HiFlecs: Innovative Technologies for Low-Latency Wireless Closed-Loop Industrial Automation Systems[i]

C. Bockelmann[*], A. Dekorsy[*], A. Gnad[♣], L. Rauchhaupt[♣], A. Neumann[$], D. Block[$], U. Meier[$], J. Rust[+], St. Paul[+], F. Mackenthun[#], A. Weinand[§], H. Schotten[§], J. Siemons[♦], T. Neugebauer[†], M. Ehlich[‡]

[*]{bockelmann, dekorsy}@ant.uni-bremen.de, University of Bremen, Department of Comm. Engineering, Germany

[♣]{andre.gnad, lutz.rauchhaupt}@ifak.eu, Institut f. Automation and Kommunikation e.V., Magdeburg, Germany

[$]{arne.neumann, dimitri.block, uwe.meier}@hs-owl.de, inIT - Institute Industrial IT, Lemgo, Germany

[+]{rust, steffen.paul}@me.uni-bremen.de, University of Bremen, Department of Communication Electronics, Germany

[#]fabian.mackenthun@nxp.com, NXP Semiconductors Germany GmbH, Hamburg, Germany

[§]{weinand, schotten}@eit.uni-kl.de, University of Kaiserslautern, Institute for Wireless Comm. and Navigation, Germany

[♦]siemons@imst.de, IMST GmbH, Kamp-Linfort, Germany

[†]neugebauer@goetting.de, Götting KG, Lehrte, Germany

[‡]martin.ehlich@lenze.com, Lenze SE, Aerzen, Germany

Abstract

The current paradigm shift from human to machine communication impacts the design of wireless communication systems on a fundamental level. Especially, closed-loop control applications from industrial automation and manufacturing require completely new solutions to achieve latencies below 1 ms with extremely high reliabilities and stringent requirements on message timing and repetitive packet losses. The research project "Innovative technologies for industrial automation (HiFlecs)" funded by the German ministry of education and research provides a comprehensive system design for industrial radio and novel solutions in various areas as coexistence management, physical and mac layer design as well as security.

1 Introduction

Currently, many research activities for the design of industrial radio access technologies (RATs) are ongoing worldwide under keywords as Industrial Internet of Things (IIoT) and Industry 4.0 (I40). Industrial RATs must support diverse and often contradicting communication characteristics such as low latency, high reliability, ubiquitous coverage, deterministic behavior, secure and massive connectivity. Given the heterogeneous landscape of wireless and wireline communication technologies, it is apparent that future industrial RATs will complement the set of communication technologies rather than fully replacing the state-of-the-art (SotA).

In the context of 5G, industrial radio as well as other machine type communications are summarized by two services: (i) massive Machine Type Communication (mMTC or MMC) and (ii) Ultra Reliable Low Latency Communication (URLLC). Extensive pre-standardization research on both services is conducted in the 5G-PPP EU program. Over the last years, many application scenarios from IIoT and I40 have been adopted either by operators [1] or through individual research projects (METIS I, FANTASTIC-5G) to develop technologies for novel MMC and URLLC services in future cellular communications. Currently, these activities do not cover the full extent of closed-loop control applications, but may serve as an umbrella for specialized industrial RATs. Hence, there is still a need for local wireless network solutions that can operate in exclusive or shared spectrum and provide the necessary improvements over available solutions to enable new I40 applications.

Nationally, the German ministry of education and research (BMBF) outlined the challenges for such wireless industrial communication systems in the research initiative "Reliable wireless communication in the industry" (ZDKI). The objectives of ZDKI projects were defined to strive for an overall latency below 1ms and reliability in the order of packet loss rates below 10^{-9}. In the following we present the general outline, concept and current results of the ZDKI research project "Innovative wireless technologies for industrial automation" (HiFlecs). The HiFlecs project aims to develop novel radio technologies for industrial wireless communication with a focus on closed-loop control applications. The core of HiFlecs is the comprehensive design of an industrial radio system based on four core technologies.

