Wireless Sensor Networks: VAN-Project Perspectives*

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Abstract. *The emergence of wireless sensor networks and their potential for a multitude of novel applications, especially in the industrial automation domain, are noteworthy. This paper presents research and development perspectives on wireless sensor networks from the Virtual Automation Networks project in terms of prototype development and coexistence with other chosen wireless technologies. The project-specific design and specification aspects, implementation and integration issues, and coexistence tests, measurements and results are covered in detail. The paper illustrates the successful integration of wireless sensor networks into the overall prototype and shows that they can coexist with other wireless technologies.*

Keywords

Wireless sensor networks, industrial automation, ZigBee, wireless prototypes, coexistence of wireless technologies.

1. Virtual Automation Networks

Many of the major information and communication technologies (ICT) do not completely match the requirements of the industrial standards in areas such as security, wireless, safety, and real-time due to their origin in the office world. Hence, one of the main objectives of the Virtual Automation Networks (VAN) project is to adapt, modify and extend common office communication and IT solutions according to industrial standards for the creation of real, knowledge-based, intelligent, networked, and agile manufacturing enterprises. In this context, VAN can be described as an open, universal, seamless, multi-vendor networking solution that aims to link worldwide components in process and factory automation environments. It also aims to strengthen European leadership in the field of industrial communication and automation [1].

The intended interoperable communication in VAN is planned to be realized via field-busses, office networks and even the public communication infrastructure - wired and/or wireless. By means of a common engineering model, the user may not see the single building blocks of the underlying communication infrastructure but will regard the whole network as a homogeneous system. To realize this novel concept, the VAN solution provides scalable real-time, safety and security strategies that are required to meet quality of service requirements over the whole network. Fig. 1 depicts the concept of VAN in a nutshell.

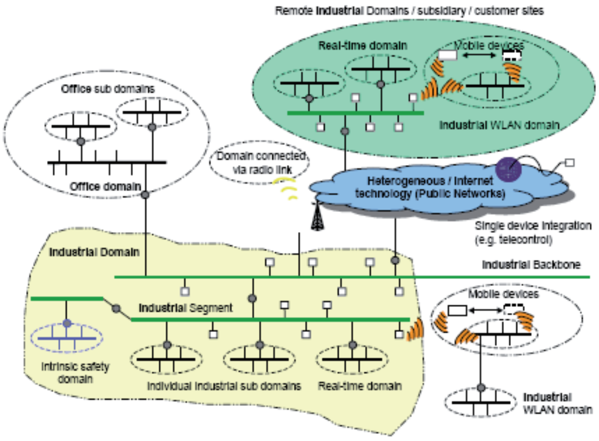

Fig. 1. The concept of a virtual automation network.

2. Wireless Sensor Networks

2.1 Introduction

The IEEE 802.15.4 standard specifies physical layer and MAC layer for wireless sensor networks (WSN). Based on this standard several proprietary higher layer implementations are known. However, today ZigBee is the only specification which has been worked out by an international non-profit organization, the ZigBee Alliance. The ZigBee specification considers industrial automation applications as well [2]. These specifications enable the use of multiple, very low-powered nodes to cover wide areas

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of interest offering low data rates. They are typically used to overcome the physical and economical constraints of traditional wired sensor solutions, and consequently find applications in some of the following fields of industrial automation [3]:

- Plant and process monitoring via sensor reading (indoors and outdoors).
- Non-critical closed loop applications (e.g. simple switching applications).
- Wireless network extensions for existing wired field devices.
- Location-aware applications (e.g. inventory tracking and asset management).
- Plant building automation and management (e.g. lighting, HVAC, security).

From the above list, it is obvious that the application fields for devices based on IEEE 802.15.4/ZigBee are not meant to compete with the existing wireless solutions such as WLAN and Bluetooth, but to rather complement them. Due to their relatively low data rates (up to 250 kbps) it is not envisaged that WSNs will be used to provide wireless bridging capabilities for traffic intensive data networks (e.g. multimedia data). Instead, domains where they could be prevalent are applications that employ battery-operated devices, which operate for several months or years.

