock synchronization protocol SAE AS6802 which we currently translate into the wireless domain. On the other hand, we would also like to synchronize several TTEthernet networks or subnetworks to each other using wireless connections. Therefore, we are also looking into alternatives/extensions to SAE AS6802.

GPS (Global Positioning System) is such a potential extension. Not only is GPS used to provide accurate positioning, but is one of the main suppliers of accurate time [18]. Hence, the GPS approach allows us to provide the same notion of time to all nodes, switches, access points, and stations in the system. At locations that are not accessible to GPS, a wired TTEthernet network or a wired IEEE 1588 network could route the information to the remote location and implement a repeater of the GPS information at its edges.

Once a system-wide timebase has been established, TT traffic can be statically scheduled throughout the entire system. We are, thus, also looking into more general scheduling problem that arises of the combined wired/wireless TTEthernet networks. In particular concurrent wireless TT transmissions may only take place when the access points are sufficiently far apart such that interference cannot occur.

A specific problem that needs to be addressed with this approach is the potential of interference of the IEEE 802.11 beacon sent by the access point with the data traffic sent by the stations according the TT schedule. Ideally, the transmission times of the beacon signal can also be scheduled according to the GPS time and, thus, interference is avoided by means of static scheduling. However, if synchronization of the beacon is not possible, we need to consider and resolve the additional latency as introduced by beacon colliding with data traffic.

7.5 Conclusion

With the advent of wireless communication in several industrial areas, we are looking to complement the TTEthernet technology with a wireless solution. We are primarily looking into variants and extensions of IEEE 802.11 as they meet our expectations of data rates, system size, and compatibility to IEEE 802.1 standards. Real-time solutions based on IEEE 802.11 have already been studied and most promising build on synchronous communication (e.g., time-division multiple-access). However, there are certain shortcomings that we want to address building on a system-wide time-triggered communication principle. We are therefore working in multiple directions: first we research alternatives to establish a synchronized global timebase (translating SAE AS6802 into the wireless domain and assessing GPS) and secondly we extend the current scheduling problem of TT traffic to also consider wireless links.

Acknowledgements

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Chapter 8

Paper B: A Wireless MAC Method with Support for Heterogeneous Data Traffic

Pablo Gutiérrez Peón, Elisabeth Uhlemann, Wilfried Steiner, and Mats Björkman.
In Proceedings of the 41st Annual Conference of the IEEE Industrial Electronics Society (IECON), Yokohama, Japan, November 2015.

Abstract

An important aspect of any communication technology is its medium access method, being responsible for sharing the medium among users. For delay-sensitive applications, such as industrial control systems, timely and reliable channel access is of essence. Hence, existing protocols like HART and TTEthernet use a time-triggered medium access approach. However, as the nature of industrial control systems change and evolve, there is a growing need to provide wireless access and support data traffic with mixed requirements. While technologies like WirelessHART can offer timely and reliable access to the wireless medium, only one type of data traffic is usually supported. In this paper, we therefore propose and evaluate three different medium access methods for wireless communications, all capable of supporting three different data traffic classes: time-triggered, rate-constrained and best-effort traffic. In particular, different options on how to handle best-effort traffic, using scheduled time-slots or contention, are evaluated, showing for all the proposals different drawbacks and benefits depending on additional requirements on e.g., hardware, protocol overhead and resistance to interference.

8.1 Introduction

Ethernet is the most spread standard for local area networks (LAN). It was originally designed for office environments, but its success in this application domain caused Ethernet to be adopted in other scenarios like industrial control applications [1]. The typical communication requirements of industrial applications are high reliability and predictable latency regarding data delivery [2], both difficult to support for a best-effort protocol like Ethernet. Consequently, many Ethernet-inspired technologies are available with add-ons to satisfy different types of industrial requirements. One of them, TTEthernet [3], is based on the time-triggered communication paradigm to provide deterministic data delivery with low latency.

TTEhernet has been successfully applied in several use cases, one important example is being the backbone for the new generation of spacecrafts developed by NASA (the Orion Multi-Purpose Crew Vehicle). Nevertheless, TTEthernet is a wired technology, and communication without wires is thought to cover several new application use cases that are of great interest. Among its advantages, wireless links allow the possibility of connecting mobile components. Reduced wiring and installation costs, easier network deployment, easier maintenance, and the lack of problems like broken wires are important benefits too. Wireless communication technologies also enable new use cases, like quick deployment of temporary monitoring and diagnostic networks in machinery. These advantages are not new to industry and have already been envisaged by standards like WirelessHART [4].

In WirelessHART, the wired HART fieldbus protocol was extended with wireless capabilities providing a multi-vendor, inter-operable wireless standard for secure and reliable industrial communications. However, only one type of data traffic, namely time-triggered periodic messages, is typically supported in WirelessHART. A subset of all time-slots can also be shared dynamically, but through contention only, implying a random channel access delay. To guarantee a deterministic delay, all periodic traffic flows have to be pre-scheduled, consequently limiting the support for dynamic traffic flows.

In contrast, TTEthernet can support three different types of traffic with different quality-of-service levels. This allows to integrate several traffic flows used by applications with mixed-critically communication requirements. Traffic prioritization is imposed between the flows such that critical delay-sensitive traffic is completely deterministic, while low priority traffic can suffer from starvation. The highest priority traffic flow is the time-triggered (TT) traffic class, intended for time-critical communication, with predefined instants in time when a message must be sent and received. The next priority level is given to the rate-constrained (RC) traffic class, which supports traffic flows that are characterized by an average bandwidth requirement, usually employed for data streaming. Finally, the best-effort (BE) traffic class is for asynchronous traffic (legacy Ethernet traffic) and is sent without any delivery guarantee whenever no TT or RC packets are transmitted. The support of flows with different requirements under the same infrastructure is of great value for industry, since emerging industrial control applications need to combine periodic traffic for monitoring and control with event-driven traffic from autonomous or mobile nodes, if possible using standard-based technologies.

A key aspect of any wireless solution with industrial requirements is the media access control (MAC) protocol. In essence, it is responsible for sharing the medium among users. To give support to traffic flows from time-critical applications, deterministic medium access is required. This means that any device that tries to access the medium will have a guarantee in terms of an upper-bounded channel access delay. Furthermore, the jitter, i.e., the difference between the minimum and maximum access delay is also a requirement for periodic traffic.

This paper proposes three different MAC methods with deterministic channel access delay, as in WirelessHART, but with support for the three different traffic classes of TTEthernet namely TT, RC and BE. Different options on how to handle best-effort traffic, using scheduled time-slots or contention, are evaluated, and the three MAC proposals all show different drawbacks and benefits in terms of best- and worst-case channel access delay and utilization. In addition, a set of non-functional requirements, such as required changes to existing hardware, protocol overhead and resistance to interference are also discussed. We aim for a solution that is implementable on top of standardized protocols such as IEEE 802.11 and IEEE 802.15.4 without requiring any changes to the hardware.

The rest of the paper is structured as follows. Section 8.2 covers the related work, with special attention given to the MAC layer and solutions to provide deterministic access. The characteristics and requirements of the three different data traffic classes are explained in Section 8.3. The set of evaluation criteria for the MAC methods is in 8.4. Our three proposed wireless MAC schemes with support for heterogeneous data traffic are detailed in Section 8.5 and evaluated in Section 8.6. Finally, we conclude the paper in Section 8.7.

8.2 Related Work

One very widely used MAC protocol in wireless LAN is carrier sense multiple access (CSMA), present in standards like Ethernet, CAN, IEEE 802.11 and IEEE 802.15.4. CSMA senses if the medium is free for a duration of an Interframe Space (IFS) before transmitting. If the medium is occupied during the IFS, the node defer its access until it becomes free again. After IFS, several nodes could try to transmit at the same moment, causing a collision. Hence, a random backoff value is also added to the IFS. Clearly, this behaviour does not fulfil the requirements of bounded access delay that industrial applications have, as the carrier sense function makes channel access random and unpredictable.

In the CAN bus protocol nodes are connected to the same bus and transmit event-driven traffic using CSMA after a deterministic arbitration phase based on node priorities. Unfortunately, this arbitration mechanism does not work in wireless settings due to the need to listen while transmitting. FlexRay is another wired technology that supports time- and event-driven traffic by the definition of static and dynamic phases that are cyclically repeated. During the static time-triggered phase, time-slots are used based on a previously agreed schedule. The event-driven phase is also divided into time-slots, but these are assigned dynamically according to priorities that are given by the message ID.

The IEEE 802.15.4 is a wireless standard which works with CSMA, but also defines a non-mandatory phase, called Guaranteed Time-Slots (GTS). These GTS are assigned to nodes that previously requested them from a special node, the network coordinator. When a GTS is assigned, all nodes are aware of this so no other device than the granted one will try to transmit during this time-slot. However, since the GTS are reserved during the CSMA phase when channel access is random, it is not certain that a GTS can be assigned and thus the channel access delay is still random and unbounded.

The IEEE 802.11 standard generally uses CSMA, but also has a guaranteed access functionality. This is performed via the point coordination function (PCF) in IEEE 802.11, which is basically a polling mechanism placed on top of CSMA. By using a shorter IFS, the so-called point coordinator (PC) will get prioritized access to the channel. Channel access is then granted by the PC by sending a poll frame to a node, which permits the node to transmit a frame to the PC. In case the polled node does not have any frames to send, it must transmit a null frame. Consequently, this method implies a lot of overhead and in some cases wasted resources. In addition, PCF suffers from problems with hidden nodes. The IEEE 802.11e amendment defines new mechanisms intended for an improved quality of service: Enhanced Distributed Channel Access (EDCA) and HCF Coordinated Channel Access (HCCA). EDCA is based on different IFS values (named AIFS) as well as different backoff values to provide several priority levels. HCCA defines separated contention and contention-free periods inside a superframe structure, where the contention-free phase is based on a polling mechanism. Both EDCA and HCCA are of limited use for industrial traffic. The first one due to the underlying CSMA, that cannot support determinism. The second one due to the polling communication overhead [5] and the fact that it is not commercially implemented yet.

In contrast, time division multiple access (TDMA) is a MAC mechanism able to provide deterministic channel access. It divides time into slots that are assigned to nodes. This implies that some sort of central coordinator is needed if time-slots should be assigned during run-time, or that all time-slots need to be assigned offline. Another consequence of the use of TDMA is the need to share a common time notion among the involved nodes, usually via a clock synchronization mechanism in order for them to agree on the delimitation of time-slots.

WirelessHART uses IEEE 802.15.4, and thus CSMA, but places a TDMA scheme on top of the built-in MAC. Transmissions are then performed using time-slots that are assigned to time-triggered traffic offline. These time-slots can also be shared dynamically though contention, so channel access delay is random.

IsoMAC [6] is an example of a MAC protocol that uses TDMA on top of IEEE 802.11. It has a centralized manager that assigns time-slots to the nodes based on the requirements that they specify in resource request messages, sent using CSMA. The coordinator decides about the requested traffic flows based on the remaining resources and constructs the communication cycles that start after every beacon frame. Beacons are used to convey the traffic schedule, and time synchronization information for the current cycle. Similarly to IEEE 802.15.4, a contention and a scheduled phase are defined. The contention phase is based on ordinary CSMA and is used for BE traffic and to request time-slots. The scheduled phase is in turn divided into time-slots that are assigned to the admitted flows. Like with PCF, a shorter IFS is used to get access to scheduled time-slots. IsoMAC has the same problem with random and unbounded channel access delay as IEEE 802.15.4. Devices asking for time-slots have to do it during a contention phase.

8.3 Heterogeneous Data Traffic

The time-triggered paradigm [7], the foundation for TTEthernet and WirelessHART, states that messages must be sent according to a strict time schedule. This has the great advantage of determinism, making it very appropriate for safety-critical systems. A benefit of TTEthernet is that it supports time-triggered traffic flows, and integrates it with rate-constrained traffic, guaranteeing the isolation of the first one with respect to the second. In TT flows, all messages are sent at predefined points in time. In case the application that booked these time-slots decides not to use some of them, event-triggered flows could take their place. In RC traffic flows, there is a guarantee in terms of a minimum inter-arrival time and sufficient bandwidth, such that delay and jitter have defined limits. RC messages are not sent at predefined points in time and its arrival pattern is asynchronous. BE traffic is random and there is no guarantee at all for BE messages to be delivered. All three traffic classes have separated buffers from where messages are taken to be sent on the network.

