Requirements and current solutions of wireless communication in industrial automation

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***Abstract*—The industrial wireless automation sector exhibits a huge market growth in the last years. Today, many applications already use wireless technologies. However, the existing wireless solutions do not yet offer sufficient performance with respect to real-time and reliability requirements, particularly for closed-loop control applications. As a result, low latency wireless communication technologies will bridge the gap and can become a key factor for the wide-spread penetration of wireless in industrial communication systems. It is therefore the main goal of this paper to provide a comprehensive overview on requirements, current solutions, and challenges as well as opportunities for future wireless industrial systems. Thereby, presented requirement figures, analysis results, and performance evaluations are based on numerous practical examples from industry.**

I. Introduction and Motivation

Wireless communication systems are employed in industrial automation applications (IAA) for already more than ten years. The industrial automation is sub-divided into the process automation (e.g. chemical industry) and discrete factory automation (e.g. assembly line production). Typical application fields of wireless systems in both areas are the connection of movable machine parts or mobile machines integrated in distributed control systems. Furthermore, wireless networks are increasingly used for connecting machine parts or machines in difficult or dangerous environments, e.g. large distances or explosive areas. In the past and still nowadays, the connection of movable machine parts are realized by trailing cable systems, slip rings or sliding contacts. These solutions lack from high installation and maintenance costs, wear and thus lower reliability. In contrast to wired communication systems, wireless systems cause very low installation cost. Therefore, they are suited for connecting machine parts being subsequently installed during modernization processes.

Initially wireless systems are used almost only in monitoring and open-loop control applications at all different layers of the automation pyramid [1]. In the last years, they are increasingly considered for closed-loop control applications, especially in the factory automation sector, e.g. screen process machines, packaging machines and filling stations. The major challenge for currently employed wireless systems are the high requirements of IAA regarding latency, synchronism and reliability. This has delayed the market penetration of wireless systems in the industrial automation sector.

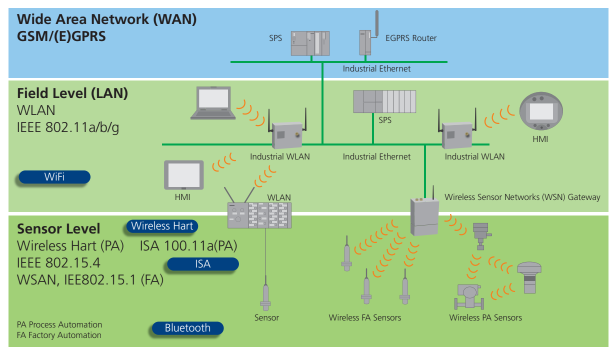

Fig. 1. Industrial Wireless Systems

Due to cost reasons and market acceptance, component providers of industrial wireless communication systems in the factory automation use typically existing WLAN and Bluetooth conform standard transceiver components and partly add proprietary protocol extensions, e.g. the IWLAN system of Siemens [2] and the WISA system of ABB [3]. In 2012, the PROFIBUS and PROFINET user organization (PNO) published the WSAN-FA standard [4], basing on WISA. In the process automation, the standards WirelessHART and ISA 100.11a were developed by the HART communication foundation and the international society of automation (ISA), respectively. The PNO adopted WirelessHART for the WSAN-PA standard. In some industrial applications the Digital Enhanced Cordless Telephone (DECT) technology is used. Due to its deterministic medium access, it is getting more attention in the last years [5]. Radio frequency identification (RFID) systems are used in the industrial automation in several areas, e.g. transport, logistic, material handling, asset management and product tracking. However, as typical RFID applications do not require very short end-to-end latency values, they are beyond the scope of this paper. Cellular communication systems are employed in IAA almost only in remote service applications or alert systems [6]. Thus, current industrial automation applications utilize preferably wireless technologies operating in the

ISM frequency bands 2.4 GHz and 5 GHz. Since the wireless technologies described above are not appropriate for all control applications, some system integrators developed proprietary wireless systems operating in the ISM bands. Figure 1 gives an overview of the different wireless technologies and their application fields in the industrial automation.

Due to the increasing use of wireless technologies in industrial automation applications, several organizations developed guidelines for the installation, deployment and maintenance of such systems, e.g. the German Electrical and Electronic Manufacturers' Association (ZVEI) [7], the Association of German Engineers (VDI) [8] or the International User Association for Automation in Process Industries (NAMUR) [9]–[11].

