Wireless Communication for Factory Automation: An Opportunity for LTE and 5G Systems

Bernd Holfeld, Dennis Wieruch, Thomas Wirth, Lars Thiele, Shehzad Ali Ashraf, Jörg Huschke, Ismet Aktas, and Junaid Ansari

Wireless factory automation is an application area with highly demanding communication requirements. The authors classify these requirements and identify the opportunities for the current LTE air interface for factory automation applications. Moreover, they give an outlook on the relevant design considerations to be addressed by 5G communication systems.

Abstract

The evolution of wireless communication from 4G toward 5G is driven by application demands and business models envisioned for 2020 and beyond. This requires network support for novel use cases in addition to classical mobile broadband services. Wireless factory automation is an application area with highly demanding communication requirements. We classify these requirements and identify the opportunities for the current LTE air interface for factory automation applications. Moreover, we give an outlook on the relevant design considerations to be addressed by 5G communication systems.

Introduction

In the Next Generation Mobile Network (NGMN) consortium and the Third Generation Partnership Project (3GPP), the use case of machine type communication (MTC) is divided into two main groups as massive MTC (M-MTC) and mission-critical MTC (C-MTC) [1]. While M-MTC involves a large number of low-cost devices such as sensors or meters with high requirements on coverage and energy efficiency, C-MTC targets scenarios with very low latency and high reliability requirements such as process automation, intelligent transportation systems, and smart grid, as well as factory automation.

In this article, we focus on the highly challenging factory automation applications with strict demands on latency and reliability. In this context, reliability refers to guaranteed message delivery within the required latency bound. It is typically quantified as the residual block error rate (BLER) at the physical layer (PHY) or the packet error rate (PER) at higher layers of the protocol stack. Latency is considered end-to-end (e2e) in factory automation, where one end is formed by sensors measuring data and providing it to the process logic controller (PLC). The PLC comprises the essential logic to process the collected sensor data and instructs the actuators forming the other communication end.

In recent years, using wireless technologies for factory applications has received significant attention from the automation and communication industry. This is mainly attributed to the following. First, installation and maintenance cost for cables are high as they often experience wear and tear, need additional protection and housing, and limit mobility due to interleaving. Therefore, from time to time cables have to be replaced manually, which requires intervention of trained personnel and interruption of production processes. In contrast, wireless technologies have very low installation and maintenance costs. Second, wireless technologies offer a high degree of deployment flexibility, which enables rapid realization of different production deployments, even with mobility. Finally, the shared nature of the wireless medium allows communication flexibility, where any device can communicate with any other device in its communication range.

In the scope of the KoI project [2] funded by the German Federal Ministry of Education and Research (BMBF), seven partners from industry and academia are investigating the wireless factory automation scenario. The novel communication architecture proposed in the KoI project is based on two-tier radio resource coordination as illustrated in Fig. 1. The two-tier architecture is chosen to realize a logical separation of mission-critical functionalities from generic functionalities. Note that in practical implementations, these functionalities could potentially be integrated within a single entity. On the first tier, the global radio coordinator uses Long Term Evolution (LTE) as the baseline technology to realize authentication and admission control, resource coordination, and interference management among different communication cells (generic functionalities). It operates in a larger coverage area (e.g., a factory hall) and handles functionalities requiring longer timescales. On the second tier, local radio coordinators operate in a smaller area and on a much more granular timescale, that is, enabling the required low-latency and high-reliability transmissions (mission-critical functionalities). Local coordinators can operate in two modes: a "centralized" mode, where both the user and control plane messages are transmitted via the local coordinators, and an "assisted device-to-device (D2D)" mode, where user and control planes are separated. The latter allows the direct exchange of user data between

Bernd Holfeld, Dennis Wieruch, Thomas Wirth, and Lars Thiele are with Fraunhofer Heinrich Hertz Institute; Shehzad Ali Ashraf, Jörg Huschke, Ismet Aktas, and Junaid Ansari are with Ericsson Research.

devices (e.g., sensors and actuators) while control information routes via local coordinators. For critical factory applications, the assisted D2D mode may provide advantages over the centralized mode with respect to latency, thanks to the gains due to proximity of devices and a reduced number of communication hops.

In the following sections, we outline our major findings in relevance to the KoI project. We focus here on the air interface design of the local radio coordinator requiring reliable low-latency transmissions. We start with a discussion about the state-of-the-art technologies used in factory environments and their limitations in achieving the low-latency and high-reliability requirements. Furthermore, we describe the proposed medium access control (MAC) and PHY schemes for this specific use case in the context of 3GPP technologies. In particular, we discuss whether wireless communication for factory automation can be provided as an evolution of LTE; that is, it benefits from a backward-compatible mobile standard, or will require more substantial modifications toward a non-backward-compatible fifth generation (5G) system. Here, backward compatibility means that the legacy and 5G devices could share the same frequency carrier.

Requirements in Factory Automation

In the context of the KoI project, we have conducted a detailed questionnaire-based survey to gather first-hand information from notable industrial players involved in a broad range of factory automation processes. Table 1 summarizes the key findings from the survey in terms of the communication requirements. Depending on the specific application scenario, these requirements may differ within the shown ranges. To exemplify, we particularly provide the requirements of two factory applications being targeted by the wireless community in the table.

