Cortés Aguilar, T. A., Cantoral Ceballos, J. A., y Tovar Arriaga, A. (2023). sWSN3: A simulation tool for reliability calculation in WSN. *Nova Scientia*, *15*(30), 1-15.
https://doi.org/10.21640/ns.v15i30.3159

Nova Scientia
Revista de Investigación de la Universidad De La Salle Bajío

sWSN3: A simulation tool for reliability calculation in WSN
sWSN3: Una herramienta de simulación para el cálculo de confiabilidad en WSN

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Recepción: 04-04-2022 / Aceptación: 21-06-2022

Abstract

Knowledge about the reliability of a wireless sensor network is important in industry. Indeed, in holonic manufacturing, it is convenient to ensure that decisions are made with reliable data. However, experimental evaluation in a real environment is a task that consumes time and financial resources, it also depends on several factors such as the technical characteristics of the transceiver and the location of the nodes. Thus, the use of simulation and calculation software in Industry 4.0 can potentially reduce costs and implementation time significantly, nonetheless some simulators deal with power consumption and network reliability with theoretical models that have limitations for commercial devices. This paper presents the sWSN3 tool that, through an intuitive graphical interface allows placing sensor nodes on the virtual environment of a plant layout and calculates the reliability of a wireless sensor network using parameters such as signal to noise ratio, received packet rate, and battery life time. Results show that sWSN3 can accurately estimate the reliability of a virtual WSN.

Keywords: wireless sensor networks; telecommunication network reliability; cyber-physical systems; industry; software; parameters; energy; reliability; optimization; resources

Resumen

Conocer la confiabilidad de una red de sensores inalámbricos es importante en la industria. En particular, en la fabricación holónica conviene asegurar que las decisiones se toman con datos confiables. Sin embargo, la evaluación experimental en un entorno real es una tarea que consume tiempo y recursos económicos, y también depende de varios factores, como las características técnicas del transceptor y la ubicación de los nodos. El uso de *software* de simulación y cálculo en la Industria 4.0 puede reducir costos y tiempo de implementación; sin embargo, algunos simuladores tratan el consumo de energía y la confiabilidad de la red con modelos teóricos que tienen limitaciones para dispositivos comerciales. Este artículo presenta la herramienta sWSN3 que, a través de una interfaz gráfica intuitiva, permite colocar nodos de sensores en el entorno virtual de un diseño de planta y, a través de modelos validados por investigaciones publicadas sobre comunicación y consumo de energía, calcula la confiabilidad de una red de sensores inalámbricos utilizando parámetros, como la relación señal a ruido, la tasa de paquetes recibidos y la duración de la batería. Para un ejemplo de configuración, los resultados muestran que sWSN3 puede estimar la confiabilidad de una WSN virtual.

Palabras clave: redes de sensores inalámbricos; confiabilidad de redes de telecomunicaciones; sistemas ciber-físicos; industria; *software*; parámetros; energía; confiabilidad; optimización; recursos

1. Introduction

Wireless sensor networks WSN have unique properties to acquire, process, transfer, and provide information from the physical environment when compared to wired networks. However, each sensor node has operational restrictions (Aalsalem et al., 2018), such as range, bit rate, sensor data sampling, bandwidth, latency and more importantly, network reliability (defined as a measure of the percentage of accurate data that reach their intended destination) and energy consumption, which is related to the battery lifetime (Radmand et al*.,* 2010). Development of wireless sensor networks involves three early stages: 1) Idea, 2) Design and 3) Test, however the latter one could be expensive and sometimes delay the implementation. Networks that are tested by software before its deployment can solve many problems of a physical network in an industrial environment. Duan et al*.* (2018) mention that the virtualization of a network can improve energy consumption and performance, as they suggested for a network analysis under the IEEE 802.15.4 protocol of the warehouse and production area of a pharmaceutical factory. Moreover, Khan et al*.* (2011) suggest that simulation tools for WSN can be used to save time and cost in industrial applications. Hence, within the context of Industry 4.0, simulation tools for cyber-physical systems help preventing errors, optimizing parameters, and predicting process behaviors, supporting Industry 4.0 principles: adaptability, flexibility, integration, decentralization, virtualization, reliability, autonomy, and speed to satisfy custom manufacturing orders (Belman et al*.*, 2020), which is in contrast to the hierarchical control structures found in traditional manufacturing.

Therefore, in order to meet these requirements, it is necessary to develop technologies for new smart manufacturing systems such as holonic manufacturing, that assumes real time adaptability of the whole company to external or internal changes, such as perturbations during production. For this, it is of paramount importance to use data efficiently to maximize value creation, which in turn highlights the crucial need to define information systems equipped with connected, interoperable, flexible and reactive control architectures. This way, real-time decisions supported with data and accurate information are essential in holonic manufacturing, where indicator towers are an affordable option to begin the digitization by reacting to the failure of one machine and directing production to another. For the aforementioned reasons, we consider that our simulator sWSN3 is a suitable tool for holonic manufacturing within the scope of Industry 4.0

Holonic Manufacturing

Wireless sensor networks can provide real time data for a holonic manufacturing that can optimize decision making. Wan et al*.* (2019) describe the project entitled McBIM for industry 4.0 with a holonic manufacturing approach, where smart products connected via a WSN can send data and connect with their environment. However, for its implementation in the physical environment, they mention that the conservation of energy in the wireless network and the management of data in the digital environment is one of the main challenges to overcome.

