Reliable Low Latency Wireless Communication Enabling Industrial Mobile Control and Safety Applications

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Abstract—Advanced industrial applications for human-machine interaction such as augmented reality support for maintenance works or mobile control panels for operating production facility set high demands on underlying wireless connectivity solution. Based on 802.11 standard, this paper proposes a concept of a new system, which is capable of those requirements. For increasing reliability, an agile triple-band (2.4 GHz, 5 GHz and 60 GHz) communication system can be used. In order to deal with latency and deterministic channel access, PHY and MAC techniques such as new waveforms or hybrid MAC schemes are investigated. Integration of precise localization introduces new possibilities for safety-critical applications.

Index Terms—industrial radio, industrial internet, communication, reliable wireless, new waveform, mmWave, low-latency, ToF ranging, localization/positioning, multi-band, quality of service, HMI, AR, mobile panel, safety

I. INTRODUCTION

Shifting manufacturing facilities to cyber-physical production systems (CPPS) provides new opportunities to the industry for organising and controlling the manufacturing process. However, only by using wireless communication systems, CPPS becomes flexible and easily scalable. There are several initiatives, which are supporting the development of Industrial Internet. One of them is the German initiative “Industrie 4.0” [1].

The majority of current activities are considering process or factory automation. Closed-loop applications set advanced requirements on wireless solutions. Besides the flexibility and reliability, communication latency below 1 ms is required, whereas the data rate is moderate. This makes the development of dedicated systems necessary [2].

Another large field of industrial applications, which future development also relies on the quality of wireless connection, is human-machine interaction. By using such techniques as interactive augmented reality (AR), mobile control or others which are supporting field personnel, productivity of the manufacturing processes could be significantly increased. On the one hand, HMI applications have moderate requirements on latency as compared to automation applications. On the other hand, they demand high data rates in order to e.g. realise offloading of comprehensive video processing or high link reliability for implementing safety protocols over wireless [3].

Most of established industrial wireless solutions, such as WirelessHART, primarily address automation applications. Besides, solutions known from home and office sector as for example Bluetooth or WLAN are about to find their way into the manufacturing area [4]. The latter is also well suited for HMI applications as it is designed to deal with high data rate and heterogeneous traffic. However, it still lacks deterministic channel access or appropriate reliability prohibiting its application in an industrial environment.

In this paper, we investigate some improvements, which could make WLAN capable of industrial HMI support. First, we propose a concept of agile triple-band communication (2.4 GHz, 5 GHz and 60 GHz) for increasing reliability by multi-connectivity. As to deal with latency and deterministic channel access, some techniques for physical (PHY) and medium access (MAC) layer such as new waveforms or hybrid MAC schemes are investigated. Last but not least, the integration of precise localization system can introduce new possibilities such as safety zones for safety-critical applications.

The rest of the paper is organised as follows. Section II describes the industrial HMI applications we concentrated on in our work. Further, it presents their requirements on the communication system. In Section III we propose a system concept, which would help to fulfil the aforementioned requirements. Section IV gives a deep insight into the proposed solutions and technologies. Finally, our work is summarised by Section V.
II. APPLICATIONS AND REQUIREMENTS

In our work, we target those future-oriented applications, user-experience and acceptance of which highly depend on the performance of the applied wireless communication solution. More details are given in the following subsections, whereas Figure 1 depicts overall requirements.

A. Augmented Reality Applications

Augmented Reality is a technique of putting additional information (augmentations) to live pictures in realtime. This technique may be applied on a videostream shown on a screen or tablet as well as on a head-up display. Possible applications may be e.g. overlaying service data at a glance or providing service staff with live manuals augmenting next service steps.

The core part of any augmented reality application is a stable localization based on video data processing. This method only allows a precise definition of the camera position and orientation with respect to every video frame. Afterwards, augmentations can be integrated to the real world by rendering them on the proper positions. However, greedy processing algorithms cannot be run on mobile devices due to their low computation performance. One possible solution is to offload the computations to a powerful server.