2 Requirements

The system design approach of HiFlecs builds on a sound analysis and categorization of industrial application scenarios. The methodology used was developed by the accompanying research project BZKI [2] and is a result of cooperation between all partners of the ZDKI program. The requirements of applications were grouped into three requirement profiles, which are assigned to the following application scenarios:

Requirement profile A:

- Driverless transport of large goods
- Marriage in vehicle assembly
- Shuttle vehicles in packaging machines

Requirement profile B:

- Industrial plant with decentralized drive technology

- Robot cell with product feed and removal of the peripheral axes
- Storage and retrieval machines or shuttle systems

Requirement profile C:

- High bay warehouse
- Robot cells with interchangeable tools

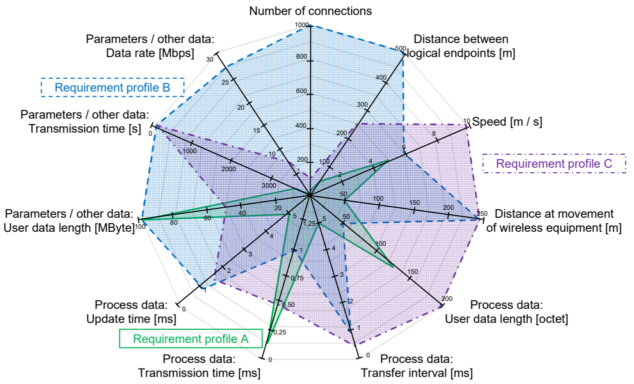

Figure 1 – Spider chart for HiFlecs requirement profiles A, B and C.

A selection of key parameters and their setting required of each profile is summarized in the spider chart depicted in Figure 1. Each profile has a unique combination of requirements, the sum of which cannot be addressed by any industrial radio currently available.
Additionally, Table 1 specifically highlights the most important parameters for the radio air interface design. Since HiFlecs needs to be interconnected with the cyclic process of data exchange, viz. the control process, Figure 2 illustrates the difference of transmission time and update time. Both are often termed latency.
In contrast to rather vague assumptions such as "below 1ms" Table 1 clearly indicates that industrial uses cases need to be addressed more specifically in terms of latencies. Same holds for the term reliability. For example, for many manufacturing processes the loss of a single packet has no impact, but consecutive losses might lead to highly costly factory stops.

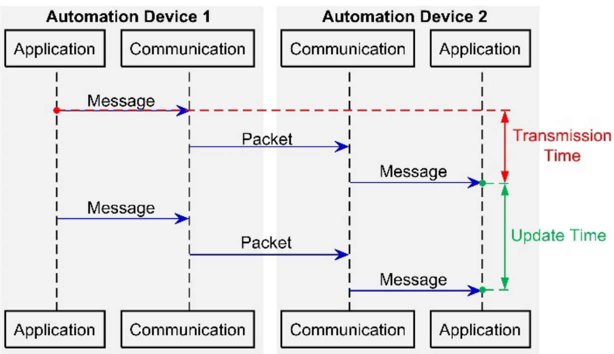

Figure 2 – Illustration of transmission and update time.

In addition to the quantitative requirements mentioned above, there exist several functional requirements such as

Table 1 – Selection of parameters from HiFlecs requirement profiles A, B and C.

Parameter	A	B	C
Transmission time [ms]	0,15	1,00	0,50
Update time [ms]	5,00	1,00	1,50
Data length [Bit]	1024	400	1600
Packet Loss Rate	$5 * 10^{-7}$	N/A	N/A
Consecutive Losses	2	N/A	2
No. of devices	32	1000	100

adaptability to different profiles and environmental conditions, support of plug and trust device integration and exchange as well as possibilities for diagnosis and time synchronization.

3 HiFlecs Core Technologies

The HiFlecs project aims to develop novel radio technologies for industrial wireless communication with a focus on closed-loop control applications.
To build the design basis, HiFlecs started with the identification and characterization of various applications. Section 2 summarizes the corresponding application profiles. Further, special focus has been put on understanding the wireless propagation environment for the design of the physical layer. The results of the channel measurement campaigns conducted in HiFlecs can be found in [3]. To achieve the latency and reliability requirements outlined in Table 1 numerous advances beyond the SotA are required at the technology level as well as in system design. Therefore, HiFlecs makes a point of considering a comprehensive system design from hardware implementation of the RF frontend and baseband implementation, PHY/MAC design and processing to resource and network management as well as distributed application functionality. Consequently, HiFlecs activities are structured along four core technologies:

Adaptive PHC/MAC technologies consist of scalable and flexible resource usage to achieve high reliability and low latency, aim to exploit the broadcast nature of the wireless channel and include dynamically reconfigurable hardware concepts

Integrated information security consists of concepts for Plug & Trust to allow easy and sustainable authentication, physical layer security approaches to lower the security overhead and latency optimized encryption

Coexistence Management consists of cognitive spectrum sensing methods to assess the current spectrum usage in crowded spectra and self-regulated coexistence management concepts to allow for locally well managed and efficient spectrum exploitation

Mapping of distributed application functions consists of well-defined interfaces between the air interface and applications as well as dynamic and distributed object models for distributed control

Each core technology provides fundamental building blocks separately but only the interaction and combination of these in a comprehensive system architecture may achieve all requirements.