In this paper a comprehensive overview on requirements, current solutions, and challenges as well as opportunities of future wireless industrial systems are given. The outline of the paper is as follows. The next section details the requirements of industrial automation applications on communication systems and introduces the relevant key parameters. Furthermore example values of these parameters for different applications are given. Section III presents some examples of existing applications of wireless technologies in industrial automation and introduces the coexistence problem of wireless networks operating in the ISM bands. Furthermore, existing solution approaches for the coexistence issue are presented. In Sec. IV the requirements of industrial automation applications on future wireless are summarized. Finally, Sec. V concludes this contribution.

II. Requirements of Industrial Applications

The currently defined application profiles for wireless automation [8], [12] do not consider closed-loop control applications, a class of field level applications which put outermost challenges on the real-time behavior of their associated communication system. This gap is addressed in the following.

A. Real-Time Characteristics

When classifying industrial applications with respect to their real-time characteristics, most applications in process automation are representatives of the class of soft real-time. Otherwise, closed-loop control applications belong to the class of hard real-time, i.e. given temporal deadlines have to be strictly met, or isochronous real-time, i.e. hard real-time plus additional constraints on the jitter [13]. Thereby, closed-loop control algorithms are executed cyclically. The period of a control cycle is referred to as cycle time T_{cyc}, which is a characteristic measure in industrial automation determining performance and accuracy of the given application. The timing parameters related to a control cycle are illustrated in Fig. 2(a). First of all, the application's control algorithm in the master computes a set of command values. Next, the master transmits these command values to slave n and finally waits for reception of actual values from slave n at response time $T_{re,n}$, where the response time corresponds to the round trip delay. Here, the application's real-time requirement is satisfied if

$$T_{cyc} - T_{re,n} > \Delta_p \quad \forall n \in [1, N] \tag{1}$$

with Δ_p denoting the processing time of the master's control algorithm. Accordingly, slave n receives command values from the master after transmission delay $D_{c,n}$. Slave n has to apply its command values at valid time T_v which requires

$$T_v - D_{c,n} > \Delta_v \quad \forall n \in [1, N]\,, \tag{2}$$

where Δ_v designates some margin for slave n to prepare for applying its command values. Then, slave n senses its newly applied command values after settling time T_a and transmits these actual values back to the master with transmission delay $D_{a,n}$.

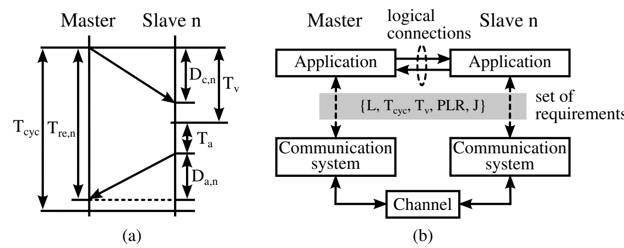

Fig. 2. Industrial control application: (a) control cycle and timing parameters, (b) system model and set of requirements.

Further on, it is crucial that all N slaves apply their command values isochronously at valid time T_v, which requires a common time base for all N slaves. For that purpose, state of the art fieldbus systems incorporate dedicated synchronization mechanisms [14] to bound the instantaneous jitter $T_{j,n}$ of slave n's valid time estimate $\hat{T}_{v,n}$ to an application specific threshold J

$$|\hat{T}_{v,n} - T_v| = T_{j,n} < J \quad \forall n \in [1, N]. \tag{3}$$

In this context, the property of a communication system to provide accurate time instants on a common time base (cf. eq. (3)) is referred to as *synchronism*. Otherwise, the term *determinism* corresponds to the capability of a system to provide guaranteed upper-bounded deadlines for response time (cf. eq. (1)) and transmission delay (cf. eq. (2)) [8].

B. Application and Communication Parameters

Figure 2(b) sketches the cyclic data processing model of an industrial application together with its basic parameters. Thereby, an application consists of a master device and N slaves typically arranged in logical star topology. Formally, the master sets up logical connections to each slave $n \in [1, N]$ on application level. More precisely, each slave n is assigned two logical connections, one as the consumer of command values from the master and another one as the producer of actual values to the master. Each logical connection is associated with a parameter set $\{L, T_{cyc}, T_v, PLR, J\}$ with payload L, cycle time T_{cyc}, valid time T_v, packet loss rate PLR, and threshold J for the jitter.

