Integration of IEEE 802.1AS-based Time Synchronization in IEEE 802.11 as an Enabler for Novel Industrial Use Cases

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Abstract—Industry 4.0 introduces new use cases, with more and more mobile devices appearing in the industrial landscape. These applications require both new technologies and smooth integration into existing “brownfield” deployments. Emerging mobile use cases can be divided into optional mobile and mandatory mobile, where the first point considers the use of wireless communications due to soft criteria such as cost savings and the second means use cases that cannot be covered by wireline technologies due to their movement, such as AGVs. For most industrial applications, high determinism, E2E latency and synchronicity are most important. Therefore, we provide a common table, based on these requirements, listing both existing and emerging mobile use cases. Since time synchronization is particularly demanding for wireless use cases, we propose a concept for a simple but precise synchronization in IEEE 802.11 wireless local area network (WLAN) and a suitable integration using TSN in combination with OPC UA technology as examples. Furthermore, the concept is evaluated with the help of a testbed utilizing state-of-the-art hardware. This means that this concept can be directly applied in existing industry solutions. It can be shown that the concept is already suitable for a wide range of the mandatory mobile applications.

Index Terms—IEEE 802.11, Wi-Fi, IEEE 802.1AS, WLAN, TSN, Industrial Communication, Industrial Automation, Time Synchronization

I. INTRODUCTION

Many novel use cases are emerging in the context of Industry 4.0 [1]. These use cases enhance the traditional applications in order to ensure the required flexibility of a smart manufacturing. One of the major differences is the requirement of wireless communications in order to allow the increasing number of mobile use cases. Tab. I sums up important use cases into classes and lists selected requirements, whereby the real-time classes are named from 1-3, or from A-C, dependant on the specific reference. In the following we use latter.

Typical use cases that can be found in the remote control and monitoring use case class are predictive maintenance and those that are part of the augmented reality (AR) domain. These applications, which belong to the lowest real-time class A, require time synchronization better than 1 s. The challenges for these use cases are usually the data rates that need to be supported due to the number of sensor nodes or video transmissions and the coverage of a large area, but this is not the subject of this paper. For mobile use cases, which are the main objective of the work in this paper and belong to the second class, the realization is particularly challenging, as they require wireless communication links with higher performance. Very challenging are those use cases where several mobile devices have a collaborative task, as here the most accurate time and state synchronization is required, where better synchronicity leads to faster robot interaction and thus to higher productivity. Typically, these use cases require a synchronicity of <1 ms. Since use case class III has the highest requirements for end-to-end (E2E) latency and synchronicity, and cannot be addressed by current wireless communications, the use cases that belong to this class are based on wireline systems, such as industrial Ethernet. Here concepts for the combination of IEEE time-sensitive networking (TSN) and 5th generation wireless communication systems (5G) [2], as well as TSN and WLAN [3], [4] were introduced. The main arguments for replacing cables with wireless communication in this class are high cost savings [3], [5], [6]. Since the goal of our investigations is the use of existing hardware to enable mobile use cases, which necessarily require both wireless communication links and precise time synchronization, we will not deal with use case class III in our work.

Therefore, the following contributions can be found in this paper:

• Integration of IEEE 802.1AS in IEEE 802.11 in order to fulfill the synchronicity imposed by industrial mobile use cases.

• Performance evaluation of the proposed concept based on a testbed.

Accordingly, the paper is structured as follows: Sec. II gives an overview about core technologies, while Sec. III gives insights into related work on this topic. Details on the integration of IEEE 802.1AS and IEEE 802.11 are given in Sec. IV. This is followed by a performance evaluation of the proposed concept based on a testbed consisting mainly of commercial off-the-shelf (COTS) hardware (Sec. V). Finally, the paper is concluded in Sec. VI.
IEEE 802.11 defines a family of standards for WLAN, which target high data rate communication with wide coverage area for high number of stations. It includes a set of communication protocols for licence exempt bands of 2.4 GHz, 5 GHz and 60 GHz such as IEEE 802.11a/b/g/n/ac/ad. The current standard, also referred as Wi-Fi 5, utilises such techniques as Orthogonal Frequency-Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) in order to increase throughput. On 2.4 GHz frequency band, theoretical data rate of up to 600 Mbps may be achieved with 4 x 4-MIMO. On 5 GHz frequency band, data rate of up to 6.933 Gbps might be possible by means of 8 x 8-MIMO [14]. Since Wave 2 extension, the standard introduces multi-user MIMO (MU-MIMO) technique among others, which allows the AP to transmit to several stations simultaneously. Furthermore, a new version of the standard, the IEEE 802.11ax or Wi-Fi 6, is recently emerged. Compared to the previous standard, its physical layer techniques further improve the data throughput. On the one hand, higher modulation schemes are available, and parallel uplink transmission is made possible by means of Orthogonal Frequency-Division Multiple Access (OFDMA). WLAN stations, which belong to the same network, carry out their communication via an AP by using a common channel. Based on a carrier sense multiple access with collision avoidance (CSMA-CA) scheme, any station needs to ensure, that it would not cause interference with ongoing communication, prior to starting a transmission. The particular methods to realise CSMA-CA are defined by amendment IEEE 802.11e, which enhances the initial access schemes with quality of service (QoS) capabilities by means of hybrid coordination function (HCF) [15].

