A STUDY ON INTERFERENCE BETWEEN INDUSTRIAL AND ASSISTIVE BODY AREA WIRELESS NETWORKS

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Abstract— Nowadays the interest in using wireless communication technologies has grown considerably, as e.g. Industrial Wireless Sensor-Actuator Networks (WSANs) and Wireless Body Area Networks (WBANs). The main advantages of the use of WSANs are node mobility and the possibility of placing sensors and actuators in difficult locations. In this context, WirelessHART is an outstanding protocol developed to support industrial applications. However, this technology requires careful study to ensure that coexistence with other networks will not cause packet loss and failures in communications. A possible undesirable interaction can happen with health telemonitoring systems using WBAN. The sensors can be used by workers in industrial plants instrumented with WirelessHART. Although, this use could affect the performance of both networks. This work studies the interference effects in the coexistence of these two types of Wireless Sensor Networks (WSNs), highlighting the importance of managing the shared environment in order to avoid quality of service degradation.

Keywords— Wireless Sensor-Actuator Networks, Coexistence, Wireless Body Area Network.

1 Introduction

The accelerated growth of the wireless technologies and the miniaturization of electronic components are enabling their use in sensors capable of monitoring people's vital signs by means of WBANs. The demand for this technology is growing, mainly by health services providers, with the objective of monitoring and sharing the vital signs of their associates with the health care professionals (Domenicali et al., 2009). The data collection allowed by the WBANs can bring also a significant gain when crossing information from different patients with similar diseases in order to improve treatments.

Observing the benefit in continuously collecting data from patients, medical equipment manufacturers are using radio-frequency (RF) technologies into their medical devices. Communication is accomplished using either published IEEE standards or proprietary protocols, many of them operating at unlicensed frequencies in the Industrial, Scientific, and Medical (ISM) bands. The 2.4 GHz ISM band is an attractive spectrum to be used in medical applications due to the simplicity of the electronic circuits, high reliability, and low power radio. These characteristics are important, especially when an emergency or alarm communication needs to be established (Zhang and et al, 2017).

In the last years, several industries started using industrial wireless sensor-actuator networks in their plants. Standards as ISA SP100.11a and WirelessHART were developed for these applications (Muller et al., 2011). These standards take into account the direct communication node and neighboring node for data transfer and automatically switch to another route based on the Packet Error Rate (PER) and RSSI (Received Signal Strength Indicator) if one node goes down. The main advantages of the use of WSANs are the greater flexibility to changes in the setup of the plant, expansion capability, equipment mobility, and reduction of costs with installation and maintenance (Winter et al., 2014).

A relevant aspect in the using WSANs and WBANs in the same local is related to network coexistence (Cavallari et al., 2014). Network coexistence refers to the capability of a wireless network operate properly in an environment in which interference from the operation of another wireless network is present (Singhal and Rotvold, 2007). Coexistence among wireless devices is dependent on three main factors: frequency, space and time. In terms of frequency, the probability of coexistence increases as the frequency separation of channels decreases between wireless networks. In terms of space, the probability of coexistence increases as the signal-to-interference-ratio (SIR) of the intended received signal increases. In terms of time, the probability of coexistence increases as the overall channel occupancy of the wireless channel increase (Jin et al., 2015).

Observing the importance of the coexistence between WSANs and WBANs, this paper studies the effects of interference between these two types of networks (Bults et al., 2017). The coexistence problem occurs when two or more transmitted packets with sufficient energy from the different networks collide or overlap each other in time and frequency. Fig. 1 shows the relationship between channels and transmission power used in IEEE 802.11 and IEEE 802.15.4 standards, typically used in wireless applications.

This paper studies the stages of planning and analysis used to determine the influence of certain factors on packets transmission. The results obtained and experimental tests can be analyzed using statistical methods, and the design of the experiment should also follow a statistical methodology. The factorial design allows the study of the effects of certain factors on a response variable (Montgomery, 2005).

In the context of the wireless networks coexistence, the main contributions of this paper are the evaluation of the wireless interference between WSANs and WBANs and the analysis of the main issues concerning the design of a WBAN used in coexistence with a WSAN, i.e. the impact of the battery lifetime and quality of service (QoS).