An offline computed schedule is spread to the switches and end systems that constitute a TTEthernet network, in order to make them aware of the instants when they have to take TT messages from the buffers and place them on the output ports. The same applies to the instants when they should expect the reception of TT messages. For RC messages, an average bandwidth is assured by the scheduler, implying that TT messages leave enough unused time for guaranteeing this RC bandwidth. In the worst case, RC traffic is periodic, so the scheduler can leave free slots periodically after allocation of TT slots. BE messages are placed during run-time in the free periods of time left by TT and RC. Clock drift [8] can affect the rate at which RC traffic is generated, meaning that in the worst case a RC sender has more messages to send than allocated RC slots when working under an early clock. However, for reasons of simplicity we assume that clock drifts are negligibly and that TT and RC will be periodic. The scheduling problem of TT and RC messages can be modelled via first-order logic constraints [9], that reflect the network infrastructure and the traffic flows. An important aspect of the schedule is its period of validity. The schedule will be run cyclically and is valid for all the time the network is up and running.

8.4 Evaluation Criteria

This section provides a set of evaluation criteria, targeting different aspects to consider when developing MAC protocols capable of supporting heterogeneous traffic over wireless links.

Protocol overhead and efficiency. A MAC protocol based on TDMA introduces a relatively small overhead if compared to polling- or token-based MAC mechanisms. This criterion is intended to evaluate the amount of control traffic introduced by the proposed MAC protocol, as well as any potential unused pre-scheduled resources. For example, this can be evaluated by comparing the difference in utilization between MAC methods.

Channel access delay. For periodic traffic, the channel access delay should be known and constant, so that the jitter can be set to zero. However, for BE traffic, the time until channel is granted is an important performance measure. Hence, since some of our proposed MAC schemes use contention for BE traffic, the best- and worst-case delay until a node can transmit in the contention phase is evaluated.

Reliability. The reliability of the wireless medium is lower than the wired, mainly due to multipath fading, shadowing, and interferences from other devices. Therefore, it is likely needed to add mechanisms to increase the reliability in the wireless segment to make a better balance towards the wired one. Replication, that is to send more than one copy of the data to be delivered, is an example of a mechanism for increased reliability. Hence, this feature relates to the ease of adding extra redundancy to the MAC method for increased reliability.

Hardware requirements. The proposed MAC protocol is thought to be implemented over standard IEEE 802.11 or IEEE 802.15.4 hardware. Both standards have native support for CSMA, making it a tractable option for contention. Some of the standard compliant chipsets allow to make changes on the MAC layer, but the most likely option is to place the proposed MAC on top of the standard MAC. Besides, CSMA parameters can be tuned to reduce the overhead of an extra layer. This criterion evaluates the amount of hardware changes needed.

Integration with wired networks. The traffic integration between wired networks such as TTEthernet and a wireless complement can be achieved thanks to the way the TT traffic is scheduled, using first-order logic constraints. Besides, wired and wireless segments will have different time-slot sizes tied to the particularities of the medium. This can be solved by the addition of constraints to the scheduler to place traffic on slots with different size. The singularity of the wireless MAC protocols can also end in the addition of new constraints to the scheduler, e.g. telling the scheduler not to place traffic when a beacon is to be sent, or booking more slots for increased reliability on the wireless medium. This criterion evaluates how easy integration with TTEthernet can be made.

Interferences from other CSMA devices. Other nodes working on the same frequency as our network can cause interference, but if they use CSMA, they have to listen before they transmit. This aspect can be used to get faster access to the medium if waiting less time before a transmission. This criterion relates to the sensitivity of the proposed MAC to interference from other nodes using CSMA.

8.5 Proposed Wireless MAC

Due to the requirement of deterministic access to the wireless medium, we will use a centralized network topology with an access point (AP). All messages must go though the AP which can also connect to a potential wired segment. In addition, the selected infrastructure network topology is thereby similar to e.g., the wired TTEthernet switch topology.

We can guarantee deterministic access to the wireless medium if we propose a MAC mechanism that has an upper-bounded channel access delay. Based on the outlined evaluation criteria, we have opted for a TDMA-based approach. The resource that the wireless scheduler will manage is then time-slots. Dividing periods of time into slots fits easily with the time-triggered paradigm and the requirement of deterministic access to the medium. The actual allocation of the three different

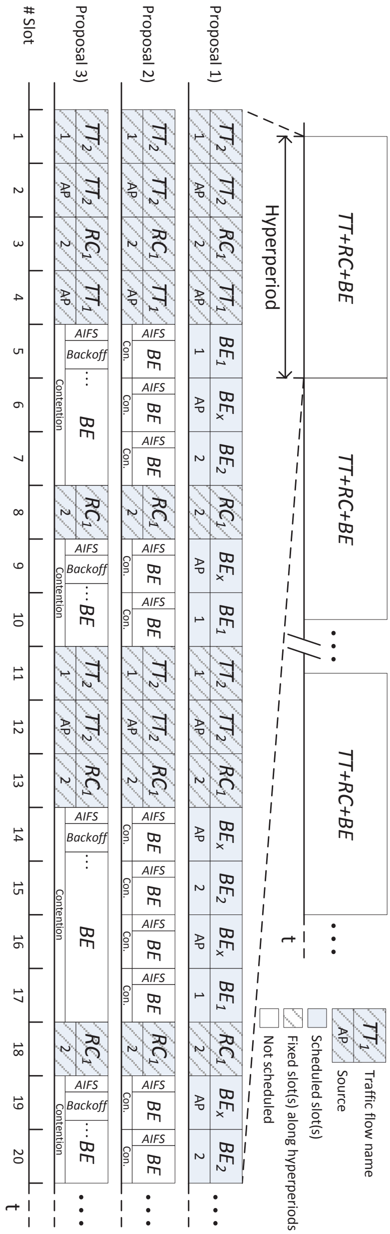


Figure 8.1: Example of slot allocation for the three MAC proposals.

TTEthernet traffic flows to those time-slots opens a range of possibilities with different implications, from which three of them are selected in this paper. In all of them, the TT traffic class will be scheduled offline, guaranteeing its deterministic access to the wireless medium, similarly to what is done in WirelessHART. In the worst case, RC flows are periodic, so they can be modelled as TT flows and therefore added to the scheduler offline. Based on the individual periods of the TT and RC traffic, a hyperperiod, being the least common denominator of the individual periods, can be defined. In the case of BE, the packets are just placed in the internal queues of the nodes by the user applications at runtime, without any predefined traffic pattern. Their characteristics are not known at the moment of creating the schedule, so it is not possible to assign time-slots to specific frames. As a consequence, its access will not be deterministic, but still this is consistent with the definition of BE traffic in TTEthernet. The schedule will be repeated continuously during the system run-time. It is important to notice that the receiver in a slot does not need to be specified for the wireless schedule due to its broadcast nature. The only time it could be good to schedule a receiver is to preserve energy, but this is out of the scope of the current paper. Also, by allowing more than one receiver, the future implementation of steps to increase reliability is left opened.

Pre-scheduled time-slots only

This approach does an offline allocation of time-slots for all three types of traffic and all transmitters (i.e., in each slot, there is one unique transmitter and one unique traffic class allowed). The specific allocation of slots for TT and RC will be given by the scheduler. Next, BE traffic will be placed on the remaining slots after the allocation of TT and RC traffic. As BE traffic characteristics are not known in advance, the remaining slots cannot be directly assigned, so the most fair way of sharing these resources is using a round-robin schedule, giving the same amount of time-slots to each node in a circular order. This approach could also be implemented in WirelessHART, with the difference that all pre-scheduled slots in WirelessHART are typically placed at the beginning of the superframe, while our proposal may allow a more even distribution of BE traffic, yielding a shorter delay until access is granted. Still, this scheme can be seen as a benchmark of how WirelessHART would perform.

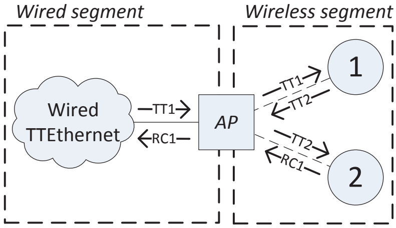
Pre-scheduled time-slots and contention-based time-slots

This approach is similar to Proposal 1, but the remaining time-slots not used by TT and RC can be used for BE traffic flows following a contention process, similar to the shared slots in WirelessHART. Further, one single node in each slot is given a higher priority, using a higher priority class in IEEE 802.11e, yielding a shorter T_{AIFS}. Thereby prioritized access is given to nodes in a round-robin fashion. However, using CSMA-based contention, all nodes waiting exactly for a AIFS in the beginning of a slot is not recommended, as when more than one node wants to transmit in a slot, they will collide when starting to transmit. Therefore, we will add a random time in addition to the AIFS to help to avoid collisions. However, the high priority node will not add any backoff. The approach is similar to the dynamic phase in FlexRay, but different from WirelessHART, where shared contention slots use slotted ALOHA.

Pre-scheduled time-slots and contention-based phase

Here the proposed mechanism establishes a contention-based continuous phase for BE traffic, and a scheduled phase for TT and RC traffic. The ratio of the contention-based phase and the scheduled phase can be determined using schedulability analysis [10]. The two extreme cases are that all TT and RC traffic is grouped together in one long scheduled phase, leaving the reminder of the hyperperiod to the contention-based phase, or alternatively, that each TT and RC instance is evenly spread in the hyperperiod, leaving the space in between for BE traffic. During a contention phase, access is granted after waiting a AIFS plus a random backoff value. The benefit of having the scheduled phases evenly spread over the hyperframe, is that the best-case channel access delay is reduced for BE. The drawback is that, as the contention phase size is multiple of a scheduled slot size (to facilitate scheduling), the spaces between scheduled slots may not be big enough to accommodate the time it takes for contention and transmission. This MAC approach is similar to IEEE 802.15.4 GTS, but with the advantage that slots are guaranteed to be booked as they are not reserved during a contention phase.

An example showing the three different MAC proposals is depicted in Figure 8.1, using the simple traffic scenario in Figure 8.2. The traffic scenario accounts two TT and one RC traffic flows expressed using slots as the time unit. TT flows are characterized by their period. RC flows are characterized by a bandwidth, expressed as the maximum number of slots that can be needed in a period (e.g. 1 out of 5 slots for the RC1 flow). In the worst case (maximum rate), RC1 will use 1 slot every 5, so it can be modelled as a periodic message with period 5. The TT together with the RC traffic from Figure 8.2 results in a hyperperiod of 20, meaning that the slot allocation for TT and RC will be repeated every 20 slots. Note that the slot size between proposals is not the same.



Name	Characteristics	Path
TT1	Period: 20 slots	Wired→AP→1
TT2	Period: 10 slots	1→AP→2
RC1	Rate: max 1/5 slots	2→AP→Wired
BE	Unknown pattern	-

Figure 8.2: Example of wireless traffic scenario.

8.6 Performance Evaluation

Protocol overhead and efficiency. We have used schedulability analysis [11] to calculate the minimum bandwidth that needs to be reserved for TT and RC traffic while still guaranteeing its timely delivery. The time left for BE traffic can thereby be determined. Schedulability analysis was first conceived for task scheduling in processors, but can easily be adapted to scheduling of messages that share a wireless link. However, this requires the scheduling policy to be earliest deadline first (EDF), i.e. when selecting the next message to transmit, the message closest to its deadline is selected. This will be automatically enforced in our MAC proposals, since the assignment of time-slots to nodes is made offline.

