Fast Spectrum Monitoring System for the 2.45 GHz ISM-Band Based on Standard RF-Transciever Chips

Schnelles Spektrumüberwachungssystem für das 2,45 GHz ISM-Band basierend auf Standard HF-Transceiver Chips

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Abstract

To ensure a high quality of service for industrial radio systems, frequency planning is indispensable. Frequency monitoring is very advantageous for minimizing possible collisions in the exchanged data packets and for quickly detecting unwanted interferers.

Spectrum analyzers currently available on the market for the ISM band are significantly above the price level of the radio systems used. The measurement data and analyses from these measurement systems are also not made available online.

The fast spectrum monitoring system is intended to remedy this situation. In addition to continuous online monitoring of the 2.45 GHz ISM band, it offers the possibility of providing evaluations and analyses of occupied frequency channels with low latency. In addition, detected radio systems can be quickly classified and interferers extracted. The analysis results can be transmitted directly to the operational radio systems using suitable communication interfaces or made available in the cloud for long-term evaluations.

The development was based on the premise of combining this system with an IO-Link wireless system. The focus was on the rapid provision of analysis results from radio systems with fast frequency changes, as is typical for Bluetooth. With the help of this analysis data, the possible uses in the area of safety & security applications should also be discussed.

Kurzfassung

Um eine hohe Servicequalität für industrielle Funksysteme zu gewährleisten, ist eine Frequenzplanung unabdingbar. Eine Frequenzüberwachung ist über dies sehr vorteilhaft um mögliche Kollisionen in den ausgetauschten Datenpaketen zu minimieren und um unerwünschte Störer schnell zu erkennen.

Aktuell am Markt verfügbare Spektralanalysatoren für das ISM-Band liegen deutlich über dem Preisniveau der verwendeten Funksysteme. Von diesen Messsystemen werden die Messdaten und Analysen auch nicht online bereitgestellt.

Das hier vorgestellte schnelle Spektrum-Monitoring-System soll hierfür Abhilfe schaffen. Es bietet neben einem kontinuierlichen Online-Monitoring des 2,45 GHz ISM-Bandes die Möglichkeit, Auswertungen und Analysen belegter Frequenzkanäle mit geringer Latenzzeit bereit zu stellen. Zudem können detektierte Funksysteme schnell klassifiziert und Störer extrahiert werden. Die Analyseergebnisse können mittels geeigneter Kommunikationsschnittstellen direkt zu den operativen Funksystemen übertragen werden oder für Langzeit-Auswertungen in der Cloud bereitgestellt werden.

Die Entwicklung wurde unter der Prämisse durchgeführt, diese Systeme mit einem IO-Link Wireless-System zu kombinieren. Dabei stand die schnelle Bereitstellung der Analyseergebnisse von Funksystemen mit schnellen Frequenzwechseln, wie sie für Bluetooth typisch sind, im Vordergrund. Mit Hilfe dieser Analysedaten sollen so auch die Einsatzmöglichkeiten im Bereich von Safety & Security - Anwendungen diskutiert werden.

1 Introduction

Factory automation in the context of Industry 4.0 is increasingly utilizing wireless technologies [1][2]. Despite new technological possibilities, such as the fifth-generation of mobile cellular communications technologies (5G) operating in dedicated frequency bands, the ISM (Industrial, Scientific and Medical) frequency bands are still being used intensively due to worldwide availability. In addition to the common wireless standards in the 2.45 GHz ISM band, for instance IEEE 802.11 b/g/n (WLAN)[3], IEEE 802.15.1 (Bluetooth)[4] or IEEE 802.15.4 (Zigbee)[5], other wireless radio systems, such as WirelessHART or IO-Link Wireless[6] are typically employed. To ensure a high quality of service, especially when industrial

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processes are to be controlled, frequency planning and frequency monitoring are indispensable. Wireless standards like WLAN or Zigbee often cause only a minor problem in frequency planning, since these systems typically do not change the radio channel. Difficulties are caused by systems with fast frequency hopping methods such as Bluetooth. These are built into mobile devices, e.g. cell phones or headsets, and also integrated in various industrial communication systems.

Especially for safety critical automation systems, availability is a key aspect, and thus frequency management, planning and monitoring is essential. Furthermore, restoring operation after the occurrence of a disruption or collision, a fast spectrum measurement system can reduce the recovery time to operation[7].