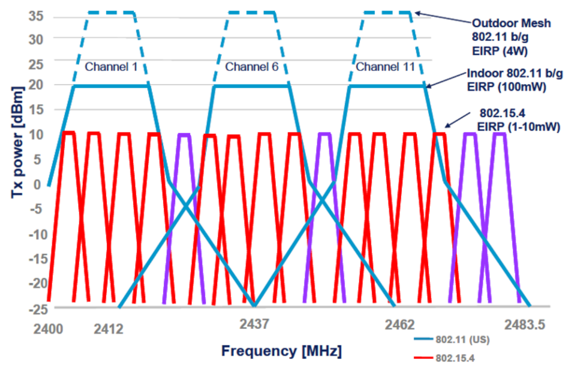

Figure 1: Areas of coexistence between IEEE 802.11 and IEEE 802.15.4 wireless networks. Source: Adapted (Singhal, R. and Rotvold, E. 2007).

The rest of the paper is structured as follows. Section 2 provides a review of the literature. Section 3 describes the developed approach for the proposed study. Section 4 presents the experiments to implement the proposed study along with the acquired results, while discusses these results and their application to actual setups. Section 5 concludes the paper proving directions for future work.

2 Background and Related Work

According to (Cavallari et al., 2014), WBANs have requirements related to reliability, energy efficiency, low latency and low device complexity. The design of these networks requires the definition of new protocols with respect to those used in general purpose wireless networks, such as IEEE 802.11, which presents no strong commitment to energy savings. Due to these requirements, the IEEE 802.15.4 standard is a suitable alternative for these environments (Hayajneh et al., 2014). Although, WBANs are vulnerable to interference from other technologies.

The IEEE 802.15.4 standard (IEEE, 2003) can work in different channels of the ISM frequency bands. The operation frequency bands are 868 MHz, 915 MHz or 2.4 GHz and the common data rate is 250 kbit/s. The IEEE 802.15.4 standard defines a MAC and a physical layer for low data rate wireless devices as WBANs. The ZigBee Alliance released IEEE 802.15.4 technology enhanced with higher level protocols. ZigBee became a widespread technology for embedded systems with high reliability and versatility requirements while is designed for low-cost industry control (Yang et al., 2016).

According to (Chen and et al, 2016), a WBAN is comprised of a complex system of multiple wireless sensor nodes which are usually deployed on, or in close proximity to a person's body. Essentially, it is necessary to develop and simulate a WBAN model in order to understand its behavior prior to real-world deployment.

The work in (Hayajneh et al., 2014) presents an extensive simulation with several real-life scenarios to evaluate the impact of coexistence interference between Wi-Fi and WBAN. However, their approach does not consider the coexistence with an industrial wireless network. They provide information about performance and parameters used to analyze the coexistence problem in the report of their experiments.

IEEE 802.15.6 is a new standard for body area networks allowing nodes in a single WBAN to avoid interference by using multiple access techniques such as time division, as well as it provides lower power consumption, extended lifetime and security mechanisms (Martelli and Verdone, 2012).

An investigation of wireless networks coexistence issues through an interference-aware simulator is presented in (Bertocco and et al, 2008). The authors present an analysis of interference between IEEE 802.15.4 and IEEE 802.11 standards using OMNeT++ (Vargas, 2003) simulating a WSN. According to authors, in the coexistence analysis of wireless networks operating in the 2.4 GHz ISM band, a critical coexistence issue could easily arise among WSNs and WLANs, particularly related to parameters like throughput, bit error rate, and delay.

In (Movassaghi et al., 2016), the authors simulate the coexistence between three common standard protocols used in WSANs industrial solutions: Zigbee, WirelessHART, and ISA 100.11a. The experiments are performed in an OMNeT++ based simulation platform called Castalia (Boulis, 2016), which is a simulator for WSNs, WBANs and general low-power wireless networks for embedded devices. The results show that IPV6 helps ISA100 to coexist with any other legacy network and is better than HART and far better than ZigBee protocol.

The work in (Sarra and Ezzedine, 2016) studies the problem of WBAN's interference in the presence of Wi-Fi transmitter using OMNET++ simulator with MiXiM framework to model the posture of the body and the movement's behavior. The framework can be configured for performance evaluation in different scenarios. The acquired results show that WBANs with a low number of nodes show better results than with higher number, and the nearby Wi-Fi nodes have an impact on packets reception and the packets transmission of the WBAN.

