RSSI-Based Evaluation of Wireless Personal Area Networks Nodes Noise Immunity in Industrial Buildings

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***Abstract*—Results of a study of the influence of manufacturing environment factors on wireless personal networks are presented in the paper. A classification of such factors is proposed, and the noise immunity of wireless personal networks is determined using a real production as an example. A method for evaluating noise immunity based on a received signal strength indicator (RSSI) is proposed. RSSI values can be obtained natively from almost any receiver and transmitter, which makes this method affordable compared to using network analyzers and other specialized equipment. In the conducted experiment the receiver and transmitter were located at a distance ranging from 0.5 to 25 m from each other. The act of signal transfer was carried out alternately under the influence of each production environment factor. Then measured RSSI values were analyzed and converted into the maximum permissible distance between the receiver and the transmitter in accordance with the proposed method. As a result, data on the influence of a production environment on the noise immunity of wireless personal networks was obtained. Nevertheless, it is concluded that the influence is not significant enough to decide against the use of wireless personal networks, since the influence of many factors can be offset by the use of mesh topology and a dense arrangement of receivers and transmitters. The results are particularly interesting in the context of manufacturing digitalization, where the wireless method of data transmission from field level sensors becomes preferable to the wired due to the requirement for flexibility and mobility of a production process.**

Keywords—industrial environment, wireless personal area network, noise immunity evaluation, received signal strength indicator, power electronic equipment

I. Introduction

Industrial production has always been considered a knowledge-intensive and high-tech area of human activity. Since the advent of steam engines at the beginning of the 18th century, manufactory has gone through three industrial revolutions, constantly incorporating new technologies. Modern industry is currently at the next stage of development (Industry 4.0) and is undergoing a digital transformation. The development of the technology of industrial Internet of things and cyber-physical systems has led to the emergence of a new concept—digital manufacturing. The main idea of digital manufacturing is the deep integration of computer technology into the production process, which allows the development of digital models (or “digital twin”) and act on them in real time. However, a complete and relevant data set of all elements and participants of a production process is required to carry out such simulations.

Therefore MDC/MDA class systems (Machine Data Collection/Machine Data Acquisition) are being actively developed, which allows collecting data of this type. Simultaneously, other systems, which allow not only data collection, but also provide a Machine-to-Machine (M2M) interaction at lower levels of production. The introduction of the above-mentioned systems in production is accompanied by the development of an appropriate network infrastructure. The deployment of network infrastructure entails significant financial, labor and time costs. Therefore, most companies delay decisive steps towards switching to digital production, waiting for an optimal solution that would minimize these costs. However, the market is constantly changing, and approaches that were used earlier in production process organization are becoming obsolete [1]. Manufacturing becomes more personalized and it leads to an emergence of a new approach—“production as a service”. As a result, a requirement for flexibility and mobility of a manufacturing process arises. Accordingly, the use of wireless networks is preferable, since it leads to lower costs [2], and fulfills new requirements for the production process organization.

Nevertheless, there are many factors in production that can affect the noise immunity of a wireless signal. Therefore, various researches of the influence of a production environment on a wireless signal are being carried out and criteria for its evaluation are being determined. For example, scientists from Linkoping University and Gavle University in Sweden evaluated the effect of electromagnetic noise in workshops for various frequency ranges of a wireless signal [3], [4]. In the study, they determined the power delay profile in various manufacturing rooms with different levels of signal reflection and absorption. Similar studies were also carried out

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at Beijing Jiaotong University [5], where the amplitude and time characteristics of electromagnetic noise at frequencies of 315, 433, and 915 MHz, occurring during welding robot operation, were determined. In [6], a description of a setup for measuring parameters of a wireless signal in the 2.4 GHz band as well as a measurement technique is given. By using this setup, scientists obtained the dependence between wireless signal stability and the time required to transmit the IEEE 802.15.4 standard packet. The paper [7] addresses the issue of noise pollution in the 2.4 GHz band by other networks and sources of interference. A mathematical model of electromagnetic noise in this range is proposed, which can be used for a preliminary assessment of noise immunity in production premises. Other studies of the ISM range using the RSSI parameter have also been carried out. But all of them either did not take into account the peculiarities of the production environment or were focused on Wi-Fi technology [8], [9], [10].

The article is organized as follows. Section II is dedicated to an overview of wireless personal area networks. In Section III wireless signal immunity assessment is provided. Section IV describes the experimental plan of research. Section V focuses on the results at this stage of development. Finally, Sections VI contains conclusions.