A periodic message is defined by a duration C, a period T, and a deadline D, where D is usually equal to T. The analysis assumes preemptive messages, but as this is not possible in communications, further delays must be taken into account. Therefore, the original deadline is reduced to d by subtracting the maximum blocking time a message can suffer $T_{blocking}$, that is given by the transmission time of a message T_{transm}, and the propagation of the packet itself T_{prop}. For simplicity we assume that T_{prop} is negligible. Thus $d = D - T_{transm}$.

The schedulability analysis consists of two steps and checks if two conditions are met. The first condition says that the utilization U of the wireless link must not exceed one. The second says that the workload function $h(t)$, that is the sum of the transmission times of all messages before instant t, must be less than or equal to t. Given a set of periodic messages $i = 1, .., N$, each one with duration C_i, period T_i, and reduced deadline d_i, the utilization of the link U is given by:

$$U = \sum_{i=1}^{N} \frac{C_i}{T_i} \leq 1, \tag{8.1}$$

while the workload function $h(t)$ is given by:

$$h(t) \geq \sum_{i=1}^{N} \left\lfloor \frac{t + T_i - d_i}{T_i} \right\rfloor C_i. \tag{8.2}$$

A numerical evaluation of the utilization using Matlab has been conducted to obtain the time remaining for BE after allocation of the scheduled TT and RC messages for each of the three MAC proposals. A set of TT and RC messages corresponding to low, medium and high utilization (occupying close to 25%, 50% and 75% of a total time of 10000 μs), is created to determine the corresponding utilization in each of the three MAC proposals. A relatively small packet with size of 62 bytes is used for all flows and the data rate is 6 Mbps. These numbers were selected to reflect that packets in industrial networks are usually small and reliability is often more important than throughput. For the schedulability analysis we have selected $T_{AIFS} = 2\mu$s for contention, representing the highest priority class in IEEE 802.11e and thereby introducing less protocol overhead. Given the above numbers, the size of the slot in Proposal 1 and Proposal 3 is $T_{slot_1} = T_{slot_3} = T_{transm}$ since contention is not needed in these slots and the propagation time is neglected. For Proposal 2 the slot size is $T_{slot_2} = T_{transm} + T_{AIFS}$, since all slots need to be of the same size to facilitate synchronization and contention is needed in some of them. The resulting time left for BE traffic transmission for the different MAC proposals, named BE busy time, is shown in Figure 8.3. We can see that the contention mechanisms introduce overhead in both Proposal 2 and Proposal 3. For Proposal 3, it depends on how the scheduled slots are distributed, evenly over the entire superframe (maximum fragmentation) or grouped together (minimum fragmentation). Both options are shown in Figure 8.3. With only one contention period, Proposal 3 is better than Proposal 2 because there is more time left for BE during the hyperperiod due to $T_{slot_3} < T_{slot_2}$. However, when having the maximum number of contention phases, Proposal 3 suffers as for medium- and high-scheduled traffic load, all the remaining space can be considered as dead and not valid for BE traffic transmission. This is due to the fact that the minimum size a BE phase must have to allow a transmission is $T_{transm} + T_{AIFS}$, which corresponds to a node that waits the AIFS and randomizes a backoff value of 0. This means that a contention phase of at least two slots must be left between a pair of scheduled slots if a contention-based transmission should fit. Note also that the effective utilization for BE traffic depends on its distribution among the nodes. For Proposal 1, performance is reduced as some scheduled slots are not used if they are assigned to nodes which do not have BE traffic.

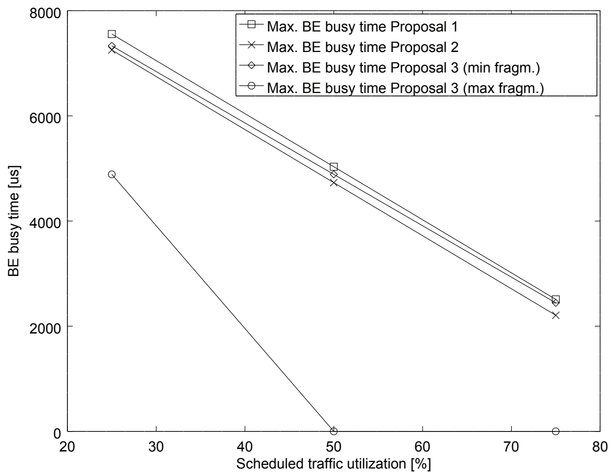


Figure 8.3: Best-effort busy size per scheduled traffic load for the three MAC proposals given a hyperperiod of 10000μs.

Channel access delay. We have analysed the channel access delay that a node can experience in the best and worst case for BE traffic. In Proposal 1, the best case is to not have to wait at all, while the worst-case access delay for BE traffic occurs when a message is generated just after the node's scheduled BE slot and this is followed by a period of consecutive slots scheduled for TT and RC traffic. The node then has to wait until all scheduled slots S have finished, and then it has to wait for all the other $N-1$ devices to get access to their BE slots. We therefore have $T_{BE\_worst\_delay_1} = (S+N-1)T_{transm}$ In Proposal 2, the best case for BE is immediate access to the slot, implying a delay of T_{AIFS}, while the worst case is when the message is generated just after the longest possible consecutive scheduled phase, as the node then has to wait until all scheduled slots S have finished and all other BE slots where other nodes have higher priority before it can begin the contention. Note that the worst case is that all other nodes have BE traffic and they have higher priority in the respective slot: $T_{BE\_worst\_delay_2} = (S+N-1)(T_{transm}+T_{AIFS})$. In Proposal 3, the best case for BE traffic is to access directly after waiting T_{AIFS}, while the worst case is that access is never granted and thus the delay is, in theory, infinite.

Given the expressions above, Proposal 1 and 2 have a similar worst case, except for T_{AIFS} due to contention, whereas Proposal 3 have an unbounded worst case. However, the worst case in Proposal 3 has low likelihood of occurring in practice, and for the fragmented case, it is not necessary to wait for the entire scheduled phase if an opportunity is missed but only for a fragment of it, implying several cases with reasonably low albeit not deterministic delay. Consequently, the best choice depends on the type of BE traffic in the system. If it is generated by all nodes or only from some nodes which are known in advance, Proposal 1 is best. However, if the origin of BE traffic is random, unknown or varying, Proposal 2 is best if a bounded delay is needed and Proposal 3 is best if a low average delay is preferred.

Reliability. Proposal 1 does not include contention. When using contention, there is a non-zero probability to have a collision, reducing reliability. Proposal 1 is therefore the best in terms of inherent reliability, Proposal 3 second best in case of not fragmented contention phase, and Proposal 2 is the worst, as the contention is synchronized at the beginning of each slot, aligning the moment in time when the devices start to listen and therefore increasing the probability of a collision.

In addition, mechanisms for increased reliability based on replication can be introduced. Two options are considered: TT and RC traffic classes need more redundancy through the scheduling of more slots. In this case the proposal which already has a lower utilization from the beginning suffers. Alternatively, these retransmissions are placed as if they were BE traffic. In this latter case, the proposal starving BE traffic will also starve retransmissions.

Hardware requirements. The only difference between the proposals is that the first one does not have any contention-based phase and therefore CSMA is not required, while for the other two it is. This latter case can be problematic, as CSMA is not needed during the scheduled phases, but is used in the contention ones. Turning on and off CSMA will most likely involve some overhead that will be inefficient. However, all solutions can be implemented on top of standardized chipset without major changes to the hardware.

Integration with wired networks. There are differences in the way BE traffic is treated in the three proposals. However, given that in e.g., TTEthernet there is no guarantee for BE traffic to be delivered at all, it does not affect integration.

Interferences from other CSMA devices. All proposals except Proposal 1 suffer from the same problem when trying to start a contention-based phase in an environment with co-located CSMA-based devices. If there are any other ongoing transmissions by these devices, the transmissions in the contention-based phase may be postponed. However, in Proposal 1, the CSMA functionality can be turned off, and thus no AIFS needs to be included and the scheduled nodes will get access first. In Proposals 2 and 3, nodes in contention-based phases can have prioritized access if using a shorter waiting time than interfering devices. For that, we should assure that the AIFS plus the randomized time is still lower than the legacy AIFS waiting time of these other external devices.

8.7 Conclusion

The support for different types of traffic with different reliability requirements is already working successfully in TTEthernet, but only under wired network settings. The possibility of using heterogeneous traffic with the same characteristics but in a wireless setting is desired. In this paper we have proposed three different MAC protocols suitable for time-critical wireless communications, with support for three different traffic classes. A comparative study of them has been performed considering different aspects such as delay, reliability and efficiency. Proposal 1 is best if high predictability is needed and BE traffic is evenly distributed among all nodes. Proposal 3 has the highest flexibility, and works best when BE traffic is uneven or changes often.

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Chapter 9

Paper C: Medium Access Control for Wireless Networks with Diverse Time and Safety Real-Time Requirements

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Abstract

The communication in-between embedded systems present in cars and planes, requires real-time networks. Up to now, fieldbus technologies like PROFIBUS and CAN have covered the demand for predictable communications in embedded systems. However, these fieldbuses do not suit some of the emerging application domains, that need more flexibility, support for dynamic traffic flows, different traffic classes, high throughput, and the inclusion of wireless capabilities. To this end, we propose several different medium access control (MAC) schemes with support for traffic with diverse time and safety requirements. We have calculated the worst case channel access delay for each proposal, and also simulated them in OMNeT++ to analyse and compare their performance in terms of average access delay and packet collisions as a function of different protocol settings and traffic patterns e.g., the channel load, data traffic emerging from one sender only versus evenly distributed between all senders. Our results indicate that the more that is known about the data traffic, the better performance can be achieved by selecting an appropriate MAC protocol. Conversely, when nothing is known, one MAC protocol emerges as the best trade-off.

9.1 Introduction

In real-time networks, a guarantee to not exceed a certain maximum delay is given. Providing an upper bounded channel access delay is therefore one of the main tasks of the medium access control (MAC) layer in real-time networks. To accomplish this, the MAC layer should assure that a transmission through the shared medium will be done within a limited amount of time, regardless of the amount of data requested to be sent by other participants in the network. One of the most commonly found MAC protocols in wireless networks is carrier sense multiple access with collision avoidance (CSMA/CA). It is used as part of the widely known standards IEEE 802.11 for LAN and IEEE 802.15.4 for wireless personal area networks (WPANs), with the benefit that it is not too complex to implement, and in lightly loaded settings it can achieve good throughput. However, CSMA does not provide a predictable channel access delay since access to the medium is random and packets can collide. Consequently, several mechanisms have been designed to provide channel access in a bounded amount of time with CSMA. In [1], the authors use polling, i.e., triggering response transmissions upon reception of a special (polling) message, usually sent by a central coordinator. This method is, however, not very bandwidth efficient. In [2], the authors present VTP-CSMA, a token passing approach for IEEE 802.11. The token passing techniques provide access to the medium upon reception of a token message that circulates among the nodes, normally in a round-robin fashion. However, token protocols typically suffer from jitter, which can be problematic for periodic data traffic. In contrast, in time division multiple access (TDMA) techniques, where access is based on time-slots, the jitter can be negligible. TDMA can be found in protocols like IsoMac [3], and RT-WiFi [4]. In both cases, a centralized controller is in charge of assigning the time-slot access opportunities, resulting in a single-point-of-failure.

The demand for real-time communications in embedded systems has, for many years, been covered by fieldbus technologies like PROFIBUS or CAN. However, their quite limited throughput and lack of flexibility have intensified the efforts towards faster, cheaper and more flexible standardized solutions. Furthermore, many emerging applications require support for both time-triggered and event-driven data traffic and demand wireless capabilities to connect embedded systems due to ease and flexibility in deployment and reduced wiring costs. An example of a hybrid wired-wireless network with support for time-triggered data traffic is the HART/WirelessHART protocol [5]. However, even if a subset of all time-slots can be shared dynamically, WirelessHART still only provides deterministic delay to one type of data traffic, namely time-triggered periodic messages. In the other end, there are some recent work on wireless MAC protocols with support for event-driven real-time traffic, namely WirArb [6] and PriorityMAC [7]. Still, these protocols basically target either time-triggered or priority-based event-driven data traffic, not integrated levels of both. The work in [8] do provide support for both time-triggered and event-driven data traffic in IEEE 802.11 by traffic prioritization and an offline TDMA slot assignment, but guarantees are still given only with restrictions on the channel load as well as the periodicity of real-time traffic. Time-Triggered Ethernet (TTE) [9], is a communication technology that allows the integration of time-triggered and event-based rate-constrained data traffic. TTE is also compatible with Ethernet, meaning that legacy best-effort Ethernet traffic is also supported. Due to this, TTE emerges as a tractable option to be used in real-time networks in emerging application domains. Unfortunately, TTE does not have wireless capabilities.