In (Martelli and Verdone, 2012), the coexistence issues for WBANs at 2.45 GHz are evaluated. The authors propose a characterization between two different sources of interference. The study characterizes WBAN's performance achievable when interfering sources are present. However, their approach does not consider an industrial network such as the WirelessHART.

The work presented in (Yang et al., 2011) reveals how critical the coexistence problem between IEEE 802.15.4 and IEEE 802.11 can be. They present the analysis models of the coexistence problem along with mathematical analysis. However, their study does not include wireless body networks.

3 Methods

This study investigates the interference between the WirelessHART (Martelli and Verdone, 2012) protocol and the WBAN for e-healthcare systems. This investigation is performed by means of simulations in which the coexistence between those networks is analyzed. Castalia (Domenicali et al., 2009) is the chosen simulator for the experiments. The advantages of using Castalia in the simulations are mainly related to the availability of the IEEE 802.15.4 MAC code in its library, thus with all support needed to perform the proposed study.

The rules applied in the use of unlicensed bands, such as the ISM band, are very little restrictive. Therefore, the simultaneous use of the same band of nodes belonging to different systems may be a disadvantage, as there may be a high risk of interference, which may affect the quality levels of packets received.

Radio links in a WBAN are more susceptible to interference from other wide range networks. The interference problem has been studied widely in WBANs (Cavallari et al., 2014). The IEEE 802.15.4 radio links are short-range low-data-rate links and they are mostly exposed to interference from other high data rate bands like devices operating on the same 2.4 GHz band.

The performed simulations aim to identify the interference problem and to verify if the WSN fails to guarantee the required QoS when it shares the same channel with an industrial network. The study shows the radio simulation with tests reception, as a node WBAN moving through the area of others static nodes of a WirelessHART network, as shown in Figure 2. In this work, the nodes are equipped with Castalia parameters of CC2420 radio (Hauer et al., 2009) distributed in the simulated environment.

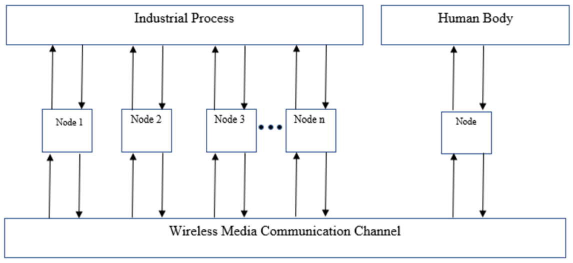

Figure 2: The modules and their connections in Castalia. Source: Adapted (Boulis, A. 2011).

Fig. 2 shows the basic module structure of Castalia for the planned simulation. The channel module is based on empirically measured data. Each node is connected to wireless channel and one industrial process. Since a node might communicate on different frequencies, there are multiple wireless channels.

This work addresses an use for sensor nodes based on data collection in an industrial environment where sensors monitor an equipment (communication without mobility) or where sensors are deployed on a person for data collection, such as their location and health status parameters (communication with mobility).

According to (Montgomery, 2005), the design of experiments studies the planning and execution, reducing the influence of uncontrollable variables and thus, with greater accuracy. The factorial design allows studying the effects of certain factors on a response variable. The results obtained, and experimental tests can be analyzed using statistical methods.

For the conduction of the experiments in Castalia, before a simulation, parameters have to be set in the omnet.ini configuration file. There are many sections grouping the parameters inside the configuration file, as e.g. MAC protocol, Mobility or General. The Simulation Process Structure is shown in Fig. 3 and the simulation parameters involved in the experiments are summarized in Listing 1.