Measurement equipment manufacturers offer real-time spectrum analyzers[8] or oscilloscopes with Fast Fourier Transform analysis functions that can analyze and display the spectral occupancy of the radio channel. However, the price level of these devices is typically significantly higher than the price of the radio communication systems used. These measurement devices are also not suitable for continuous spectrum monitoring, nor do they make this data available online for smart cloud-based data analysis. Significantly cheaper software-defined radio solutions (SDR) are often bandwidth-limited to a maximum of 40 MHz or lower[9][10], for example an ADALM-Pluto from Analog-Devices [9]. For this reason, such SDRs cannot map the entire frequency band of about 84 MHz.

In this paper, a fast spectrum measurement system (FSMS) is presented, which meets the requirements for online monitoring of the entire 2.45 GHz ISM band and can be directly be connected to radio systems such as IO-Link Wireless (IOLW).

In chapter 2, the entire FSMS, the communication interfaces and in particular in chapter 2.1 the multiple transceiver unit (MTU) is described.

In chapter 3, different evaluations of the system are depicted, which are still computed before the transmission on the system.

Chapter 4 outlines possible areas of applications for the FSMS. The focus here is specifically on use in safety and security applications.

A conclusion is given in chapter 5.

2 System Overview

In order to monitor the 84 frequency channels of the 2.45 GHz ISM band continuously , each frequency channel is tracked by a discrete RF-transceivers. This realization of the fast spectrum measurement system (FSMS) shown in Figure 1 allows to scan the entire spectrum with a resolution of 1 MHz bandwidth in parallel. The 1:1 assignment of an RF transceiver to a RF radio channel eliminates the need for frequency changes, which significantly increases the speed compared with other solutions, e.g.[11]. The use of commercially available components and standardized interfaces, such as SPI, enables the system to be built cost efficient, because no RF components need to be developed. To observe other radio systems, only the Received Signal Strength Indicator (RSSI) of each transceiver is used for evaluation during monitoring.

Figure 1 Fast spectrum measurement system (FSMS)

2.1 System Structure and Interfaces

The FSMS is a modular system and is based on 88 discrete radio modules of the type CC2650MODA[12] from Texas Instruments. These are installed on 11 multiple transceiver units (MTUs), which are plugged onto the base board.

To process the measurement data, the System on a Chip (SoC) module TE0720-03 SoC[13] from Trenz Electronics is used. This module has a Zynq XC7Z020-2CLG484 SoC with a Cortex-A9 dual core, 1 GB DDR3 RAM, 8 GB EMMC, 32 MB Flash memory. Figure 2 shows the variety of communication interfaces as well as the option to provide the data for cloud applications via Ethernet. Four out of the 88 RF-transceivers are freely programmable radio modules and are available to directly communicate with the operational radio systems like IOLW in use. Also a WLAN module (ATWIN1500)[14] and a Zigbee module (XB24CZ)[15] are also installed. By using the WLAN and Zigbee modules, additional information can be correlated with the measurement data, which improves identification and categorization. Two digital inputs and outputs are available for further applications, as well as a virtual COM port, a USB2.0 and an HDMI interface for the development process.

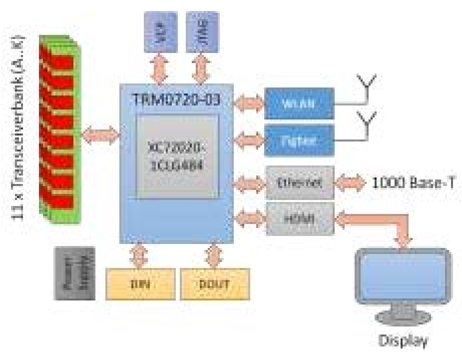

Figure 2 Communication interfaces of the FSMS

2.2 Multiple Transceiver Unit

The core element of the FSMS are the 11 MTUs. Each MTU consists of eight CC2650MODA radio modules as shown in Figure 3. A MTU supports two different modes: sensor mode and transceiver mode.

Figure 3 Top view of the multiple transceiver unit with eight CC2650MODA transceivers

The mode of the MTU is controlled via an I/O pin (MODE pin), as depicted in Figure 4. This enables identical production and programming of all MTUs. The plug-in position of the MTU on the FSMS determines the respective mode. In this case, two of the 11 MTUs are configured in transceiver mode, the others are in sensor mode. Further I/O pins are used to control the measurements of the radio modules. After the measurement of the RSSI values, the data can be read out from the MTU via differential lines. The SPI interface of the modules is used for configuration.
In the following, the individual modes and the sequence of a measurement are described in more detail.