To this end, we proposed and evaluated several different wireless MAC protocols supporting the same type of traffic classes as TTE, namely time- triggered (TT), rate-constrained (RC) and best-effort (BE), and operating on top of IEEE 802.11, rather than the lower rate protocol IEEE 802.15.4 that WirelessHART is based upon [10]. TT and RC traffic were given predictable channel access delays by assignment of prescheduled time-slots, whereas the remaining time was made available for event-driven traffic. The proposed MAC schemes where evaluated and compared in terms of how they handle event-driven traffic. A comparative study considering aspects such as delay, reliability and efficiency was made. However, the channel access delay was only evaluated in terms of the worst case. In this paper, we not only refine and improve the three MAC proposals, but we also evaluate the maximum and the average channel access delay for different data traffic patterns. The MAC proposals have been implemented in OMNeT++ [11], to thoroughly evaluate and differentiate their performance in terms of average channel access delay and number of collisions, as a function of different data traffic patterns and loads, e.g., the ratio of time-triggered traffic, the channel load, data traffic emerging from one sender only versus evenly distributed between all senders. Our results indicate that the more that is known about the BE traffic, or alternatively, the event-driven traffic, the better performance can be achieved by selection of a proper MAC protocol. Conversely, when nothing is known, one MAC protocol emerges as the best trade-off.

The reminder of the paper is structured as follows. In Section 9.2, we present our wireless MAC protocol proposals coping with diverse time and safety requirements together with an analytical evaluation of the worst case access delay. Section 9.3 describes the simulator, and the results obtained from the simulation. Finally, we conclude in Section 9.4.

9.2 Wireless MAC Proposals Suitable for Diverse Time and Safety Real-Time Traffic Requirements

The design of our wireless MAC method is focused on guaranteeing a bounded access delay to the wireless medium, in the context of a hybrid wired-wireless network that supports three traffic classes: TT, RC and BE.

9.2.1 Hybrid Network Topology

We consider TTE a good candidate for being the core technology in the wired segment, since it provides support for diverse time and safety traffic requirements, including standard Ethernet. On the wireless side, we have selected IEEE 802.11 over other standard technologies, due to the high-speed data rates, and also its similarity to Ethernet.

The architecture of TTE is based on switched Ethernet, with networks comprised by end-systems and switches. Every end-system is connected to a switch through a full-duplex link, conforming a star topology. Switches are not only restricted to connect end-systems, but can also be connected to each other, so the network topology becomes a star of stars, commonly referred to as snowflake topology. On the wireless side, we also adopt a star topology using the IEEE 802.11 infrastructure topology. This becomes beneficial for the integration between the wired and wireless segments, considering that it does not add more complexity to the task of scheduling the traffic. In a star topology, the wireless end-systems communicate through the access point (AP), that is also responsible for interfacing the wired segment. An important difference between the wired and the wireless segments comes by the collision domains they define (Figure 9.1). A collision domain is a section of the network in where devices cannot transmit at the same time because their transmissions would overlap. In full-duplex links, each link defines two collision domains, one for sending and one for receiving. In half-duplex links, there is only one collision domain, for both sending and receiving. In wireless networks, the particularity is that all devices in range constitute a single collision domain, also referred as broadcast domain. Therefore, all wireless end-systems should be properly installed to be in the range of the corresponding AP. To avoid interferences between wireless collision domains, overlapping areas should either use different frequencies or coordinate transmissions using a wireless MAC with support for real-time traffic. The MAC protocols considered here are intended for a single hop network, where the access point acts as either receiver or as transmitter.

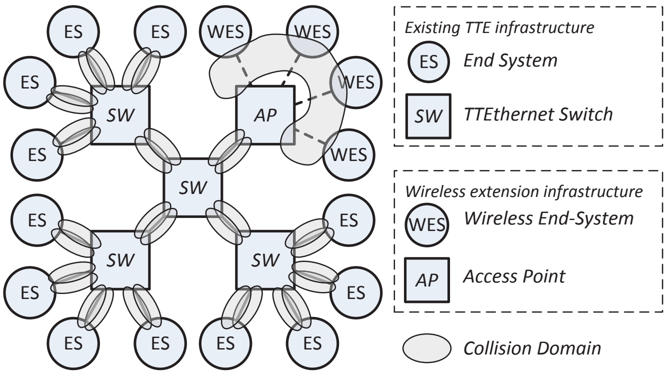

Figure 9.1: Example of the proposed wired-wireless scenario, with switches (SW) and access points (AP) connecting the end-systems (ES, WES) forming recursive star topologies (snowflake topology). Note that every wired connection forms two collision domains, while the wireless systems constitute a single collision domain.

9.2.2 Real-Time Traffic Management

The support for applications with diverse time and safety requirements in TTE is made by means of three different traffic classes. The TT traffic class is based on the time-triggered communication paradigm, with offline scheduled traffic based on the user requirements that specify the periods of the traffic flows. Applications making use of TT flows are provided with real-time capabilities, with a bounded time to access the medium. This bounded time is equal to the period of the flow, since the worst case comes when the application just missed the current message slot and has to wait for the next one. The second traffic class with real-time capabilities is RC. This class provides a guarantee given a certain minimum inter-arrival time for the messages. In the extreme case of having something to transmit at a rate equal to the inter-arrival time, the traffic flow behaves as a periodic TT flow. The difference between RC when compared to TT is that the network does not force periodic slots, but allows longer periods between messages if needed via online allocation of RC on the time left by TT. The RC traffic class is a perfect fit for e.g., audio and video streaming applications. Apart from the real-time support, an additional class named BE gives support for non-real-time legacy Ethernet traffic. BE traffic can occupy the free time left by TT or RC traffic, and our goal in this paper is to be able to provide an upper bound on the channel access delay also for this traffic class, such that it could be used to support event-driven real-time data traffic.

9.2.3 Scheduling

In order to provide real-time capabilities to the traffic flows sharing the same network infrastructure, all transmissions of real-time traffic flows must be done according to a schedule, that is known by all the network participants. In the simplest scenario, a network is composed by one switch and several end-systems that are connected to the switch. The problem of traffic scheduling becomes quite complex when dealing with topologies that account more than one switch, like in multi-hop switched networks. TTE solves this complex scheduling problem with a mathematical model of the network topology and the traffic, based on first-order logic constraints [12]. These constraints address the mutual exclusion of the dataflow links (contention-freedom), and others like having received the data on one hop before sending it again (pathdependencies). To obtain a schedule, the mathematical model is solved using satisfiability modulo theories (SMT) solvers [13].

The TTE scheduler is the tool we use to perform the integration of wired and wireless segments at traffic level for real-time (TT and RC) flows. For this, we need to extend the TTE scheduler in order to give support to the traffic traversing the wireless segment. This can be done through the definition of new first-order logic constrains that reflect the particularities of the wireless medium. Specifically, it is necessary to define a contention-free constraint that models the broadcast nature of the wireless medium, that is, it does not allow concurrent transmissions on the links included on each of the wireless collision domains. An optional constraint for the scheduler can model the differences in the transmission speed between the wired and wireless medium. In case this constraint is not defined, the slot size, that should be big enough to accommodate the transmissions plus any kind of protocol overhead, will be the same for the entire network, and adapted to the slowest transmission medium. The obtained schedule has a duration of the so-called hyperperiod.

9.2.4 Enabling Event-Driven Real-Time Data

The time left after the allocation of the TT and RC traffic flows is available for BE traffic. Since BE is a non-real-time type of traffic, TTE does not provide any guarantee of delivery. When an application wants to send BE packets, these are enqueued in end-systems and switches and sent whenever the link is not used for TT or RC traffic. Due to its random generation pattern, BE can overflow the queues causing packets to be dropped. The problem can worsen in wireless networks with reduced bandwidth given by the half-duplex links and lowered robustness. To mitigate this, we propose three different wireless MAC protocols (Figure 9.2) that extend the ones proposed in our previous paper [10].

MAC #1. Pre-scheduled time-slots: The time available for BE is divided into time-slots that are pre-assigned to the nodes using a round-robin schedule. If a node wants to send a BE packet, it has to wait until the round-robin assigned BE slot comes. As there is no other protocol overhead, each slot has to accommodate only one transmission together with some small guard time, and thus the size of the slot can approximately be equal to the transmission time. Given a set of slots reserved for TT and RC data traffic S, a certain number of nodes N,

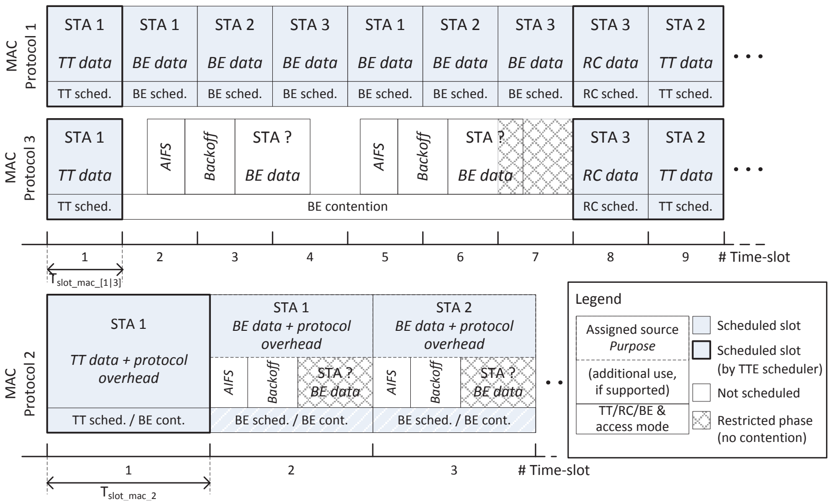

Figure 9.2: Traffic scenario example for the proposed wireless MAC protocols.

and the transmission time T_{transm}, yields a worst channel access delay which is bounded and equal to $T_{BE\_worst\_delay_1} = (S + N - 1)T_{transm}$.

MAC #2. Contention-based time-slots: In MAC Protocol 1, if a node does not have anything to send in its assigned time-slot, the slot is left unused. In MAC 2 if the slot is not used by the assigned node, the rest of the nodes can try to get access through a contention process whenever they have something to send. To implement this, all nodes perform channel sensing, but with one prioritized node using a shorter AIFS than the rest. In case the prioritized node does not have anything to send, the rest of the nodes will notice that the channel is still idle, since they sense the channel for a larger AIFS. To decrease the probability of collisions, the non-prioritized nodes wait for an additional random time (backoff), selected from a contention window (CW). The size of the slot in this proposal must therefore at least be big enough to fit a transmission and the larger AIFS, plus a guard interval. Alternatively, the slot can be made even bigger so that more values from the CW can fit, thereby reducing the likelihood of the slot remaining empty even further. The shortest possible slot (MAC 2A) only allows a transmission from the node having prioritized access, or alternatively from any other node that randomized a backoff value of zero. Note that several non-prioritized nodes can randomize the same backoff value, so the approach increases the chance of collisions. If the slot is bigger (MAC 2B), more values from the CW can fit, and therefore more chances are given to the non-prioritized nodes (but fewer slots can be allocated in total). IEEE 802.11e defines different AIFS and CW values to provide four priority levels aimed to support different types of applications. For the prioritized node we use the AIFS corresponding to voice applications (AC_VO), and for the rest of the nodes, the AIFS for best effort applications (AC_BE). When having a CW, we have chosen the CW size used in video applications (AC_VI), since the CW then had enough levels to reduce collisions without increasing the maximum delay too much. Note that the size of the CW does not increase after each collision, since we do not incorporate retransmissions. For Protocol 2, the worst channel access delay then becomes $T_{BE\_worst\_delay_2} = (S+N-1)(T_{transm}+T_{AIFS}+T_{CW})$ since the worst case is that BE can only be transmitted in the prioritized slot.

