Wireless Sensor Networks in Industrial Environment: Real-Life Evaluation Results

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Abstract— **The paper summarizes the results of the RealFusion project. One of the main objectives of this project was to study the Wireless Sensor Networks (WSN) in real-life industrial environment. The results for the evaluation of different radios utilizing 433 MHz, 868 MHz and 2.4 GHz license-free industrial, scientific and medical (ISM) bands in real-life industrial environment are presented in the paper. Also, the paper discusses the results of development and evaluation of two real-life industrial WSN use cases: the WSN for remote monitoring the amount of bulk substances in the silos of a refractory materials factory and the WSN for remote warehouse monitoring.**

Keywords-Wireless Sensor Networks; WSN; Industrial, Scientific and Medical; ISM; Industry; Environment; Application; Frequency

I. INTRODUCTION

The Wireless Sensor Networks are nowadays widely considered as a one of the most important technologies for the twenty-first century [1]. Over recent years, the WSN and their applications were under the focus of both academia and industry all over the world. Nowadays, the WSN are widely used in various applications areas, including but not limiting to: health care and medicine [2,3,4]; home or office automation [5,6]; industry [7,8]; road traffic control [9,10]; farming and forestry [11,12]; civil infrastructure monitoring [13,14]; disaster detection and alarm systems [15]. Each of these areas has specific environment and certain application requirements for the WSN. We are presenting the results and lessons learned during evaluating WSN in the *real-life industrial environment* and *two industrial WSN applications development and deployment* that have been done within the RealFusion project.

II. SPECIFICS OF INDUSTRIAL WSN

The major technical challenges for developing Industrial WSN (IWSN) applications can be outlined as follows [7,8,16]:

- *Resource constraints*: IWSN nodes often have strict limitation in size, weight and costs for nodes. Besides, like many other WSN applications, nodes for IWSN often have limited amount of energy and computational power [17].
- *Dynamic topologies and harsh radio wave propagation condition*: the radio channel in industrial environment is often characterized by the presence of multipath propagation, interferences from other devices and noise generated by equipment or heavy machinery [16]. Besides, link condition in industrial environment is subject to change in time due to industrial processes and activities (e.g. cars or workers moving, goods replacement).
- *Harsh environment conditions*: the IWSN can require to work for the wide range of operating temperatures and to sustain strong vibrations, atmospheric precipitation, condensation and airborne contaminants [7,16].
- *Quality-of-service (QoS) requirements:* depending on the application specifics, the IWSN will have different QoS requirements and specifications. Mostly often, an industrial application will impose a constraint on data delivery time and communication robustness through the WSN.
- *Security:* security is an essential feature for IWSN. The IWSN should be able to handle both external denial-of-service (DoS) attacks and intrusion [8].
- *Scalability:* nowadays the IWSN can contain hundreds or even thousands nodes that are spread over huge territories [8]. Besides, in some IWSN applications network topology is subject to periodical changes or IWSN has to support mobile nodes.
- *Integration with other systems and networks:* the integration of IWSN into the existing industrial infrastructure (which is the point for majority of real-life IWSN use cases) often requires from WSN nodes to support the specific interfaces that are already used by deployed industrial machinery. Besides, rather often, the IWSN data has to be remotely accessible from Internet and thus have to support Internet Protocol (IP) [8].

Therefore the IWSN have multiple various concerns that require a lot of further research. In the work that has been conducted within the RealFusion project, one major focus was the evaluation of radios utilizing different industrial, scientific and medical (ISM) bands in real-life industrial environment. The results of this research are presented in Section III. Some other concerns that have been discussed above were taken into account during the development and evaluation of two real-life IWSN use cases that are discussed in Section IV.

TABLE II. ISM BANDS AVAILABLE FOR IWSN IN FINALAND [19,20]

Parameter	***433 MHz band***			***868 MHz band***						***2.4 GHz band***
Minimum frequency, MHz	433.050	433.050	434.040	863	868	868.7	869.4	869.7	869.7	2400
Maximum. frequency, MHz	434.790	434.790	434.790	870	868.6	869.2	869.65	870	870	2483.5
Maximum power	25 mW ERP[a]	1 mW ERP[a]	10 mW ERP[a]	25 mW ERP[a]	25 mW ERP[a]	25 mW ERP[a]	500 mW ERP[a]	5 mW ERP[a]	25 mW ERP[a]	10 mW EIRP[b]
Maximum duty-cycle[c]	10 %	no	no	0.1%	1%	0.1%	10%	no	1%	-
Other restrictions	-	-	[d]	Some sub bands are not included	-	-	[d]	-	-	-
Allowed applications[e]	V+DA+ DV	V [f]	V [f]	V+DA+ DV	V+A+ DV	V+A+ DV	V+A+ DV	V [f]	V+A+ DV	-