4 HiFlecs Architecture and System Concept

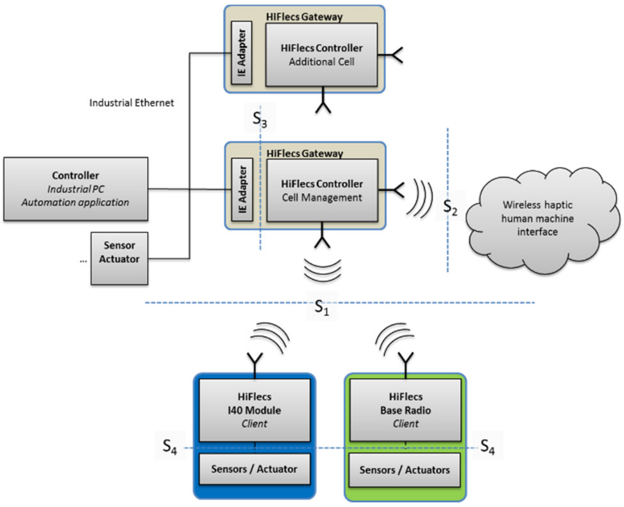

Figure 3 – HiFlecs architecture and interfaces.

HiFlecs proposes a single radio cell approach that can be integrated into real-time network topologies and that supports distributed applications and their changing requirements. Central component of the system is the HiFlecs Controller acting as access point to the HiFlecs Clients through the S1 interface as depicted in Figure 3. Two types of clients are foreseen: (i) the base radio that connects standard sensor/actuator-type devices and (ii) the I40 module that includes application layer functionality and may be part of distributed control processes.
HiFlecs specified four data channels on the S1 interface for the information exchange between the Controller and the Clients with the process data channel bearing the highest priority to fulfill the most critical requirements regarding timing and reliability. The parameter and management data channels convey acyclic information and the client-to-client channel is only a logical channel, which is physically mapped through the Controller.
The HiFlecs system also provide the external interfaces S3 and S4 at Controller and Client for the exchange of process data to the application. The mapping to specific Industrial Ethernet (IE) environments is realized by an IE Adapter which is coupled to the Controller. Additionally, there are interfaces provided by the control and management planes. They comprise functionality to exchange information

- for monitoring and diagnostics of the radio cell,
- for indicating dynamic QoS requirements from the external application and
- for indicating changes in environmental conditions.

5 HiFlecs Technologies

In the following we present selected technology components developed by HiFlecs partners. Further information on advances of HiFlecs core technologies can be found in [2], [3], [5], [8], [9], [11], [16].

5.1 Coexistence management

Table 2 – Convolutional Neural Network Design

#	Layer type	Input size	Parameters	Dropout	Activation fct.
1	Preprocessing layer	128 x 2	FFT	-	-
2	Convolutional layer	128 x 2	64 feature maps with 3x1 filter kernel	-	Rectified linear
3	Convolutional layer	64 x 126 x 2	1024 feature maps with 3x2 filter kernel	60%	Rectified linear
4	Dense layer	126976 x 1	128 neurons	60%	Rectified linear
5	Dense layer	128 x 1	15 neurons	-	Softmax

HiFlecs assumes coexistence in a shared band per regulation requirements. Therefore, coexistence management is a necessity in every industrial radio system. IEC 62657-2 recommends an active coexistence management for industrial radio communication systems [4]. Hence, awareness of coexisting wireless systems based on wireless interference identification (WII) is a requirement for automatic robust coexistence management approaches.
We propose a WII approach based upon self-optimizing multi-layer convolutional neural networks (CNNs) [5]. The design of the CNN-based WII approach was derived from O'Shea et al. [6]. Table 2 lists the CNN design.