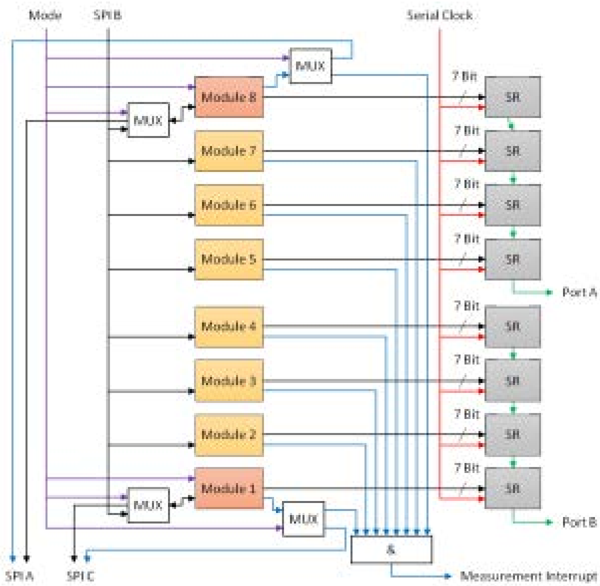

Figure 4 Signal overview of the multiple transceiver unit

2.2.1 Spectral Measurement

After all radio modules have been configured on the MTU via SPI interface, the RSSI measurements of the individual channels can be performed. To get a time-synchronous image of the 84 MHz wide 2.45 GHz ISM band, all radio modules must start measuring at the same time. This is achieved via an I/O line, which is connected to all transceiver banks via the baseboard.

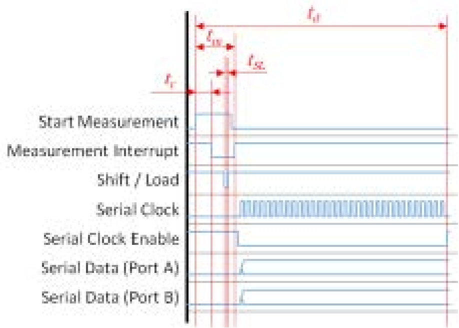

Figure 5 Measurement timings of a RSSI-Capture

When the RSSI values has been measured on the specified frequency channels, the values are transferred to the shift register[16] via I/O pins. Since all RSSI values are negative and are given in two's complement format in the range from -1 to -127 [17], the transmission of the seven least significant bits to the shift registers is sufficient. The most significant bit is always set to '1' by the hardware. The shift registers are necessary because data transmission over the SPI interface is only possible with a maximum clock rate of 4 MHz. When the transfer into the shift register is completed, each radio module triggers an interrupt to indicate the end of transmission to the shift registers. All interrupt lines of one MTU are bundled and indicating the end of the measurement process of the MTU. Now the RSSI values are ready for readout from the shift registers. To double the readout speed, four shift registers are combined to one output port. The shift registers can be read out with up to 90 MHz. This makes it possible to transmit all measured values of a MTU within 356 ns at maximum speed.
Figure 5 shows the signals for a measurement and the readout of the data using the example of a module. The measurement of the response time t_r of the individual radio modules resulted in values between 0.97 µs and 1.03 µs. This response time is fixed by the hardware of the radio module CC2650 and cannot be reduced. The load time to the shift registers t_{SL} is indicated by an I/O pin. According to the data sheet of the shift register, this time must not be less than 7.5 ns [16]. However, this is not possible due to the processor clock of the radio module with 48 MHz, because the setting of an I/O pin takes 20.8 ns. After the data has been loaded into the shift register, an interrupt is set by each radio module, which is summarized via an AND gate for the entire bank. The time t_m from the start of the measurement until all interrupts are set takes between 1.5 µs and 2.1 µs. The fluctuations result from interrupt calls, which interrupt the loading of the data into the shift register. The time to read the data depends on the used frequency of the serial clock (SER_CLK) and can be up to 90 MHz. To transfer the data of all transceiver banks to the processor within 1 µs, a clock rate of 32 MHz is required. The total duration t_d of a measurement of the entire spectrum is between 2.5 µs and 3.1 µs. By pipelining measurement and transmission, a maximum measurement speed can be achieved, which is limited to the maximum duration of t_m.