Holonic manufacturing proposes the distribution of decision making in autonomous virtual entities called holons that have a certain degree of independence, but subject to various authorities. The procedure begins by creating order holons and asking each machine holon if it is available for manufacturing its operations. After checking their database, machine holons respond by indicating if they can execute the operation and if so, they also indicate the execution time. Thereby, order holons can associate the order within the machine that can execute it (Araúzo et al., 2015). In a cyber-physical system, a sensor node installed in each of the machines can send its current state of availability to the coordinator node, figure 1 a).

A holon is made up of a physical processing unit and a software control unit. In figure 1 a) the sensor node Tx and the coordinator node Rx are part of the communication interface of the software control unit. Something to consider is that the amount of data, and the information payload, that the sensor node of each machine sends to the coordinator node can vary and thus modify the size of the communication frame. In order to know the operational status of the machinery, we may use indicator towers, as shown in figure 1, which function as a network of wireless sensors that transfer their information to the coordinator node, usually connected to a computer. The sWSN3 use free space communication models, as expressed by (8) and (9) to calculate the power at the receiver. We suppose line of sight between Tx and Rx nodes because transceivers are located at the top of the machines, as shown in figure 1 b). In addition, the sWSN3´s user can select the mean and standard deviation of a normal distribution for the noise floor that can affect the communication in an industrial environment.

Machine status monitoring

Today we may find readily available indicator towers in the market with wireless data transmission that allow monitoring machine status, making them are an affordable option to begin the digitization of the modern factory according to Industry 4.0 paradigm. For example, the NH-3FV2W model from the Patlite Company (2020) is an indicator tower that receives digital inputs from sensors and transmits the information to the cloud. Users can access the process remotely and control visual or acoustic signals in real time. The TL70 Indicator Tower from Banner Engineering Corporation (2019) provides fast recognition of machine status at the factory and by wireless communication, it can connect to other indicator towers, PLCs, HMIs, computers and other mobile devices. The SmartMonitor system from Werma Signaltechnik (2017) is a low cost option for manufacturing companies to collect data and monitor the status of machinery, it supports more than 50 indicator towers nodes and data are transmitted wirelessly to a radio frequency receiver that is connected to a computer. Also, Smart Monitor is a software that can graph the productivity of the machinery over a period of time.

The indicator towers use visual signals of red, amber, green, blue and white colors according to the international standard IEC 60073:2002. The International Electrotechnical Commission (2002) defines visual coding, for instance, a red signal sends a message of machine failure or emergency stop, an amber color sends a warning signal for operation in an abnormal condition of the process or state of initialization of the machinery, whilst a green color sends a normal operation signal. Finally, a blue and white color send signals defined by the user for any state of the machinery that does not correspond to the previous ones.

The indicator towers with visual signals have expanded from traditional alarm systems in the factory towards a network system of wireless sensors in Industry 4.0 that allows detecting the operational status of machinery. Additional software would allow calculating the execution time of an operation and provide useful information for a holonic manufacturing system.

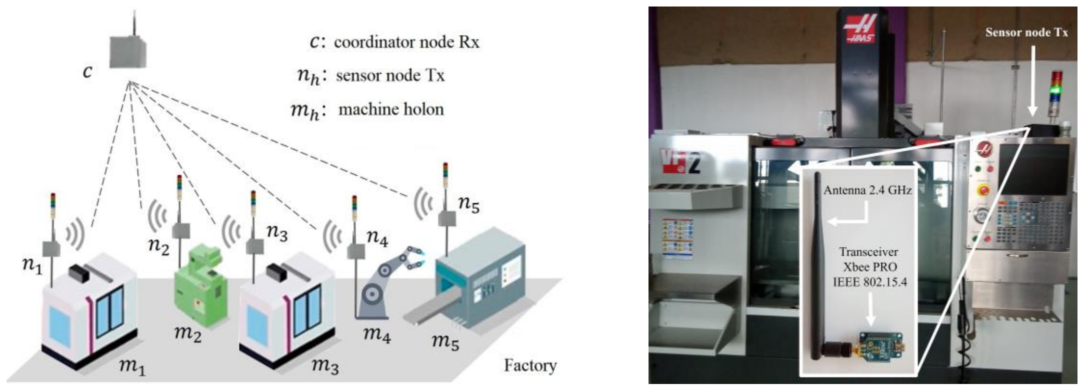
In the traditional factory, it is common that the indicator towers are connected to the electrical network supply. However, as a consequence of the high flexibility in Industry 4.0, the power supply for new systems to monitore the status of machinery or products, may require batteries. This is particularly the case for robots installed on automatically guided vehicles AGV, automated storage and retrieval systems AS/RS, and even in mobile process units for adaptable manufacturing environments (Nielsen et al., 2017). Therefore, the sWSN3 tool considers power consumption as an important feature of network reliability, as well as the size of the data frame according to the message, as indicator towers do.