Table I enumerates characteristic use cases of field level applications. Both the requirements of profile manufacturing cell [12], which comprises e.g. the control of robot arms, and of profile sensor-actuator [3] are fulfilled with state of the art narrowband wireless systems, i.e. Bluetooth, WISA

TABLE I
PARAMETERS OF EXAMPLE FIELD LEVEL APPLICATIONS

Example	N	L [Byte]	T_{cyc} [ms]	T_v [ms]	J [μs]
Manufacturing cell [12]	30	< 16	50	5	500
Sensor-actuator [3]	120	< 20	n.s.	15	n.s.
Closed-loop control [15]	high	low	n.s.	1	20
- Machine Tools	20	50	0.5	0.25	1
- Printing Machines	50	30	2	1	5
- Packaging Machines	30	15	5	2.5	20

or WSAN-FA, respectively. In contrast, closed-loop control applications [15] require shorter transmission delays as well as higher data rates. Here, throughput, data rate and system capacity of a communication system can be derived from cycle time T_{cyc} and payload L, which differ significantly between use cases. For instance, printing machines with their motion control applications nowadays almost fully exploit the system capacity of Fast-Ethernet based wired fieldbus systems while higher cycle times of simple sensor-actuator networks result in moderate data rates and relaxed duty cycles. Note that all given use cases of Tab. I require packet loss rates $PLR < 10^{-9}$ on application level, which is mandatory for field level applications in factory automation. Therefore, besides real-time requirements the transmission reliability represents a second major challenge for wireless industrial communication systems (cf. Sec. III-C).

Closed-loop control applications on the field level are executed by machines, each of which consists of a master control unit and a set of slaves. Thereby, a machine is typically build up of locally fixed slaves distributed around some tens of meters from the master, e.g. electric drives in a printing press or most numerical control applications of machine tools. However, dedicated machines, e.g. in packaging technologies, do contain moving machine components, in particular continuously rotating parts with angular velocities of around 100 rpm. Complex moving components quickly demand sophisticated and maintenance intensive connecting techniques (cf. Sec. I). Moreover, factory halls consist of a multitude of machines. Thus, using wireless technology for intra-machine communication requires an explicit network and frequency planning combined with carefully organized medium access mechanisms to avoid blocking conditions in the available system bandwidth. In this context, the term *availability* refers to the ability of a communication system to accomplish a dedicated data transmission regardless of channel conditions and unintended or interfering data traffic [8].

III. STATE-OF-THE-ART SOLUTIONS

A. Existing wireless automation applications

Magnetic induction and nearfield communication: For applications in a deterministic moving environment, for example along a stationary track or when modules need to be quickly disconnected and reliably reconnected, i.e. tool heads in robot cells, inductive coupling for non-contact power transmission and data transfer is a very beneficial wireless solution, that can replace traditional slip rings, sliding contacts etc. and thus can solve many application problems. Inductive coupling allows transmission of power and signals over an air gap of typically up to 15 mm, depending on the diameter of the coils. The power transmission can reach up to 50 W in sensor actuator applications. The technology uses a magnetic alternating field in the range of 20 to 200 kHz, which is generated by a transmitter coil and induces energy into a receiver coil. Due to the huge wavelength compared to the size of the coils, coexistence problems with other systems can hardly occur. The transmission of low data rates is realized by load modulation on the coil current. For higher data rates, usually a second pair of coils with higher resonance frequency is utilized. The signal delay is very low and stable, some systems achieve 1 ms.

Directed antennas and waveguides: Except for automated guided vehicles many moving machine components on the field level are often characterized by their well-known trajectory, i.e. network nodes propagate along fixed routes described by rotary tables, sliding carriages or robot arms. This in turn enables the use of application specific antenna solutions (e.g. waveguides or directed antennas) with reduced transmit powers to limit the signal propagation of wireless networks.