On the one hand, HCF defines a probabilistic enhanced distributed channel access (EDCA) scheme. Prior to a transmission, a station has to generate a random back-off time period, which is a count down to start the transmission. In the case, some other transmission is detected during this period, the count down is paused until the channel is freed. This procedure lowers the collision probability as well as ensures fair channel access for any station. Furthermore, EDCA introduces four QoS traffic classes, which are prioritised to each other. The higher the priority, the shorter back-off time is assigned to the traffic. In this way, the channel access probability is increased for higher priority traffic. In the case of the idle channel, the latency of below 10 ms could be achieved with EDCA [16]. However, the raise of data traffic leads to significant raise of latency as well as the drop of throughput due to increasing number of collisions. Furthermore, it is not possible to provide any latency guarantee despite the traffic prioritisation mechanisms. On the other hand, HCF controlled channel access (HCCA) provides a deterministic access scheme for WLAN. It introduces contention-free period, which is periodically advertised by the AP. During this phase, AP takes the control on channel access. By polling the stations...
accordingly, a scheduling approach can be realised. Even though HCCA allows very flexible traffic scheduling, only a simple static scheduler is proposed by the standard. However, in [13] was shown, that by means of sophisticated scheduling schemes, the latency requirement of 8 ms could be guaranteed within a heterogeneous industrial environment. Furthermore, the authors in [14] give a comprehensive overview on currently available HCCA scheduling algorithms and their performance. It should be mentioned, that the HCCA scheme is barely implemented. To the best of authors’ knowledge, the only commercial solution available is iWLAN by Siemens [13]. It provides a proprietary iPCF functionality, which is capable of traffic scheduling for industrial applications. Unfortunately, no reliable numbers on the performance could be found in the literature.

Last but not least, a time division multiple access (TDMA) approach in WLAN for automation purposes is described by [15]. Instead of HCCA contention-free period, authors propose to introduce TDMA phase in order to provide dynamic scheduling of real-time traffic. The major advantages compared to HCCA are reduced protocol overhead as well as improved deterministic behaviour.

III. RELATED WORK

Precise clock synchronization in wireline systems is based on a constant time for data transmission between devices. Since wireless devices are often mobile and the propagation path of the communication signal changes during operation, this feature cannot be assumed for these systems. Therefore, the time synchronization of wireless systems requires other approaches. The different possibilities for time synchronization of wireless communications are described in [16], while [5] focuses on IEEE 802.11 WLAN. Furthermore, [16] proposed a concept to adopt the state-of-the-art by using the received power of the station in order to estimate the distance to the AP. In addition, [17] focuses on the integration of Precision Time Protocol (PTP), that has been defined in IEEE 1588 [18] and IEEE 802.11 using Reference Broadcast Infrastructure Synchronization (RBIS) protocol. This method uses the broadcast character of wireless medium and is well suited for a simple but precise time synchronization of IEEE 802.11 stations. Therefore, this method has also been adopted for the synchronization of 3rd Generation Partnership Project (3GPP) 4G and 5G systems [19]. Moreover, [19] used a IEEE 802.1AS Grandmaster as clock source to be TSN confrom and transmitted the time offset with OPC UA PubSub which is going to be the de-facto standard for application layer protocols in industrial automation.