Although wireless communication offers several advantages over wired networks, it is not adequately leveraged in factory automation scenarios. Among others, this can be attributed to the fact that the currently available wireless technologies do not fulfill the ultra-high reliability requirements of $1 - 10^{-9}$ with very low (e2e) latency bounds down to 1 ms needed by factory automation applications. As a comparison, current cellular systems, such as LTE, are optimized for mobile broadband (MBB) traffic and target a BLER of 10^{-1} before retransmission with (e2e) latency bounds of several milliseconds. In addition, the factory automation use case is not only different due to the reliability and latency requirements, but also due to very different propagation conditions as discussed below, traffic characteristics (e.g., periodic and sporadic), and deployment peculiarities.

State-of-the-Art-Technologies and Their Limitations

Currently, factory automation applications are heavily dominated by wired technologies such as PROFIBUS/ PROFINET, SERCOS, HART, and CAN [3]. However, in wireless domain, the most commonly used factory communication solutions rely on customized radio stacks based

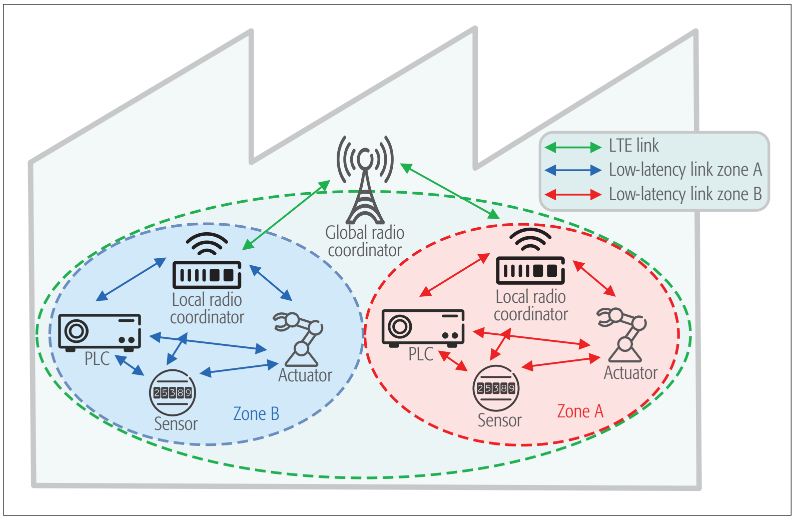

Figure 1. A communication architecture for wireless factory automation as envisioned in the project KoI [2].

on IEEE layer 1 (L1) and layer 2 (L2) technologies, as listed in Table 2. These IEEE-based standards operate in the unlicensed bands (below 6 GHz) and hence suffer from potential interference from other collocated networks sharing the same wireless spectrum.

Spectrum availability in unlicensed frequency spectrum inhibits guaranteed medium access and limits the scalability of the deployed solutions. This is associated with the regulatory policies for unlicensed spectrum that mandate features such as listen-before-talk (LBT), restriction of radio duty cycles, and transmit power limitation in order to facilitate coexistence. Under these policies, the stringent timing and reliability requirements of the C-MTC use case cannot be fulfilled. While wireless technologies operating in the licensed frequencies seem highly promising, these have still not surfaced for several C-MTC use cases, especially for factory automation applications. Operation in the licensed spectrum permits high transmit power levels and does not suffer from the drawbacks of mandatory coexistence regulations. Hence, it enables the implementation of deterministic medium access schemes. 3GPP's licensing-based LTE standard brings inherent advantages to fulfill the requirements of C-MTC applications. It allows deterministic multi-user scheduling by utilizing frequency multiplexing per time instance, support for quality of service, and flexible interference management for multiple cells. Therefore, by putting a focus on C-MTC besides the IoT-driven M-MTC market, 3GPP can deliver a favorable air interface for wireless factory automation and could certainly provide a single flexible solution for various requirements in this application area. In the following, we compare LTE to the currently used wireless standards for factory automation.

In Table 2, we highlight several layer 1/2 (L1/L2) features of the current LTE Release 12 and IEEE-based wireless technologies for factory automation. While LTE was initially designed for cellular macro networks with inter-site distances in the kilometer range, including support of up to 100 km coverage nowadays, other wireless technologies were specifically adjusted for

The physical layer and medium access mechanisms are major contributors to end-to-end latency from the radio communication perspective. Therefore, it is important to design lower layer protocols imparting as little latency as possible for mission-critical applications while fulfilling the reliability requirements.

e2e latency	Reliability	Data size	Communication range between devices	No. of devices per factory hall	Machine mobility (indoors)
Summarized results					
1 to 50 ms	$1 - 10^{-6}$ to $1 - 10^{-9}$	10 to 300 bytes	2 to 100 m	10 to 1000	0 to 10 m/s
Application scenario: Manufacturing processes					
< 10 ms	$1 - 10^{-9}$	< 50 bytes	< 100 m	< 1000	~ 1 m/s
Application scenario: Automated guided vehicles					
10 to 50 ms	$1 - 10^{-6}$ to $1 - 10^{-9}$	< 300 bytes	~ 2 m	< 1000	< 10 m/s

Table 1. Communication requirements for wireless factory automation gathered within the KoI project.