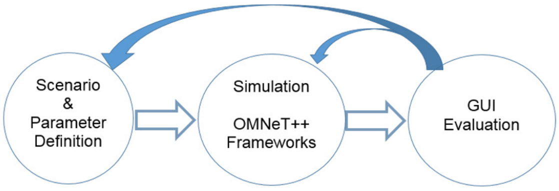

Figure 3: Simulation Process Structure.

```
[General]
include ../Parameters/Castalia.ini
sim-time-limit = 51s # 50 secs of data + 1 sec
of MAC setup
SN.field_x = 400     # meters
SN.field_y = 400     # meters
SN.numNodes = 3
.
.
.
SN.node[*].Communication.Radio.RadioParametersFile
= "../Parameters/Radio/CC2420.txt"
SN.node[*].Communication.Radio.RadioParametersFile
= "../Parameters/Radio/BANRadio.txt"
.
.
```

Listing 1: General Parameters in Castalia for the performed simulation.

The number of nodes defines how many instances of the generic 802.15.4 node are created in a simulation scenario. The OMNeT – Castalia configuration file has a General section that defines the scenario as shown in Listing 1.

The simulation time is as e.g. assigned in seconds. The network takes such as the field size, the number of nodes, and the deployment type. In Castalia, the radio parameters are set as e.g. CC2420 radio parameters as presented in Listing 1.

The communication model used between nodes is presented in Listing 1 and 2. The network consists of nodes distributed in an environment and the wireless link that can sustain reliable communication. According to the different understanding and application of WirelessHART features, some scheduling schemes are based on single-channel communication and the wireless link between node pairs that can sustain reliable communication. The radios were chosen because they are relatively low data rate and power consumption characteristics are inherited from IEEE 802.15.4 suited to wireless process control applications.

The interference test parameters as e.g. LineMobilityManager module moves the node in a defined by the starting location of a node and the destination location in meters given by the *xCoorDestination*, *yCoorDestination* parameters and the speed and the update interval that the wireless channel module will be updated with the node's current position.

Emerging unlicensed technologies to coexist fairly with WiFi are likely to become increasingly commonplace in internet of things networks and beyond 5G (Cano et al., 2017).

The IEEE 802.15.4 MAC is presented as ZigBeeMac in Listing 2. The BaselineMAC module is a Castalia implementation of the IEEE 802.15.6 draft proposal for body area network standard (Domenicali et al., 2009).

```
.
.
.
[Config TMAC]
SN.node[*].Communication.MACProtocolName =
"TMAC"
SN.node[*].Communication.MAC.phyDataRate =
1024

[Config ZigBeeMAC]
SN.node[*].Communication.MACProtocolName =
"Mac802154"
SN.node[0].Communication.MAC.isFFD = true
SN.node[0].Communication.MAC.isPANCoordinator
= true
SN.node[*].Communication.MAC.phyDataRate =
1024
.
.
.
[Config GTSon]
SN.node[*].Communication.MAC.requestGTS = 3
.
.
.
[Config BaselineMAC]
SN.node[*].Communication.MACProtocolName =
"BaselineBANMac"
SN.node[*].Communication.MAC.phyDataRate =
1024
.
.
.
SN.node[0].xCoor = 0
SN.node[0].yCoor = 0
SN.node[1].xCoor = 50
SN.node[1].yCoor = 50
.
.
.
SN.node[n].xCoor = 0
SN.node[n].yCoor = 0
SN.node[0].MobilityManagerName =
"LineMobilityManager"
```

Listing 2: Protocol Parameters in Castalia.

The contributions of this work can be shown in the practical analysis and evaluation insights. The simulation with several scenarios was performed to evaluate the impact of the interference in the considered WSNs.

4 Experiments Plan

The test scenario works with three TxPower-WirelessHART, three TxPower-WBAN, three different number of nodes with two, four and eight static WirelessHART nodes and always one mobile node WBAN. The goal is to analyze is how the interference affects the communication, as e.g. packet loss in the presence of interference from WSNs. For this, an application of a factorial design of experiments of type 3^k in order to identify the factors that influence of the interference in the communication of wireless sensor network nodes and packets transmission.

There are controllable factors for collision modes, and these are arranged in a factorial design. Each experiment contains all factors combinations. The results of the analysis can be performed using hypothesis testing (Montgomery, 2005).

According to (Serra and Nabi, 2015), well-designed experiments will ensure a correct evaluation of the effects that have been identified.

This test assesses the influence of the factors and their interactions on the response variable. The test used to evaluate the results is the F-type statistic test.