IV. INTEGRATION OF IEEE 802.11 WITH IEEE 802.1AS

As already mentioned, most WLAN installations use the infrastructure mode, in which the stations do not communicate with each other directly, but via an AP. To use the RBIS protocol for time synchronization of the stations, the following conditions must be satisfied:

- Each message should have a unique identifier that is not repeatable
- The frequency of message transmission should be high

In addition to the user data that applications send from one station to another via an AP, there are also control and management messages that are transmitted by the AP, for example to share metadata. One of the management messages sent by each AP is shown in the following listing:

```
IEEE 802.11 Beacon frame
  Frame Control (2 Byte)
  Duration (2 Byte)
  Destination Address (6 Byte)
  Source Address (6 Byte)
  BSS ID (6 Byte)
  Seq-Ctrl (2 Byte)
  Frame Body
    Timestamp (8 Byte)
    Beacon Interval (2 Byte)
    Capaility Info (2 Byte)
    ... 
```

These messages are called beacon frames and contain the SSID of the AP, the time interval of the transmission, and the timestamp of the beacon, i.e. the time that elapsed since the AP was powered. By default the beacon interval (BI) is 100, i.e. 102.4 ms. If the synchronization should be improved, this value can easily be adopted, but with a higher number of management frames transmitted, the maximum data rate will be reduced. In a realistic industry landscape, not only one but multiple APs are in range of each station in order to guarantee seamless coverage. Thus a station usually receives beacon frames from multiple APs. To separate them, it is useful to filter by the BSS ID, which corresponds to the Mac address of the AP and is also transmitted in the beacon frame. Because of the characteristics mentioned above, beacon frames are thus well suited for the RBIS protocol.

For the integration of time synchronization based on IEEE 802.1AS in IEEE 802.11, the concept shown in Fig. 1 will be applied. It consists of an AP, several stations, with one of them being called “Reference Station” and being part of the Reference System. What is special about this station is that it is connected to the wired TSN network and so it cannot be mobile. In addition, this station is synchronized with TSN time and must support IEEE 802.1AS. This synchronization is performed by the grandmaster (GM), which can be any TSN device.

In order to identify the correct offset to the TSN time the Reference System pairs each incoming beacon frame timestamp with the corresponding TSN timestamp, as shown in Fig. 2. Furthermore, the Reference Station sends this information to each station that has a subscription to this service. By using OPC UA PubSub for the distribution, it is possible to synchronize as many stations as are in range to the AP, with the message layers shown in Fig. 3. The transport protocol used is UDP in combination with multicast, which means that each of the stations that have joined the multicast group receives the subscribed messages. If necessary, the transport protocol can also be changed from broker-less to broker-based, e.g. MQTT.
The Subscriber is automatically updated via the OPC UA configuration methods as RawData is the most efficient format and is used if a common status and timestamp per DataSet is sufficient.

Figure 1. Concept for the distribution of the TSN time in the WLAN network.

Figure 2. Flow diagram of the Reference System

The second workflow, which is similar for all other stations, is shown in Fig. 4. Here each station derives the tuples of its local time for each incoming beacon frame and the beacon frame timestamp. These tuples are used alongside the received tuples to calculate the offset and adjust the local clock accordingly. The formula for adjusting the local clock of the mobile stations is as follows, where $t_{TSN}[bf]$ is the time of the Reference System for a specific beacon frame, $t_{station}[bf]$ is the local time of the station that gets synchronized for the given beacon frame, and $t_{bf}$ is the time of the beacon frame.

or AMQP. It is also possible to distribute the messages via multicast based on layer 2. In addition there is the so-called OPC UA NetworkMessage which forms the payload of the UDP datagram, each NetworkMessage having the OPC UA specific header and footer and containing one or more DataSetMessages, which in turn have so-called DataSetMessage fields. In our case, the NetworkMessage contains only one DataSetMessage, which consists of its header and the following two DataSetMessage fields: $t_{bf}, t_{TSN}[bf]$. 

Figure 3. OPC UA PubSub message layers [10]
\( t_{station[\text{current}]} \) is the current time of the station:

\[
t_{TSN} = t_{TSN[tf]} - t_{station[tf]} + t_{station[\text{current}]} \tag{1}
\]

V. TESTBED & EVALUATION

This section aims to evaluate the proposed concept. Therefore, Fig. 5 shows the testbed, on basis of which the evaluation has been done. It mainly consists of the COTS components, listed in Tab. II.