2.2.2 Sensor Mode

In sensor mode all eight radio modules are used to measure the RSSI values. As presented in Figure 6, in this case the interrupt lines to the AND gate are activated by all radio modules as well as the I/O pins for the output of the RSSI value to the shift registers. All modules are set via a common SPI bus (SPI B). Thereby the radio modules work operate as SPI bus slave. The maximum speed of the SPI transmission is limited to 4 MBit/s by the radio modules and is used for configuration and status messages.

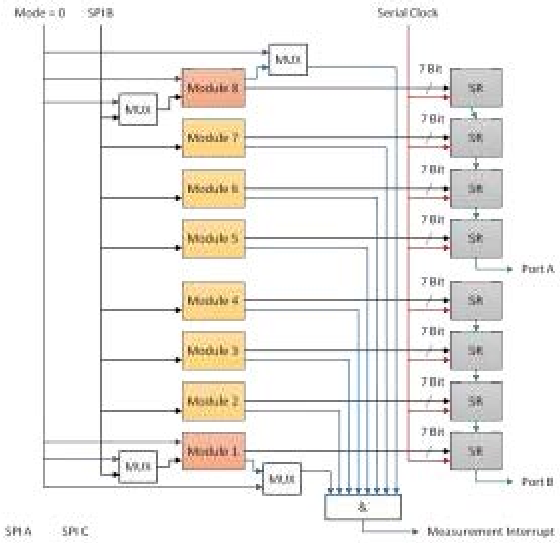

Figure 6 Signal-flow plan of a multiple transceiver unit in sensor mode

2.2.3 Transceiver Mode

In transceiver mode only the radio modules #2 to #6 are used as RSSI sensors. These work as in the sensor mode

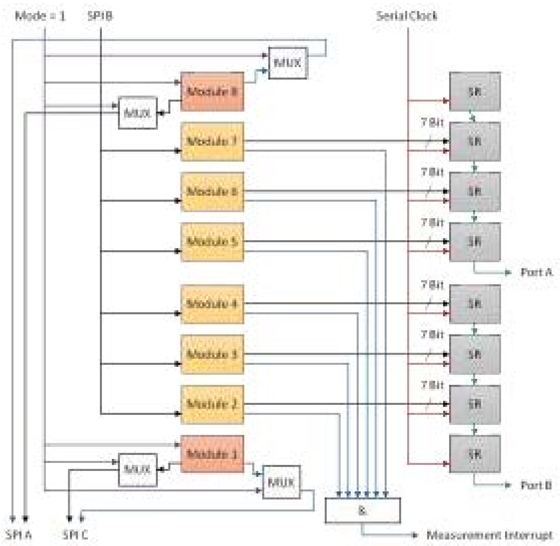

Figure 7 Signal overview of the transceiver mode of a multiple transceiver unit

and provide their data in the same way. Especially in this mode, the shift registers for radio modules #1 and #8 are always filled with 0x80 which indicates an invalid value. So 32 bits can still be read out of the shift registers. Thus, the timing for the measurements remains unchanged.
The radio modules #1 and #8 are freely programmable and work as SPI masters. As shown as in Figure 7, each has its own SPI bus (SPI A and C). This allows data to be transferred to the processor at up to 12 MBit/s. To signal the radio module that data from the processor is available, an interrupt line is used from the processor to the radio module. For this reason, this is separated from the measurement logic. In this way, the radio modules can be used for communication with other radio systems such as, e.g. IO-Link Wireless.

3 Evaluation of Measurement Data

The evaluation of the measurement data is performed in several consecutive steps as described in [18]. Firstly, the noise level of each transceiver is calculated dynamically during runtime. Due to external influences such as temperature, the noise level in the RSSI measurement of the individual CC2650 modules varies. Therefore a calibration process is needed to detect signals close to the actual noise level. After noise compensation, the remaining signals are classified using pattern matching and subsequent data fusion with additional information coming from the WLAN and Zigbee modules. A-priori specified systems are then filtered out. Unknown signals are marked as interferers.

3.1 Dynamic Noise Adjustment

The calculation of the mean value $\hat{\mu}(ch)$ of the dynamic noise level of each frequency channel $ch = 0 \ldots 83$, which corresponds to the frequencies $f = 2.400\ GHz\ \ldots\ 2.483\ GHz$ with 1 MHz bandwidth, is based on the measured RSSI values. These are represented as data vector $\overrightarrow{RSSI_t}$ at time t.

$$\overrightarrow{RSSI_t} = \begin{bmatrix} RSSI_{t,0} \\ \vdots \\ RSSI_{t,83} \end{bmatrix} \quad (1)$$

To determine the value $\hat{\mu}(ch)$ of each measured frequency channel, a Gaussian-shaped probability density function P_N is assumed. By previous measurements, the typical parameters of P_N are obtained. The standard deviation was determined with $\sigma_N = 4/3\ dB$. The Parameter $\mu_N(ch) = -100\ dBm$ varies in usual range of $\pm 10\ dB$.