2.2 WSN Development in VAN

The abstract way in which the integration of the IEEE 802.15.4-based WSN devices into the VAN domain takes place is depicted in Fig. 2. As can be seen in the figure, the end-devices, namely sensors, are connected to the VAN domain via a VAN virtual device (VD) and a VAN proxy device (PD). The VAN VD acts as a ZigBee coordinator. The address mapping is handled by the VAN PD. This would enable the proxy device to cater to more than one virtual device. The ZigBee side of the VAN PD also takes care of all the ZigBee-specific tasks and communicates accordingly with the particular VAN VD. Also, as the figure illustrates, the VAN PD connects to a VAN access point within the VAN domain and subsequently to various VAN automation devices (AD).

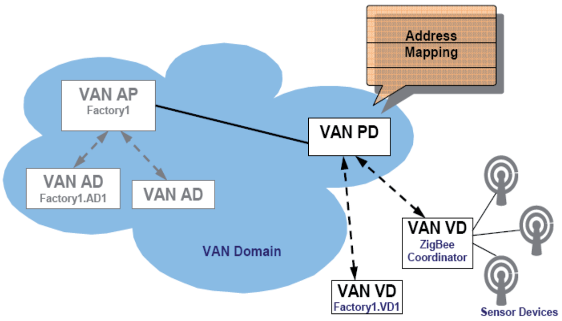

Fig. 2. Integration of wireless sensor networks into VAN domain.

One of the important aspects of implementation of all the wireless prototypes in VAN is the definition of Application Service Elements (ASE), which include attributes of Wireless Device Configuration Class, Wireless Security Configuration Class, and Wireless Diagnosis Class. The ZIGBEE DEVICE CONFIG ASE object specifies the attributes that can be used to configure IEEE 802.15.4/ZigBee devices/networks [4]. It is derived from WIRELESS DEVICES CONFIG as shown in Fig. 3.

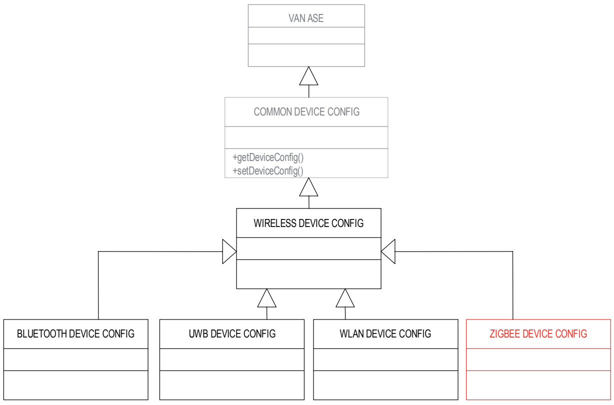

Fig. 3. Deduction of the ZIGBEE DEVICE CONFIG class structure.

On the application front for VAN prototype demonstrations, a temperature sensing/measurement application is considered from the IEEE 802.15.4/ZigBee perspective and is illustrated in Fig. 4. Extending the abstract view depicted in Fig. 2, it illustrates how a ZigBee coordinator and end-devices, which are essentially temperature sensors, could be connected to the VAN domain. Its salient features include:

- The application comprises of five end-devices and one coordinator connected via the star topology.
- One-way data communication (device to coordinator) is supported. The other way of communication is also possible by a simple extension of functionality.
- The application provides periodical sensing and measurement of temperatures.
- The IEEE 802.15.4 MAC is used and the overall application is built upon this MAC in a reference way.

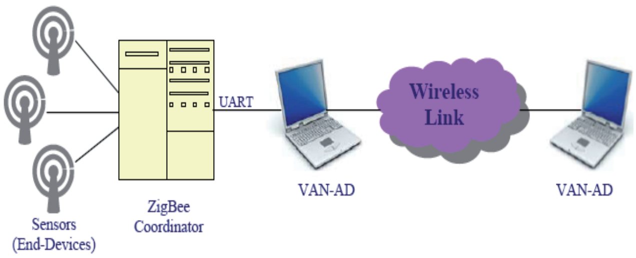

Fig. 4. A wireless sensor network application in VAN.

