Towards a Reliable and High-Speed Wireless Complement to TTEthernet

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***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.

I. 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 III 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 IV. Finally, we conclude in Section V.

II. 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.

III. WIRELESS COMMUNICATION BASED ON IEEE 802.11

A. *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].

B. *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 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 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.

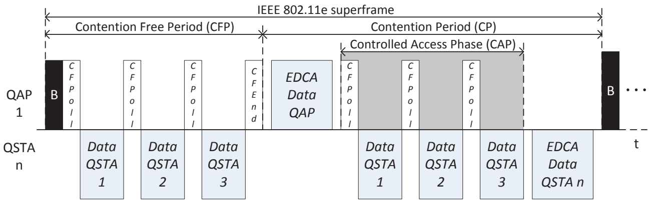

Fig. 1. IEEE 802.11e MAC superframe

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.

C. *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 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 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.

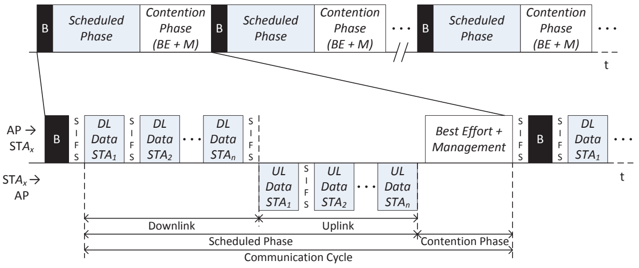

Fig. 2. IsoMAC channel access [12]

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 retransmissions. 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.

IV. Candidate Solutions for TTEthernet

An example of a wired TTEthernet network is depicted in Figure 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 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.

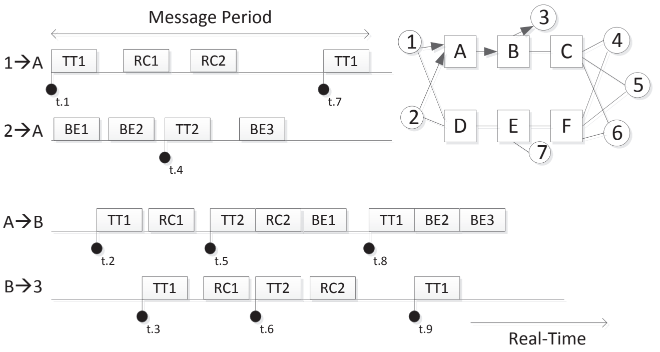

Fig. 3. Example scenario of integrated time-triggered and non-time-triggered communication

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 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.

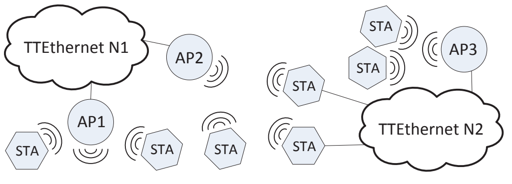

Fig. 4. Combined wired/wireless TTEthernet use case

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.

V. 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.

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REFERENCES

[1] W. Steiner, G. Bauer, B. Hall, and M. Paulitsch, "TTEthernet: Time-Triggered Ethernet," in *Time-Triggered Communication*, R. Obermaisser, Ed. CRC Press, Aug 2011.

[2] J. Song, S. Han, A. K. Mok, D. Chen, M. Lucas, M. Nixon, and W. Pratt, "WirelessHART: Applying Wireless Technology in Real-Time Industrial Process Control," *IEEE RTAS*, pp. 377–386, 2008.

[3] S. Han, A. K. Mok, J. Meng, Y.-H. Wei, P.-C. Huang, Q. Leng, X. Zhu, L. Sentis, K. S. Kim, and R. Miikkulainen, "Architecture of a Cyberphysical Avatar," *ICCPS*, pp. 189–198, 2013.

[4] A. Willig, "Recent and Emerging Topics in Wireless Industrial Communications: A Selection," *Ind. Informatics, IEEE Trans. on*, vol. 4, no. 2, pp. 102–124, 2008.

[5] J.-S. Lee, Y.-W. Su, and C.-C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *IEEE IECON*. IEEE, 2007, pp. 46–51.

[6] F. De Pellegrini, D. Miorandi, S. Vitturi, and A. Zanella, "On the Use of Wireless Networks at Low Level of Factory Automation Systems," *Ind. Informatics, IEEE Trans. on*, vol. 2, no. 2, pp. 129–143, 2006.

[7] F. Ring, A. Mahmood, L. Wisniewski, and H. Trsek, "Wireless Real-time Communication for Industrial Automation Systems in Simulation and Reality," *Mechatronics Forum International Conference*, 2012.

[8] A. F. Molisch, *Wireless communications*. John Wiley & Sons, 2010, vol. 15.

[9] L. Seno, S. Vitturi, and C. Zunino, "Analysis of Ethernet powerlink wireless extensions based on the IEEE 802.11 WLAN," *Ind. Informatics, IEEE Trans. on*, vol. 5, no. 2, pp. 86–98, 2009.

[10] G. Cena, L. Seno, A. Valenzano, and C. Zunino, "On the performance of IEEE 802.11e wireless infrastructures for soft-real-time industrial applications," *Ind. Informatics, IEEE Trans. on*, vol. 6, no. 3, pp. 425–437, 2010.

[11] M. Hameed, H. Trsek, O. Graeser, and J. Jasperneite, "Performance investigation and optimization of IEEE 802.15.4 for industrial wireless sensor networks," in *IEEE ETFA*. IEEE, 2008, pp. 1016–1022.

[12] H. Trsek and J. Jasperneite, "An isochronous medium access for real-time wireless communications in industrial automation systems - A use case for wireless clock synchronization," in *IEEE ISPCS*. IEEE, 2011, pp. 81–86.

[13] C. Casetti, C. Chiasserini, M. Fiore, and M. Garetto, "Notes on the Inefficiency of 802.11e HCCA," in *IEEE Vehicular Technology Conference*, vol. 62, no. 4. IEEE; 1999, 2005, p. 2513.

[14] R. Moraes, F. Vasques, P. Portugal, and J. A. Fonseca, "VTP-CSMA: A Virtual Token Passing Approach for Real-Time Communication in IEEE 802.11 Wireless Networks," *Ind. Informatics, IEEE Trans. on*, vol. 3, no. 3, pp. 215–224, 2007.

[15] C. Cicconetti, L. Lenzini, E. Mingozzi, and G. Stea, "Design and performance analysis of the Real-Time HCCA scheduler for IEEE 802.11e WLANs," *Comp. Networks*, vol. 51, no. 9, pp. 2311–2325, 2007.

[16] J. Son, H. Choi, and S.-C. Park, "An Effective Polling MAC Scheme for IEEE 802.11e," in *IEEE ISCIT*, vol. 1. IEEE, 2004, pp. 296–301.

[17] H. Trsek, S. Schwalowsky, B. Czybik, and J. Jasperneite, "Implementation of an advanced IEEE 802.11 WLAN AP for real-time wireless communications," in *IEEE ETFA*. IEEE, 2011, pp. 1–4.

[18] D. W. Allan, N. Ashby, and C. C. Hodge, *The Science of Timekeeping*. Hewlett-Packard, 1997.