Safety-Application via WLAN: Safety related applications can be fast motion control, emergency-stop or a electric overhead traveling crane application as described in [16]. These applications define short safety reaction times to prevent physical damage to humans or material. Since standard wired or wireless data transmission channels cannot be developed according to safety regulation procedures of IEC 61508, the so-called black-channel principle [17] must be utilized. This means, that the transmission channel is generally regarded as unsafe and must be supervised by a mechanism, developed according to the procedures of IEC 61508.

This supervision mechanism is a usually a so-called safety protocol, e.g ProfiSafe, CIPSafety, OpenSafety, CANOpen Safety. The protocol checks constantly the already mentioned performance parameters of the transmission channel such as latency, synchronicity and reliability in form of packet loss and correct sequence numbering. If one of these performance rules is violated, the safety protocol detects it and switches the safety application into an unsafe or fail-safe state. However, when this happens, the availability of the application gets degraded. That means, when the transmission channel is unreliable, the safety application has a bad availability. In case of a standard wireless system such as IEEE 802.11 and short cycle times, the transmission reliability can quickly degrade to a point unsuitable for operation of safety applications. Special wireless transmission systems like WSAN-FA or Parallel Redundant WLAN [17], [18] are required for such applications.

B. Coexistence in ISM bands

As discussed above, IAA's typically employ wideband communication technologies operating in the 2.4 GHz and 5 GHz ISM bands, because of the worldwide permitted unlicensed operation. However, operators of wireless systems have no regulatory protection against interference by other wireless systems using the same frequency band. Since no central medium access control is available, all wireless nodes compete for using the spectral resource. The coexistence of several spatial dense located wireless systems using the same frequency band will introduce interference and can lead to decreased quality of service (QoS) and severe packet loss [19], [20].

The European Telecommunications Standards Institute (ETSI) published several norms, specifying medium access mechanisms to be used by wireless technologies within these frequency bands. The EN 300 328 V1.8.1 norm [21] applies to wireless wideband technologies operating within the 2.4 GHz ISM band with a maximum transmit power between 10 dBm and 100 dBm (equivalent isotropically radiated power). This includes frequency hopping spread spectrum (FHSS) and all other spread spectrum techniques, e.g. direct sequence spread spectrum (DSSS) and orthogonal frequency division duplex (OFDM). In compliance with this norm, each wireless device must perform either a clear channel assessment (CCA) check before each transmission, i.e. it has to sense by energy detection if the channel is free, or other types of Detect and Avoid (DAA) mechanisms. Although the DAA techniques improve the coexistence between competing wireless nodes and networks, packet collisions can still occur, especially in case of the *hidden-node* scenarios. Furthermore, wireless networks employing the CCA procedure suffer from a significant latency offset due to the medium sensing and a low determinism due to the medium congestion. These two facts are significant limitations for closed-loop control applications in the discrete factory automation, demanding for data transmissions with low latency and high determinism.

In order to improve the determinism of wireless wideband networks in the ISM bands, the ZVEI and the VDI developed guidelines for the installation, configuration and maintenance of wireless networks in industrial automation applications to alleviate the coexistence problem [22], [23]. The guidelines aim at a central frequency planning by a cell based exclusive frequency channel allocation to non-FHSS wireless network. Since industrial automation applications are characterized by a large number of spatially dense located control systems (sensor, actors and controllers) communicating typically by small datagram sizes, the exclusive channel allocation to each wireless interconnected control system yields an inefficient spectrum usage. This limits significantly the achievable number of coexisting wireless networks within a specific production site.

Another problem of wireless technologies using the ISM bands occurs when a new wireless interconnected control system shall be installed in a production environment with already existing wireless infrastructure. The coexistence between the new wireless network and existing wireless infrastructure is not known a-priori. The work in [24] presents an approach for analyzing the coexistence between the networks in a test environment before installing the new wireless interconnected control system in the production site. The approach bases on emulating the existing wireless network of the production site in the test environment.

In order to give an insight into the performance of some wireless systems used in the discrete factory automation, the communication parameters of WLAN, Bluetooth, WSAN-FA and accordingly WISA are summarized in Tab. II. Since consistent practical data cannot be found in the literature, typical values of selected papers are summarized for comparison. In case specific values cannot be guaranteed by the wireless technology, estimations are given in parentheses. Table II shows clearly, that WLAN provides very high data rates but can only support significantly large cycle times due to the CCA procedure. In contrast to this, Bluetooth achieves the shortest cycle times due to the TDMA medium access, but it offers only a very limited number of nodes per network. WSAN-FA supports a very low cycle time and a very high number of nodes per network, but can achieve only a low data rate. As a consequence, the discussed wireless technologies pose significant limitations for closed-loop control applications with very challenging requirements as listed in Tab. I.