short- to medium-range communications below 200 m. Consequently, the symbol duration of IEEE-based technologies is much smaller, which in turn affects the (e2e) latency. However, to achieve a fair comparison of the latency impact between LTE and IEEE-based standards, we need to consider more than the pure time symbol duration. First, in IEEE-based standards the channel occupation time for a single transmitter is governed by additional symbols for synchronization preambles, control signaling, and LBT backoff, while LTE allows spreading data and control information over the frequency domain within the time symbol duration. Second, only LTE exploits multi-user access by frequency and space multiplexing, whereas IEEE-based standards predominantly rely on user multiplexing over time. Therefore, increasing the number of nodes has a significant impact on (e2e) latency for these standards. With increasing number of nodes, the LBT-based non-deterministic medium access schemes, for example, carrier sense medium access with collision avoidance (CSMA/CA), start to be inefficient. Even if the deterministic slotted medium access mode is used instead of CSMA/CA, the IEEE technologies can only support limited numbers of users to meet the latency requirements. In short, when comparing both technologies, we identify LTE as the choice for latency-critical factory applications.

Besides latency, factory automation also demands ultra-reliable transmission, as mentioned previously. Reliability is ensured by the use of forward error correction (FEC) schemes and exploiting the diversity gains. However, as specified in [9], LTE transmission is typically configured to operate for the target BLER of 10^{-1} before retransmission, which is considered to be a good trade-off between latency and system capacity for MBB services. In addition, it is to be noted that the turbo codes chosen for LTE have an error floor. For small packet size and code rate, the floor is below BLER of 10^{-5}. The coding efficiency decreases with the number of decoding iterations that can be executed within the tight latency requirement typical in C-MTC. Low-complexity convolutional codes that do not experience error floors and show similar performance for user data with small packet sizes are promising candidates. We study changes in coding and other L1/L2 modifications that are needed to enable mission-critical services using LTE later.

Key Design Features

The key design targets for C-MTC include low latency and ultra-high reliability. This requires exploiting certain design features at both layer 1 and layer 2 of the communication system, which are briefly described in the following. Please note that these design principles hold for C-MTC in general and factory automation in particular.

Enabling Ultra-Low Latency

For a communication system, delays at various protocol layers contribute to the (e2e) latency. The major contributors to the latency include protocol stacks, signal processing, medium access, transmission, and propagation delays. Processing delays are governed by the encoding and decoding complexity of the data at transmitter and receiver side, respectively. The physical layer and medium access mechanisms are major contributors to end-to-end latency from the radio communication perspective. Therefore, it is important to design lower layer protocols imparting as little latency as possible for mission-critical applications while fulfilling the reliability requirements.

Enabling Ultra-High Reliability

Diversity is one of the most significant techniques of the PHY layer for achieving highly reliable communication in a fading channel. As shown in [10], Fig. 2 illustrates that without diversity gains, a 90 dB margin is needed for guaranteeing lower than 10^{-9} probability of fading-induced outage. With diversity orders 8 and 16, the needed margin reduces to 18 dB and 9 dB, respectively. Time, frequency, and/or space are the three dimensions of achieving such high diversity gains. However, time diversity is not considered to be a suitable option for applications with strict latency bounds. It is also shown in [10] that hybrid automatic repeat request (HARQ) gains are not significant with such low latency requirements. Nevertheless, frequency diversity can be exploited on top of spatial diversity for C-MTC. Since D2D transmission cannot exploit high diversity gains only via spatial diversity, frequency diversity is of particular importance for the assisted D2D mode. Further details on diversity are described later.

L1/L2 technology	IEEE 802.11n (WLAN)	IEEE 802.11ac (WLAN)	IEEE 802.15.1 (WPAN)	Bluetooth 4.2 (WPAN)	IEEE 802.15.4 (WPAN)	3GPP LTE Rel-12 (4G cellular)	
Industrial solution/standard	IWLAN		Bluetooth 1.2, WISA	Bluetooth	ZigBee, ISA100.11a, WirelessHART		
Spec. release	2009	2013	2005	2014	2011	2015	
Range	< 200 m	< 200 m	< 100 m	< 100 m	< 10 m	< 100 km	
Licensing	Unlicensed	Unlicensed	Unlicensed	Unlicensed	Unlicensed	Licensed	
User multiplexing	Time	Time, space	Time	Time	Time	Time, space, frequency	
Antenna support	4	8	1	1	1	8	
Target error rate	PER: 0.1	PER: 0.1	BER: 0.001	BER: 0.0002 - 0.001	PER: 0.01	BLER: 0.1	
FEC	Convolutional code, LDPC, STBC	Convolutional code, LDPC, STBC	No FEC, repetition-code, Hamming code	No FEC, repetition-code, Hamming code	No FEC, convolutional code, RSC	Turbo code, STBC	
Frequency band	2.4 GHz, 5 GHz	5 GHz	2.4 GHz	2.4 GHz	780 MHz, 868 MHz, 915 MHz, 950 MHz, 2.45 GHz	400 MHz–4GHz	
Bandwidth	20 MHz–40 MHz	20 MHz–160 MHz	1 MHz	1 MHz	200 kHz–5 MHz;	1.4 MHz–100 MHz	
Time symbol duration	3.6 μs	3.6 μs	1 μs	1 μs	> 6 μs	71.4 μs	
Theoretical peak data rate	< 600 Mb/s	< 6.93 Gb/s	1 Mb/s	24 Mb/s	< 1 Mb/s	DL: < 4 Gb/s	UL: < 1.5 Gb/s
Signaling	OFDM	OFDM	Single carrier with spread spectrum	Single carrier with spread spectrum	Single carrier with spread spectrum	DL: OFDMA	UL: SCFDMA
Modulation	Up to 64-QAM	Up to 256-QAM	GFSK	PSK, GFSK	Chirp-SK/FSK/PSK/ASK	DL: up to 256-QAM	UL: up to 64-QAM
Channel access scheme	CSMA/CA and slotted	CSMA/CA and slotted	Slotted	Slotted	CSMA/CA and slotted	Scheduled	