![Testbed Diagram](image)

**Table II** HARDWARE CONFIGURATIONS

| Equipment            | QTY | Specification                                      |
|----------------------|-----|---------------------------------------------------|
| Mini PC              | 2   | Intel Core i7-8809G, 2x16 GB DDR4, Intel i210-AT & i219-LM Gigabit NICs, Ubuntu 18.04.3 LTS 64-bit, Linux 4.18.0-18-lowlatency |
| Wi-Fi Adapter        | 2   | USB, IEEE 802.11a/g/b/n/ac, Wi-Fi 5               |
| Wi-Fi Router         | 1   | IEEE 802.11a/g/b/n/ac, Wi-Fi 5                   |
| TSN Evaluation Kit   | 1   | RAPID-TSNEK-V0001, IEEE 802.1AS                   |

It consists of two identical mini personal computers (PCs), that are connected wireless to a Wi-Fi router that serves as AP. In order to receive each beacon frame, the WLAN network interfaces have to be set in “monitor mode” by using aricrack-ng module [20]. Afterwards, the channel can be monitored, but the IPv4 connectivity gets lost. In order to transfer the NetworkMessages, an additional Wi-Fi adapter was added per mini PC via USB. Next, the mini PC that serves as Reference Station is connected to TSN Evaluation Kit. It supports the IEEE 802.1AS and 802.1AS-REV specifications and can consequently serve as GM for other TSN devices. Furthermore, Linux PTP is a free and open source software PTP implementation that complies with the IEEE 1588 standard [21]. This implementation is one of the most frequently used. Besides aiming to provide a robust implementation of the standard Linux PTP tries to make use of the most relevant and modern application programming interfaces (APIs) offered by the Linux kernel. The Linux PTP project provides several executables to run two-stage synchronization mechanism. The one which was used in our testbed is *ptp4l*.

The *ptp4l* tool synchronizes the PTP hardware clock with the master clock in the network. If there is no PTP hardware clock, it automatically synchronizes the system clock with a master clock using software timestamps. As extension, the tool supports the IEEE 802.1AS specification for TSN end stations, by using the generalized Precision Time Protocol (gPTP) configuration file, which modifies the default procedure of the executable.

As shown in Fig. 6 a synchronicity of ±350ns between TSN Evaluation Kit and the Reference Station can be reached, by using the minimum sync interval of 31.25ms (2\^5s).

In order to evaluate the quality of the time synchronization, the time difference between both stations has to be identified. For this reason, the TSN Evaluation Kit is also connected to the second station and synchronizes the hardware clock of one of the built in network interfaces. Now, the time difference between the internal clock and the hardware clock can be measured. In addition to our implementation, the state-of-the art for time synchronization of wireline systems has also been applied to the testbed. The results of both measurements are shown in Fig. 7.

In the first figure (Fig. 7a), in which the IEEE 1588 protocol is transmitted directly via Wi-Fi, it can be seen that there are at least some use cases of class II can be fulfilled by the synchronization. This is also reflected in the median value, which is with \( \leq 0.95 \text{ ms} \) below the limit of \( < 1 \text{ ms} \). However,
there are many values in the 1-2 ms range derived from the already mentioned drawbacks of this method and even some values that exceed this value. The maximum, which is above 30 ms, is not acceptable for use case class II.

Fig. [7b] which is based on the method presented in this paper, has a median of 13 µs and a maximum value of 38 µs. Thus, this approach is suitable to fulfill the different use cases of group II and III. This means that the required time synchronization of all mandatory mobile use cases required for Industry 4.0 can be achieved by this approach using COTS hardware that can be found in existing industrial facilities.

VI. CONCLUSION

In this work, we proposed a concept for the time synchronization of IEEE 802.11-based WLAN and the corresponding integration into IEEE 802.1AS systems. Using a testbed consisting of COTS Wi-Fi components, it can be shown that this solution can provide better time synchronization than if wired algorithms were applied to the wireless communication. In addition, the results show that a wide range of so-called mandatory mobile use cases, such as AGVs that transport a workpiece together, can be covered by this approach.

REFERENCES

[1] M. Gundall, J. Schneider, H. D. Schotten, M. Aleksy, et al., “5G as Enabler for Industrie 4.0 Use Cases: Challenges and Concepts,” in 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), vol. 1, Sep. 2018, pp. 1401–1408. DOI: 10.1109/ETFA2018.8502649

[2] C. Mannweiler, B. Gajic, P. Rost, R. S. Ganesan, et al., “Reliable and Deterministic Mobile Communications for Industry 4.0: Key Challenges and Solutions for the Integration of the 3GPP 5G System with IEEE,” in Mobile Communication - Technologies and Applications; 24. ITG-Symposium, May 2019, pp. 1–6.