TABLE II
COMPARISON OF WIRELESS COMMUNICATION TECHNOLOGIES IN DISCRETE FACTORY AUTOMATION

Name	WLAN [25], [26]	Bluetooth [27]	WSAN-FA and WISA [3], [28]
max. gross system data rate	600 Mbps	3 Mbps	1 Mbps
network topology	star	star	star
nodes per network	(50)	7	120
min. cycle time T_{cyc}	(100 ms)	8.75 ms	10 ms

C. Current Solutions

As discussed before, performance requirements for industrial automation applications are closely related to low transmission latency, strong determinism, reliability and, in the case of wireless mobility, seamless handover. But wireless communication in the ISM bands generally depends on a shared medium and has to coexist with other stations regarding medium access. For improving wireless determinism in a non-stochastic manner, measures in the time domain can be applied, such as centrally coordinated medium access like IEEE 802.11s Point Coordination Function (PCF) or Time Division Multiple Access (TDMA).

WSAN-FA: One example is the Wireless Sensor Actuator Network for Factory Automation (WSAN-FA) [4]. Similar to WISA, WSAN-FA utilizes the PHY-Layer of Bluetooth (IEEE 802.15.1) and provides improved synchronization by Frequency Hopping Multiple Access, which is a combination of TDMA and Frequency Hopping, but often imprecisely referred to as FHSS. This system is especially designed for the need of factory automation on sensor actuator level and uses the data format according to the IO-Link standard [29].

WSAN-FA is able to address 120 subscribers in a wireless star topology within a cycle time $T_{cyc} = 2.4$ ms. To achieve a high reliability, four retransmissions on different frequencies are performed, which yields a system cycle time of $T_{cyc} = 10$ ms. WSAN-FA provides blacklisting to exclude channels from frequency hopping to enable coexistence with

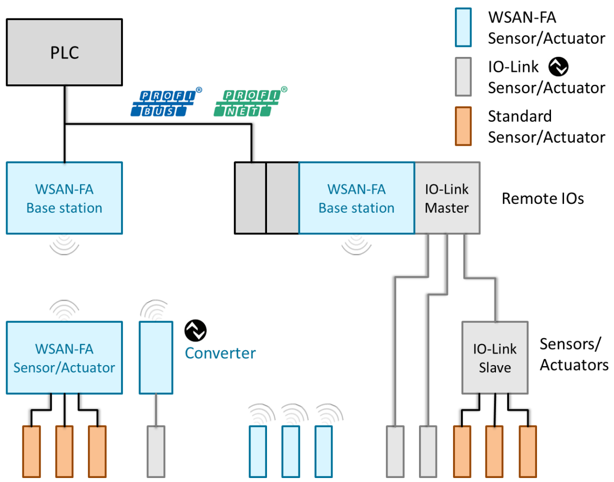

Fig. 3. System structure of WSAN-FA

other systems. It is even possible to use all 3 WLAN channels in the 2.4GHz band and one WSAN system in the gaps in between [30].

Currently, WSAN-FA is the only open standard optimized for the requirements of the sensor actuator level and seems to come close to the performance requirements for closed-loop applications. Beyond this, WSAN-FA has still some optimization potential regarding performance characteristics.

WLAN: IEEE 802.11 defines the Distributed Coordination Function (DCF) and Point Coordination Function (PCF) for managing the medium access within the networks. With DCF, all stations of a network compete equally for the medium access using the CSMA/CA mechanism and a random back-off timer. With PCF, all stations use the CSMA/CA technique as well, but the Access Point (AP) coordinates the medium access of its own client stations. The resulting polling scheme is intended for transmission of real-time traffic as well as for asynchronous data traffic. However, so far no component provider has implemented the PCF mechanism in real products except for Siemens with its proprietary form IPCF [2].