In order to avoid the occurrence of cyber sickness, end-to-end latency of the offloaded processing steps may not exceed 70 ms and in the best case it should stay below 20 ms. Video streaming produces high datarate traffic and depending on the quality of the video stream as well as compression method, the required bandwidth may reach from 500 Mbit/s up to 6.6 Gbit/s.

B. Safety-Critical Applications

Operation of machines or production units by means of a mobile control panel (MCP) provides flexibility and increases user experience of workers, leading to increased productivity. In order to guarantee the safety of personnel, mobile devices need to be equipped with safety guard functionalities. In order to fulfill the IEC 61508 standard on automation safety, a dedicated protocol such as PROFI safe or OpenSafety needs to be used on networked communication technologies.

The principle behind those kind of protocols is sending “Sign-of-Live” messages from the controller device to programmable logic controller (PLC) of the targeted machine. Hereby, cycle time of 4−8 ms is required. If such kind of message does not arrive during a defined time window (watchdog interval), the machine would perform an emergency stop. Typical watchdog intervals are below 30 ms and for some applications even below 10 ms. This makes safety critical applications also critical to communication delay, i.e. latency. In addition, safety protocols are particularly depending on the reliability of the network since losing any safety packet would lead to an emergency stop of the machine.

III. COMMUNICATION SYSTEM CONCEPT

Based on our previous investigations of state of the art communication systems, WLAN standard IEEE 802.11 n/ac offers the best coverage of the above requirements as compared to other systems. However, WLAN still lacks sufficient data rate, reliability, deterministic channel access etc. Nevertheless, we would like to propose some technologies, which are able to turn WLAN to promising technology for industrial use.

In order to overcome the shortcomings of the 2.4 GHz and 5 GHz frequency bands, communication in 60 GHz band is introduced. It is able to handle high data rates due to the high channel bandwidth available. Furthermore, the available bandwidth facilitates high precision of localization setup. We propose to realize an agile multiband communication system which is able to communicate in any of the 2.4 GHz, 5 GHz and 60 GHz frequency bands. An appropriate communication band is to be chosen based on the requirements of the application. Moreover, several bands can be used for increasing reliability of the communication link due to redundancy.

Integration of a required positioning system into communication hardware can significantly reduce deployment costs and efforts. In this paper, a two way ranging (TWR) approach is proposed which can be implemented for any of the desired frequency bands and can be alternately used together with data transmission.

Further improvements on latency and throughput can be achieved by using new flexible waveforms. We suggest the usage of Generalized Frequency Division Multiplexing (GFDM), also we present its PHY realization. It allows, due to its flexibility, to adjust the waveform and frame structure with regard to application requirements.

Last but not least, deterministic channel access needs to be provided in order to guarantee deadlines of HMI protocols. Here, we suggest the usage of hybrid MAC algorithms providing a contention free period (CFP) controlled by an access point (AP). Our investigations showed that the usage of appropriate scheduling algorithms lead to a deterministic behavior of the network which is appropriate for safety critical applications.

Detailed results on aforementioned improvements and technologies are depicted in the next section.
In this section, we discuss single technologies of presented system concept. Additionally, we provide our recent research results on these topics.

A. 60 GHz System

The 60 GHz beamforming system developed in Prowilan is shown in Figure 2. The analog front-end (AFE) consists of a beamforming (BF) integrated circuit (IC), up-conversion and down-conversion ICs.

The 60 GHz BF IC is designed in IHP’s 130 nm SiGe:C BiCMOS technology [9] performing beamforming in transmit mode and beam combining in received mode. The chip integrates eight bidirectional channels, each consisting of an antenna switch for Tx/Rx-path selection, a Tx-path with power amplifier and Tx vector modulator and an Rx-path with low-noise amplifier and Rx vector modulator. Additionally, a Tx/Rx-path selection switch and a compensation amplifier are included at the interface to the corresponding 60 GHz up/down mixer. The Figure 3a shows the chip block diagram. Since RF switches are included in the Tx path and in the Rx path, the IC can be used in TDD systems with one TRx antenna. For the use in a stand-alone Rx or Tx module, the IC can be set to single Tx/Rx operation through a dedicated pin or through the digital control. The chip has an integrated SPI controller, and eight registers for storing eight beams for fast selection in less than 20 ns. More details are given in [9]. The functionality of the beamforming IC is tested on a RF test board having an antenna array with eight dual-patch elements with a max gain around 11 dBi. The results of the beamforming measurement are depicted in Figure 3b.