The application data format is as follows: <sensor device number>; <timestamp>; <temperature from onboard

battery monitor in °C>; <device status >; <dropout count>; <rssi of last packet> and a typical log contains the following readings: <device_no=5>; <time=0h0m55s>; <temp=26>; <status=7>; <dropouts=0>; <rssi=162>. Along with temperature, a few diagnostic data are also measured.

3. VAN Prototypes

3.1 Wireless Prototype in VAN

The overall wireless prototype in VAN includes devices pertaining to three chosen technologies: Bluetooth, WLAN and IEEE 802.15.4-based WSN. The architecture of such a prototype, which forms the basis for integration of wireless technologies into VAN demonstrators, is shown in Fig. 5.

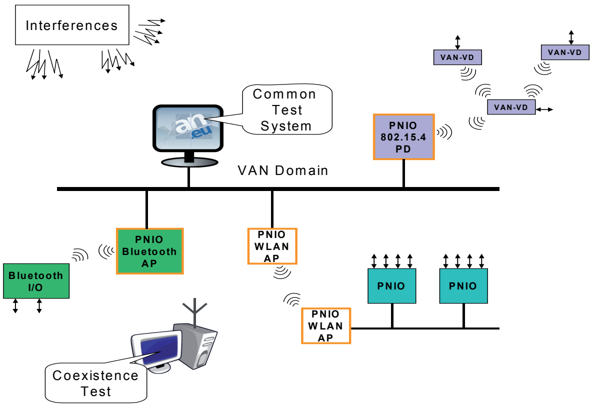

Fig. 5. Architecture of the overall wireless prototype in VAN.

The architecture defined above conforms to the idea of having a common platform to test and integrate the selected wireless technologies in VAN. It has the following features:

- The prototype devices are specified as a stand-alone Bluetooth PNIO device, a stand-alone WLAN PNIO device and an 802.15.4 WSN system all integrated into the VAN common prototype.
- It includes a common test system in order to make cross-tests between the selected wireless technologies.
- WLAN devices are integrated by means of an access point.
- Bluetooth and 802.15.4 WSN devices are integrated using VAN Proxy Devices.
- Interfaces between wireless technologies and the VAN domain are based on PROFINET technology.
- It has the ability to carry out coexistence tests in order to verify the robustness of such wireless technologies against different types of interferences as well as assess the usability of such technologies in industrial automation and their coexistence.

3.2 Wireless Sensor Network Prototype

The IEEE 802.15.4-based WSN prototype is designed to perform as a temperature sensing/measurement application as illustrated in section 2.2. It consists of two 802.15.4 devices, one acting as a coordinator and the other as a sensor device. Integration of the WSN prototype into the overall wireless prototype in VAN is basically via IEC 61158 Type 10 Remote IO. Fig. 6 depicts such a scenario, where the 802.15.4 devices are integrated via an RS-485 interface to the PROFINET input/output (PNIO) Bus Coupler, which in turn is connected to the PNIO Controller as illustrated in Fig. 7. The 802.15.4 full-function device (FFD) acts as a PAN coordinator, whereas the sensor device in the form of a reduced-function device (RFD) mounted on the PCB senses and measures the temperature, and transmits it to the coordinator via the 802.15.4 wireless link.

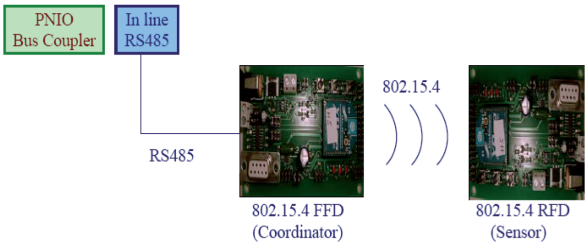

Fig. 6. Block diagram of the WSN prototype in VAN.