The assumptions used in this work are:

1. Influence of the A factor (TxPower-WirelessHART) in the packets transmission.
   H_0:τ_i=0 - Factor A has no effect on the response variable.
   H_1:$\tau_i \neq 0$ - Factor A has effect on the response variable.

2. Influence of the B factor (TxPower-WBAN) in the packets transmission.
   H_0:β_j=0 - Factor B has no effect on the response variable.
   H_1:$\beta_j \neq 0$ - Factor B has effect on the response variable.

3. Influence of the C factor (Number-Nodes-WirelessHart) in packets transmission.
   H_0:ϕ_k=0 - Factor C has no effect on the response variable.
   H_1:$\phi_k \neq 0$ - Factor C has effect on the response variable.

4. Influence of the interaction A.B in packets transmission.
   H_0:$(\tau.\beta)_{i,j}$=0 - Interaction factors A.B has no effect on the response variable.
   H_1:$(\tau.\beta)_{i,j} \neq 0$ - Interaction factors A.B has effect on the response.

5. Influence of the interaction B.C in packets transmission.
   H_0:$(\beta.\phi)_{j,k}$=0 - Interaction factors B.C has no effect on the response variable.
   H_1:$(\beta.\phi)_{j,k} \neq 0$ - Interaction factors B.C has effect on the response variable.

6. Influence of the interaction A.B.C in packets transmission.
   H_0:$(\tau.\beta.\phi)_{i,j,k}$=0 - Interaction factors A.B.C has no effect on the response variable.
   H_1:$(\tau.\beta.\phi)_{i,j,k} \neq 0$ - Interaction factors A.B.C has effect on the response.

In this study, a hypothesis is whether or not rejected with a significance level of 95 %. This level demands an experiment with a 53 ($n3^k - 1$) degrees of freedom, with two and four to the numerator factor and 18 to denominator factor, which is expressed by a tabulated value $F_{0.05,2,18}$=3,55 and $F_{0.05,4,18}$=2,93 obtained in (Montgomery, 2005). Simplifying, the hypothesis is rejected if its F value is greater than the critical value earlier presented.

5 Results, Discussion and Further Investigation

In this work, the ANOVA results generated by Minitab® (*MINITAB18*, 2005) analysis was conducted in the experimental variance, in which the values are presented in Table 1.

Table 1: Description of the ANOVA results generated by Minitab®.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	18	1235197	68622	360,71	0,00
Linear	6	784272	130712	687,09	0,00
A	2	490159	245079	1288,27	0,00
B	2	1665	832	4,38	0,020
C	2	292448	146224	768,63	0,00
2-Way	12	450925	37577	197,53	0,00
AB	4	3329	832	4,37	0,006
AC	4	444267	111067	583,83	0,00
BC	4	3329	832	4,38	0,006
Error	35	6658	190		
Total	53	1241855			

It is possible to notice that in Table 1 the factors feature value F is greater than the critical value, which leads to the rejection of the null hypothesis in this case. The second order interactions between factors and their effects on packets received can be better observed by observing Figure 4.

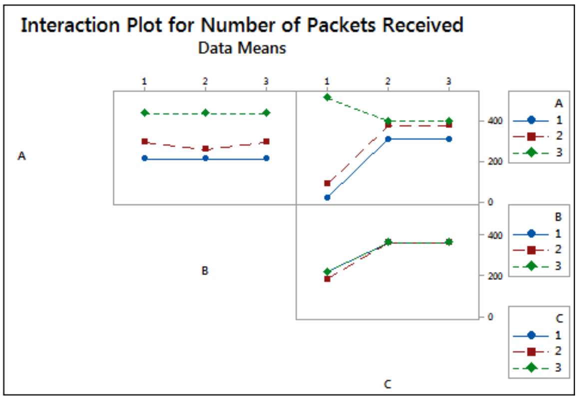

Figure 4: Description of the ANOVA results generated by Minitab®.

The independence of the data is ensured through the randomization of the order of the rounds of the experiment available in Minitab®. As shown in Figure 4, the TxPower WBAN factor appears quite significant to the packets received when there are no collisions happening.

The assumptions of analysis of variance of the residuals are normally distributed with zero mean and constant standard derivation should be checked (Montgomery, 2005). The premises assumptions made in this work are normality, independence, and equal variance. The factorial design proved quite simple and practical, providing a solid analysis of the data collected during the experiment.