MAC #3. Contention-based phases: In Protocol 2, if two or more BE slots occur one after another, the channel sensing must be restarted, ignoring previous information about the state of the channel that could help to access it more efficiently. In Protocol 3 we merge consecutive BE slots into a continuous phase, where nodes access the medium via contention without any pre-assigned priority. Due to the larger contention period, it is possible that more than one transmission fits, given that the size of each slot is the transmission time plus again some small guard time. When finishing a contention-based phase we further propose two alternatives, either to keep the current backoff counters and resume them at the beginning of the next phase (MAC 3A), or to randomize a new backoff value at the beginning of each contention phase (MAC 3B). The first option is thought to perform better, since the value of the backoff at each point in time depends not only on the original value randomized from the CW, but also on how long the node has been waiting to access the channel. If we randomize a new backoff value, this waiting time is likely increased. The worst case channel access delay is however still unbounded in both cases for Protocol 3, since it depends on the instantaneous channel load.

Besides the mechanisms described for each of the proposals, Protocol 2 and 3 also need an additional mechanism to avoid that a message being sent at the end of a BE slot/phase overlaps with the following TT or RC slot, interfering with their real-time behaviour. For this, we define a restricted phase at the end of the slot/phase, in which no messages can be sent and the channel cannot be sensed and thus no backoff counters are decremented. The duration of the restricted phase is exactly the time it takes for a transmission to complete, so that a message can be sent just before the restricted phase starts, and it will be finished at the end of the restricted phase without interfering with the next TT or RC slot.

9.3 Simulation and Results

In order to simulate the wireless MAC protocols, we have created a model for each of them in OMNeT++, a discrete event C++ library and simulation framework[1]. Concretely, the models are implemented using the INET network simulation framework [14], that supports the simulation of the IEEE 802.11b physical and MAC layer. The simulation registers a value for the channel access delay for every packet sent. The channel access delay reflects the time it takes for a packet from the instant it enters the MAC layer, to the instant when it is going to be sent. Furthermore, the average channel access delay including queuing is also evaluated. The queuing occurs when two or more packets from the same traffic class are waiting to be sent. The aim of the simulation is to test how the different configurations for each of the MAC protocols behave under different traffic patterns. Apart from the channel access delay, the simulation accounts also the number of collisions. This way, it is possible to analyse the connection between the two performance metrics, and detect situations in where, e.g., a MAC protocol performing well in regards to channel access delay is paying the price of having a great number of collisions.

The setup we have used to compare the different configurations comprises a small wireless network in infrastructure mode, having five end-nodes and one AP, big enough to obtain results that allow to see the differences between the configurations. The traffic goes only from the nodes to the AP (uplink), a setup that is common in industrial sensor networks. The size of the exchanged packets is relatively small (62 bytes, of which 4 bytes are payload), and has been selected as packets in industrial networks usually are small. The selected bitrate is 11 Mbps, the

[1] A complete report about the simulator is available at `www.es.mdh.se/publications/4302-`.

highest possible in 802.11b. For MAC Protocol 2, we test two protocol variations: either we include time for contention in each slot (Protocol 2B: $T_{slot} = T_{transm} + T_{AIFS} + T_{CW}$) or we only include time for the longest AIFS and thus only zero as randomized backoff value (Protocol 2A: $T_{slot} = T_{transm} + T_{AIFS}$). For MAC Protocol 3, we also have two options: storing the backoff value from a previous phase (Protocol 3A) or restarting and randomizing a new one every time (Protocol 3B). Concerning the data traffic, TT/RC packets are generated periodically, while BE packets are randomly generated according to the specified packet load. The load is defined as the percentage of slots that are occupied within each hyperperiod. To make the results comparable, the application generating packets adjusts the rate to the protocol with the largest slot size, so that for a load of 100%, only the protocol with the largest slot size is fully loaded, whereas all other protocols with smaller slot sizes are not, i.e., do not have a packet to send in each slot. Regarding the traffic patterns, we have selected a low-medium load of 40% and a high load of 100%. These loads can be achieved by the combination of different types of traffic. We have selected combinations in where there is a majority of TT/RC, a majority of BE, or a balance between them. Furthermore, this load can be generated by a single sending node, or be shared such that all the nodes are sending. Further, all the MAC protocols have been tested under different BE slot distributions. The BE slot distribution refers to how the BE slots are allocated along the hyperperiod: either all packed together after the TT/RC traffic or evenly distributed in between TT/RC traffic. All traffic-related simulation parameters are summarized in Table 9.1. The combination of different MAC protocol variations and different traffic patterns resulted in a total of 140 different tests. The simulator has been run for enough time to have around 500 channel access delay records for each of these combinations.

When evaluating MAC Protocol 3 for different BE slot distributions (all packed together or evenly distributed in between TT/RC slots), it became clear that channel access was not possible when the BE slot distribution was evenly distributed and there was 50% or more TT/RC traffic. This is due to the fact that when there is 50% or more TT/RC traffic, it is not possible to have two or more consecutive BE slots which in turn means that there is not enough time to finish a transmission in a single slot. Hence, if it is not possible to influence the scheduler such that BE slots can be scheduled consecutively, Protocol 3 should not be used. Conversely, the BE slot distribution only have negligible

Table 9.1: Traffic pattern related simulation parameters.

Load per traffic type	Low-medium load	20% (TT/RC) - 20% (BE)
		10% (TT/RC) - 30% (BE)
		30% (TT/RC) - 10% (BE)
	High load	0% (TT/RC) - 100% (BE)
		20% (TT/RC) - 80% (BE)
		50% (TT/RC) - 50% (BE)
		80% (TT/RC) - 20% (BE)
BE load distribution	One sending node	
	All sending nodes	
BE slot distribution	Packed together	
	Evenly distributed	

effect on Protocol 1 and Protocol 2 (it does affect the minimum delay, but only marginally influence the average delay), and consequently, our evaluation henceforth only considers the case when then the BE slots occur consecutively.

In Figure 9.3, the average channel access delay for MAC Protocol 1 is presented. We can see that Protocol 1 is not good when having only one sender, but performs very well when having all the nodes sending. This is a clear benefit of the round-robin mechanism, that evenly distributes the opportunities to access the medium. If there is only one sender, all the channel access opportunities assigned to the non-sender nodes are lost, and the channel access delay for the sender node is significantly increased. We can also see that the delay increases with the traffic load, and BE traffic is especially harmed by the amount of TT/RC. However, the main benefit of Protocol 1 is that it does not suffer any collisions and thereby provides predictable upper-bounded channel access delay for all three traffic classes.

Figure 9.4 shows the average channel access delay for Protocol 2. If no contention is allowed, Protocol 2 performs similarly to Protocol 1. However, when allowing contention, the difference in channel access delay between traffic being sent from one or from all the nodes is negligible. Unfortunately, in Figure 9.5, we see that collisions occur when data emanates from several nodes, and the number of collisions increase when contention is allowed.

Figure 9.6 shows the results for the average channel access delay

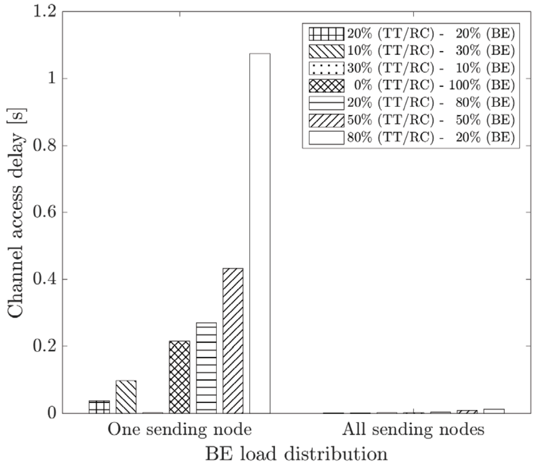

Figure 9.3: Average channel access delay for MAC Protocol 1 for different loads and distributions of load.

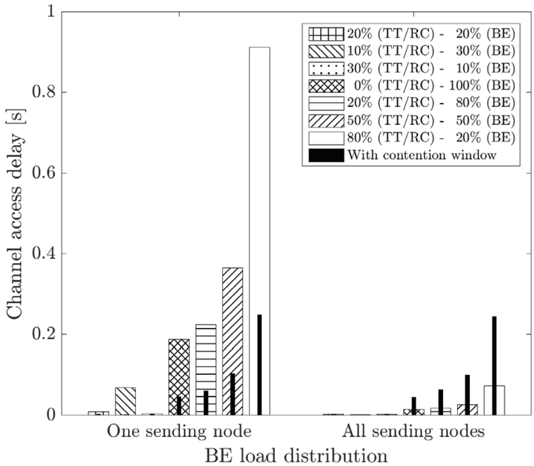

Figure 9.4: Average channel access delay for MAC Protocol 2A for different loads and distributions of load. Thin black bars are for MAC 2B.

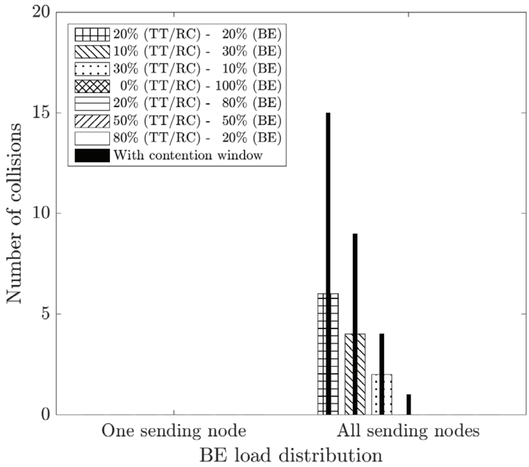

Figure 9.5: Number of collisions for MAC Protocol 2A for different loads and distributions of load. Thin black bars are for MAC 2B.

with MAC Protocol 3. We can see that the protocol option of storing or restarting the backoff counter at every phase does not have any significant effect, and is only slightly lower in the case of storing the backoff value between phases. We can also see that the channel access delay is generally much lower than with Protocol 1 and Protocol 2. However in Figure 9.7, we see that the price to pay is that the number of collisions is quite high when all nodes are sending.

Figure 9.8 summarizes the mean values for the channel access delay for all the different MAC protocols. Given these results, we can say that Protocol 3 yields the lowest average channel access delay, unless 50% or more of the traffic is reserved for TT/RC and the slots are evenly distributed. Protocol 1 is best when all the nodes are sending traffic, both in terms of average and guaranteed maximum channel access delay. In regards to the number of collisions, Protocol 2 and 3 obviously do not suffer from collisions when having only one sender, and since they have lower channel access delay than Protocol 1, they are the preferred options when the data traffic emerges from only one node. When the load distribution is unknown, Protocol 2 with contention provides the best tradeoff as the worst case delay is bounded and collisions only occur when the prioritized node has nothing to send.

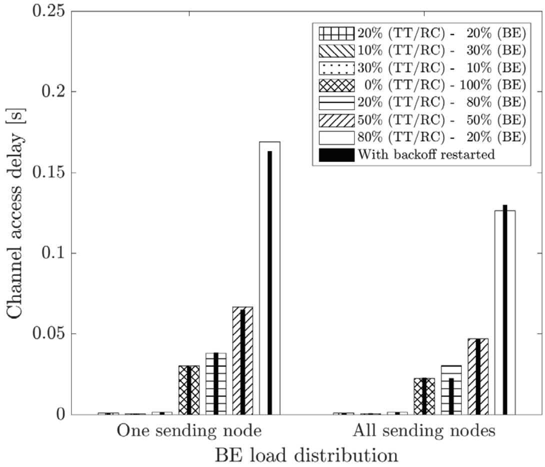

Figure 9.6: Average channel access delay for MAC Protocol 3A for different loads and distributions of load. Thin black bars are for MAC 3B.