II. Wireless Personal Area Networks

Manufacturing is usually considered to be a hierarchical system consisting of levels. At each level, there are elements of network infrastructure that provide both horizontal and vertical data transmission. Simultaneously, the types of computer networks used vary at different levels. This happens since, depending on the position in the hierarchical system, various requirements for data transfer speed, security, channel width, topology, reliability, and energy efficiency are put forward. Moreover, various computer networks can coexist on the same level, depending on the tasks performed. Therefore, network infrastructure of an enterprise is hybrid. To understand at what levels a wireless personal network functions, it is necessary to determine "digital twins" that operate with the data transmitted via the network. For example, data received from a computer numerical control (CNC) machine tool and/or from sensors installed on it can be used to create a "digital twin" of this equipment. Apart from that, a good example is the situation when it is necessary to maintain a certain temperature and humidity in a shop for specific technological operations. In this case, data will be used for the "digital twin" of the workshop.

Wireless personal area networks (WPANs) are used at levels of the control system, equipment, production cell, workshop and, less commonly, in case of small industries, at the enterprise level. WPANs have such a wide coverage and are applicable in a production environment due to the active support of the IEEE committee (Institute of Electrical and Electronics Engineers). This resulted in a range of technologies covered by the IEEE 802.15.4 set of standards, including well-known technologies like Bluetooth, ZigBee, and Thread. Simultaneously, the hardware base is experiencing a rapid growth. Currently, there is a large selection of chips and ready-made boards that support several WPAN technologies at once on the market. Despite the initially small signal transmission distance, the use of a mesh topology allows achieving an almost unlimited range. The possibility of building a WPAN with a TCP/IP stack, which is convenient when working with other networks, is also worth noting. The disadvantages of WPAN include the frequency ranges in which these networks operate: 868 MHz, 915 MHz, and 2.4 GHz. In Russia they are not licensed but have restrictions on the power of a transmitter [11]. These bands are called "ISM frequencies" (ISM—Industrial, Scientific, Medical). As the name implies, a large amount of equipment operates in ranges that could interfere with the network [12], [13].

III. Wireless Signal Immunity Assessment

There are many factors at a manufacturing site that can attenuate and distort a wireless signal: physical objects, radio frequency interference, electrical interference, environmental factors. Identifying these aspects before deploying a wireless network is an important procedure. When designing a new enterprise, many of these factors can already be determined at a stage of developing the layout of equipment and units. For example, the type of environment can be determined by the functional purpose of the room. And knowing the final units' layout, it is possible to identify where the 2.4 GHz office Wi-Fi networks will intersect with an industrial wireless network. Considering this, it is possible to adjust in order to increase the noise immunity of the network. However, the introduction of a wireless network at an already operating manufacturing site is currently a more relevant task. In addition, to obtain an accurate enough picture, measurements should be carried out directly at the enterprise. There are various characteristics that are used to determine the signal quality. They include the power attenuation profile, amplitude and time characteristics, Signal to Noise Ratio (SNR) [14], etc. Unfortunately, obtaining values of these parameters requires the use of expensive instruments—a spectrum analyzer, a vector network analyzer, and special antennas. And the qualification requirements for the person performing the measurements are very high.

In the proposed methodology, the Received Signal Strength Indicator (RSSI) is used. Its main advantage is being natively supported on almost any network equipment, including the hardware platform used in the experiment. It means that you can get the RSSI value from a receiver without the use of additional measuring equipment. However, RSSI cannot be used directly to measure the quality of a wireless signal, since this parameter can contain a significant interference component. I. e. strong interference can lead to packet loss, while increasing the RSSI value [15]. Simultaneously, theoretical RSSI ($RSSI_T$) is calculated based on antennas characteristics of the receiver and transmitter, and taking into account the frequency of a wireless signal and the reference attenuation parameter equations (1) to (3):

$$RSSI_T = A - 10\,\mu\, log(d), \tag{1}$$

where d is the distance from source, m; μ is an attenuation exponent, $\mu = 2$;

$$A = P_{out} + G_{tx} + G_{rx} - FSPL, \tag{2}$$

where P_{out} is the transmitter output power, dBm; G_{tx} is the source antenna gain, dBi; G_{rx} is the receiver antenna gain, dBi; *FSPL* is the free-space path loss, dB;

$$FSPL = 10\ log(d) + 20\ log(f) + 20\ log(4\pi/c), \tag{3}$$

where f is the frequency, Hz; c = 299792458 m/s.