B. Flexible GFDM Waveform

In industrial environments, wireless networks operating in unlicensed bands typically suffer because multiple radio technologies share the same frequency resources, causing cross-technology interference. However, in the industrial scenarios considered in this paper, usually various technologies have to be supported in order to enable connect augmented reality and safety critical applications. One solution to solve those challenges is to use a flexible waveform, which can be adapted to the different requirements of the respective application. Therefore, in this paper, a Generalized Frequency Division Multiplexing (GFDM) based frame structure [10] is investigated, which can be easily adjusted to an application specific waveform, including most state-of-the-art waveforms, in order to fulfill the requirements of industrial services. Another benefit of GFDM, as described in [last paper] is the increase in spectral efficiency due to low out-of-bounds emission. This is because the subcarrier of the GFDM waveform and the communication channels as well can be allocated more tightly together without introducing adjacent channel of sub-channel interference.

1) Flexible Physical Layer: As described before, in industrial scenarios, multiple different services with various needs have to be supported at the same time. These services have different requirements regarding data rates, reliability, and latency and usually have to be supported by multiple radio access techniques, including various waveform configurations. In order to avoid interference and channel access competition, advanced techniques like network slicing has to be used, where all RATs are harmonized with each other. However, the synchronization of these different technologies is non-trivial. Additionally, in order to provide network coverage to various industrial applications, different access points for radio access technology have to be deployed in the area. An approach to reduce this effort is usage of a flexible physical layer (PHY) chip set, which is capable of providing multiple application-specific transmissions. In order to support multiple application at the same time, the physical layer has to be reconfigured quickly to different frame structures and waveforms. Therefore, in [11] a flexible PHY based on GFDM has been developed whose architecture will be presented in the following section.

2) Transceiver Architecture: The block diagram of flexible GFDM-based PHY in Figure 4 shows components needed for the generation of a flexible waveform based on GFDM. First description of the block functionalities has been published already in [12] and [11] and will be shortly summarized. Beside PHY components like channel encoder, QAM-Mapper synchronizacion, channel estimation which are found in most state-of-the-art implementation, it also consists of special PHY blocks which have been developed to support GFDM-based waveforms. First special block is the resource mapper, which maps complex constellation symbols to a two dimensional resource grid. The resource grid strongly depends on the frame structure and targeted waveform configuration. The modulator can be divided into discrete Fourier transformation and the modulation process itself. The modulator splits the output

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**Figure 2: 60 GHz beamforming system**

![Beamforming system](image)

**Figure 3: (a) Beamformer block diagram; (b) Beamforming measurements**

![Beamforming measurements](image)
of inverse discrete Fourier transformation into sub-symbols and samples. Afterwards pulse shaping is performed. Subsequently, outcomes of all parallel branches are added together. After modulation, additional time window and preamble have to be added. Here, the preamble is used for synchronization and channel estimation. Cyclic prefix and cyclic suffix can be applied on both preamble and data block. The synchronization is based on the Schmidl-Cox algorithm [13], [14].

For estimation, a frequency domain least-square estimator with subsequent linear interpolation is used. The principle of the resource demapper and demodulator is the inverse as for counterpart in the transmitter chain.

4) Measurement Results: The implemented PHY transceiver architecture of figure 4 is evaluated in a laboratory environment using a cable setup where latency and performance behavior has been analyzed. As result of PHY implementation on an FPGA, configuration between different frame structures and waveforms can be switched every 20 clock cycles, which gives enough time to support different services simultaneously. However, depending on the on the waveform configuration, the number of used processing blocks differs and thus required latency varies. Therefore, single-carrier waveform configuration has the lowest latency and in contrast to that GFDM, where all processing blocks of 4 are used, has the highest latency. Nevertheless, for all configurations the latency is always below 100μs and therefore fulfills the latency requirements for targeted HMI applications in industry. Evaluation of bit error ratio (BER) performance shows that BER of $10^{-5}$ can be achieved below measured 5dB. This can be further improved by further multi-connectivity concepts on PHY, MAC or higher Layers as presented in MAC-Chapter and [15].