[3] A. Mildner, “Time Sensitive Networking for Wireless Networks-A State of the Art Analysis,” Network, vol. 33, 2019.

[4] T. Adame, M. Carrascosa, and B. Bellalta, “Time-Sensitive Networking in IEEE 802.11 be: On the Way to Low-latency WiFi 7,” arXiv preprint arXiv:1912.06086, 2019.

[5] A. Mahmood, R. Exel, H. Trsek, and T. Sauter, “Clock Synchronization Over IEEE 802.11—A Survey of Methodologies and Protocols,” IEEE Transactions on Industrial Informatics, vol. 13, no. 2, pp. 907–922, 2017. DOI: 10.1109/TII.2016.2629669

[6] M. Wolfschluger, T. Sauter, and J. Jasperneite, “The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0,” 1, vol. 11, Mar. 2017, pp. 17–27. DOI: 10.1109/MIE.2017.2649104

[7] IEEE 802.1AS Task Group, TSN Standard, 2020. [Online]. Available: https://1.ieee802.org/tsn/

[8] J. L. Messenger, “Time-Sensitive Networking: An Introduction,” IEEE Communications Standards Magazine, vol. 2, no. 2, pp. 29–33, Jun. 2018. DOI: 10.1109/MCOMSTD.2018.1700047

[9] “IEC 62541-1, OPC Unified Architecture - Part 1: Overview and concepts,” 2010.

[10] “IEC 62541-14, OPC Unified Architecture - Part 14: PubSub,” 2019.

[11] S. Melnyk, A. Tesfay, H. Schotten, J. Rambach, et al., “Next Generation Industrial Radio LAN for Tactile and Safety Applications,” in 22. VDE/ITG Fachtagung Mobilkommunikation, Mar. 2017.

[12] Y. Xiao and J. Rosdahl, “Throughput and delay limits of IEEE 802.11,” IEEE Communications letters, vol. 6, no. 8, pp. 355–357, 2002.

[13] S. Melnyk, K. Alam, A. G. Tesfay, and H. D. Schotten, “Hybrid MAC for Low Latency Wireless Communication Enabling Industrial HMI Applications,” in 2018 IEEE 4th International Symposium on Wireless Systems within the International Conferences on Intelligent Data Acquisition and Advanced Computing Systems (IDAC-SWS), IEEE, 2018, pp. 21–24.

[14] A. L. Ruscelli and G. Cecchetti, “AIIEEE 802.11e HCCA scheduler with a reclaiming mechanism for multimedia applications.” Advances in Multimedia, vol. 2014, pp. 777–780, 2014.

[15] Y.-H. Wei, Q. Leng, S. Han, A. K. Mok, et al., “RT-WiFi: Real-time high-speed communication protocol for wireless cyber-physical control applications,” in Real-Time Systems Symposium (RTSS), 2013 IEEE 34th, IEEE, 2013, pp. 140–149.

[16] D. Krummacker, C. Fischer, K. Alam, M. Karrenbauer, et al., “Intra-Network Clock Synchronization for Wireless Networks: From State of the Art Systems to an Improved Solution,” in 2020 2nd International Conference on Computer Communication and the Internet (ICCCI), 2020, pp. 36–44. DOI: 10.1109/ICCCI49374.2020.9145977

[17] G. Cena, S. Scanzio, A. Valenzano, and C. Zunino, “Implementation and Evaluation of the Reference Broadcast Infrastructure Synchronization Protocol,” IEEE Transactions on Industrial Informatics, vol. 11, no. 3, pp. 801–811, 2015. DOI: 10.1109/TII.2015.2396003

[18] “IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems,” Jul. 2008, pp. 1–300. DOI: 10.1109/IEEESTD.2008.4579760

[19] M. Gundall, C. Huber, P. Rost, R. Halfmann, et al., “Integration of 5G with TSN as Prerequisite for a Highly Flexible Future Industrial Automation: Time Synchronization based on IEEE 802.1AS,” in 2020 46th Annual Conference of the IEEE Industrial Electronics Society (IECON), IEEE, vol. 1, 2020, pp. 3823–3830.

[20] Aircrack-ng. [Online]. Available: http://www.aircrack-ng.org/

[21] R. Cochran et al., The Linux PTP Project, 2015. [Online]. Available: http://linuxptp.sourceforge.net/