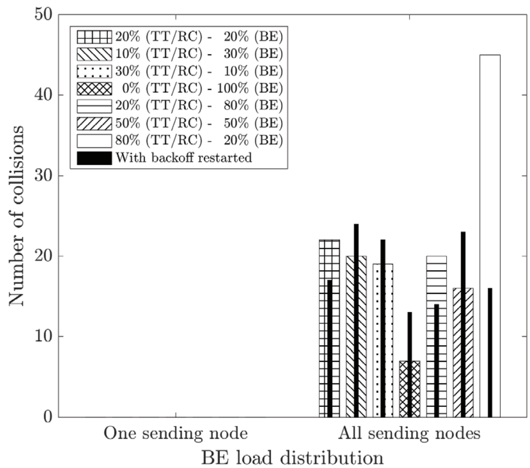

Figure 9.7: Number of collisions for MAC Protocol 3A for different loads and distributions of load. Thin black bars are for MAC 3B.

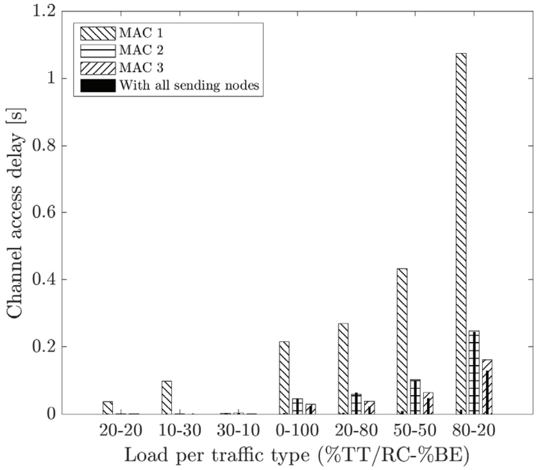

Figure 9.8: Average channel access delay for the different MAC protocols under different loads and distributions of load. For MAC 2 and MAC 3, only the best configurations are shown (MAC 2B and MAC 3B). Thin black bars represent the case when traffic comes from all nodes.

9.4 Conclusion

In this paper, we have presented three proposals of wireless MAC protocols that based on their worst case channel access delay (evaluated analytically) are able to support traffic with diverse time and safety requirements, and be used to extend an existing wired real-time network. We have also implemented our proposals in the well-known network simulator INET (for OMNeT++), and retrieved average values for the channel access delays, and the number of collisions for the protocols tested under different protocol configurations and traffic patterns. For the TT and RC traffic classes, the delays are known and predictable, but for BE traffic this is generally not the case. Our goal in this paper is to be able to provide an upper bound on the channel access delay also for this traffic class, such that it could be used to support event-driven real-time data traffic. Based on our simulations, we can conclude that the selection of the best MAC protocol and its settings depends on the traffic pattern. The more that is known about the data traffic, the better performance can be achieved by selecting an appropriate MAC protocol. Specifically, if data emerges from one node, MAC Protocols 2 or 3 are preferred, whereas when data is evenly distributed among the nodes Protocol 1 is best. Conversely, when nothing is known, MAC Protocol 2 emerges as the best trade-off.

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Chapter 10

Paper D: Applying Time Diversity for Improved Reliability in a Real-Time Wireless MAC Protocol

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Abstract

Supporting real-time applications over wireless networks is challenging for several reasons. However, the inherent advantages due to wireless access like reduced wiring or the possibility to transmit between moving components are still desirable in many application domains. In particular, wireless support to applications with traffic having diverse time and safety requirements is desirable. The medium access control (MAC) layer plays a key role in enabling real-time guarantees, since it provides access to the transmission medium. Unfortunately, even if timely access is guaranteed, transmissions can still be compromised due to the unreliable wireless medium. A common way to increase the reliability of a communication system is to apply redundancy in the form of time diversity, i.e., transmitting several copies of the same message at different points in time. In this paper we propose a wireless MAC method in where transmissions and retransmissions are tailored to deadlines, so that the reliability of the communication system is increased and real-time guarantees can be provided. The proposal enables coexistence of three different traffic classes: time-triggered, rate-constrained and best-effort. Further, we have analysed the effect of different protocol configurations subject to interference with different duration, frequency, and level of persistence. The results show that different protocol settings can be successfully applied to combat different kinds of interference to improve transmission reliability and timeliness.

10.1 Introduction

In some networking scenarios, like industrial networks, real-time communications are mainly provided by wired communication technologies, specially due to the advantages offered by the transmission medium, that is generally better at coping with, e.g. interference, noise, and pathloss. Yet, the possibilities enabled by wireless communications are desirable in many application domains. These advantages include, e.g. reduced wiring, more flexible and easier network deployments, and ability to communicate in scenarios with mobility. At the same time, real-time networks have evolved from supporting only strict time and safety requirements, towards the support of applications with more relaxed requirements, using the same communication infrastructure. An example of this is Time-Triggered Ethernet (TTE) [1], a wired communication technology based on switched Ethernet that provides support to traffic with diverse time and safety requirements by means of three different traffic classes: time-triggered (TT), for applications requiring periodic transmissions with jitter in the range of a few microseconds; rate-constrained (RC), for traffic characterised by an average bandwidth not necessarily periodic; and best-effort (BE), for non real-time traffic. A wireless extension of TTE would therefore meet both the emerging demands on mobility and increased flexibility, while at the same time supporting applications with diverse real-time and safety requirements.

A reasonable step for porting TTE to wireless is to base it on the IEEE 802.11 standard, as it is similar to Ethernet. Unfortunately, the contention-based access method offered by IEEE 802.11 is not suitable for real-time. In communication systems, the medium access control (MAC) layer is in charge of providing access to the transmission medium. A MAC layer in a real-time network has the additional task of providing this access in a bounded amount of time to prevent deadlines from being missed. An additional mechanism based on polling, called HCCA, is also included in the IEEE 802.11 standard but it introduces a considerable protocol overhead. To overcome the limitations of the IEEE 802.11 MAC protocol, our approach is to use time-slots on top of the contention-based MAC, and pre-schedule a subset of these for TT and RC traffic [2]. However, even if timely channel access is granted, wireless transmissions are still subject to errors due to fading, which can lead to deadline misses. Hence, we additionally propose to use time diversity to increase the reliability of the wireless system, so that it is able to keep real-time guarantees under different error scenarios. With TTE, the scheduler is in charge of providing real-time guarantees to TT and RC traffic. By adapting the TTE scheduler to cope with wireless channels, we can make both transmissions and retransmissions of real-time traffic to be tied to deadlines, and scheduled to appear at a certain time. Since wireless interference can appear with different levels of intensity, duration, and persistence, we propose to make retransmissions happen either immediately, or to be deferred closer to the real-time deadline in an attempt to avoid error bursts. Finally, we evaluate different protocol configurations subject to interference causing errors with different duration, frequency, and level of persistence.

The remainder of the paper is structured as follows. In Section 10.2 we present the background and related work. Section 10.3 describes our proposed protocols, whereas Section 10.4 covers the simulation analysis for different interference scenarios. We conclude with Section 10.5.

10.2 Background and Related Work

The problem of interference affecting IEEE 802.11 and IEEE 802.15.4 networks, together with the causes, consequences and possible countermeasures has been widely covered in literature. Anastasi et al. [3] investigate the reasons for low reliability in IEEE 802.15.4 and discover that the problem is mainly caused by the contention-based MAC protocol. The authors show that with more appropriate MAC parameter settings, it is possible to achieve better delivery ratios in scenarios with several sources of interference. Similarly, Seno et al. [4] state that one of the main problems to support real-time deadlines in IEEE 802.11 are the backoff procedures and MAC layer retransmissions, that do not meet any time boundaries. Lo Bello et al. [5] show that interference in IEEE 802.15.4 can be caused not only by overlapping channels, but also by adjacent channels. The use of retransmissions is a commonly found countermeasure in literature. Dominguez-Jaimes et al. [6] characterize the behaviour of retransmissions in standard IEEE 802.11 for industrial channels, where interference is considerable, showing that in their scenario one retransmission attempt performed immediately after the transmission is enough, and showing also that smaller frames result in fewer retransmissions. Many papers address the effect of retransmissions with respect to the additional requirements they impose on real-time traffic. Jonsson et al. [7] perform a real-time scheduling analysis to guarantee that retransmissions are made without any deadline misses in scenarios with error rates that are typically experienced in wireless communications. In [4], multi-rate support is also investigated, based on the IEEE 802.11 mechanism allowing the nodes to adapt the transmission rate to the signal-to-noise ratio (SNR). The paper proposes to decrease the rate after a certain number of failures, and to increase it after a certain number of succeeds. The rate can also be set to the lowest possible, so that the timing performance is kept constant under varying SNR level values. Willig et al. [8] address the problem of increasing reliability through retransmissions in a time division multiple access (TDMA) protocol that includes relaying nodes. Demarch et al. [9] deal with the problem of scheduling transmissions and retransmissions under real-time constraints by proposing a new mechanism called Integrated Scheduling and Retransmission Approach (ISRA). Reliability is achieved by providing a probabilistic provisioning of retransmissions, with each node calculating the number of retransmissions that is needed for the given channel error model, and sending the requirements in a message to the scheduler. Two retransmission schemes are proposed, either they happen immediately, or they are enqueued and happen later. Parsch et al. [10] present a MAC protocol for WSN in where the number of retransmissions is estimated based on the probability of interference and the desired reliability level. Berger et al. [11] target reliability in WSN with typical error rates from industrial channels by proposing a TDMA protocol in where several sensed samples are sent at once in a packet, and in case the transmission fails, it is enqueued to be transmitted later. However, since the packet can be waiting in the queue for an unbounded amount of time, the mechanism is not suitable for real-time, so the authors propose an alternative based on forcing all retransmissions to happen inside a longer time-slot. To the best of our knowledge, our proposed protocols are the first to consider a heterogeneous wired-wireless network with support for three different traffic classes with different timing and safety requirements, in which retransmissions are scheduled to meet real-time deadlines, and where protocol parameters can be tuned to cope with different interference scenarios.

10.3 MAC Protocol with Increased Reliability for Time and Safety Critical Traffic

10.3.1 Network Model and Scheduling

We consider a MAC protocol intended for wireless communications that supports three different traffic classes from TTE: TT, RC and BE. The characterization of the traffic is as follows: TT is periodic, therefore defined by t_{period} and d_{length}. RC is determined by its minimun interarrival time t_{MIA} and d_{length}. Finally, BE is defined only by d_{length}. In order to combine these different types of traffic under a single communication infrastructure, an offline schedule is created for all the TT traffic flows in the entire network, so that every hop of a message between the network devices is scheduled until destination. TTE is based on TDMA, in where the nodes are given channel access opportunities in the form of time-slots. For the sake of simplicity, we model RC traffic also as periodic (in the worst case it is), so that $t_{period} = t_{MIA}$, and the allocation of both TT and RC slots is given by the scheduler. Once we get the schedule, we distribute it among the nodes prior to operation. Once TT and RC traffic has been allocated, the remaining time can be claimed dynamically by BE or retransmissions.