LDPC: Low-density parity check
STBC: Space-time block coding
RSC: Reed-Solomon code

Table 2. Layer 1 and 2 features of relevant wireless standards retrieved from standardization documents of IEEE 802.11n 2009 [4], IEEE 802.11ac 2013 [5], IEEE 802.15.1 2005 [6], IEEE 802.15.4 2011 [7], Bluetooth core v4.2 [8], and LTE 3GPP Rel-12 [9].

Radio Channels in Factory Environments

In factory automation, the communication system needs to be adapted for indoor radio propagation. Here, this means the building structure, that is, the existence of metallic ceilings and open metallic joists, as well as close-by production cells comprising active machine tools and industrial robots alter the scattering and reflection characteristics of the radio channel. Therefore, when proposing L1/L2 modifications for an LTE-based C-MTC air interface, the time dispersion of the multi-path channel and the evolution of the wireless signal over time are of high relevance. These parameters deliver design constraints on the minimum symbol length needed for the transmission without inter-symbol interference (ISI) and improved link adaptation.

Motivated by existing technologies in unlicensed spectrum, the use of spectrum below 6 GHz is the current choice for the automation industry. To gain insight into typical channel characteristics, we performed a wideband channel measurement campaign within the KoI project, recording the channel delay statistics in a representative factory

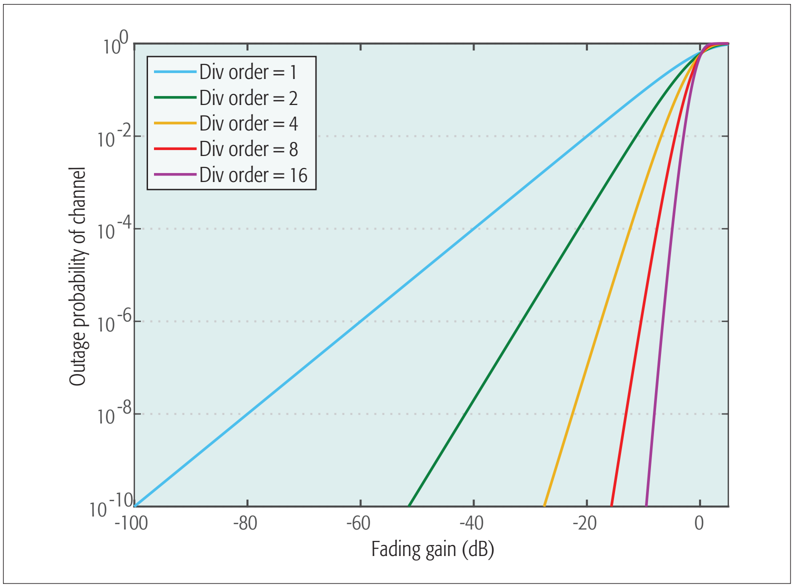

Figure 2. Outage probability of Rayleigh fading channels or different diversity orders [10].

automation cell at 5.8 GHz [11]. This carrier frequency was chosen due to its availability without licensing and complements other measurements performed for industrial applications at 2.4 GHz. Although the measurements were performed in unlicensed frequency bands of 5.8 GHz, the results could also be extended for neighboring frequency bands under a licensed regime. The addressed application scenario was the wireless control of industrial robots that repeatedly performed a pick-and-place process on a predefined trajectory at almost constant speed. The communication link was observed between a robot control unit placed within the automation cell and an antenna installed at the gripper of the moving robot arm. The 90th-percentile excess delay for non-line-of-sight (NLOS) transmission was 202 ns, but in a few cases of this setup the channel excess delays reached up to 350 ns (Fig. 3). To evolve LTE for communication in factory halls, the cyclic prefix (CP) length could be adapted based on these lower excess delays. Furthermore, the results also give a baseline for the D2D waveform design. Figure 3 exemplifies the power-delay profile of a measurement snapshot in which we estimated the set of dominant multipath components from the recorded channel impulse response (CIR). Also, we observed from the measurement data a high correlation between channel snapshots at the same positions of the repeated manufacturing process over time. The knowledge of the future position combined with the prediction of the link quality by previous channel estimates offers advantages in the design of feedback mechanisms and control data aspects. Channel quality indicator (CQI) feedback could be reduced while preserving high reliability and performance of the communication link. Hence, precise channel forecasts facilitate improved but simplified link adaptation in terms of pre-selection of modulation and coding schemes and optimized scheduling decisions. As a consequence, the L1/L2 processing of the air interface can be optimized for low-latency and reliable radio access for short-range industrial radios.