Therefore, the proposed method uses the deviation of $\Delta RSSI$ obtained as the difference between the measured RSSIP and theoretical value $RSSI_T$ (4).

$$\Delta RSSI = RSSI_T - RSSI_P \tag{4}$$

Nevertheless, when designing a network, especially in the case of a mesh topology, the nodes location in a premise is firstly determined. Therefore, it is possible to go from the deviation of $\Delta RSSI$ to the maximum distance between nodes D_{max} (5), a more convenient parameter for the task under consideration. A signal with an RSSI value of less than -80 dBm is considered weak [16]. Based on this statement and (4), it is possible to calculate $RSSI_T$ (6) at a certain distance from a transmitter, taking into account the average deviation of $\Delta RSSI$, which is influenced by factors of a specific production environment (7).

$$D_{max} = 10^{\frac{A-RSSI_T}{10\mu}} \tag{5}$$

$$RSSI_T = -80 - \overline{\Delta RSSI} \tag{6}$$

$$\overline{\Delta RSSI} = \frac{1}{n} \sum_{0<i<n} \Delta RSSI_i, \tag{7}$$

where n is a count of measurements. In this case, $n = 25$.

IV. Experiment Plan

The experiment was conducted to determine significant factors that weaken the wireless signal in a production environment. To achieve that a set of experimental data had to be collected and a WPAN noise immunity under the influence of given factors had to be evaluated, according to the developed technique. Measurements were obtained using the experimental setup shown in Fig. 1.

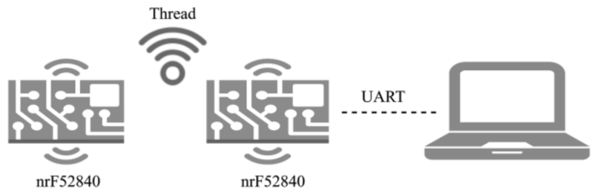

Fig. 1. The experimental setup.

The setup consists of two boards based on the nRF52840 chip [17], which act as a receiver and a transmitter. Chip antennas with linear polarization and standing wave ratio less than 3 are installed on the boards. In addition, a personal computer is used for data logging. The personal computer is connected to the receiver via the Universal Asynchronous Receiver-Transmitter (UART) interface to obtain the measured RSSI values. Inside the WPAN, the message is transmitted via the Thread protocol [18]. The experiment was carried out on manufacturing premises of the company “Lar Technologies”, specializing in the development of technological equipment. The influence of each of the following factors of different types was studied separately:

- a metal rolling warehouse as a reflecting medium factor.
- power equipment (induction motor, stepper motor, TIG welding machine).
- Thick walled steel pipe (wall thickness 20 mm) as an obstacle factor.
- Networks (Wi-Fi and ZigBee networks).

RSSI values under the influence of 2.4 GHz networks were recorded in an apartment building since they were not found in industrial premises. Open air measurements without the influence of the listed factors were also obtained. The experiment was carried out in range between 0.5 and 24.5 m with a 1 m increment. At each step, a series of measurements was performed for one minute with a 1 s period.

V. Experimental Results

As the distance between the receiver and transmitter increases the RSSI value decreases, which can be explained by the phenomenon of propagation path loss. In this case, the RSSI value decreases logarithmically depending on the distance (1). This happens in accordance with the law of conservation of energy. Since the wave transfers energy and spreads spherically, the energy, with the increasing distance, is distributed over an increasing surface area of the sphere [19]. It should also be noted that the "path lost exponent" criterion is not used due to its inconvenience for the specialists involved in planning the workshop space, since these specialists do not always understand sufficient details of setting up wireless networks.

The parameter of the maximum allowable distance between nodes is more rational in this case. Fig 2a shows a plot reflecting the theoretical curve of RSSI values obtained in accordance with (1), and the dependence between RSSI and distance in open air measurements. It can be noted that curves turned out to be similar in shape. However, there are small RSSI deviations, which values are shown in Fig. 2b. One of the distinguishing characteristics of industrial production is the type of medium where the wireless signal travels. Production is most often characterized by a reflective environment with certain exceptions, for example, pulp and paper and wood processing enterprises, where absorbing medium predominate. Signal propagation in a reflecting medium is subject to the effect of multipath propagation [20]. As a result, not only direct, but also reflected rays are received, which leads to fluctuations in the amplitude, phase, and angle of an input signal.