C. Channel Access

Channel access strategy is one of the most important components of a wireless system, which among others influences its scalability, reliability and determinism. Channel access method which is mandatory in 802.11 standard is called distributed coordination function (DCF) and is a realisation of collision avoidance mechanism. The amendment .11e of the standard further defines enhanced distributed channel access as a part of hybrid coordination function (HCF). It improves DCF by traffic prioritisation. These two techniques are well established in commercial hardware. However, they are known to be non-deterministic due to contention based channel access.

Besides, there exists point coordination function (PCF), which introduces contention free period (CFP). During this period, AP takes the control of the medium and sequentially polls registered stations. Whereas PCF is provided to guarantee time based access, it suffers from unknown transmission time, unpredictable beacon delays and more [16]. An improvement is provided by HCF controlled channel access (HCCA), which is capable of traffic class differentiation, transmit time control and some more features. [15]

1) Comparison of Channel Access Methods: In this section, we provide a comparison between DCF, PCF and HCCA with respect to their latency performance. For our investigation, we created MATLAB models of that three channel access methods. In the case of HCCA, reference scheduler proposed by the standard was used. We differentiated safety and AR stations. Safety stations produce cyclic traffic every 8 ms and have maximum service interval (MSI) of 8 ms. The number of safety stations was fixed to 2. AR stations produce high data rate traffic with MSI of 50 ms. The number of stations vary from 5 to 50. For PCF and HCCA, both stations types were scheduled on the CFP. Figure 5 shows the simulation results.

As expected, DCF features the worst performance. Whereas the mean delay of safety packets is below MSI for less AR stations, maximum delay is always above the deadline. Also, it should be noticed, that maximum latency drastically increases by increasing number of stations due to increasing number of collisions. Therefore, MSI can be reached in average, but it cannot be guaranteed.

For PCF, the performance is slightly better as compared to DCF. However, average delay of safety stations is suitable for less than 12 stations, whereas maximum delay exceeds the MSI for more than 5 stations. In contrast to DCF, this delay can be guaranteed due to polling technique used by PCF. However, both safety and AR traffic show similar delay performance. As PCF does not differentiate traffic classes, safety and AR traffic are treated in the same manner. It means that superframe duration of PCF should be always adopted with respect to lowest MSI, which considerably limits PCF performance for heterogeneous traffic.

In contrast to both other access methods, HCCA can deal with heterogeneous traffic. For safety traffic, average delay almost reaches maximum delay values. Furthermore, latency never exceeds the MSI. However, the maximum delay of AR

![Figure 4: Flexible PHY architecture](image-url)

![Figure 5: Latency vs. number of AR stations](image-url)
traffic exceeds the MSI for more than 30 stations. That is, HCCA cannot serve more than 30 AR stations. Nevertheless, it should be noticed, that safety traffic could be scheduled for any number of AR stations, which significantly overperforms PCF.

2) Comparison of HCCA scheduling techniques: In this section, we provide an investigation of HCCA scheduling techniques. We consider two different schedulers: reference scheduler provided by the standard and Earliest Deadline First (EDF) scheduler [12]. Reference scheduler polls registered stations in round robin fashion, however, it is able to distinguish between traffic classes with different MSIs. A scheduling table is generated once the MSIs are known, and it is updated on significant traffic change only. In contrast, EDF scheduler steadily updates its scheduling table. The packets are sorted based on their deadline. The packet with the closest deadline is also the first to be delivered.

The simulations we carried out are similar to those in previous section. The only difference is that the MSI of safety traffic was increased to 24 ms. As we can see from Fig. 6 both schedulers perform similar with respect to safety traffic. Also, average delay of AR traffic is similar. However, for reference scheduler, maximum delay reaches MSI for already low number of stations due to fixed polling intervals. In contrast, max. delay of EDF scheduler rises linearly with number of AR stations. Also, EDF is able to schedule at least 45 AR stations, which significantly overperforms reference scheduler. This result shows the flexibility of EDF scheduler as compared to reference scheduler.