L1/L2 Modifications within LTE

Taking into account the aforementioned requirements, design principles, and channel peculiarities for the factory automation use case, this section outlines the key modifications required and/or being considered in LTE systems from the layer 1 and layer 2 perspectives.

Transmission Time Interval Shortening

The total latency between the time when data arrives in the transmission buffer and the time when a packet is delivered at the receiver is typically several times larger than 1 transmission time interval (TTI). For instance, in the case of uplink transmission, the device may also first send a scheduling request (SR) and wait for the uplink resource allocation from the base station. Hence, in order to achieve the requirement of 1 ms latency with an LTE system, the TTI should be redesigned to be significantly smaller.

LTE Release 13 is currently investigating the concept of TTI shortening for latency reduction. A TTI can be defined as the duration of an independent decodable transmission. Since in LTE systems the processing times are based on the TTI, a shorter TTI results in faster processing times. Therefore, TTI shortening leads to multiple benefits including lower transmission time, faster HARQ retransmissions, and lower processing time. Hence, in factory automation scenarios with typically small data size, TTI shortening would help in achieving lower latency. Moreover, TTI shortening allows scheduling flexibility as more user equipment (UE) can be scheduled in the same subframe using the same frequency resource. While current LTE systems use a TTI of 1 ms, LTE Release 13 is considering a TTI of duration 0.5 ms, and even the minimum possible duration consisting of only 1 OFDM symbol (i.e., 71.4 μs including the cyclic prefix). We believe that by shortening the TTI to 1 OFDM symbol, the minimum required e2e latency of 1 ms in factory automation can be fulfilled. Nevertheless, the cyclic prefix in LTE is optimized for macro scenarios operating at traditional LTE frequencies, which is not an efficient design regarding the factory deployments described above. We give further details on design complexities with respect to TTI shortening later.

Instant Uplink Access

Primarily, the LTE link layer is not designed to address latency-critical communication requirements. In an LTE system, the channel access and radio resource management are centrally coordinated by the LTE base station, or eNodeB. While the eNodeB is able to efficiently handle downlink transmissions, uplink transmissions involve high signaling overhead leading to undesired communication latency. For an uplink transmission, the device first needs to send a scheduling request (SR). Corresponding to the SR, the eNodeB sends the scheduling grant (SG) to the device, thereby indicating the schedule and the resources to be used. Finally, the user can transmit its data only after receiving the SG. Hence, the cycle of SR-SG-data induces a high degree of latency (at best this can be on average 9.5 ms with 1 ms TTI size). In order to deal with the uplink dynamic scheduling, the concept of so-called instant uplink access (IUA) is being investigated in LTE Release 13, where the SR-SG overhead is proposed to be eliminated. The eNodeB reserves prior uplink resources for a given device, and when the data arrives, it is directly sent out without any SR. While blocking some uplink resources in every subframe results in lower resource utilization when there is no uplink traffic, this scheme helps in substantially reducing the uplink latency. Besides latency reduction, system-level simulation results indicate that IUA also allows lower energy consumption for the device [12].

It is to be noted that the IUA concept is complementary to TTI shortening. These two concepts can lead to minimizing (e2e) latency of the existing LTE system, and thus are very well suited to the requirements of a wide range of factory automation applications.

Modulation and Coding Schemes

Modulation and coding selection impacts both the required received signal power and the required bandwidth [13]. In general, higher modulation order and code rate require additional signal power, but reduce the needed bandwidth. When it comes to modulation, there are practical limitations, such as transmitter and receiver impairments, which typically limit the highest modulation order. Considering LTE, the available modulation levels are quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), 64-QAM, and 256-QAM.

Although many modern communication systems such as LTE and IEEE 802.11ac use turbo or LDPC codes as FEC for data (Table 1), it is preferred to use convolutional codes in the low-latency and high-reliability C-MTC use cases such as factory automation. Convolutional codes have similar performance as turbo and LDPC codes for small block lengths that are typical for this use case (e.g., up to a few hundred bits). In contrast to convolutional codes, turbo and LDPC codes have an error floor, which makes these codes less efficient when the BLER reaches very low levels (e.g., 10^{-9}). Considering latency, decoding convolutional codes imparts shorter delay compared to the iterative decoders typically used for turbo and LDPC decoding. This is due to lower decoding complexity, and the property of convolutional codes that the decoder can process the code block while it is being received, thereby obtaining the decoded bits with very little delay. This requires that interleaving is only performed over frequency and not over time. However, for control channels that have block lengths smaller than 10 bits, block codes are preferred due to better performance and manageable decoding complexity [14].

Diversity

Another important use of coding is to harvest diversity. As discussed previously, diversity is a powerful tool for achieving high reliability, and to achieve spatial and frequency diversity in an OFDM system, it is essential to spread the coded bits over different diversity channels. Ideally, if the correct and erroneous code words differ in d positions, it is desired that these d positions are mapped to independent frequency bins or transmit antennas. If a deployment has M diversity channels, the code rate needs to be low enough to have free distance (convolutional codes) or minimum Hamming distance (block codes) sufficiently larger than M.