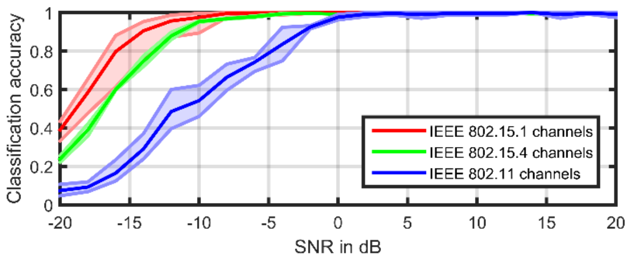

Figure 4 – CNN-based wireless interference identification accuracy of allocated frequency channels from 2.4 GHz-ISM radio band for varying signal-to-noise ratios.

To consider realistic wireless device capabilities, the CNN uses snapshots of short duration (12.8 µs) and limited acquisition bandwidth (10 MHz) corrupted by additive white Gaussian noise. Each snapshot is classified into one of the following classes: (i) one of the 15 frequency channels of IEEE 802.15.4, (ii) IEEE 802.15.1, and (iii) partly in-band IEEE 802.11 b/g compliant packet transmissions from the license-free 2.4-GHz-ISM radio band.

The proposed CNN shows promising results with high classification accuracy for signals with low SNR as shown in Figure 4. The classification of narrowband packet transmissions, e.g., compliant to IEEE 802.15.1 and IEEE 802.15.4, exceeds 97% accuracy for SNR greater than -5 dB. The performance only drops for wide-band signals such as IEEE 802.11 compliant packet transmissions.

5.2 Physical and MAC layer

5.2.1 Flexible multi-carrier system with low latency

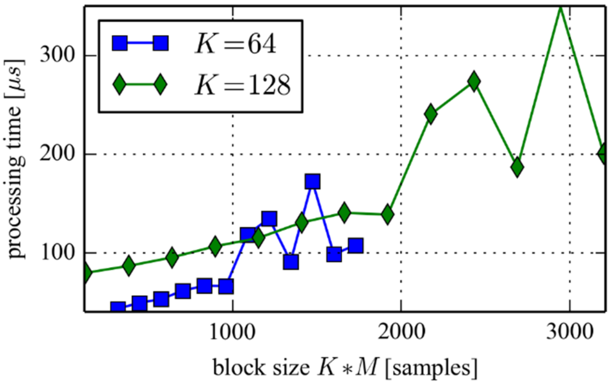

Figure 5 – Latency benchmark of GFDM physical layer processing in dependence of the total block size for two subcarrier choices *K* and various timeslots *M*.

Current 4G systems and some local area solutions rely on OFDM, a simple and effective multi-carrier system at the physical layer. However, several shortcomings of OFDM were identified [7]. These shortcomings include poor out-of-band (OOB) emission properties, strict synchronization requirements and poor spectral efficiency. Generalized Frequency Division Multiplex (GFDM) was identified as a suitable multi-carrier waveform. Generally, GFDM is a highly flexible non-orthogonal waveform well addressing the mentioned OFDM shortcomings.

GFDM is a prime candidate for industrial radio that requires low latency and needs to coexist in crowded frequency bands. With careful design, large filter delays can be avoided and OOB emissions minimized if GFDM with circular filters is employed. A single cyclic prefix and suffix for the whole GFDM frame saves overhead compared to a CP for every multi-carrier symbol like in OFDM and achieves the same cyclic structure.

In addition to over-the-air latencies that are only determined by the frame duration, the baseband signal processing adds significant delays to a communication system. The introduced latencies of all individual processing steps need to be characterized to enable the design of reliable low-latency systems. In HiFlecs, a GFDM system has been implemented in software as a Software Defined Radio (SDR) and its components have been carefully benchmarked. Such an SDR implementation can reveal first figures for latencies in an I40-GFDM system and hint at the performance that can be achieved by flexible hardware implementation (cf. Section 5.2.2).

In Figure 5 the results for different parameterizations of the SDR GFDM physical layer processing chain are presented. The number of subcarriers is denoted by K and the used timeslots are denoted by M. This results in a system with $M \cdot K$ symbols per frame. It is shown that the sum processing latencies for such a GFDM baseband processing chain are kept well below 1ms. For a thorough analysis of the different processing steps please refer to [8].

5.2.2 Flexible hardware architecture

To reach the demanding requirements of the HiFlecs system design, novel sophisticated hardware concepts are a key ingredient. Due to the challenging requirements formulated above, the hardware-based signal processing has to address several applications with different demands each. Hence, reconfigurable computing is an important feature of the HiFlecs wireless technology. To this end, selected hardware modules, e.g., the (i) FFT processing on the PHY layer, are implemented in a reconfigurable fashion.