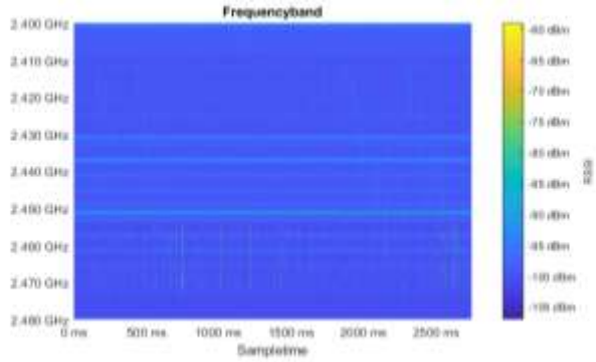

Figure 8 Measured frequency band with noise deviations

To calculate the average noise power, a histogram $H_N(ch)$ is calculated for each frequency channel ch of several data vectors $\overrightarrow{RSSI_t}$ as shown in Figure 9 utilizing steps of $1\,MHz$ steps and classes $c = -1\,dBm\ \ldots -127\,dBm$ in $1\,dB$ steps. Experimental evaluations have shown, that at least 1000 data vectors should be used for the following calculation to get stable results.

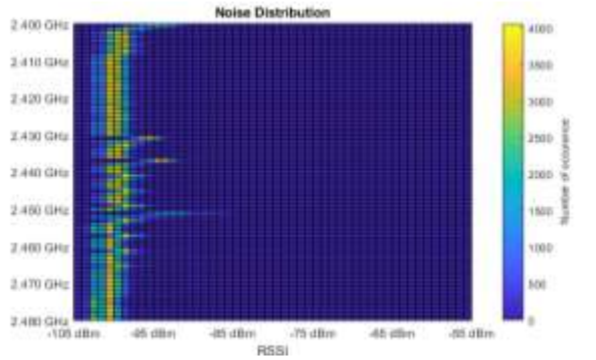

Figure 9 Histogram of RSSI value distribution of the shown frequency band Figure 8

By correlating P_N and $H_N(ch)$ for each frequency channel ch, the maximum correlation value $\hat{P}(ch)$ for the present average noise power is determined.
In order to be able to determine the dynamic noise level even with heavily loaded frequency channels (frequency channel occupancy >> 50%), it is assumed that no frequency channel is constantly 100% occupied. Furthermore, it is assumed that the dynamic noise level is in the range of μ_N and has a distribution P_N. The dynamic noise level $\hat{\mu}(ch)$ is determined by calculating the similarity of the histogram values $H_N(ch)$ with the distribution P_N in the range of μ_N.
By filtering with the previously calculated dynamic noise level $\hat{\mu}(ch)$, assuming the previous boundary conditions, the signal components of $RSSI_t$ for further calculations can be determined and results in the signal vector $\vec{S}_t$.

3.2 Wireless Standard Detection

The description of WLAN and Zigbee signal $S(K, bw, t, \Delta t, \rho, ID)$ contains the parameters of the channel number K, the bandwidth bw, start of transmission t, packet length Δt, the mean signal strength ρ. For WLAN signals the ID-value contains the SSID, for Zigbee signals the ID contains the PAN ID. Since narrow-band systems use a frequency hopping scheme, additional parameters are needed, e.g for an IOLW system the hopping table H_S and the periodicity ω_t.
In order to classify the wireless standards in use, a modified KMP algorithm (Knuth-Morris-Pratt pattern matching algorithm [19][20]) is employed. The patterns for the individual wireless standards are taken from the transmit masks. The used transmit masks contains the bandwidth bw and the signal strength values ρ_i over the bandwidth in steps of 1 MHz. The center of the bandwidth corresponds to the frequency of the channel number K_S of the wireless standard.
At first, the matching probabilities of broadband standards WLAN ($bw = 21$) and Zigbee ($bw = 3$) are calculated from the signal vector $\vec{S}_t$. Subsequently, the start of each transmission $t_{S,K}$ and the packet duration $\Delta t_{S,K}$ are determined.
By filtering out the detected wireless standards, the signal parts of narrowband standards like Bluetooth or IOLW are remaining [21]. No pattern matching is required to detect these narrow-band standards, as they have a bandwidth of 1 MHz. By this, the channel number K corresponds to the frequency channel ch. The transmission parameters signal strength ρ_{ch}, start of transmission t_{ch} as well as duration Δt_{ch} are calculated. By comparing the data, the periodicity ω_t and the possible hopping table H_S are determined.