In Fig. 3 plots of RSSI and ΔRSSI depending on distance are shown respectively. Plots present significant fluctuations caused by the above effect. Obstacles encountered on the signal propagation path have a similar effect. In addition, a diffraction phenomenon (on surfaces with sharp irregularities) and

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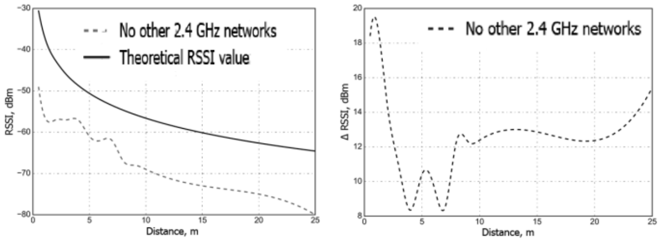
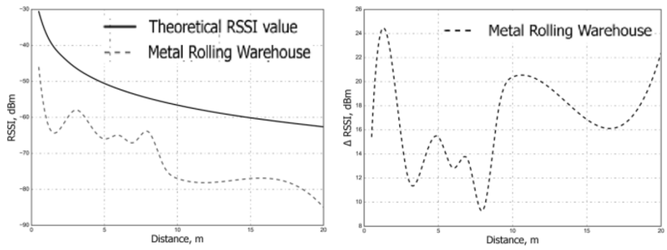
scattering (on rough surfaces) can also occur. Walls between workshops and production cells can reflect the signal due to the presence of fittings, and, on the other hand, absorb it due to sound insulation. Moreover, there are situations in manufacturing premises when a receiver or transmitter can only be located behind a certain obstacle or inside a box. Fig. 4 shows data for this case.



(a) (b)

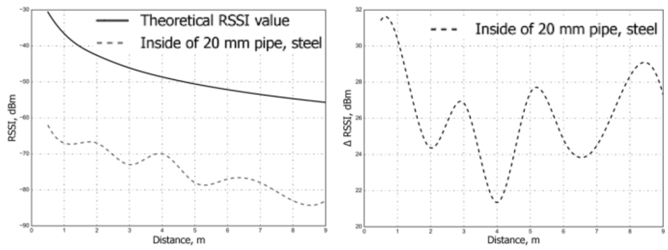
Fig. 2. The influence of open air and hardware features of the receiver andtransmitter on:RSSI(a) andRSSIdeviation from theoretical value (b).

The obtained result is like the one shown in Fig. 3; however, the RSSI deviation is greater since the obstacle surrounded the receiver and was near it.



(a) (b)

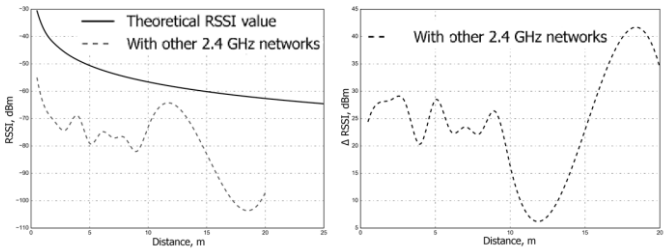
Fig. 3. The influence of the reflective medium on: RSSI (a) and RSSI deviation from theoretical value (b).



(a) (b)

Fig. 4. The influence of obstacles in a manufacturing room on: RSSI (a) and RSSI deviation from theoretical value (b).

Since the production network infrastructure is characterized by heterogeneity, it is likely that several wireless networks will operate simultaneously on the same frequency range. In this case, interference may occur, coherent waves are superimposed, which leads to an increase or decrease in the resulting amplitude. This effect can be especially pronounced when devices operate on the same channel, which is typical for the 2.4 GHz band, where Wi-Fi, Bluetooth, ZigBee, and Thread networks intersect [21]. The resulting plots in Fig. 5 show a significant influence of this factor.

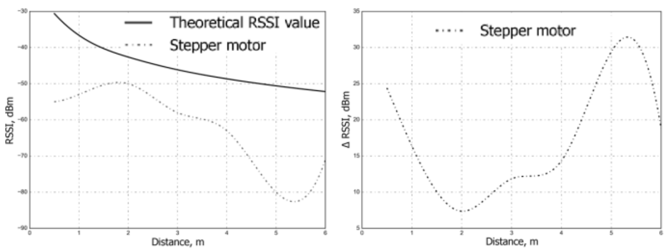


(a) (b)

Fig. 5. The influence of neighboring 2.4 GHz networks on: RSSI (a) and RSSI deviation from theoretical value (b).