The physical topology of this multi-hop network is given by the undirected graph $G(V, E)$, where V stands for the network nodes, and E represents the communication links between the nodes. In our network, the physical links are bi-directional and referred to as dataflow links, and the set of dataflow links as L, so that

$$\forall [v_1, v_2] \in V : (v_1, v_2) \in E \Rightarrow [v_1, v_2], [v_2, v_1] \in L. \tag{10.1}$$

A message that needs to be transmitted from a sender to a receiver is decomposed in a set of message instances, with every instance being transmitted in one link from the set of links L. The network schedule includes the instances of all the TT and RC messages, that are defined by $m^{[v_i,v_j]} = \{m.t_{period}, m.d_{length}, m^{[v_i,v_j]}.t_{offset}\}$. Further, t_{offset} specifies the transmission time of the instance of a message and has to be calculated. The task of calculating t_{offset} is performed by the TTE scheduler, that is based on the use of first-order logic constraints to model the network topology and traffic flows [12]. The first-order logic constraints are a powerful mathematical tool able to model many scenarios, including multi-hop or hybrid wired-wireless networks among others. Several scheduling constraints are defined on TTE, but for the purpose of this paper we only cite the ones referred as *avoid-collision* constraints, that prevent the instances of messages to be placed concurrently in the same link. Given M representing the set of all messages, and $LCM(M.t_{period})$ standing for the least common multiple of all message periods (harmonic periods), the following equation models the avoid-collision constraint on TTE [12]:

$$\begin{aligned}
&\forall [v_k, v_l] \in L, \forall m_i, m_j \in M, \\
&\forall a \in \left[0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_i.t_{period}} - 1\right)\right], \\
&\forall b \in \left[0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_j.t_{period}} - 1\right)\right] : \\
&((m_i \neq m_j) \wedge \exists m_i^{[v_k,v_l]} \wedge \exists m_j^{[v_k,v_l]}) \Rightarrow \\
&((a \times m_i.t_{period}) + m_i^{[v_k,v_l]}.t_{offset} \neq \\
&(b \times m_j.t_{period}) + m_j^{[v_k,v_l]}.t_{offset}).
\end{aligned} \tag{10.2}$$

When supporting wireless communication, we additionally require to avoid concurrent transmissions on all wireless links within range of each other. We therefore redefine E, so that it is now composed of both wired E_{wd} and wireless links E_{wl}, $E = E_{wd} \cup E_{wl}$. For simplicity, we assume that the slot size is the same for both the wired and wireless segments. Given the previous assumptions, the following equation describes the avoid-collision constraints for the network composed of wired and wireless links:

$$\begin{aligned}
&\forall [v_k, v_l], [v_q, v_r] \in L, \forall m_i, m_j \in M, \\
&\forall a \in \left[0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_i.t_{period}} - 1\right)\right], \\
&\forall b \in \left[0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_j.t_{period}} - 1\right)\right] : \\
&((m_i \neq m_j) \wedge \exists m_i^{[v_k,v_l]} \wedge \exists m_j^{[v_q,v_r]} \\
&\wedge ([v_k, v_l], [v_q, v_r] \in E_{wl})) \Rightarrow \\
&((a \times m_i.t_{period}) + m_i^{[v_k,v_l]}.t_{offset} \neq \\
&(b \times m_j.t_{period}) + m_j^{[v_q,v_r]}.t_{offset}).
\end{aligned} \tag{10.3}$$

The constraints are solved using satisfiability modulo theories (SMT) solvers [13].

With the definition of the constraints above, the MAC protocol is provided with a schedule that avoids the problem of interference from devices inside the network. Still, the problem of external interference remains to be solved.

10.3.2 Scheduling Retransmissions

We schedule retransmissions to increase the reliability of the TT and RC traffic. To increase the reliability of TT traffic, the period can be reduced (e.g., by oversampling the sensor), such that some lost transmissions can be tolerated. Alternatively, if the TT data is used for majority voting for increased safety, retransmissions made before the deadline expires are tractable. RC traffic can be used for event-driven data, in which case timely retransmission for increased reliability is desirable. To schedule retransmissions in addition to the original transmissions, it is sufficient to add a constraint to the scheduler that forces the allocation of one or several retransmissions after the first scheduled transmission. Given R the number of retransmissions, and the inter-transmission time t_{ITI}, that is the time difference between a transmission and its corresponding retransmission, the following equation adds retransmissions to Equation 10.3:

$$\begin{aligned}
&\forall [v_k, v_l], [v_q, v_r] \in L, \forall m_i, m_j \in M, \\
&\forall a \in \left[0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_i.t_{period}} - 1\right)\right], \\
&\forall b \in \left[0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_j.t_{period}} - 1\right)\right], \\
&\forall c \in \{0..R\} \in \mathbb{N}^0 : \qquad (10.4) \\
&((m_i \neq m_j) \wedge \exists m_i^{[v_k,v_l]} \wedge \exists m_j^{[v_q,v_r]} \\
&\wedge ([v_k, v_l], [v_q, v_r] \in E_{wl})) \Rightarrow \\
&((a \times m_i.t_{period}) + m_i^{[v_k,v_l]}.t_{offset} + c \times t_{ITI} \neq \\
&(b \times m_j.t_{period}) + m_j^{[v_q,v_r]}.t_{offset} + c \times t_{ITI}).
\end{aligned}$$

The jitter in this case is defined as the time difference between the minimum delay that happens if and when the first transmission is successful, and the maximum delay that happens if and when the last allowed retransmission does not succeed (infinite delay). This parameter will be affected both by the number of allowed retransmissions R, and by t_{ITI}. Depending on the specific value adopted by t_{ITI}, retransmissions can happen either closer to or further from the original transmission.

10.3.3 Slot Size and Use of Feedback Mechanism

The benefit of using retransmissions is present only when both the following conditions are met: previous transmission attempts have failed, and data is still useful at the time the retransmission is performed. If something gets retransmitted after it has been successfully received, or if the retransmitted data is not useful any more, the bandwidth is wasted. For this reason, the sender can be informed of the success of a transmission, so that it can decide whether to retransmit or not. These mechanisms based on retransmissions after receiving feedback are commonly referred as to automatic repeat request (ARQ). The feedback is normally conceived as an acknowledgement message (ACK), sent by the destination upon arrival of a correct message. The information carried by the ACK message can in our case be useful for cancelling further retransmissions and instead using this time for BE traffic or retransmissions from other flows. In systems where there is no such feedback (e.g. simplex communication, or due to necessity to avoid overhead), retransmissions always take place. We offer two MAC protocol variations, one without feedback, and one with feedback. In the first version of the MAC, that we refer to as Protocol 1, we propose to not provide feedback, such that slots are pre-allocated and retransmissions always take place, in a similar way as it is being done in the well-known WirelessHART protocol for industrial wireless sensor networks. The slot size $t_{slot\_mac\_1}$ required to implement this option therefore only needs to accommodate the data transmission t_{data}, and the slot time t_{ST}, where t_{ST} is a guard interval used before every transmission to avoid collisions due to propagation delay. The specific value for t_{ST} comes from the IEEE 802.11 physical layer. This makes the slot size for Protocol 1 to be $t_{slot\_mac\_1} = t_{ST} + t_{data}$.

In contrast to Protocol 1, in Protocol 2 we allow using feedback so that retransmissions do not take place if the previous message transmission or retransmissions were successful. The advantage of this approach is that the usage of a slot can be changed dynamically, from being scheduled for retransmissions of critical traffic, to a contention-access slot that can be used by other traffic like BE. We will send the ACK message in the same slot just after the data has been received. Note that if the data was able to arrive, it is likely that the channel is still in good condition also for the ACK, so chances of successful ACK delivery are higher. This in turn implies that the size of the slot $t_{slot\_mac\_2}$ in Protocol 2 must have enough space for the two supported uses: either a prioritized node accessing the slot and using the feedback mechanism, or the slot is accessed via contention. For the first case, that we refer to as Protocol 2A, the slot must accommodate the t_{data} and t_{ST}, as in Protocol 1, plus the ACK t_{ack}, and the turn-around time represented by a short interframe space t_{SIFS}. This value comes also from the physical layer of IEEE 802.11. The resulting slot size for 2A is $t_{slot\_mac\_2A} = t_{ST} + t_{data} + t_{SIFS} + t_{ack}$. For the second case, Protocol 2B, both t_{IFS} and the contention window t_{CW} are needed, together with the t_{data}, resulting in $t_{slot\_mac\_2B} = t_{IFS} + t_{CW} + t_{data}$. All in all, the size of a slot for Protocol 2 is calculated as follows: $t_{slot\_mac\_2} = max\{t_{slot\_mac\_2A}, t_{slot\_mac\_2B}\}$.

10.3.4 Retransmission Schemes

An important factor to consider when designing retransmission schemes is that interference can occur in bursts, characterized by a duration t_{burst}. Given this, we propose two retransmission schemes (both applied to Protocol 1 as well as 2): one scheduling retransmissions right after its corresponding transmission slot, called Consecutive, and another one with spread retransmissions, called Spread. The former is expected to provide a lower jitter, whereas the latter is expected to be better against bursts of interference implying that the retransmission takes place a few slots after its corresponding transmission.

Consecutive retransmissions. A straightforward way to include retransmissions consist in placing each one consecutively after the first transmission attempt. This could be implemented by just making each slot bigger, and allocating both the transmission and the retransmission inside the slot. However, we discarded this option, since then the unused retransmission time cannot be reclaimed by other traffic. Hence, we use the mechanism as shown in Figure 10.1, where the transmission and retransmissions (one in this case), are placed in separated slots. To schedule this scheme, the scheduler will first place the transmission, and then the retransmissions, with a shift between them of the duration of the slot: $t_{ITI\_cons} = t_{slot}$.

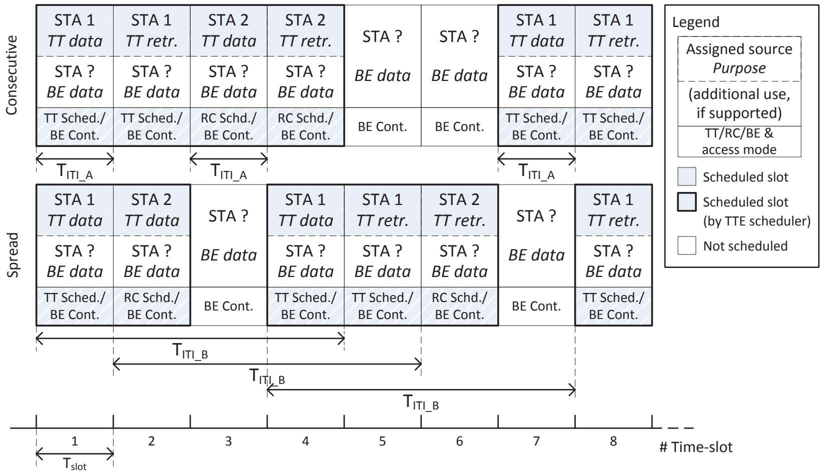

Figure 10.1: Proposed retransmission schemes. Note that the size of the slot is the same for both retransmission schemes, but differs from the case it is applied to MAC Protocol 1 or Protocol 2. Also note that scheduled slots can only be reused by BE traffic in Protocol 2.

Spread retransmissions. In the Spread scheme (Figure 10.1), we propose to spread the retransmissions so that the time between the transmission and the retransmission is larger than in the Consecutive scheme: $t_{ITI\_sprd} > t_{ITI\_cons}$. The specific value of t_{ITI_sprd} must be a trade-off between two factors. On one hand having as low value as possible, so that it is easier to get a schedule given that the traffic flow cannot meet its deadline if the value is too big, and a lower value also decreases the transmission jitter. On the other hand, having a large enough value that makes possible to avoid bursts of interference ($t_{ITI\_sprd} > t_{burst}$). In this respect, it is beneficial to characterize the interference that is normally present so that characteristics like the maximum interference burst size can be estimated. Also, note that although a low jitter is very relevant for TT, that is not necessarily the case for RC, suggesting that different strategies could be used for TT and RC traffic.