3.3 Interfearer Detection

In order to detect and classify interferers, it is firstly necessary to know the radio systems in use and their parameters. Otherwise all systems will be classified as interferers. For parameterization of WLAN or Zigbee systems, it is sufficient to specify the used channel K, the bandwidth bw and especially the SSID. These are correlated with the data from the wireless standard detection. As a result, all WLAN and Zigbee transmissions that cannot be assigned to these parameters are output as interferers.
The assignment of the individual narrowband radio systems is more complex. The main describing parameters are the hopping behavior and the periodicity. While IOLW has a fixed hop table, generally, Bluetooth hopping is based on an algorithm with different input parameters. An IOLW system can be detected by correlating the parameters of the hopping table and the periodicity.
Since the input parameters of the Bluetooth devices are typically unknown, the hopping behavior cannot be calculated at runtime. Thus, Bluetooth signals are initially detected as interferers.

4 Fields of Application

The FSMS provides possible application fields and use cases for the infrastructure of the production automation as well as for communication systems.
Especially for safety critical automation systems and applications for IOLW e.g. described in [22] all-time availability of sufficient communication channels is a key performance indicator regarding residual error probability (REP), reaction times, timeliness, dependability and scalability being. These critical parameters influence the possible Safety Integrity Level (SIL) [23] with a stringent reliability; as lower the REP as higher the possible SIL.
The IEC 62657 series specifies wireless communications networks, including requirements and coexistence management [7][24][25]. With the focus on the automated concept, a central coordination point relies on one or more spectrum sensing systems in combination with spectrum sensing nodes and spectrum sensing functions. In this case, the FSMS is able to act as a CCP with SSS. If necessary additional SSS entities can be represented by multiple FSMS in one environment.
For these cases, spectrum awareness to deliver information of coverage and occupancy of the frequency band is beneficial and spectrum monitoring with frequency usage planning can influence critical safety parameter vital. Therefore, the FSMS previously described can deliver real-time frequency occupancy of the 2.45 GHz ISM band using its interfaces to the IOLW Master or to a superior frequency management system. The hopping-tables of each IOLW communication can be adjusted to prevent collisions and to increase the performance of the communication system achieving the highest possible "load".
A dynamic adjustment for cyclic occupancy of specific frequencies may include a prediction model for frequency collision prevention. This requires permanent monitoring and logging of the frequency band, which can lead to the detection of anomalies and be reported to a vulnerable database for further security analysis.
The FSMS is also advantageous to enhance the security of the communication system. Therefore, digital I/Os of the FSMS are accessible to directly block specific frequencies and detect/prevent communication through intruders. This is necessary if security threats [26] such as DoS/DDoS, MITM attacks or e.g. eavesdropping occur. An advantageous measure provided by the FSMS is the RSSI values of each W-Device. If comparing the RSSI values describing the signal strength of each W-Device with historical logged information, e.g. MITM are detectable and, in regard to safety critical applications, the position information of each W-Device is also vital.

5 Conclusion

Based on a discrete RF-transceivers hardware architecture, the FSMS offers a cost-effective way to permanently monitoring the 2.45 GHz ISM band. Due to the modular design, the system is also suitable for expansion for monitoring in other frequency ranges.
With the help of the evaluation in the FSMS and the implemented communication interfaces, the system can already independently identify interferers and provide this information for individual radio systems in order to reduce the reaction time for adjustments. Furthermore, the system can provide the data and evaluations online for cloud and monitoring applications such that an overall view of the radio environment by combining multiple FSMS can be provided. Cloud-based evaluations can support the system in long-term evaluations.
The detection of wireless standards is fast, so the provision of the interference information by the system is possible in less than one millisecond by the system. The FSMS can be integrated within IOLW as part of an AI frequency management system for IoT systems. This possibly contribute to an increase in transmission reliability and enable functional safety applications for connected systems. Therefore, the FSMS is for wireless communication systems a crucial tool to enhance functional safety and (cyber-) security in the field of production automation as well.

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