Other improvement approaches are based on diversity, which is basically the redundant transmission of information over uncorrelated channels or resources [31]. MIMO technologies, as implemented in WiMAX, HSPA+, LTE and IEEE 802.11n utilize spatial multiplexing by space-time coding and signal transmission over several antennas to achieve both coding gain and diversity gain.

Instead or in combination to such pre-detection combining approaches, one can also utilize post-detection combining methods in the higher layers of the information processing chain of the communication system, yielding specific gains especially in packet transmission schemes [32]. A recently presented example is Parallel Redundant WLAN (see Fig. 4), which utilizes the Parallel Redundancy Protocol (PRP) according to IEC 62439-3 on the Ethernet level and yields significant improvements [17]. Such a parallel redundancy strategy could also be employed to improve other wireless systems, such as WSAN-FA.

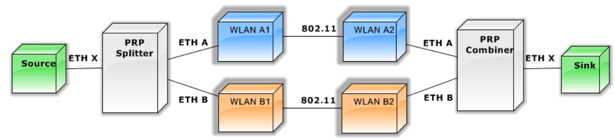

Fig. 4. Parallel Redundant WLAN system with PRP

IV. Requirements on Future Wireless Communication Systems

The solutions described in the previous section offer some improvement for the transmission latency and reliability. However, the challenging requirements set by closed-loop control applications in the discrete factory automation can not be reached. In order to address this application type, future wireless communication systems must fulfill several requirements, which are explained in the following.

As stated in Tab. I closed-loop control applications require a very low transmission latency of less than 1 ms at a very low jitter of a few microseconds, a high degree of synchronism and high availability in time and space. These points might be achieved by a central coordinated medium access in combination with a local network planning and management. Furthermore, a high reliability (packet error rate $< 10^{-9}$) is mandatory, to minimize the retransmission of packets. The packet overhead should be kept very small to ensure a tolerable spectral efficiency with small packet payloads. In order to address the multitude of industrial automation applications (e.g. closed-loop control, open-loop control or monitoring applications), different QoS classes should be supported with different requirements regarding cycle time, latency, jitter, packet payload.

The use of the unlicensed ISM bands is a significant advantage in terms of costs, but it is also the main drawback of currently employed wireless systems in the industrial automation, because of the coexistence problem. Thus, the wireless automation sector will depend on the cost efficient availability of frequency spectrum. This can be realized either by using license-free frequency bands, dedicated only for automation purposes, with robust wireless technology and a local coordinated medium access or an automatic coexistence management. Another possibility might be the use of licensed frequency spectrum (e.g. mobile networks). However, this sets several requirements on the network providers. First, the providers must establish transparent, simple and cost efficient billing models. Second, the network provider should install specific small cells (e.g. pico cells) in the production site for realizing the wireless communication on sensor actuator level or above. These cells should only be accessible for the addressed automation applications. Third, the sensor actuator communication of the automation application should be decoupled from the core mobile communication network, to ensure very low transmission latencies.

V. Conclusion

The main goal of this paper was to illustrate the heterogeneity of the possible fields of application for wireless systems in industrial automation accompanied by numerous examples.

Nowadays, state of the art wireless solutions already fit a certain amount of industrial applications' requirements, e.g. in process automation, for sensor actuator networks, or generally for upper levels in the automation pyramid. Typically, these solutions are built up on proven consumer standards like WLAN and Bluetooth and gradually enhanced by means of MAC tuning to improve the determinism as well as diversity schemes to increase reliability of data transmission. Furthermore, many industrial applications, in particular those implementing closed-loop control algorithms on the field level of discrete factory automation, require hard or isochronous real-time with cycle times in the low milliseconds. Obviously, these requirements cannot be served with current state of the art wireless solutions. However, if low latency wireless solutions could be provided many use cases with moving machine parts would significantly benefit from wireless technologies and thus, reducing cost, simplifying installation, and even enabling new application opportunities.

Finally, besides technical means to mitigate the coexistence problems in the ISM-bands which are recognized as the bottleneck for a further increase use of wireless in automation, the industrial community launched concerted actions to bundle their collective interests. This primarily concerns the harmonized ETSI EN 300 328 V1.8.1 norm as well as the efforts for allocation of a dedicated spectrum for wireless industrial automation. In a subsequent step, the industrial community might consider new business models in collaboration with network operators to facilitate the QoS required by industrial automation applications.

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