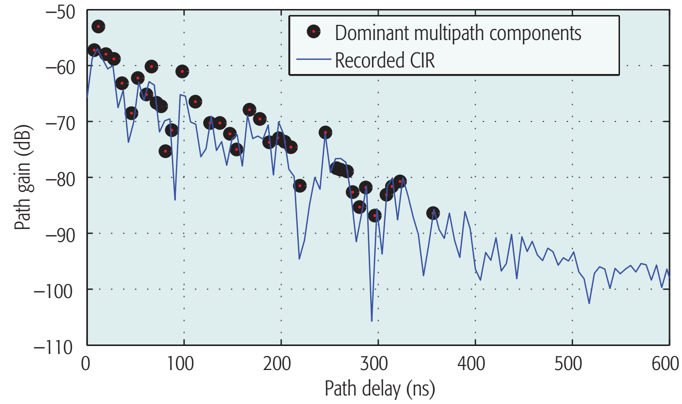

Figure 3. Typical power-delay profile obtained during the KoI channel measurement campaign in a factory automation setup at 5.8GHz [11].

In order to enable multi-cell factory deployments to work with a small frequency reuse factor, not only is the SNR of importance, but the system also has to work reliably at a low average SINR. A BLER of 10^{-9} at low average SINR of 3–10 dB can only be achieved with a very high diversity order of 16 (e.g., 8 × 2 or 2 × 8 antennas), unless transmitter-side channel state information is available. This can be seen in Fig. 4, assuming for simplicity that the SNR and SINR requirements for the same BLER are equal. We consider here up to 8 transmit antennas and a code rate of 1/2 with a free distance of 10 combined with Alamouti code, which can exploit the transmit-side diversity order to a large extent. However, there is a diversity loss associated with the use of Alamouti code for more than two transmit antennas. For example, with BLER of 10^{-9}, the required SNR for 8 transmit antennas (using binary PSK, BPSK, and a code rate of 1/2) is approximately 2.3 dB higher compared to when maximum diversity gains can be exploited, (i.e., ideal full diversity).

An 8 × 2 configuration is possible for communication where one endpoint is a base station that typically has the deployment space and complexity constraints allowing for a high number of antennas. For D2D, where only a few antennas can be accommodated, such high diversity order might not be achieved even after exploiting gains from frequency diversity.

Performance degradation due to antenna correlation is also shown in Fig. 4. We illustrate the effect of receive antenna correlation for an 8 × 2 antenna configuration as well as the effect of transmit antenna correlation for a 2 × 8 antenna configuration. We see that with antenna correlation of 0.5, the BLER slope is approximately the same as when there is no antenna correlation, although there is a small SNR penalty at lower BLER. This indicates that the diversity order is very well preserved. With antenna correlation

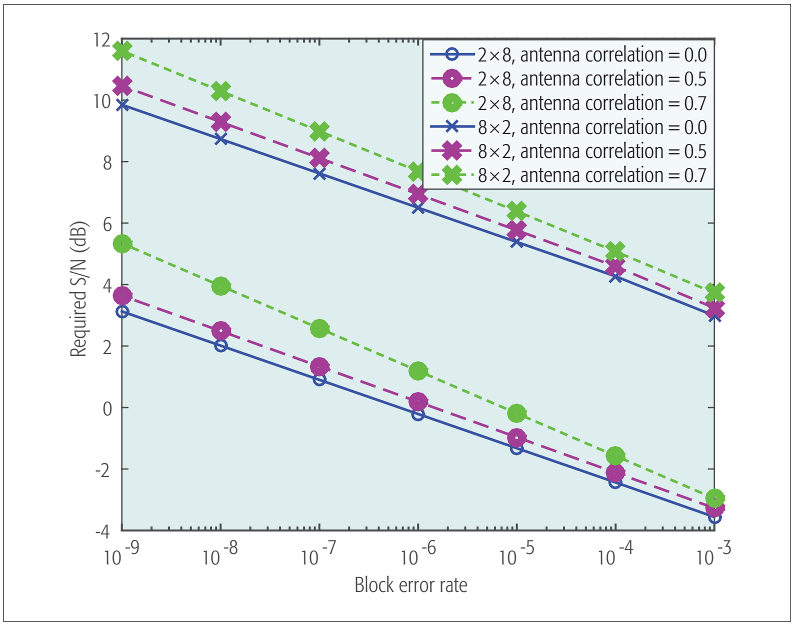

Figure 4. Impact of antenna correlation on link performance for the 8 × 2 and 2 × 8 antenna configurations with QPSK and rate 1/2 coding [10].

as high as 0.7, there is a more noticeable effect on the BLER slope. However, even in this case, the SNR penalty at 10^{-9} BLER is approximately 2 dB.