The results acquired in the simulations with the two types of WSN coexisting studied in this work made possible to analyze the effect of their applications and the impact of their performance imposed by interference. The conducted experiments investigated these effects of interference in packets transmission, considering the use of mobile and static equipment in different randomized tests scenarios. The results show that it was possible to reject at 95% significance level the hypothesis that the presented factors do not influence in packets transmission.

To properly deal with these effects, a special effort is required just at the early stage of a design. For instance, in (Bertocco et al., 2008) the presence of interference is investigated through a set of experimental tests. Considering the premises reported in this reference, the experiments presented in this current paper explores the interference effects as presented and discussed in the following. The experimental setups were performed adjusting the parameters TxPower-WirelessHART, TxPower-WBAN and the number of nodes, following a randomization of simulation rounds. The procedures are repeated until all the necessary observations are obtained with 54 rounds. After running all results were processed and tabulated with Minitab ANOVA.

Table 2 summarizes the parameters of the performed simulations elaborated in the design of experiments presented in Section IV, in which the first column, named Factor Code, provides one controllable factor code for each value. The second column is named TxPower-WirelessHART and provides the values for the transmission power of the WirelessHART nodes in dBm. The third column, named TxPower-WBAN, provided the test values for the transmission power of the WBAN nodes in dBm. The numbers presented in the last column indicate the number of WirelessHART nodes used in the corresponding experiment. Only one WBAN node is used in the performed tests. The experiments are performed combining the varying factor according to the codes, for instance, an experiment with 2 WirelessHART nodes transmitting at -15 dBm and the WBAN node transmitting at -25 dBm is represented by A1B1C1.

Table 2: Design of experiments parameters.

Factor Code	TxPower-WH	TxPower-WBAN	Nodes-WH
A1	-15dBm	-	-
A2	-10dBm	-	-
A3	-1dBm	-	-
B1	-	-25dBm	-
B2	-	-15dBm	-
B3	-	-10dBm	-
C1	-	-	2
C2	-	-	4
C3	-	-	8

Figure 5 shows a deployment of the WirelessHART nodes and the WBAM (node 1), initially at the position (0,0). The number of WirelessHART nodes vary according Table 2. In the test with 2 WirelessHART nodes, node 0 and node 2 are these represented WirelessHART nodes. In the case with 4 WirelessHART nodes, they are represented in by nodes 0, 2, 3 and 4. Finally, in the experiments with 8 WirelessHART nodes, they are all represented, as shown in Figure 5. As explained above, the combination of the Factor Codes (A, B and C) defines the parameters of each performed experimental setup, as the exemplified A1B1C1 case with 2 WirelessHART nodes with TxPower-WirelessHART at -15 dBm and the WBAN node with TxPower-WBAN at -25 dBm.

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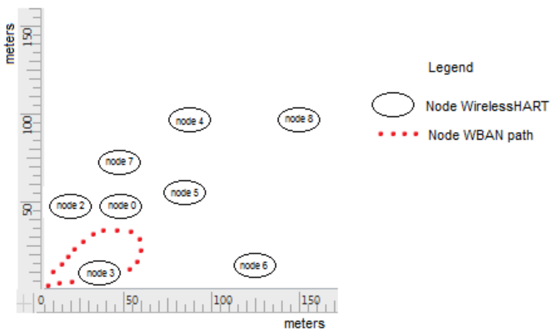

Figure 5: Nodes deployment.

To handle packets delivery, Castalia provides a dynamic calculation of radio Signal Interference and Noise Ratio (SINR) based on the modulation type, signal strength and other parameters according to the particular interest of the experiment. The link reliability is measured in terms of the RSSI, which is an indication of the radio energy in the communication channel during the transmission of a packet.

The signal may be affected by interference caused by coexistence between different WSNs. In all performed experiments, the WBAN node was continuously moving and the WirelesHART nodes are deployed in different specific locations in the test area, as depicted in Figure 5, and they were sending 20 packets per second to the sink node during 51 seconds. Analyzing the errors in receiving the sent packets, it is possible to observe in Figure 6 that there is a fluctuation of the PER affected by the generated interference due to the coexistence of the other wireless network.