Wireless Sensor Network

In a hierarchical wireless network architecture, communication occurs between two types of devices, a coordinator node that manages communication with sensor nodes and the sensor nodes that transmit the sensor data to the coordinator node. The figure 1 b) shows the experimental prototype of the sensor node installed at the top of the machine. The transceiver uses the same IEEE 802.15.4 protocol as the communications model described in the method section. Mendoza et al*.* (2020) suggest the use of star subnets with coordinator nodes connected to each other, in a tree topology, as an alternative to overcome the limitations of scope and obstacles. It should be noted that the sWSN3 tool only allows the case of a single coordinator node connected to several sensor nodes, in a star topology, as in some systems to recognize machine status that use indicator towers in a network.

In addition, energy consumption and the probability of receiving erroneous packets increase with the parameters that have the greatest impact on the performance of the protocols used in wireless sensor networks, such as the size of the frame and the rate of change of the sensor node from inactive state to active state (Leyva et al., 2016).

Thus, the quality of radio frequency communication between low power devices is affected by spatial and temporal issues. The spatial issues refer to the surrounding environment such as obstacles and the distance between the transmitter and receiver. And the temporary issues refers to environmental changes like temperature and relative humidity. Tahir et al. (2013) report simulation results where adjusting the transmitter power level can change the quality of the link, and reduce power consumption and excess demand for data packets.



a) b)

Figure 1. a) *Example of WSN for holonic manufacturing*. b) *Experimental prototype of indicator tower located in TecMM U.A. Zapopan*.

This article presents a simulation tool for wireless sensor networks sWSN3, which allows to predict their performance before the implementation stage, according to the proposed models of communication and energy consumption. In contrast with other simulations tools that work with implemented already built networks, the user of this new tool can work on the layout of a virtual factory during the design stage. Therefore, the main contribution of this paper is that the sWSN3 tool proposes the combination of the Signal to Noise Ratio SNR, the Packet Reception Rate PRR, the Packet Error Rate PER, the Received Signal Strength Indicator RSSI, and the total current consumption to calculate de Battery lifetime and consequently to estimate the reliability of a wireless sensor network in a virtual scenario.

This paper remaining sections are as follows: section 2 presents a review of previous work related to the use of wireless sensor network simulators, section 3 describes the methods and the communication model, the power consumption model, and the graphical user interface of the sWSN3. Section 4 shows the results for an example of virtual scenario, whilst section 5 presents the conclusions.

Related Works

Duan et al. (2018) show simulation results for a virtual environment of a wireless network under the IEEE 802.15.4 protocol, they use a routing algorithm to reduce two issues: power consumption and load per node. Mora et al. (2013) present a simulator called mTOSSIM that estimates the lifetime battery in a wireless sensors network. The graphs of simulated and real data show that the battery power reduces linearly with time, they also report a linear reduce of the RSSI indicator referring to distance and battery voltage.

Gautam et al. (2015) used the NS2 simulator to analyze the performance of a WSN calculating latency and the energy consumed for a scenario with 17 nodes under the IEEE 802.11 protocol. They suggest a calculation method that uses consumed energy to transmit and receive packets, as well as the consumption during sensor operation. Shelar et al. (2017) use the NS2 simulator under the IEEE 802.15.4 protocol to study the best position of the coordinator node inside a grain warehouse, they change the size of the packet and the number of connections in a two-beam propagation model, concluding that the best location to install the coordinator node is in the center. Chaari et al. (2011) use the OMNET ++ simulator in a star topology network and the protocol IEEE 802.15.4 to evaluate two scenarios, the first with different amount of sensors and the second with different data payload during the transmission.

Bakni et al. (2019) compare the power model used by the TOSSIM, NS2 and OMNET ++ network simulators. They report that NS2 does not include a model for a battery power supply, but it does consider transmission power consumption. The OMNET ++ simulator considers a power supply model but since the NS2 simulator is restricted to the radio frequency module and does not include the power consumption of the sensor and its processing unit. Further, the TOSSIM simulator has the disadvantage that parameters such as the bit rate, the data payload, and the position of the nodes do not affect the power consumption.

The tool sWSN3 uses parameters common to systems available in the industry to calculate the signal to noise ratio SNR and the packet reception rate PRR, these measurements, in turn, are more suitable to predict the reliability of a link than the received signal strength indicator RSSI used by other simulations tools (Tahir et al., 2013). The RSSI parameter calculates the signal strength at the receiver and is useful to find the best transmitter position; however, industrial environments usually restrict moving the transmitter making the SNR more useful to calculate the link quality. Furthermore, the sWSN3 tool allows adjusting the data payload for each sensor node according to the information signal to calculate the size of the communication frame which in combination with the total current consumption of the sensor, the processing unit, and the radio frequency module, allows calculating an accurate battery lifetime for each node, unlike other simulators available, as shown in Table 1.

Other tools, such as Wattics (2016), an energy management software used to monitor capable of measuring and analyzing power consumption, has the aim to reduce energy wastage in many types of commercial and industrial buildings through an analytics Dasboard. Wattics can connect with a variety of data collection systems, files and Industrial IoT Gateway, such as EpiSensor (2018) that uses IEEE 802.15.4 protocol as its wireless communications standard. It uses a mesh network topology and provide wireless coverage for 1000 m^2. The main purpose of these technologies is helping companies to comply with the ISO 50001 certification related to reducing carbon emissions and contributing to climate change reduction targets. On the other hand, the consumption model of sWSN3 is focused on analyzing the lack of quality communications in WSN, related to energy reduction supplied by batteries connected to sensor nodes.