3.3 Integration of Wireless Prototype Devices

The main objective of the overall VAN wireless prototype is to show that the three chosen wireless technologies Bluetooth, WLAN, and IEEE 802.15.4 WSN can be used in the same automation application. In addition, it is also intended that they can coexist with each other in an industrial environment [5]. The schematic diagram of the wireless prototype that integrates Bluetooth, WLAN and WSN devices into the VAN domain is shown in Fig. 7.

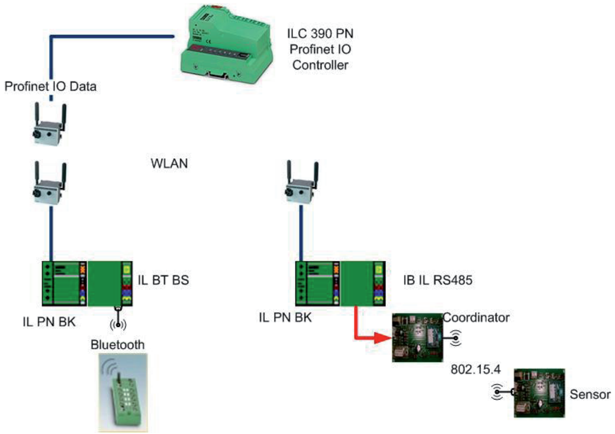

Fig. 7. The integrated wireless prototype in VAN.

The sample prototype application reads IO data from a Bluetooth IO Module transferring it via an IEC 61158 Type 10 network to the PLC. The PLC in turn executes a sample IEC 61131 program in order to react to this specific IO data and sets another IO data to an IEEE 802.15.4 slave device. The IEC 61158 Type 10 network data is in addition transparently transmitted via a WLAN communication link, thus completing the set of data communication events through all the wireless devices.

4. Coexistence of Wireless Technologies

4.1 Coexistence Issues

The definition of coexistence according to [9] reads as follows: “the ability of one system to perform a task in a given shared environment where other systems have an ability to perform their tasks and may or may not be using the same set of rules.” In general, coexistence means it is of interest whether the time and error behavior of wireless solutions are influenced by other wireless systems at the same location. In order to be able to assess the degree of fulfillment of the time and error requirement by means of simulations or measurements, a formal model is required. The abstraction of a distributed automation application using wireless communications is shown in Fig. 8.

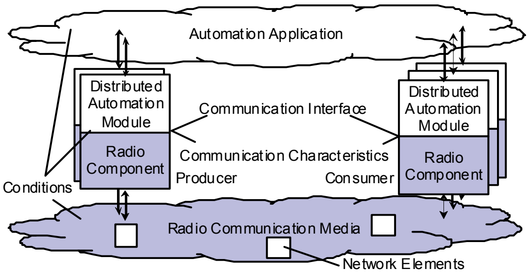

Fig. 8. Model for assessment of wireless systems.

In the case of coexistence of different wireless solutions, the main influencing parameter which has to be considered is obviously the interference from other users of the same frequency spectrum at the same time. However, there are other relevant parameters that determine the media allocation for the system under test and for the interfering system. Three characteristic parameters are selected to assess the coexistence of wireless solutions [8]:

- Transmission delay,
- Update time,
- Packet loss rate.

The transmission delay is of interest for applications that generate event-driven communication requests such as proximity sensors. In automation applications, productive data is often transferred cyclically. For these applications, it is important to know the update time provided by the wireless communication system. The packet loss rate is taken as a sign of reliability of the communication media [5]. The method to assess the reliability of wireless communication from the point of view of automation applications and the application of characteristic parameters are described in [11], [12].

4.2 Test Architecture

The test system consists of two Multifaces and a PC as shown in Fig. 9. A Multiface contains a microcontroller for communication between the PC, and the Multiface and an FPGA for time critical processes and offers a number of interfaces such as SPI, I²C, EIA232, parallel port, and so on. The communication interface between Multiface and device under test (DUT) is the serial interface EIA232. The test application on the Multiface on the Producer site generates the defined test traffic and measures the characteristic values: transmission delay and number of transmitted packets. The test application on the Multiface on the Consumer site receives the test traffic and verifies the data content. Furthermore, the test application on the Multiface on the Consumer site measures the characteristic values: update time and number of correctly received packets. The measured values are transferred via USB to the PC.