5G Outlook: Beyond the LTE Evolution

For factory automation, we target the TTI to be on the order of 100 μs to satisfy the most stringent use cases. If the LTE TTI is reduced to 1 OFDM symbol of 71.4 μs, this target could be met. However, having just a single OFDM symbol per TTI comes with the drawback of a small number of resource elements. Given that the amount of control signaling and reference symbols has to stay approximately constant regardless of the TTI duration, the overhead percentage increases accordingly. Furthermore, in factory environments, the delay spread and excess delay are much lower than those for which the LTE OFDM symbol duration was originally designed. Therefore, a scaled version of LTE numerology is more suitable for latency-critical systems in the factory environment (e.g., using a scaling factor of 5). Thus, the new scaled numerology being considered for 5G has a subcarrier spacing of 75 kHz and OFDM symbol duration of 13.3 μs excluding the cyclic prefix (CP). Moreover, early decoding is considered to be an important aspect for delay sensitive communication. Hence, the control signaling and reference symbols need to be placed at the start of the subframe to allow early decoding of the received data [14].

Although orthogonal waveforms such as LTE's OFDM have many advantages, some limitations could be addressed by a novel waveform in 5G [15]. OFDM is well suited for cellular systems. However, for D2D communication, it suffers from the stringent synchronization requirements. For cellular systems, multiple access interference within a cell is avoided in the downlink by inherently synchronized transmission. In the uplink, synchronized reception of the signals from multiple devices is achieved by adjusting the timing advance for each device accordingly. For D2D communication, if multiple D2D links are concurrently active and in interference range of each other, the timing advance of multiple transmitting devices can in general not be controlled in such a way that synchronous reception at all receiving devices is achieved.

Here, D2D systems could benefit from multi-carrier waveforms with improved frequency localization and relaxed synchronization requirements. Filtering the transmit signal achieves lower spectral side-lobes. In order to deal with the interference between asynchronous receptions on adjacent sub-bands that emerges in OFDM, the filtering could be done separately on each transmitted sub-band, using filtered OFDM. Alternatively, filtering each resource block separately as in universal filtered multicarrier (UFMC) has the benefit of not requiring allocation-dependent filters. Furthermore, filter bank multi-carrier (FBMC) could be used. This generalization of multi-carrier modulation introduces a well designed poly-phase prototype filter shape onto the modulated signal on each subcarrier. FBMC systems benefit from cyclic-prefix-free transmission, saving additional resources. Nevertheless, the drawback of the FBMC approach is degraded time-localization behavior. In particular, multiple symbols overlap in the time domain and increase the effective symbol duration. Therefore, it first needs to be analyzed if the FBMC waveform can meet the low-latency requirements of the indoor factory automation applications with short channel impulse responses. In conclusion, going with a filtered OFDM design is currently the best and most mature choice for 5G factory communication systems because of the time localization specifics of FBMC.

Summary

This article discusses the use of wireless communication in a factory automation scenario and presents the challenging communication requirements. While current wireless solutions for such applications are dominated by proprietary implementations and are mostly applied in isolated scenarios, a worldwide wireless standard could leverage the advantages of going wireless in a global market. Licensed operation naturally brings advantages in meeting the latency and reliability requirements by excluding the need to handle coexisting systems. By fulfilling the requirements of mission-critical applications, wireless technologies based on LTE will certainly enable new services in factory automation. For this, the current LTE design needs to undergo some modifications, which are partially being considered in 3GPP already and discussed in this article. While the proposed design modifications could address a broad range of factory automation services, a few mission-critical applications require revolutionary (non-backward-compatible) changes in the communication system as highlighted above. Either way, whether it be LTE's evolution or 5G that makes it to the market of factory automation, in both cases it opens up new business opportunities for vendors and operators using 3GPP technologies.

Acknowledgment

This work is part of the research project Koordinierte Industriekommunikation (KoI) under grant support of the Federal Ministry of Education and Research (BMBF) of Germany. Partners involved in the project are Ericsson, Fraunhofer Heinrich Hertz Institute, RWTH Aachen University, the University of Paderborn, WiseSense GmbH, and WeissRobotics GmbH & Co. KG.

References

[1] E. Dahlmann *et al.*, "5G Wireless Access: Requirements and Realization," *IEEE Commun. Mag.*, vol. 52, no. 12, Dec. 2014, pp. 42–47.

[2] Research project Koordinierte Industriekommunikation (KoI) supported by the Federal Ministry of Education and Research (BMBF) of Germany, Duration: 01/2015–06/2017; http://www.koi-projekt.de

[3] J.-P. Thomesse, "Fieldbus Technology in Industrial Automation," *Proc. IEEE*, vol. 93, no. 6, June 2005, pp. 1073–1101.

[4] IEEE Std 802.11n, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 5: Enhancements for Higher Throughput," Sept. 2009; http://standards.ieee.org

[5] IEEE Std 802.11ac, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz," Dec. 2013; http://standards.ieee.org.

[6] IEEE Std 802.15.1, "Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs)," June 2005; http://standards.ieee.org.

[7] IEEE Std 802.15.4, "Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)," Sept. 2011; http://standards.ieee.org.

[8] Bluetooth Special Interest Group, "Covered Core Package Version: 4.2," Bluetooth System Spec., Dec. 2014.

[9] 3GPP TS 36.201 (v12.2.0), "Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Physical Layer; General Description (Release 12)," Mar. 2015.

[10] N. A. Johansson *et al.*, "Radio Access for Ultra-reliable and Low-Latency 5G Communications," *Proc. IEEE ICC Wksp. 5G & Beyond – Enabling Technologies and Applications*, London, U.K., June 2015.