Energy models are a useful for designers of low power embedded systems, since they allow to predict the expected battery lifetime before its implementation in the real word. In this context, EnergyTrace is a power analyzer tool for embedded systems developed as a graphical user interface by Texas Instrument to optimize ultra-low power consumption. EnergyTrace is an advanced tool of Code Composer Studio and it offers information about current measurement on both CPU and its peripherals (Friesel et al., 2021). Despite low power consumption being a target for many application, in some instances, it is better to achieve a high Packet Reception Rate at the expense of high power consumption. In such a case the WSN designer must select the most convenient battery´s capacity as a function of the availability of the sensor node.

Table 1. *Comparison of simulators.*

	NS2	Wattics	EnergyTrace	OMNET ++	TOSSIM	sWSN3
IEEE.802.15.4	●	●	●		●	●
Calculate Battery lifetime		●	●	●		●
Adjusting payload				●		●
Virtual Layout		●				●
Calculate RSSI	●			●	●	●
Calculate SNR				●	●	●
Calculate PRR					●	●

2. Methods, techniques, and instruments

The sWSN3 tool is integrated by a communication model and a power consumption model, which have not been used before in a single simulator software. The first model calculates the reliability of the WSN according to PRR, SNR, PER and RSSI parameters and the second one calculates the battery lifetime based on the circuit current consumption. In a real word application, the power consumption is not constant and depends on the time between transmissions, the time required to access the radio channel and total time to turn on/off the transceiver. The distance between the node sensor and the coordinator node is another important input data used to calculate the power in the receiver. Here, obstacles in the path link can reduce the power arriving at the receiver. For this reasons, the virtual scenario in our proposed graphical user interface allows considering a configuration to avoid obstacles or noise sources that would lead to an unacceptable loss in link reliability.

This section describes the equations of the communication and power consumption models. Additionally, a description of the graphical user interface is included. Finally, we also propose an example of a virtual scenario with the aim of showing some advantages of the sWSN3 over other simulators like its adaptability to the transceiver´s parameters.

Communication Model

This section describes the communication model used by the sWSN3 tool. First, we compute the bit error rate (BER) for an offset quadrature phase-shift keying modulation OQPSK (Adly et al., 2010), according to the IEEE 802.15.4 protocol (1).

$$BER = erfc\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{1}$$

Where: *erfc* is the complementary error function (2), E_b is the energy required per bit of information, and N_0 is the thermal noise at 1 Hz of bandwidth.

$$erfc_{(x)} = \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}dt \tag{2}$$

The signal to noise ratio *SNR* is calculated by (3), where *R* is the bit rate and *B* is the channel bandwidth.

$$SNR = \frac{E_b}{N_0} \times \frac{R}{B} \tag{3}$$

The packet reception rate *PRR* is related to the bit error rate *BER* by (4) and (5), where f is the size of the frame communication in bytes, i.e., the header plus the payload data. The power term in equation (5) is multiplied by 8 bits per byte. The packet error rate *PER* is calculated by (4).

$$PER = (1 - PRR) \tag{4}$$

The packet reception rate *PRR* is a direct measurement to determine link reliability, however, in a physical environment, a reliable PRR value can only be obtained statistically over a long period of time.

$$PRR = (1 - BER)^{8f} \quad (5)$$

The received signal strength indicator *RSSI* is calculated by (6), where *Ps* is the received power and *NF* is the noise floor in dBm. The noise floor *NF* is a receiver parameter.

$$RSSI = P_S + NF \quad (6)$$

The received power *Ps* must be greater than the noise floor *NF* so that the receptor understands the data correctly. The signal to noise ratio *SNR* in dB is calculated by (7).

$$SNR = RSSI - NF \quad (7)$$

The received signal strength indicator (*RSSI)* is used as link quality parameter. Previous research (Subaashini et al*.,* 2012; Xu et al., 2010) suggest the use of the *RSSI* parameter to establish the best location of the sensors within a *WSN*. Nevertheless, the *RSSI* parameter includes both signal energy and noise energy, therefore it is not an adequate measure of link quality, unlike the signal to noise ratio *SNR*. In some routing protocols such as IEEE 802.15.4, it has been shown that under the presence of additive white gaussian noise (*AWGN)* and Rayleigh fading, the packet error rate *PER* increases with a decrease of the *SNR* (Goyal et al*.,* 2010). Usually, wireless sensor networks *WSN* use three models to predict the intensity loss of the received signal due to distance (Bakni et al*.,* 2019), *Ps1* for propagation in free space, assuming line of sight between transmitter and receiver, *Ps2* for a receiver with a direct beam, and a reflection beam, and a third model for long distances. The sWSN3 tool uses (8) and (9) to calculate the power at the receiver. We suppose line of sight between Tx and Rx nodes because transceivers are located at the top of the machines, as shown in figure 1.

$$Ps1 = C\frac{P_{tx}}{d^2} \quad (8)$$

$$Ps2 = C\frac{P_{tx}}{d^4} \quad (9)$$

Power Consumption Model

The best case battery life estimate proposed by Casilari et al. (2020) considers that the time required to transmit a frame is calculated by (10).

$$t_3(n) = \frac{8(O_{MAC} + n)}{R} \quad (10)$$

Where: O_{MAC} is the total number of bytes in the header, n is the data payload in bytes sent by the sensor, and R is the bit rate in bps. To calculate the time $t_a(n)$ and the transmitter current $I_a(n)$equations (11) and (12) are used.