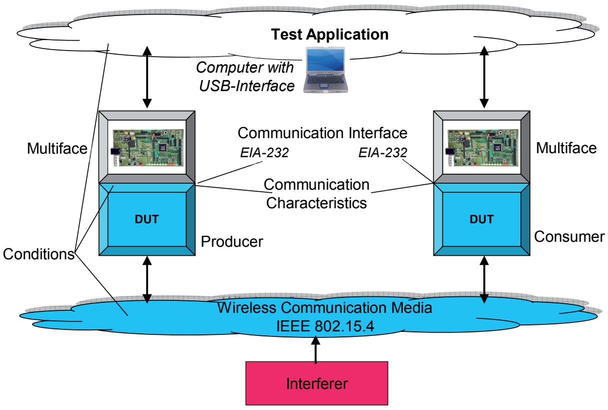

Fig. 9. Test architecture for the IEEE 802.15.4 system.

The diagram in Fig. 10 shows the structure of the tests with an IEEE 802.15.4 system. Here, it is of interest to test how the wireless sensor network can cope with interference from multiple WLAN systems. Theoretically, three separate WLAN systems and an IEEE 802.15.4 system can share the 2.4 GHz spectrum with no interference.

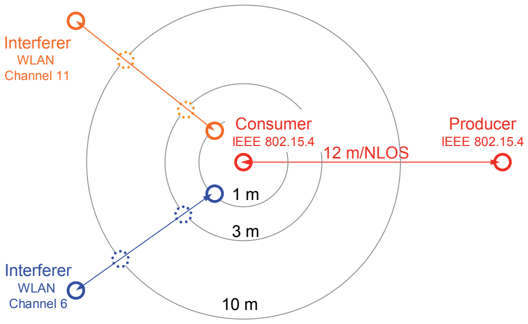

Fig. 10. Test case overview for the IEEE 802.15.4-based WSN system.

After the configuration of the test application, and the system under test according to a specified test case, the devices are positioned within a factory hall. The test case then runs automatically.

4.3 Configuration of System under Test

The system parameter values given in Tab. 1 are valid for the whole system under test (SUT).

Parameter	Value
Frequency band	2.4 GHz ISM Band
Channel	20
Centre frequency [MHz]	2450
Band width [MHz]	4
Radio Tx rate (gross) [kBit/s]	250
Media Access	CSMA/CA (Non-Beacon)

Tab. 1. Values of system parameters for SUT.

The device parameters are set differently for every single device under test (DUT) as shown in Tab. 2.

Parameter	Values of Consumer	Values of Producer
Identification	2005-13-177	2005-13-178
Device type	Coordinator	End device
Tx power [dBm]	0	0
Rx sensitivity [dBm]	-92	-92
Antenna type	Omni directional	Omni directional
Antenna gain [dBi]	2	2
Max frame retry limit	3	3
RF transceiver	CC2420	CC2420
Microcontroller	Atmel Atmega 128L	Atmel Atmega 128L
Com. interface	EIA-232	EIA-232
Com. interface transmission rate	57600 baud	57600 baud
Data bits	8	8
Stop bit	1	1
Parity	-	-
Flow control	-	-

Tab. 2. Values of device parameters for DUT.

The application parameters for the execution of tests are described in Tab. 3.

Parameter	Values of Consumer	Values of Producer
Identification	2005-13-177	2005-13-178
Data contents	-	xx AA AA AA AA
Packet length [Octet]	-	5
Application cycle [ms]	-	30

Tab. 3. Values of application parameters for DUT.

The configuration and application parameters for the interferers WLAN 1 at channel 6 and WLAN 2 at channel 11 are depicted in Tab. 4.