D. Localization

The number of users connected to a single AP is limited and, therefore, a two way ranging is used for localization. The main disadvantage of TWR is that it requires a large number of transmissions for localization. In dense scenarios this would lead to usage of large portion of the medium only for localization. Anyway, the main advantage of the TWR is that it does not require synchronization between nodes, which makes it easy for implementation. The TWR is basically consists of two transmissions, as shown in Figure 7a.

The round trip time, \( t_{\text{round}} \), and the reply time, \( t_{\text{reply}} \), are estimated in the nodes and the time of flight is easily calculated afterwards.

The localization is performed using trilateration. The mobile station (MS) performs TWR with multiple APs and obtains the distance. Having the distance from the MS to the four APs, the three dimensional position of the MS can be estimated by using trilateration.

The overall process of localization is controlled using a localization server. The entities which want to obtain information about the location of a given node should setup the localization parameters using the localization server. The server issues the commands for TWR and estimates the position based on the received (estimated) distances between the MS and the APs.

The overall concept was tested using software defined radios (SDR). In Figure 7b is shown the setup used for testing. Four SDRs are used as anchor nodes and one is used as a mobile node. A localization precision and accuracy of 1 m is achieved using a bandwidth of 25 MHz in 5 GHz band.

NLOS Identification: NLOS Identification: Non line of sight (NLOS) propagation leads to degradation in indoor wireless localization performance. When the direct path between the transmitter and the receiver is blocked, metrics such as time of arrival and angle of arrival are not correctly estimated. Therefore, approaches based on the above-mentioned metrics are expected to locate the device with an increased error margin. A reliable NLOS identification is highly recommended to achieve better indoor location and positioning accuracy.

Our proposed solution to NLOS identification problem is based on exploring features of the estimated CIR amplitude distribution from both of LOS and NLOS scenarios.

Figure 6: HCCA with reference vs. EDF scheduler

Figure 7: (a) TWR timing diagram; (b) Localization demo setup

Figure 8: (a) Mean feature. LOS in blue, NLOS in red, and the overlap in heavy red. (b) Identification performance of random forest algorithm
CIR estimation campaign has been carried out in an indoor office scenario. We chose features as the first to fourth central moments of channel impulse response (CIR) amplitude distribution: mean $\mu$, standard deviation $\sigma$, skewness $s$, and kurtosis $\kappa$. Illustration of mean feature is shown in Figure 8a.

To distinguish between LOS and NLOS scenarios, we employed the random forest (RF) machine learning algorithm [13]. The RF algorithm generates a classification model and defines some classification rules using the training dataset. These classification rules are used for prediction of new observations from the testing dataset.

We combined the best performing group of features in subsets denoted by the number of features involved, i.e. only one feature in subset $S_1$ while all four features represented in subset $S_4$ as shown in Table I. The features are extracted according to formulas in [19]. Figure 8b depicts the identification accuracy for both LOS and NLOS for each subset of features. It is noticed that, the identification accuracy increases with the number of features used.

| Subset | Feature $\mu$ | Feature $\sigma$ | Feature $s$ | Feature $\kappa$ |
|--------|---------------|-----------------|-------------|-----------------|
| $S_1$  | ✓             | ✓               | ✓           | ✓               |
| $S_2$  | ✓             | ✓               | ✓           | ✓               |
| $S_3$  | ✓             | ✓               | ✓           | ✓               |
| $S_4$  | ✓             | ✓               | ✓           | ✓               |

V. CONCLUSION

Wireless technologies are going to significantly improve the flexibility and user experience of future-oriented industrial HMI applications such as mobile control panels or augmented reality. In this paper, we proved, that PHY and MAC layer of WLAN system can be optimized for fitting strict industrial requirements. Furthermore, integration of localization system gains flexibility as compared to stand alone solutions.

Our future work concerns an integrated proof of concept system, which is capable of all described technologies. Furthermore, we did not yet address the aspects of mobility support. Here, multi-connectivity concepts can be applied in order to provide seamless handover.

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