$$t_a(n) = t_1 + t_2 + t_3(n) \quad (11)$$

$$I_a(n) = \frac{t_1 \cdot I_1 + t_2 \cdot I_2 + t_3(n) \cdot I_3}{t_a(n)} \tag{12}$$

The average current I_d at which the battery is depleted, is calculated by (13).

$$I_d = \left(\frac{t_a(n)}{T}\right) I_a(n) + \left(1 - \frac{t_a(n)}{T}\right) \cdot I_s \tag{13}$$

Where: I_1 and t_1 are the current and the total time required to turn the transceiver on and off. I_2 and t_2 are the current and time required to access the radio channel used with CSMA/CA and to receive the acknowledgement ACK from the coordinator node, respectively. I_3 is the current consumed during transmission, I_s is the current in low consumption mode, T is the data update time, i.e., the time between two consecutive transmissions sent by the sensor. The battery life time can be calculated using the equation (14), where C is the charge capacity of the battery in mAh and c_p is the percentage of battery charge.

$$TL = c_p \left(\frac{C}{I_d}\right) \tag{14}$$

Description of the Graphical User Interface

The sWSN3 tool was developed in MATLAB R2016 as a graphical user interface to facilitate data capture, such as node positions and their parameters. The sWSN3 software ran on a standard mobile computer with an INTEL core i7 processor, 8GB of RAM, and an NVIDIA GEFORCE 940MX GPU. The left button of the mouse is pressed on the image on the desired location to capture the position of the nodes, in decimeters. The plant layout simulates an area of 100x100m. In the example of virtual scenario, figure 2, each sensor node Tx is located on the position of a machine holon in the physical environment. Figure 3 shows the flow diagram of the graphical interface of the sWSN3 tool. At first, the user must load the image layout. After that, the user sets up the coordinator node position *Rx* and the amount of sensor nodes *Tx*. Subsequently, the user enters the parameters of the communication and power consumption models for each sensor nodes Tx, connected to the coordinator node in a star topology. Finally, the user enters the mean and standard deviation of a normal distribution for the noise power.

After pressing the CALCULAR button, figure 2, the sWSN3 tool calculates the PsRx power received in the coordinator node according to the selected communication model, this is, line of sight (8) or two beams with reflection (9). Also shown the signal to noise ratio SNR calculations (3), the packet reception rate PRR (5), and the packet error rate PER (4). The bit error rate is calculated with (1) according to the physical layer of the IEEE 802.15.4 protocol at 2.4 GHz [29]. The battery lifetime of the sensor node is calculated using (14) according to the energy consumption model. Then the user must press the GUARDAR button to store the parameters and calculations of the current node in memory before continuing with the next node until completing the configuration of all the network nodes.