To maximize the signal processing flexibility, the hardware architecture also provides a programmable central processing unit (CPU) which can be linked to the baseband signal processing task. Thus, the hardware architecture allows the realization of the GFDM concept from Section 5.2.1 using the FFT as an optimized core function with additional flexible CPU-based signal processing.

For an effective employment of the coexistence management also a specialized hardware accelerator is implemented. In detail, a fast-fourier-transform (FFT) and a logarithmic-converter unit (LCU) are considered to analyze the channel load in the frequency band. To keep the requirements in terms of area and energy reasonable the well-known sequential R2SDF algorithm is selected for the FFT. Further, this architecture enables dynamic reconfiguration of the size of input data at runtime [9]. For the realization of the LCU, a sophisticated function approximation technique is implemented providing the automated and accuracy-driven design of elementary functions [10]. To this end, the resulting data from the R2SDF is converted into the logarithmic number format that provides all the spectral information which is necessary for further processing by the coexistence management (cf. section 5.1).

5.3 Security

The integrated HiFlecs security concept focuses on the authenticity of HiFlecs devices and secure real-time communication between them. Only authentic, trusted devices must be part of the system and authenticity, integrity and privacy of exchanged messages should be guaranteed. Detailed results of the security requirements analysis can be found in [11].

Secure and convenient exchange and adding of HiFlecs devices to an existing HiFlecs network are mandatory in the dynamic Industry 4.0 environment. A plug and trust concept based on embedded Secure Elements has been developed to support this requirement. The Secure Elements act as tamper resistant hardware trust anchor within the HiFlecs devices and are used to securely store credentials and key material. Key material can be updated in the field using the Secure Element's contactless interface. Details on how to update credentials in the file can be found in [11].

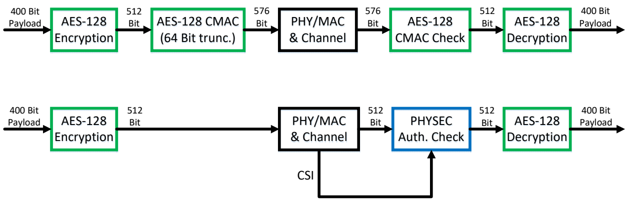

Figure 6– Comparison of conventional message authentication (top) and PHYSEC based message authentication (bottom).

To allow for secure real-time communication, the security blocks are embedded into the Media Access Control layer of the HiFlecs real-time channel shown in the top part of Figure 6 (green blocks). Authenticated encryption (encrypt-then-MAC) is used to ensure authenticity, integrity and privacy of messages. Major challenges are the time overhead caused by cryptographic calculations and the data overhead added by them [11]. To offer strong encryption, HiFlecs uses AES-128 in Counter Mode as recommended by BSI [12] and NIST [13]. The cipher is implemented and optimized in hardware to meet to latency requirements of the system. Dedicated implementations for the HiFlecs-Controller (low latency and higher throughput) and the HiFlecs-Client (low latency and lower power/area) are planned. The overhead added by the 64 Bit CMAC authentication tag (minimum recommended length [11]), as well as zero padding due to the AES-128 encryption block is especially critical for short uplink messages. If the HiFlecs requirement profile B is considered, the security overhead for a payload size of 400 Bit is 30,5% (11,1% due to the authentication tag and 19,4% due to zero padding). Therefore, HiFlecs investigates physical layer message authentication schemes (cf. Figure 6 bottom, blue blocks) to develop alternative solutions.
Additionally, physical layer security (PHYSEC) based secret key generation (SKG) schemes are considered to negotiate and update session keys for each user link. A good overview on both techniques can be found in [15].
In contrast to the SKG techniques, e.g., [14], which assume high temporal variation of the wireless channel to derive secret keys, the approach of PHYSEC based message authentication assumes low temporal variation [16]. It is assumed, that at least two subsequent channel estimations are within the coherence time of the channel. The fast spatial decorrelation property of the wireless channel implies that adversarial users with a spatial distance to legal users of at least one wavelength experience different channel conditions. Thus, they cannot extract the same secret keys as the legal users and can further be detected by a detection probability in the order of 99.9% [16] due to that difference (e.g., in case of replay attacks) yielding alternative resource efficient and lightweight security solutions.