[a] - Effective Radiated Power
[b] - Effective Isotropically Radiated Power
[c] - The duty cycle is defined as the ratio, expressed as a percentage, of the maximum transmitter "on" time, relative to a one hour period.
[d] - Channel spacing max. 25 kHz.
[e] - V – voice, A – audio, DA – digital audio, DV – digital video
[f] - Applications require specific access protocol

III. EVALUATION OF ISM RADIOS IN INDUSTRIAL ENVIRONMENT

The license free radio bands that can be used by various low-power industrial, scientific and medical (ISM) applications have been specified by International Telecommunication Union Radiocommunication Sector (ITU-R) in Radio Regulations 5.138, 5.150, and 5.280 [18]. In Finland, the Finnish Communications Regulatory Authority (FICORA) has specified the use of these bands in [19] and [20]. The most widely used by IWSN bands and restrictions for their use are summarized in Table I.

Although currently there are available multiple radio wave propagation models (e.g., [21, 22]), their use for predicting the communication for a real-life industrial site is still very complicated due to discussed in Section II concerns. Therefore, for evaluating the features of different ISM bands we have used the real-life Systems-on-Chip (SoC, that integrated a radio and 8051-based microcontroller) from Texas Instruments, namely CC1110[23] (two different modifications: one - working in 433 MHz band, the other – in 868 MHz band, both radios had whip antennas), CC2510[24] (2.4 GHz band, Frequency-shift keying (FSK) modulation, swivel antenna) and CC2430[25] (2.4 GHz band, direct-sequence spread spectrum (DSSS), IEEE 802.15.4 compatible, swivel antenna). The main parameters of tested radios are summarized in Table II.

For the tests, we have used the SmartRF04 development boards [26] and the daughter boards with appropriate SoC. The software for the boards has been developed based on SimpliciTI [27] stack from Texas Instruments for radio communication with the modifications to enabling to change "in-field" such parameters as used datarate, modulation, filter bandwidths, packet size, delay between packets, and to switch on/off the Clear Channel Assessment (CCA). During the tests, each radio was tracking the number of transmitted, received and missed packets, the average Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI) for all received packets from each source node.

TABLE I. PARAMETERS OF USED DURING EVALUATION RADIOS [23,24,25]

Parameter	***CC1110 [23]***	***CC2510 [24]***	***CC2430 [25]***
Frequency band, MHz	300-348, 391-464, 782-928	2400-2483.5	2400-2483.5
Operating voltage, V	2-3.6	2-3.6	2-3.6
Modulation	2-FSK, OOK, MSK, GFSK	2-FSK, GFSK,MSK	DSSS
Output power, dBm	-30 … 10	-30 ... 1	-25…0.6
Current consumption (receive)[a], mA	20.4	22.9	26.7
Current consumption (transmit)[b], mA	21	26	26.9
Current consumption (sleep)[c], mA	0.5	0.5	0.5
Maximum datarate, kbps	500	500	250
Sensitivity, dBm	-94	-90	-92

[a] - 250 kBaud, input at sensitivity limit, MCU running at full speed
[b] - 0 dBm output power
[c] - Power mode 2
[d] - 250 kBaud data rate, 1% PER

The tests were conducted in two stages: initially all the radios have been tested indoors in laboratory environment in single and multi-hop modes and then the devices were evaluated in the real-life industrial environment. These tests were carried outdoors in a site of a factory that manufactures monolithic refractory materials and precast shapes (see Fig. 1). The results of the test are presented in Figs. 2-6. During all the tests, all radios were using the same power level of 0 dBm.

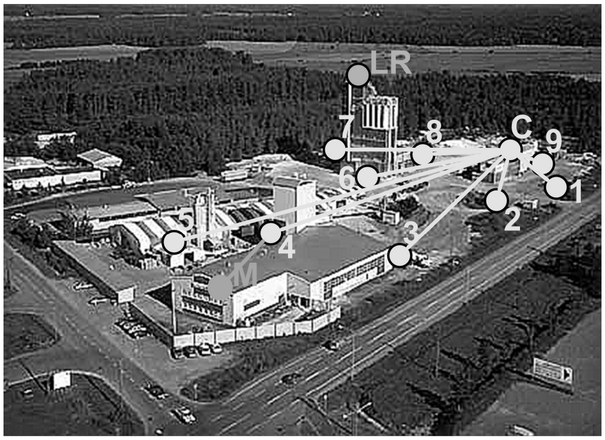

Figure 1. Industrial environment where the real-life radio tests were made.