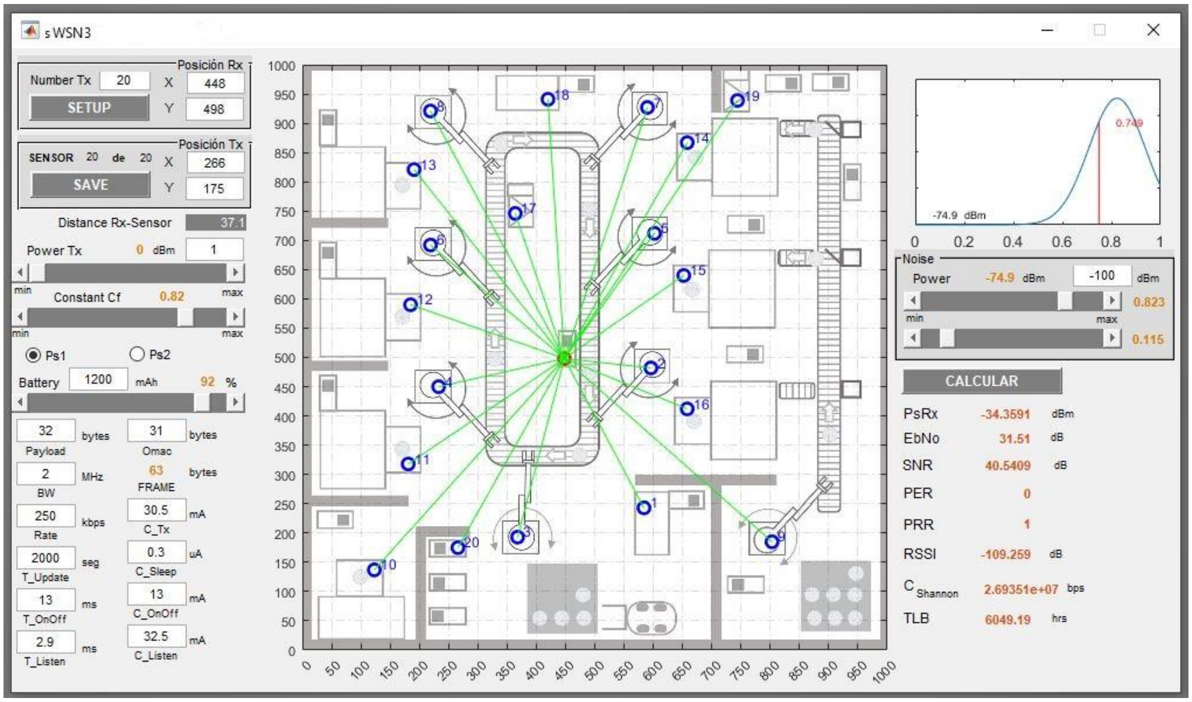


Figure 2. *sWSN3´s graphical user interface.*

Table 2 shows an example of the same configuration data for 20 sensor nodes of the scenario in figure 2. However, the sWSN3 tool is not limited to the scenario data in table 2, it also allows other data related to communication models and energy consumption, such as the sensor power node, battery charge, channel bandwidth, bit rate, frame size and header size, data update time, on and off current, time radio access, sleep current, and total current consume. Unlike other tools that only calculate the power consumed by the transceiver (Shelar et al., 2017), the sWSN3 tool calculates the total current C_Tx consumed by the entire system integrated by the sensor, microcontroller, transceiver, and amplifier.

Table 2. *Example Setup parameters.*

Sensor node power Tx		0 dBm
Battery		1200 mAh
Chanel bandwidth	BW	2 MHz
Bit rate	Rate	250 kbps
Header	Omac	31 bytes
T update time	T_Update	2000 ms
t_1 turn on/off time	T_OnOff	13 ms
t_2 access time	T_Listen	2.9 ms
I_3 current consumption	C_Tx	30.5mA
I_s sleep current	C_Sleep	0.3 µA
I_1 current on/off	C_OnOff	13 mA
I_2 access current	C_Listen	32.5mA

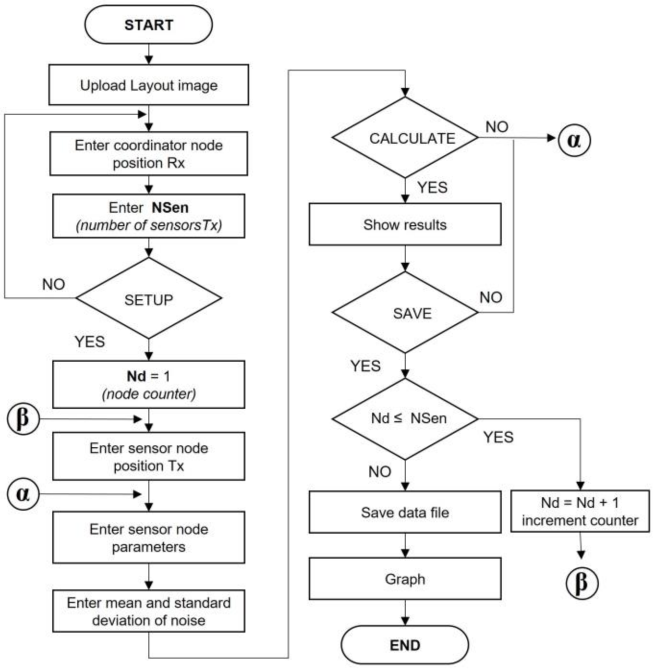


Figure 3. *Flowchart for user of the sWSN3*.

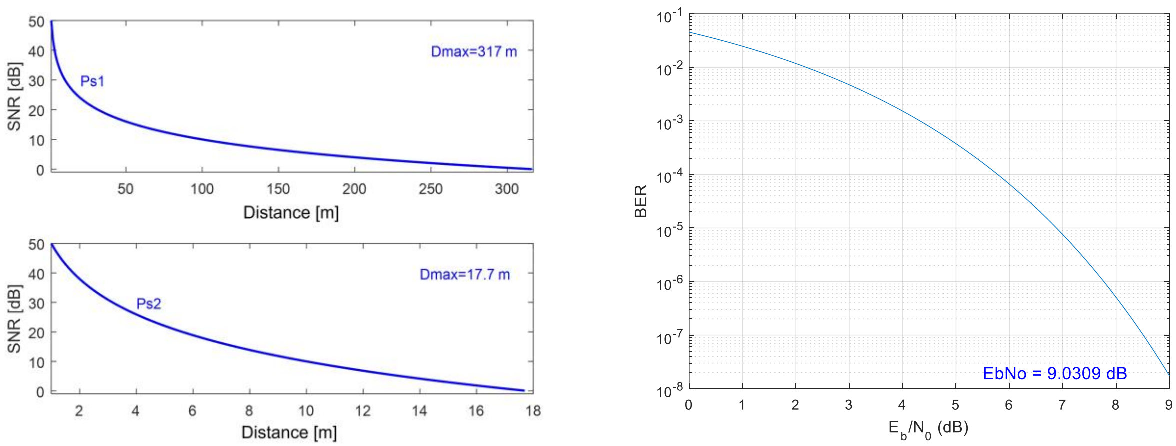
Table 3 shows the parameter for the scenario in figure 2 for each of the sensors; where the distance from the sensor node *Tx* to the coordinator node *Rx* affects the power received by the coordinating node *PsRx* measured in dBm according to the selected transmission model. The payload data *n* transmitted by the sensor is added to the bytes in the O_{MAC} header to calculate the size of the frame *f* from (10) according to the power consumption model.