Parameter	Values of WLAN 1	Values of WLAN 2
Standard	IEEE 802.11-2007	IEEE 802.11-2007
Tx power [dBm]	20	20
Modulation	DSSS-OFDM	DSSS-OFDM
Channel	6	11
Centre freq. [MHz]	2437	2462
Bandwidth [MHz]	19	19
Radio Tx rate (gross) [MBit/s]	54	54
Media Access	CSMA/CA	CSMA/CA
Number of devices	2	2
Kind of devices	Access Point / Client	Access Point / Client
Communication interface	RJ 45	RJ 45
Tx rate of com. interface [MBit/s]	100	100
Packet Length [Octet]	1518	1518
Application Cycle [ms]	0.7	0.7

Tab. 4. Values of application parameters for WLAN interferers.

4.4 Test Measurements

The channel alignment between the SUT and interferers is shown in Fig. 11. The SUT uses the IEEE 802.15.4 channel 20 (centre frequency: 2450 MHz), which is located in the gap between interferer WLAN 1 at channel 6 (centre frequency: 2437 MHz) and interferer WLAN 2 at channel 11 (centre frequency: 2462 MHz). The signal interference ratio is the lowest (SIR≈0 dB) in this gap.

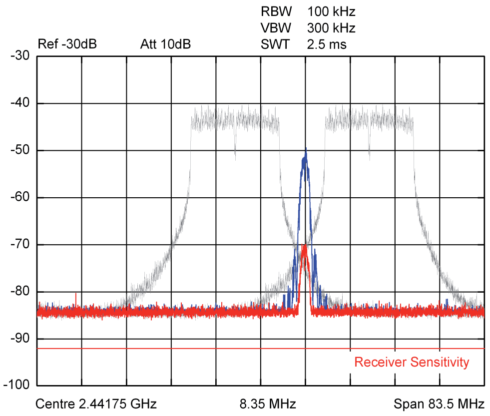

Fig. 11. Spectrum of WSN SUT with two WLAN interferers.

Fig. 11 also depicts the transmit spectrum of the producer (red), the consumer (blue) and the interferers (gray) at the position of the consumer. The distance between Producer and Consumer of the SUT is 12 m non-line of sight (see Fig. 10). The position between the Consumer of the SUT and the WLAN interference sources is 1 m. The time spectrum allocation of the SUT and the interferers is depicted in Fig. 12. It shows the time frame (in green) in which a SUT Producer needs to transmit 5 bytes of user data and the following acknowledgment frame. Furthermore, it shows the time frames (in yellow) in which the interferer needs to transmit 1518 bytes of user data and the following acknowledgment frame. Fig. 12 shows that the interference sources occupy the media periodically with a duty cycle of 35%.

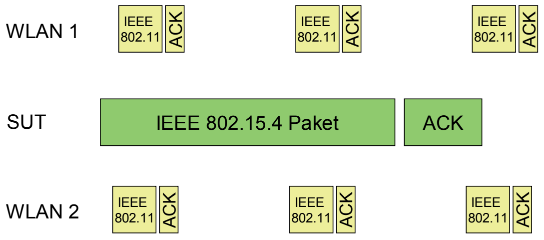

Fig. 12. Time spectrum allocation of SUT and WLAN interferers.

4.5 Performance Results

For the purpose of reference, the time and error characteristics of the IEEE 802.15.4 SUT are investigated without an interferer. The results are based on a sample size of 100000 transmissions. The class width for all histograms of the SUT is 10 µs.

Fig. 13 shows the histogram of the transmission delay between producer and consumer without an interferer.

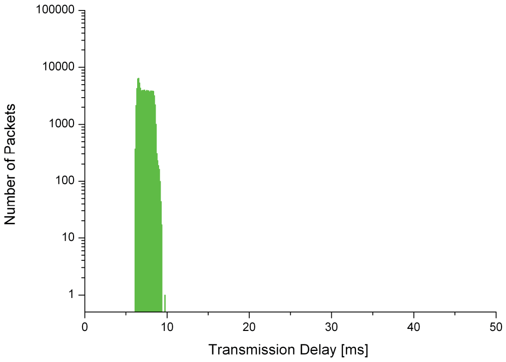

Fig. 13. Transmission delay characteristics without an interferer.