6 Demonstrator

As part of the comprehensive view on an industrial radio system HiFlecs also strives to demonstrate a subset of the achieved results in a proof-of-concept demonstrator that uses one application from automation.

6.1 Demonstrator concept

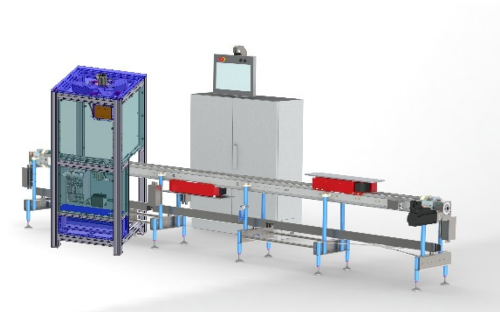

Figure 7 – Demonstrator concept for a shuttle based packaging machine (Transmodules from Schubert and Delta robot from Lenze).

The concept of the HiFlecs demonstrator is built around an existing application from the HiFlecs application profiles presented in Section 2, i.e., a shuttle system in a packaging machine per requirement profile A.
In standard packaging machines the trays will be transported by conveyor belts. So, the packaging cycles are directly associated to each other. To handle the cycles more flexible and independent from each other, the packaging machine considered in HiFlecs uses a shuttle system, called "Transmodul", to transport the trays between the packaging stations. This packaging machine is provided by Gerhard Schubert GmbH who is an associated partner in the HiFlecs project consortium. Schubert is a global player in development and manufacturing of packaging machines.
SotA packaging machines from Schubert use up to 32 transmodules that are small vehicles moving on rails. The transmodules are closed-loop controlled from the master station with a cycle time of 15 ms using a high performance real time radio system in the 2.4 GHz ISM frequency range.
In the demonstrator packaging machine (cf. Figure 7) the master station and three transmodules will be equipped with HiFlecs radio modules to replace the existing radio system. The HiFlecs radio system has a shorter cycle time of 1 ms and a very high reliability. The objective of this setup is to show, that in this closed loop application higher velocities and greater accuracies will be possible in the future. HiFlecs controller and HiFlecs client modules will be developed and integrated by Götting KG.
At the moment, the control software of the existing packaging machine cannot be accelerated to shorten the cycle

time. To highlight the advantages of HiFlecs compared to the standard radio system an additional linear measurement system and a delta-robot will be equipped with HiFlecs modules and will be synchronized with the trans-modules to demonstrate the one millisecond cycle time and so the 15 times better performance. Robot and linear measurement system will be realized by Lenze.

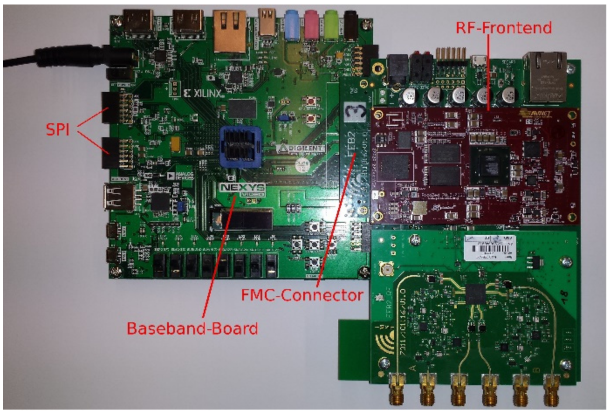

Figure 8 – HiFlecs radio module with SPI interface to the application, baseband, and frontend boards (from left to right).

6.2 Processing Board and Radio Frontend

The baseband signal processing of the HiFlecs controller as well as the HiFlecs client are implemented on a Nexys Video FPGA-board shown in Figure 8. The communication interface to the application (sensors/actors) is a SPI-interface comprising the transmission of the payload as well as QoS/CRC control data. The connection to the RF frontend is realized by an FMC-connector.

Based on the well-known RF agile transceiver (AD9361) from Analog Devices, used in many Software Defined Radio (SDR) platforms, a dedicated low-latency RF frontend has been developed for the HiFlecs project. This frontend has been optimized for the 5.8 GHz ISM band and has an output power of up to 20 dBm and a Noise Figure below 4dB. Besides that, the frontend contains a very fast Automatic Gain Control (AGC) algorithm, which is capable of operating in areas with large interferers close to the band of interest. The boards contain two complete 5.8 GHz RF-paths which can be used for diversity/MIMO techniques. An optimized isolation between the RX and TX path has been developed for faster switching between TX/RX in Time Division Duplex mode (TDD), to optimize the latency. The RF frontend board is flexible and can easily be adapted to be used in other applications. A number of boards have been fabricated and tested with, among others, a boundary scan test, and show the expected performance.