Table 3. *Example Sensor node Parameters.*

Sensor	**Distance** (m)	**Model**	**PsRx** (dBm)	**n** (bytes)
1	34.3	Ps1	-30.7	4
2	14.4	Ps1	-23.2	8
3	31.7	Ps1	-30.1	8
4	23.6	Ps1	-27.4	8
5	25.5	Ps1	-28.3	8
6	30	Ps1	-29.7	8
7	45.1	Ps1	-33.3	8
8	48.2	Ps1	-33.8	8
9	46	Ps2	-66.7	8
10	52.1	Ps2	-68.8	8
11	32.2	Ps1	-30.3	8
12	27.7	Ps1	-29.0	8
13	41	Ps1	-32.4	4
14	42.2	Ps1	-32.7	4
15	21.6	Ps1	-26.9	4
16	24.4	Ps1	-27.9	4
17	26.4	Ps1	-28.6	16
18	43.8	Ps1	-33.0	16
19	52.8	Ps1	-34.6	32
20	38.1	Ps2	-63.4	32

3. Results and discussion

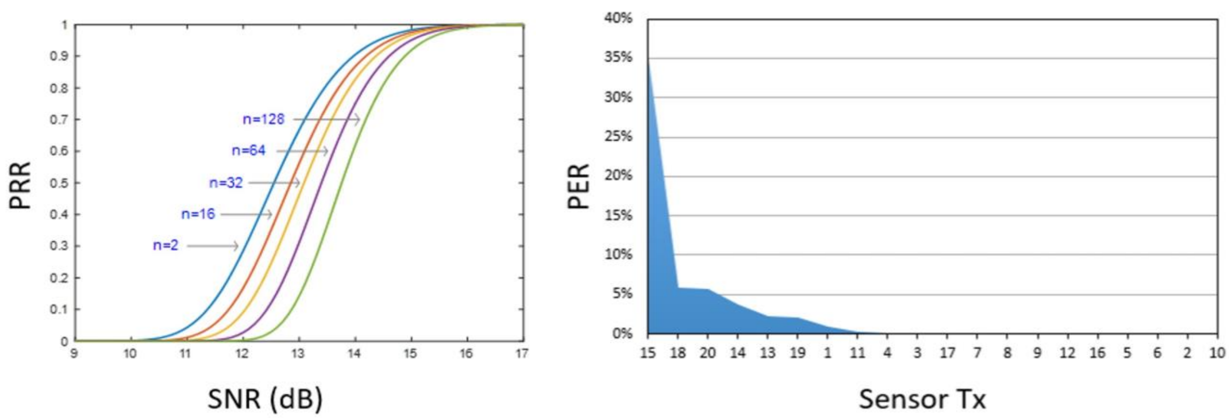
The following results were obtained for the configuration example of data in Table 2 and 3, nonetheless is should be noted that the sWSN3´s user can modify these parameters according to the characteristics of the transceiver being used. figure 4 a) shows the comparison of the SNR against distance for the communications models with line of sight Ps1 and transmission with reflection Ps2. Note that the maximum distance when SNR is 0 dB, 316 m for Ps1, and 17.7 m for Ps2. Figure 4 b) shows the bit error rate vs. the ratio of energy per information bit to the noise power EbNo, from 0 dB to 9.0309 dB, which corresponds to the calculation (in dB) of the R/B ratio of (3) when R = 250 kbps and B = 2 MHz.



a) b)

Figure 4. a) *Signal to noise ratio SNR against distance*. b) *Bit error rate BER against EbNo*.

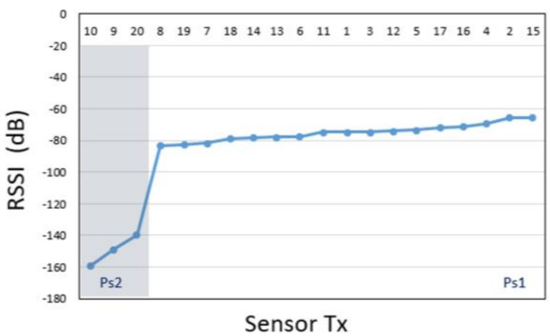
The graph in figure 5 a) shows the relationship between SNR and the packet reception rate PRR for transmissions with different payloads. Figure 5 b) shows the packet error rate PER for each sensor node. Both the packet error rate PER (5) and the packet reception rate PRR (4) depend on the size of the frame *f,* which in turn depends on the payload of data transmitted by the sensor.

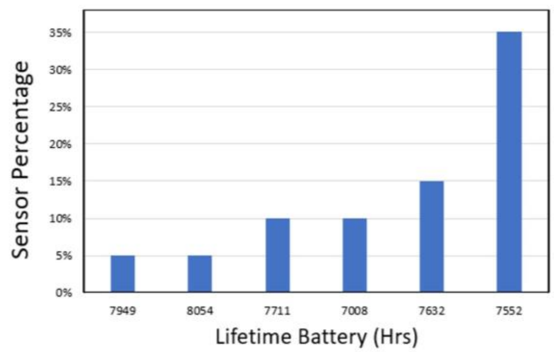


a) b)

Figure 5. a) *PRR against SNR for different payloads n data*. b) *Packet error rate PER for each sensor node*.

Figure 6 a) shows the received signal strength indicator RSSI for each sensor node Tx on the network. The shaded area indicates that in sensors 9, 10, and 20, the transmission model (9) with Ps2 reflection was used, these sensors present the worst case. The other sensors use the transmission model (8) with Ps1 line of sight, where the intensity of the signal received at the coordinating node ranges from -83 dB at node 8 to -65 dB at node 15. However, the received signal strength indicator RSSI is not an adequate measure to describe the reliability of the link, instead we propose using signal to noise ratio SNR, the packet reception rate PRR, and the packet error rate PER. Figure 6 b) shows the prediction of the percentage duration in hours of the sensor nodes, as a reference, one year is equal to 8766 hours. This is, the sensor batteries are predicted to have a life span of less than a year, before they need to be replaced.