[11] B. Holfeld *et al*., "Radio Channel Characterization at 5.85 GHz for Wireless M2M Communication of Industrial Robots," *Proc. IEEE Wireless Commun. and Networking Conf.*, Doha, Qatar, Apr. 2016.

[12] 3GPP TR 36.881 (v0.5.0), "Evolved Universal Terrestrial Radio Access (E-UTRA); Study on Latency Reduction Techniques for LTE (Release 13)," Nov. 2015.

[13] O. N. C. Yilmaz *et al*., "Analysis of Ultra-Reliable and Low-Latency 5G Communication for a Factory Automation Use Case," *Proc. IEEE ICC Wksp. 5G & Beyond Enabling Technologies and Applications*, London, U.K., June 2015.

[14] S. A. Ashraf *et al.*, "Control Channel Design Trade-offs for Ultra-Reliable and Low-Latency Communication System," *Proc. IEEE GLOBECOM Wksp. Ultra-Low Latency and Ultra-High Reliability in Wireless Communication*, San Diego, CA, Dec. 2015.

[15] G. Wunder *et al.*, "5GNOW: Non-Orthogonal, Asynchronous Waveforms for Future Mobile Applications," *IEEE Commun. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 97–105.

Biographies

BERND HOLFELD (bernd.holfeld@hhi.fraunhofer.de) joined the Fraunhofer Heinrich Hertz Institute, Berlin, Germany, in 2012 after completing his Dipl.-Ing. (M.Sc.) degree in electrical engineering at Technische Universität Dresden, Germany, the same year. In 2010, he was a visiting student researcher at the Institute for Telecommunications Research at UniSA, Adelaide, Australia. He has been involved in several research projects on 4G and 5G radio access. His current focus is on machine-to-machine communication for industrial wireless systems.

DENNIS WIERUCH (dennis.wieruch@hhi.fraunhofer.de) received his Dipl.-Ing. (M.Sc.) degree in computer engineering from Technische Universität Berlin, Germany, in 2009. In March 2009, he joined the Fraunhofer Heinrich Hertz Institute, Germany, as a research associate, where he is currently pursuing a Ph.D. degree. His research interests include wireless communications with a focus on cognitive radio, compressed sensing, software defined radio, and digital signal processing. He has participated in several European Union and German government funded research projects.

THOMAS WIRTH (thomas.wirth@hhi.fraunhofer.de) received his Dipl.-Inform. (M.Sc.) degree in computer science from the Universität Würzburg, Germany, in 2004. He joined the Fraunhofer Heinrich Hertz Institute in 2006, working as a senior researcher on LTE and LTE-Advanced technologies. Since 2011, he has headed the Software Defined Radio group with a focus on PHY and MAC algorithms and real-time implementation for future wireless networks, including industrial radio applications and 5G prototypes.

LARS THIELE (lars.thiele@hhi.fraunhofer.de) is currently associated with the Fraunhofer Heinrich Hertz Institute, where he leads the System Level Innovation group. He received his Dipl.-Ing. (M.Sc.) degree in electrical engineering from Technische Universität Berlin in 2005 and his Dr.-Ing. (Ph.D.) degree from Technische Universität München in 2013. He has co-/authored more than 50 papers and several book chapters in the fields of radio propagation modeling, large-scale system-level simulations, CoMP transmission, and massive MIMO.

SHEHZAD ALI ASHRAF (shehzad.ali.ashraf@ericsson.com) is an experienced researcher at Ericsson Research, which he joined in 2013. He holds an M.Sc. in electrical engineering from RWTH Aachen University. Since joining Ericsson, he has been deeply involved in European Union and German government funded research projects related to the development of 5G concepts. Currently, he is also involved in 3GPP standardization. His research interests include 4G and 5G radio access technologies, and machine-type communications.

JÖRG HUSCHKE (joerg.huschke@ericsson.com) is a master researcher in radio research at Ericsson Research. He has been working toward 3GPP standardization of MBMS for LTE and its performance evaluation. In 2016, he began leading the radio interface team in the German research project KoI on evolved LTE and 5G-based wireless communication in factory automation. He received his diploma degree in electrical engineering from Georg-Simon-Ohm University of Applied Sciences, Nuremberg, Germany, in 1993.

ISMET AKTAS (ismet.aktas@ericsson.com) works at Ericsson Research on concept development and evaluation for 5G. In this context, he is looking into critical machine type communication in general and wireless factory automation in particular. He obtained his Ph.D. and Diploma degrees from RWTH Aachen University. Currently, he is leading the KoI project. His research interests include cross-layer design, jamming detection, machine type communication, and industrial automation.

JUNAID ANSARI (junaid.ansari@ericsson.com) is currently associated with Ericsson Research. Previously, he worked as a postdoctoral researcher and research assistant at the Institute for Networked Systems at RWTH Aachen University. He received his Ph.D. (2012) and M.Sc. (2006) degrees from RWTH Aachen University. He has worked on several collaborative European Union and German government funded research projects. His research interests include cognitive radios, embedded intelligence, and system architecture design for next generation wireless networks.

By fulfilling the requirements of mission-critical applications, wireless technologies based on LTE will certainly enable new services in factory automation. For this, the current LTE system needs to undergo some design modifications, which are partially being considered in 3GPP already and discussed in this article.