10.4 Simulation and Results

10.4.1 Simulation Setup

To evaluate the resistance of the MAC protocols and the proposed retransmission schemes against interference, we have created a model for each of them in OMNeT++ [14], a discrete event C++ library and simulation framework. Specifically, the models are implemented using the INET simulation framework [15], that supports the simulation of the IEEE 802.11b physical and MAC layer, but results are also applicable to the standard versions up to the current IEEE 802.11-2012. The considered performance metrics are percentage of failed message transmissions, time left to be used by BE traffic, and average MAC to MAC delay. Since the scheduler guarantees that retransmissions do not take place after the packet deadline, a deadline miss is accounted every time a message is not successfully delivered after the last scheduled retransmission. With deadline miss, we evaluate to what extent the scheduled real-time traffic behaves under different interference scenarios. The percentage of time left for BE traffic allows to evaluate the differences between Protocol 1 and 2, regarding the number of slots allocated, that may differ due to the different slot sizes, and check to what extent the mechanism of reusing retransmission slots in Protocol 2 is beneficial. In regards to the average MAC to MAC delay, it is calculated as the average time it takes from the moment when a message is sent for the first time until it is sent for the last time. This performance metric allows to compare the average delay introduced by the retransmission schemes, which grows with every failed transmission attempt. The purpose of the simulation is to test how the basic implementation of the two MAC protocols (Protocol 1 and 2) without retransmissions and with the two different retransmission policies (Consecutive and Spread) behave under different traffic patterns and different types of interference.

The setup we have used is based on a small wireless network in infrastructure mode, counting five end-nodes and one AP, which is enough to see the differences that allow to compare the scenarios. Traffic travels from the end-nodes to the AP, and is evenly distributed among the nodes. The size of the exchanged packets is 62 bytes (of which 4 bytes are payload), relatively small but representative for the kind of packets typically exchanged in industrial networks. Since we want to support as high speed transfer rates as possible, we have chosen the highest bi-

Table 10.1: Protocol related simulation parameters.

MAC protocol	Protocol 1 (without ARQ)
	Protocol 2 (with ARQ)
Retransmission scheme	None
	Consecutive
	Spread
Number of retransmissions	1

trate offered by 802.11b. From IEEE 802.11b we also get the values for $t_{ST} = 20\mu s$, $t_{SIFS} = 10\mu s$, and $t_{ack} = 203\mu s$. We have tested the case of not having retransmissions as well as the Consecutive and Spread policies applied to MAC Protocol 1 and Protocol 2. The maximum number of allowed retransmissions has been fixed to 1, since this shortens the simulation time, while still showing the necessary performance differences. In addition, the results are easily extended to a larger number of retransmissions. Table 10.1 offers a summary of protocol related parameters. We have evaluated different channel conditions, including different types of interference coming from CSMA devices and jamming interference, with the latter serving to model any other source of unintentional interference. The interference appears at different levels of intensity, being present 10% and 30% of the total time. Interference is randomly generated, but can appear in bursts of different sizes. The size is a multiple of the time it takes to send a packet of 62 bytes. The worst interference scenario is represented by jamming 30% of the time, a scenario that we consider extreme , i.e., not many protocols, if any, cope with this level of interference, but we use it to test the boundaries of our proposed protocols. Table 10.2 offers a summary of interference pattern related parameters. To make results comparable, all the scenarios are tested under the same traffic conditions, and adapted to the protocol that is able to cope with the shortest amount of traffic, so that no queue overflows happen. Only TT and RC traffic is generated, and the generation is evenly distributed between the nodes. The combination of protocol and interference pattern related parameters results in 72 unique configurations/scenarios. We have run the simulations to obtain at least 100 packet losses per configuration for the presented cases.

Table 10.2: Interference pattern related simulation parameters.

Type of interference	CSMA
	Jamming
Level of interference	10%
	30%
Interference burst size (as multiple of the size of data messages)	1
	15
	30

10.4.2 Simulation Results

In Figure 10.2 and 10.3, the percentage of failed message transmissions for MAC Protocol 1 and 2 respectively under different loads and burst sizes of CSMA interference is presented. The superposed thinner bars indicate the same performance parameter but for the jamming type of interference. We can see that the jamming type of interference is more harmful than CSMA, given that CSMA devices backoff if they sense the medium as busy. The level of interference causes the expected effect, the more time that is occupied by interference, the greater is the deadline miss ratio. However, it can be seen that for the burst size, a larger one does not always mean that results will be worse. This is because with the same level of interference, a larger burst size makes the interference to be constrained to larger, but less frequent interference intervals. From the figures we see that the Consecutive retransmission policy behaves better for the CSMA type of interference, while for the jamming case, the Spread retransmission policy is much more beneficial. Unfortunately, the jamming interference pattern is still very harmful, even with the Spread retransmission policy, but can be improved by increasing the number of retransmissions.

Figure 10.4 and 10.5 show the percentage of the total time that can be used by BE transmissions by MAC Protocol 1 and 2 respectively under different patterns of CSMA interference. The superposed thinner bars indicate the same performance parameter but for the jamming type of interference. The BE slots are allocated when no retransmissions are scheduled (no retransmission scheme), and also when retransmission slots are left free in case the transmission is successful on a previous attempt. The latter only happens in Protocol 2. In the None case, a big gap between Protocol 1 and 2 can be seen, since Protocol 1 accounts

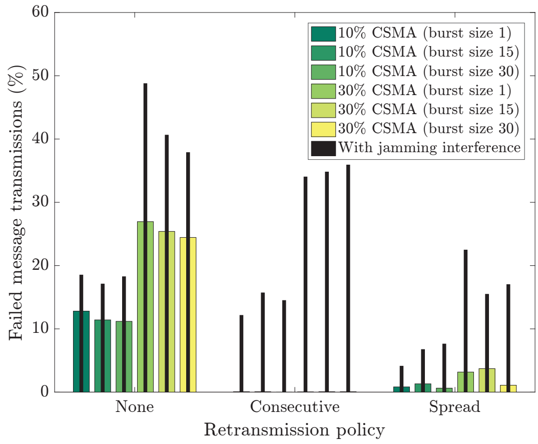

Figure 10.2: Percentage of failed message transmissions for MAC Protocol 1 with different loads and burst sizes of CSMA and jamming interference.

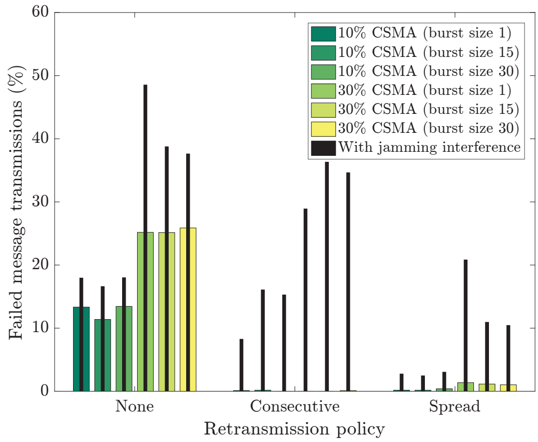

Figure 10.3: Percentage of failed message transmissions for MAC Protocol 2 with different loads and burst sizes of CSMA and jamming interference.

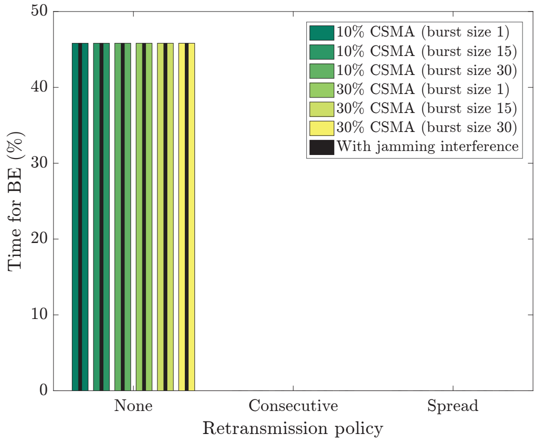

Figure 10.4: Percentage of time that can be used for BE transmissions for MAC Protocol 1 with different loads and burst sizes of CSMA and jamming interference.

shorter slots and is able to allocate a larger number of them. In this specific example, with small messages being transmitted, the overhead introduced by Protocol 2 is very noticeable, and causes Protocol 1 to allocate almost double the number of slots that Protocol 2. Better performance for Protocol 2 will be observed with an increase in the size of the data.

In Figure 10.6 and Figure 10.7, the average MAC to MAC delay under different patterns of CSMA interference is presented for MAC Protocol 1 and MAC Protocol 2 respectively. The superposed thinner bars indicate the same performance parameter but for the jamming type of interference. In both cases, the delay does not grow considerably between the cases of not having a retransmission scheme and the Consecutive scheme. In the case of the Spread scheme, the delay is much larger, since the retransmission slots are more spaced, and increases proportionally to the burst size. Note the difference between the average delay for MAC 1 and MAC 2, that is slightly larger for MAC 2 due to the larger slot size required by the protocol overhead.

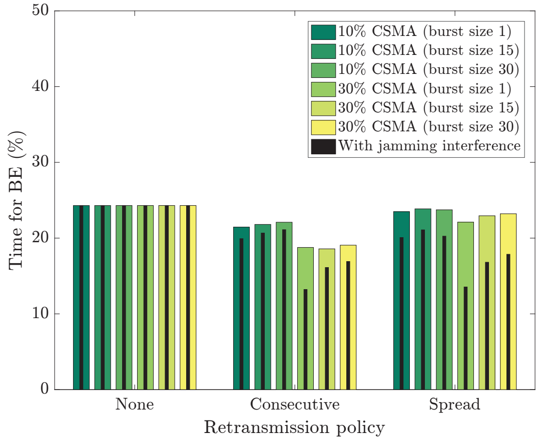

Figure 10.5: Percentage of time that can be used for BE transmissions for MAC Protocol 2 with different loads and burst sizes of CSMA and jamming interference.

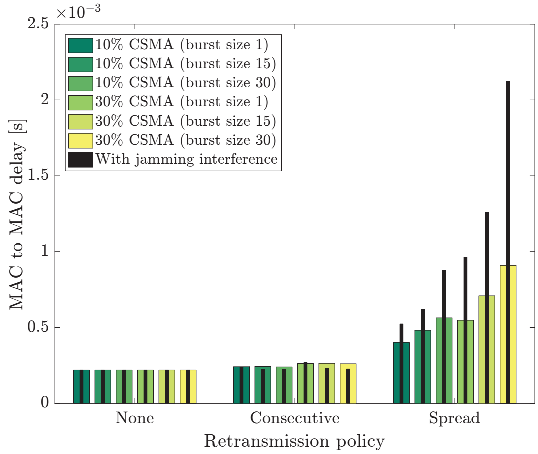

Figure 10.6: Average MAC to MAC delay for MAC Protocol 1 with different loads and burst sizes of CSMA and jamming interference.

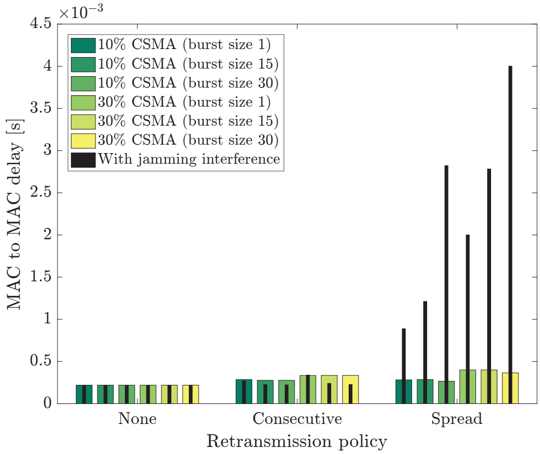

Figure 10.7: Average MAC to MAC delay for MAC Protocol 2 with different loads and burst sizes of CSMA and jamming interference.

10.5 Conclusion

In this paper we have applied time diversity retransmissions to improve the reliability of a real-time MAC protocol intended for wireless communications. The protocol is able to support traffic with diverse time and safety requirements, and is designed as an extension of the wired Ethernet-based protocol TTE. We have extended the scheduler of TTE, so that both transmissions and retransmissions are scheduled to happen at specific points in time. Then, two MAC protocol variations are addressed, one version making use of all the scheduled retransmissions, and another version based on feedback, that allows to reuse the retransmission slots that are not required. Two reliability mechanisms also are applied to these protocols, with retransmissions either happening immediately, or scheduled to happen slightly later. We have simulated the protocol and reliability versions, and the results show that retransmissions are an effective way to increase the reliability of the communication system, and that the different retransmission schemes can be applied to better fit error patterns of different levels of intensity, duration, and persistence.

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