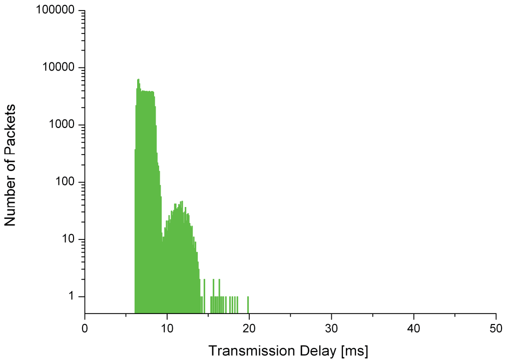

Fig. 14. Transmission delay with interferers at a distance of 1 m.

The histogram of transmission delay with interferers WLAN 1 at channel 6 and WLAN 2 at channel 11 at a distance of 1 m to the Consumer is depicted in Fig. 14. Fig. 15 depicts the transmission delay with interferers WLAN 1 and WLAN 2 at a distance of 3 m to the Consumer. As evident in Fig. 14 and Fig. 15, interferers WLAN 1 and WLAN 2 are finally activated and a considerable influence can be ascertained by a distance of 1 m between the interference source and the consumer.

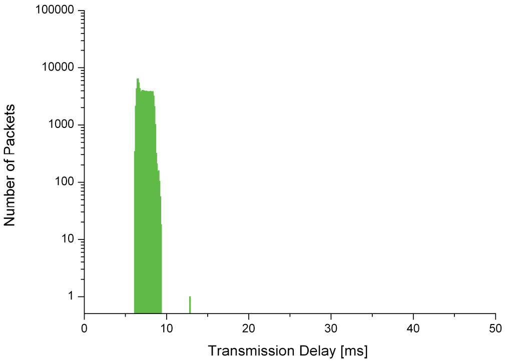

Fig. 15. Transmission delay with interferers at a distance of 3 m.

The transmission delay is a random value. To assess coexistence with the transmission delay of the SUT, well known statistical parameters such as mean and variation can be used. Our experience is that the 95th percentile value (P95) is the best indicator for relevant changes in the transmission delay. The maximum value of transmission delay is not qualified for assessment, since it is a single value of a series of measurements and it is not sure that the real maximum value is captured. However, the maximum value is considered so far as it influences the value of the 95th percentile. Tab. 5 lists the values of transmission delay of the SUT without interferer and with WLAN interferers at adjacent channels 6 and 11.

Test case	Transmission Delay [ms]		
	Min.	Max.	P95
No Interferer	6.1	9.8	8.5
WLAN Ch. 6 and 11: 1 m	6.1	19.8	8.6
WLAN Ch. 6 and 11: 3 m	6.1	12.8	8.5

Tab. 5. Values of transmission delay for the SUT.

Fig. 16 depicts the histogram of the update time at the test consumer without an interferer. The histogram of update time with the interferers WLAN 1 at channel 6 and WLAN 2 at channel 11 at a distance of 1 m to the Consumer is depicted in Fig. 17 and Fig. 18 depicts the update time with the interferers WLAN 1 and WLAN 2 at a distance of 3 m to the Consumer.

The update time is also a random value. The mean value indicates, in the first place, the usability of the wireless communication system for a certain cyclic control process. Another important parameter is the span, commonly known as jitter, which is measured as maximum minus minimum. However, the measured minimum and maximum values are most likely not the absolute extreme values, since they are a single value of a series of measurements and it is not certain whether the real minimum or maximum value is captured. Therefore, the span can only be assumed with a certain probability. Measurements have shown that the standard deviation value is well suited in order to indicate influences on the wireless communication system. Therefore, this parameter together with the span can be used to assess the coexistence of the SUT. The mean value equates to the application cycle.