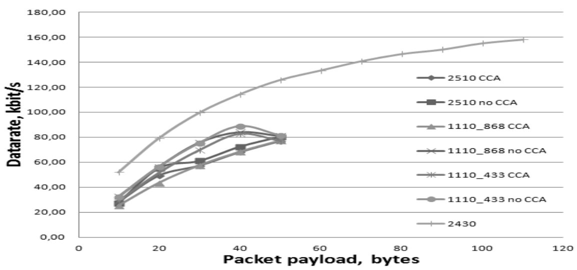

Figure 2. Maximum application data datarate for different radios over single hop in laboratory environment

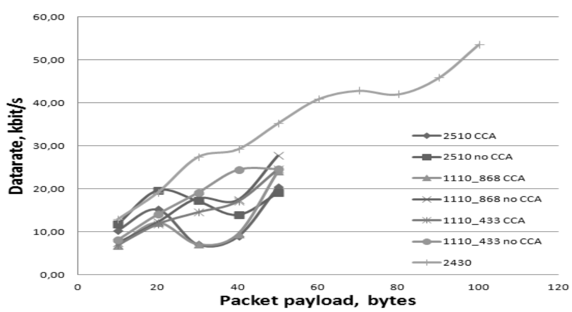

Figure 3. Maximum application data datarate for different radios over three hops in laboratory environment

As can be seen in Figs. 2 and 3, in laboratory conditions the maximum datarate for tested radios utilizing FSK appeared to be lower than of DSSS radio (the datarate was evaluated by sending 10000 packets). The main reasons for it are: the availability of hardware-implemented First In First Out (FIFO) buffer for tested DSSS radios (CC2430 radios have 128 byte FIFO while CC1110/CC2510 devices do not have hardware-implemented FIFO); the higher core clock rate (32MHz for CC2430 comparing with 26MHz for CC1110/CC2510); lower amount of overhead data (6 bytes for CC2430 and 8 bytes for CC1110/CC2510 [23-25]). As can be seen in Fig. 2, the datarate for FSK radios using packets with 40-bytes payload appears to be higher than for 50-bytes payload (the radio

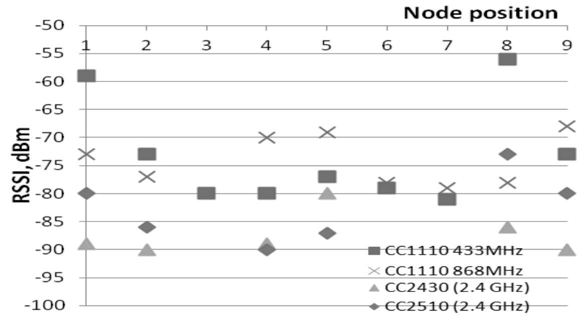

Figure 4. RSSI for signal from Coordinator(C) at different test points of industrial site (see Fig. 1 for test points location)

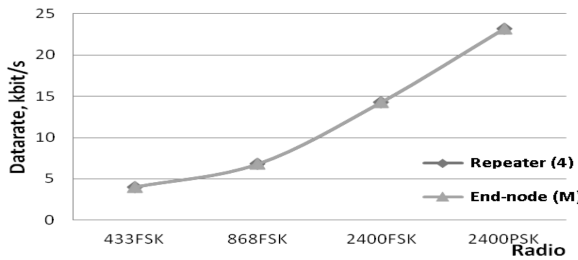

Figure 5. Maximum application data datarate for different radios over two hops in industrial environment (nodes C->4->M on Fig. 1)

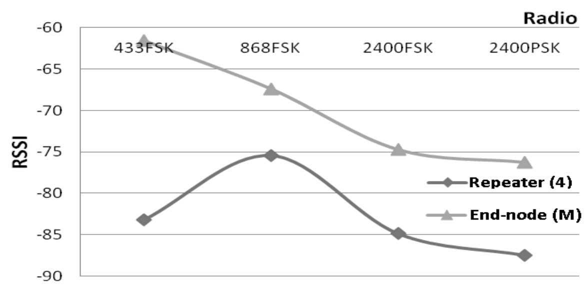

Figure 6. RSSI for different radios during two hop measurements in industrial environment (nodes C->4->M on Fig. 1)

nodes were at the distance of less than 3 meters from each other and Received Signal Strength Indicator (RSSI) was above -50 dBm). This can be the sequence of used application data format - the packet has been filled with 0xFF bytes after first 6 databytes, which could have caused the loss of bit synchronization during long packets transmission by FSK-based transceivers. The decrease of datarate for some packet sizes over the multihop connection (see Fig. 3) was caused by the interferences between the radios and the lack of on-node packet queering for SimpliciTI (a new packet was overwriting the older one if it has not been transmitted before receive of a new packet).