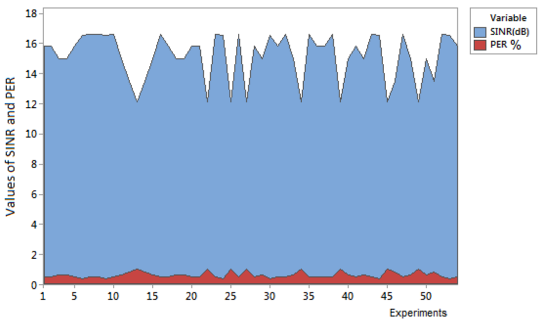

Figure 6: The SINR and PER relationship.

The conducted experiments aimed to assess the behavior of the effect of the WSN and it is possible to observe the behavior of the wireless channel considering the packets delivering and if the packets were correctly received. In order to investigate the interference impact, the probability of reception based on SINR was used. Figure 7 shows a case in which packets are more likely to arrive without errors as they have a larger margin towards the radio's sensitivity threshold, thus, they are less susceptible to the RF interference. In other words, the SINR of such packets is higher and the transmission will more likely to be successful.

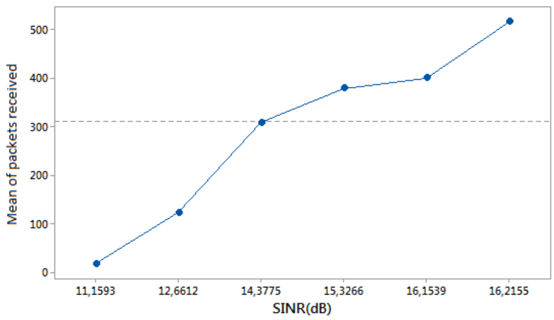

Figure 7: The SINR and packets received relationship.

The measurement of these parameters shows that the interference effects can effectively be recognized, and the network setup can be optimized taking this aspect into consideration. Figure 8 indicates that during the tests a change in WBAN transmission power results in a difference in packet delivery performance. A variation in RSSI can change a link from a good to a bad state if the link is operating near the other radios. For instance, observing the graph in Figure 8, bellow -88 dBm, the number of received packets is less than 20. When the RSSI value is above -87 dBm, the average of receive packets increases significantly, dropping a little bit around -80 dBm and increasing again close to -71 dBm. There are many random factors that play a role here, as shadowing in the wireless channel and several random decisions in the MAC layer which may explain this variation. Notice that with -83 dBm related to A3C1 and all values of B factor (see Table 2), combinations in which there are 2 WirelessHART nodes with transmission power of -1 dBm and all values of TxPower WBAN, the increase in the packets reception is even more highlighted, as it is possible to observe by the quality of the link. Considering the number of sent packets (770 in total), this results in 67,14 % of the packet delivery efficiency in the best case and 2,20 % for the worst case situation.

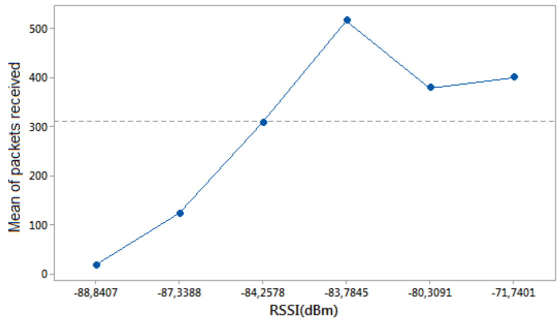

Figure 8: The RSSI and packets received relationship.

6 Conclusion

This paper reports a work studying the problem of interference in medical WBANs coexisting with an industrial WSN. This is a critical issue, especially because of the increasing use of wireless communication technology for medical purposes. The work addressed the study of why interference matters when WirelessHART and WBAN are sharing the same ISM frequency bands.

The results in a simulated environment using IEEE 802.15.4 and narrowband IEEE 802.15.6 simulation model are presented, which is implemented in OMNeT++. An experiment design for the interference tests with controllable variables was designed and performed. It was possible to reject the null hypothesis that effects of transmission power do not influence the result of packets delivery, which means that concerning the coexistence with WBAN and other wireless networks, this is a serious issue due to their low transmission power.

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