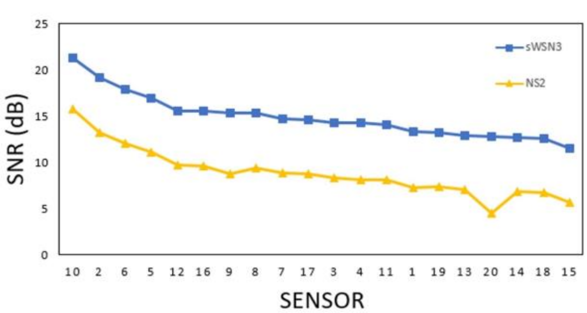


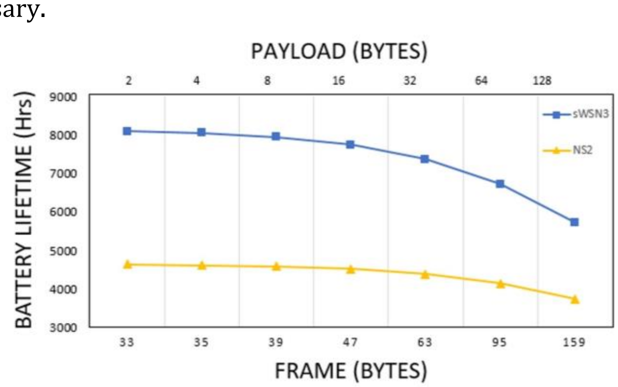


a) b)

Figure 6. a) *Received signal strength indicator RSSI for each sensor node*. b) *Distribution in percentage of the battery life in hours*.

The graph in figure 7 a) were obtained by comparing results of the sWSN3 simulator against those from the free space propagation model that uses the NS2 simulator with the same distance, frequency, data rate, and noise floor, assuming high gain antennas are used. Both graphs are similar and allow detecting sensor nodes with a low signal to noise ratio that can increase the rate of reception of erroneous packets PER. Figure 7 b) shows the lifetime prediction of a 1200 mAh battery versus frame size, the higher the number of bytes transmitted as payload of the sensor node, the more the battery lifetime is reduced. In the case of constant current consumption, NS2 predictions show that the battery will exhaust faster than the sWSN3's prediction, because an increase of data update time will reduce the power consumption. In a WSN, the sensor nodes do not send data to the coordinator node all time, only when necessary.





a) b)

Figure 7. a) *Signal to noise SNR for each sensor node*. b) *Battery lifetime against frame size for different payload*.

4. Conclusions

In this paper, we presented the sWSN3 tool for reliability analysis of wireless sensor networks in a virtual scenario. Unlike other wireless network simulation software, the sWSN3 tool uses an intuitive graphical user interface that allows easy placement of virtual wireless sensors on an image layout previously uploaded by the user. The sWSN3 tool allows the user to setup each of the sensor nodes with its parameters according to the communication model and power consumption. For example, the number of payload bytes sent by each sensor located upon a virtual machine holon. The results of the sWSN3 tool are useful for estimating the reliability of a virtual WSN. This information is relevant for decision making for holonic manufacturing in Industry 4.0.

Unlike other wireless sensor network WSN simulators that use the received signal strength indicator RSSI as the only measurement of the reliability of the link between the sensor node and the coordinator node, the sWSN3 tool proposes the combination of the SNR, the packet reception rate PRR, and the packet error rate PER. These parameters are interconnected by equations (3) to (5), and allow a better prediction of the reliability of the link, based on the amount of information sent that reaches the receiver, instead of the power received by the coordinator node. In addition, in contrast to other simulators that seek the optimal distance between the sensor node and the coordinator node to improve the signal to noise ratio SNR, in the sWSN3 tool the distance is an invariable parameter defined by the user based on the location of the machine holon in the plant layout. This is a relevant characteristic, since in a physical industrial environment, it is often not feasible to move a machine to improve the signal to noise ratio.

The communication model of the sWSN3 tool uses an offset quadrature phase-shift keying modulation OQPSK to calculate the bit error rate BER, under the IEEE 802.15.4 protocol, due to the wide acceptance of this protocol in various applications in WSN. However, to calculate the bit error rate for other modulation methods, the user only needs to modify the equations to the communication model. Further work is certainly required to integrate a selector of other modulation methods into the graphical interface of the sWSN3 tool, also other propagation models can be integrated. The equations of the power consumption model of the sWSN3 tool allow estimating the life of battery supplying power to each sensor node. Battery lifetime depends on the amount of payload data sent by the sensor node, as previous research reports show. Unlike other simulators that only consider the energy of the transmitter, the sWSN3 tool considers the total current of the system integrated by the sensor, microcontroller, and transmitter.

5. Supplementary information

No.

6. Acknowledgments

This article has been partially produced thanks to the support of the Instituto Tecnológico José Mario Molina Pasquel y Henríquez (TecMM), Tecnológico Nacional de México (TecNM,) and CIATEQ Advanced Manufacturing Center.

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