During the tests carried in the industrial environment, the wireless nodes featuring different radios (all the radios had the same output power and datarate) were placed in 10 different locations (see Fig. 1). During the first test, for all the nodes was evaluated the RSSI of the signal from the network coordinator (C on Fig. 1). The results of the measurement are presented in Fig. 4. As Fig. 4 reveals, the 433 MHz radio was the only one, which managed to receive the signal from the coordinator in all test points. Nonetheless, in five out of nine test points the RSSI values for 433 MHz band radios were lower than for 868 MHz radios. The radios at 2.4 GHz band were able to receive the signal from the coordinator only in six sites out of nine. Also it should be noted that the RSSI level for 2.4 GHz FSK radios in all test points appeared to be higher than for 2.4 GHz DSSS radios.

Besides, in industrial environment was carried out the throughput test for the communication between the coordinator note and main office of the factory (node M on Fig. 1, installed indoors, overall for each radio were transmitted 10000 packets) using the node 4 as the router (during throughput test the nodes in points 1-3 and 5-9 were not active). The results of the test are presented in Figs. 5 and 6. As reveal the presented data although RSSI levels for 433 and 868 MHz radios are higher than for 2.4 GHz radios, surprisingly the overall datarate for 2.4 GHz radios is higher than for radios using lower frequencies. We suppose that the reason for it is the cumulative influence of already discussed factors that affected the laboratory tests and of the industrial environment factors discussed in Section II.

Finally, for different radios we estimated the maximum communication distance. For it, the coordinator was placed on the top of 30 meter high tower (point LR on Fig. 1) and an end node (installed in a car) was moved away from the industrial site. The distance between the node and the tower at which the node stopped receiving the beacons from the coordinator was approximately 400 meters for CC2430 (was used datarate of 250 kbit/s), 800 meters for CC2510 (38.4 kbit/s datarate), 1300 meters for CC1110/868 MHz version (38.4 kbit/s datarate) and over 1600 meters for CC1110/433 MHz (38.4 kbit/s datarate). The further analysis revealed that for the tested FSK radios the decrease of datarate to half of the original resulted in the increase in communication distance approximately 5% thus allowing to increase the communication distance and network coverage area at a cost of throughput.

IV. INDUSTRIAL WSN USECASES

The RealFusion project included the development and evaluation of two real-life IWSN applications that are briefly discussed in Sections IV.A and IV.B.

A. *IWSN for Factory Silos Monitoring*

The first application that has been developed within the RealFusion project utilized IWSN for monitoring the amount of bulk substances in the silos of a refractory materials factory. The application was deployed at the same industrial environment, which was used for evaluating different ISM radios (see Section III), and allowed to remotely monitor the amount of substances in five silos.

To measure the amount of substances in a silo a WSN node that was equipped with the ultrasonic transducer pointing inside the silo was installed on top of each silo (see Fig.7). Based on the real-life measurements it was figured out that the output current of ultrasonic transducer changes linearly from 4 mA for completely empty silo and up to 20 mA for

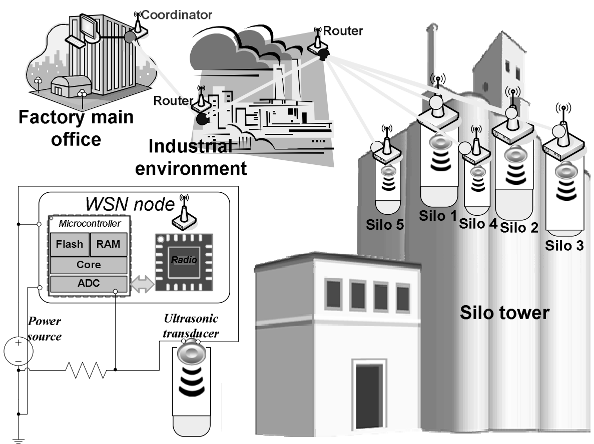

Figure 7. Structure of deployed IWSN for silos monitoring and structure of WSN node for silo level monitoring