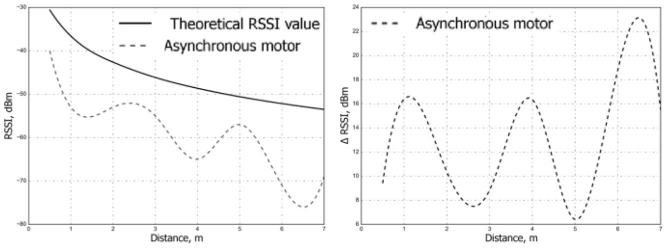
A lot of power equipment located in the workshop premises can distort the transmitted wireless signal and cause interference. This is most often observed when a pulse signal propagates along the power lines of the equipment. This occurs because when the front is formed, the signal amplitude changes at a high speed, and this leads to the appearance of many high-frequency harmonics in the signal spectrum. In the case of a stepper motor, considered in the experiment, the control is carried out by pulse-width modulation (PWM). The plots in Fig. 6 show the distortion of the wireless signal. For an induction motor (Fig. 7), strong fluctuations were not observed since the control was carried out without the use of a frequency changer.

The TIG welder showed one of the worst indicators (Fig. 8), since when switching transistor switches of the inverter during the welding process, a large number of short-term transient processes occur at the pulse fronts in the form of damped high-frequency oscillations [22]. Table I summarizes the results of the series of experiments. The worst result was obtained during an experiment where the receiver was placed in a thick-walled steel pipe. This indicates that this receiver location should be avoided, or it should be positioned no further than 6.85 m from a transmitter. The best results were shown when measuring RSSI in a free medium. A slight deviation from the theoretical value is present due to several hardware features of the antenna, that were not considered in calculations, and the mean theoretical value of the attenuation exponent.



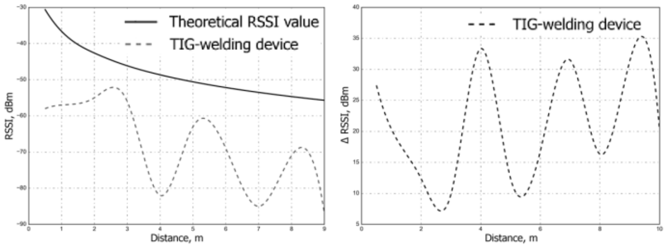
(a) (b)

Fig. 6. The influence of a working stepper motor on: RSSI (a) and RSSI deviation from theoretical value (b).



(a) (b)

Fig. 7. The influence of a working induction motor on: RSSI (a) and RSSI deviation from theoretical value (b).



(a) (b)

Fig. 8. The influence of a working TIG welding machine on: RSSI (a) and RSSI deviation from theoretical value (b).

TABLE I. THE INFLUENCE OF MANUFACTURING FACTORS ON NOISE IMMUNITY OFWIRELESS PERSONAL AREA NETWORKS(WPANS)

Factors	ΔR	ΔR_{max}	D_{max}
Free medium without other 2.4 GHz networks	12.37	18.82	34.22
Induction motor	12.69	19.37	33.99
Reflecting medium (metal storage warehouse)	16.33	23.39	22.54
Stepper motor	17.51	29.41	19.67
TIG welder	21.11	34.35	34.35
Medium with noise from other 2.4 GHz networks	25.03	32.37	8.27
Shielding with a thick-walled steel pipe	26.67	26.67	26.67

a. Mean error ΔRSSI, dBm

b. Maximum error $\Delta RSSI_{max}$, dBm

c. Maximum distance between transmitters, m

It should be noted that the possibility of organizing WPANs based on the mesh topology allows neutralizing negative effects by a dense arrangement of network nodes, according to the calculated D_{max}.

VI. CONCLUSION

To summarize, the paper describes a series of experiments that determine the noise immunity of WPAN in a production environment. A method for assessing the noise immunity of this type of networks based on the RSSI is proposed. The factors of wireless signal attenuation are identified and noise immunity values in a real production site are calculated.

Considering the obtained data, it can be concluded that many production factors have a significant impact on the signal quality of WPAN. However, the impact is not significant enough to avoid using this technology. Moreover, the influence of many factors can be reduced by the use of mesh topology and dense arrangement of receivers and transmitters. It is worth emphasizing the importance of taking appropriate measurements for each specific production, as this ensures the efficient location of receivers and transmitters in manufacturing premises.

It is important to note that an advantage of the 802.15.4 standard is its support for automatic rebuilding between channels to reduce the impact of interference between nodes. This is essential for networks with a mesh topology, where network resiliency is achieved by increasing the number of nodes.

The results are particularly interesting in the context of manufacturing digitalization, where the wireless method of data transmission from field level sensors becomes preferable to the wired due to the requirement for flexibility and mobility of a production process. The obtained optimal values of the distances between the nodes of the wireless network can be used when planning the workshop space for the most rational equipment placement.

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