7 Main results

In this paper, we outlined the status of the design of the industrial radio system HiFlecs. The HiFlecs radio system is designed for control-loop control processes to facilitate flexible and adaptive manufacturing. The paper illustrates the HiFlecs architecture and system concepts that have been designed to meet the requirements of industrial radio applications. Detailed technology results are:

- a coexistence solution based on neural networks;
- SDR GFDM implementation below 1ms latency,
- a latency optimized and integrated security concept and
- flexible hardware implementation.

HiFlecs continues to further develop its technologies and it is planned to demonstrate its achievements by implementing the HiFlecs radio system in a packaging machine in the 2017/2018-time frame.

8 Literature

[1] NGMN, "5G White Paper," 2015.
[2] L. Rauchhaupt, D. Schulze, A. Gnad and M. Krätzig, "Anforderungsprofile im ZDKI Fachgruppe 1, Version 1.1", Magdeburg, October 2016, http://www.industrialradio.de/Attachments/ZDKI-FG1_AnforderungsProfile_041116.pdf
[3] D. Block, N.H. Fliedner and U. Meier, "CRAWDAD dataset init/factory (v. 2016-06-13)", DOI: 10.15783/C76S3K, June 2016.
[4] IEC 62657-2: Industrial communication networks- Wireless communication networks- Part 2: Coexistence management, 2013.
[5] M. Schmidt, D. Block, U. Meier, "Wireless Interference Identification with Convolutional Neural Networks", arXiv:1703.00737, CoRR, 2017.
[6] O'Shea T.J., Corgan J., Clancy T.C., "Convolutional Radio Modulation Recognition Networks", In Jayne C., Iliadis L. (eds) Engineering Applications of Neural Networks. EANN 2016. Communications in Computer and Information Science, vol. 629. Springer, Cham, 2016.
[7] F. Schaich and T. Wild, "Waveform contenders for 5G - OFDM vs. FBMC vs. UFMC," 6th International Symposium on Communications, Control and Signal Processing (ISCCSP 2014), Athens, Greece, 2014.
[8] J. Demel, C. Bockelmann and A. Dekorsy, „Evaluation of a Software Defined GFDM Implementation for Industry 4.0 Applications", 18th Annual International Conference on Industrial Technology (ICIT 2017), Toronto, Canada, March 2017.
[9] L. Karsthof, M. Hao, J. Rust, D. Block, U. Meier, and St. Paul, "Dynamically Reconfigurable Real-Time Hardware Architecture for Channel Utilisation Analysis in Industrial Wireless Communication", 2016 IEEE Nordic Circuits and Systems Conference (NORCAS), November 2017.
[10] J. Rust, F. Ludwig and St. Paul, "Low complexity QR-decomposition architecture using the logarithmic number system", 2013 Design, Automation & Test in Europe Conference & Exhibition (DATE), March 2013.
[11] F. Mackenthun and J. Berg, "Secure Machine-To-Machine Communication", SmartCard Workshop 2017, Darmstadt, February 2017.
[12] BSI TR-02102-1, "Technische Richtlinie – Kryptographische Verfahren: Empfehlungen und Schlüssellängen", 2016.
[13] NIST Special Publication 800-57 Part 1 Rev. 4, „Recommendation for Key Management", 2016.
[14] A. Ambekar and H. D. Schotten, "Enhancing channel reciprocity for effective key management in wireless ad-hoc networks", Vehicular Technology Conference, Spring 2014, Seoul, Korea, May 2014.
[15] E. Jorswieck, S. Tomasin, and A. Sezgin, "Broadcasting into the uncertainty: Authentication and confidentiality by physical-layer processing", Proceedings of the IEEE, vol. 103, no. 10, pp. 1702–1724, October 2015.
[16] A. Weinand, M. Karrenbauer, J. Lianghai and H. D. Schotten, "Physical Layer Authentication for Mission Critical Machine Type Communication using Gaussian Mixture Model based Clustering", VTC-Spring 2017, Sydney, Australia, June 2017.

---

[i] This work was funded by the German ministry of education and research (BMBF) under grant 16KIS0263K.