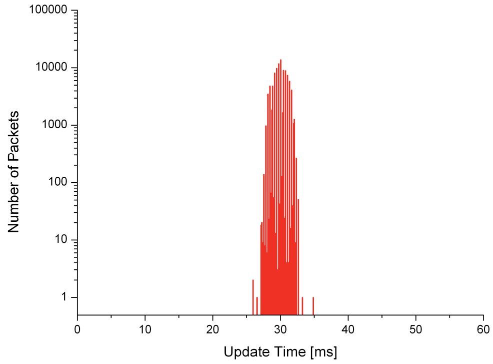

Fig. 16. Update time characteristics without an interferer.

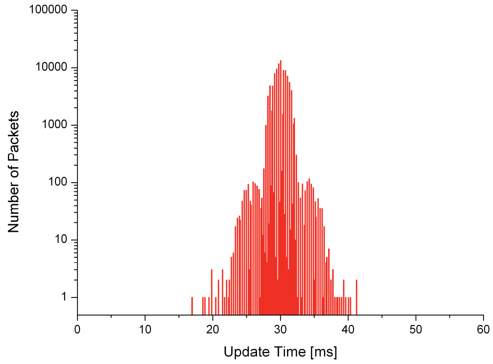

Fig. 17. Update time with interferers at a distance of 1 m.

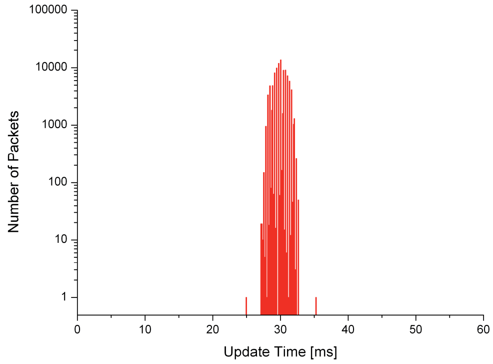

Fig. 18. Update time with interferers at a distance of 3 m.

Tab. 6 lists the values of update time for the SUT without an interferer and with WLAN interferers at adjacent channels 6 and 11.

Test case	Update Time [ms]			
	Min.	Max.	Mean	SD
No Interferer	25.9	35.2	30.0	1.0
WLAN Ch. 6 and 11: 1 m	17.0	41.3	30.0	1.2
WLAN Ch. 6 and 11: 3 m	24.9	35.2	30.0	1.0

Tab. 6. Values of update time for the SUT.

5. Conclusion

The wireless prototype development, and implementation in VAN, involving three different wireless technologies, demonstrates that they can cooperate in a coexistent way in a common industrial set-up, although they focus on different technological strengths. The IEEE 802.15.4-based wireless sensor network prototype implemented to demonstrate a temperature measurement application shows the VAN capabilities of integrating wireless slave modules via the VAN proxy device concept, as illustrated in the first half of this article. The strengths of the VAN WSN prototype include ability to operate at low-power requirements and optimum coexistence with other wireless technologies. The prototype devices developed within the scope of VAN wireless tasks have been successfully integrated into the VAN domain and they operate in an IEC 61158 Type 10 real-time Ethernet network as defined in the general VAN architecture. The overall wireless prototype is planned to be a part of the final industrial experimental setup for the factory automation demonstrator, thereby extending the VAN approach of transmitting real-time communication over heterogeneous networks to the wireless systems as well.

The second half of the paper deals with the coexistence issues of wireless sensor networks with other wireless technologies. The coexistence of IEEE 802.15.4 and WLAN in the 2.4 GHz ISM band is dependent on many parameters. The influence of channel alignment in time and frequency, and transmit power have been investigated. The measurement results show that the coexistence between WLAN and IEEE 802.15.4 can be improved by the following aspects:

- Aligning the radio channels as non-overlapping. As the energy in this guard space is lower than the energy within the channels, the interference between systems can thus be minimized.
- Reducing the level of radiated emissions from the interference system. This can be set by reducing the transmit power or by increasing the distance between the system under test and the interfering system.
- Reducing the spectrum allocation of the wireless media.
- Proper planning of the radio field that includes a process for coexistence management.

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