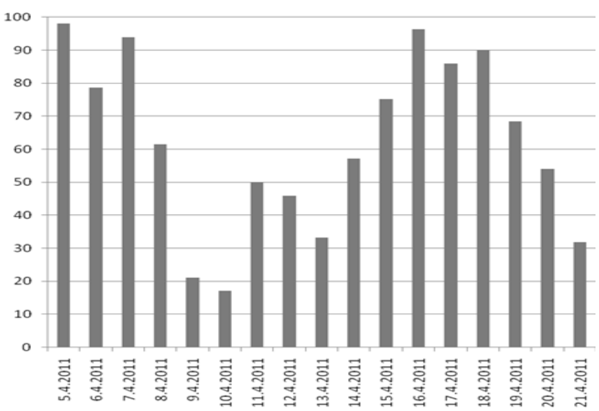

Figure 8. Percent of succesfully delivered packets over various days.

completely full silo. For converting the output signal of ultrasonic transducers into digital form were used the ADC of the WSN nodes' microcontrollers (see Fig. 7).

The measurements of the amount of bulk substances in each silo were made approximately once per eight seconds and then the measurement data, together with the time stamp, was forwarded through the routers to the coordinator node located in the factory main office (see Fig. 7).

The developed application has been evaluated for two different types of radio nodes: the 868 MHz radios from Atmel (utilizing Atmel's Bitcloud protocol stack) and 433 MHz radios from Radiocrafts.

The IWSN that has been implemented using 868 MHz radios remained operational for about one week before the radio connections abated and the network collapsed. The addition of new routers and duplication of existing communication lines was not able to significantly improve the IWSN reliability.

The utilization of 433 MHz radios provided higher communication reliability although even for those radios the communication robustness varied significantly over the time (see Fig. 8). As revealed in Fig. 8 although the average delivery probability was around 63%, on some days the number of successfully delivered packets was less than one quarter. Note, that the days with the highest packet loses (9 and 10 of April 2011) were the weekends when the factory was *not active*. Nonetheless, during the next weekend (16 and 17 of April 2011) the delivery probability stayed well above 80%.

B. WSN for Industrial Storage Monitoring

The second application utilized WSN for remote monitoring of environment conditions in an industrial warehouse (8 x 30 x 5 meters). Nine WSN nodes that have been equipped with the temperature and relative humidity sensors and 868 MHz radios from Atmel were placed in a warehouse (see Fig. 9) and were reporting the data to the access point (AP) with a period of 16 minutes. Every 25 minutes all novel data, received by AP, was stored in the database using Internet connection (see Fig. 10). The database was running on a remote server located in the main office of the company. For allowing access to this data from remote terminals was developed special Java-based application.

The radio communication within WSN has been implemented using the modification of Bitcloud radio stack (Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) was used for media access). Between the measurements, the WSN nodes utilized the low-power mode for energy saving.

The application was running for around ten weeks before the batteries' energy of WSN nodes has been exhausted (the nodes were supplied from 3 AA Alkaline batteries). Over that time, each node reported to the access point over 13 thousands measurements (quite often the measurements had to be retransmitted one or even more times). Fig. 11 represents the obtained during the tests data for six out of nine installed sensors.

As revealed in Fig. 11, at the start of operation the difference between the temperature values, reported by various wireless sensor nodes, was quite big – at different points in the warehouse the temperature was ranging from minus four up to plus four degrees Celsius. Note, that the tested warehouse had already been equipped with an automatic temperature control system that was configured to upkeep the temperature around three degrees Celsius (the control system naturally included the temperature sensor). Based on the measurements from deployed WSN, during the first week two additional heaters were installed in the warehouse. This allowed reducing the temperature variations in future (see Fig. 11). It should be noted that the warehouse, where WSN has been deployed, is used for the long-term storing of temperature sensitive goods and is usually not attended. Therefore, the environment in the warehouse is not subject to frequent changes - during the WSN operation the environment has significantly changed only once (during day 13), when some of the goods have been removed from the warehouse. This moment is clearly visible from the RSSI chart that is presented in Fig. 11.

An interesting observation can be made after further analysis of the measurement data. The sample correlation coefficient over the whole measurement period (calculated

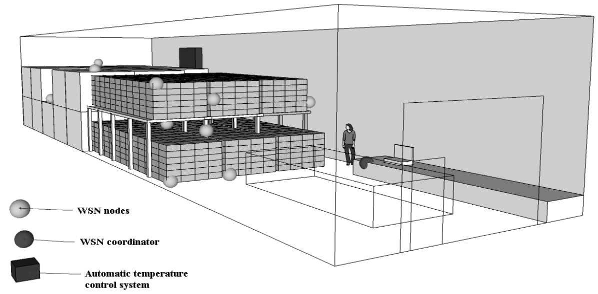

Figure 9. WSN for remote environment monitoring installation inside the warehouse

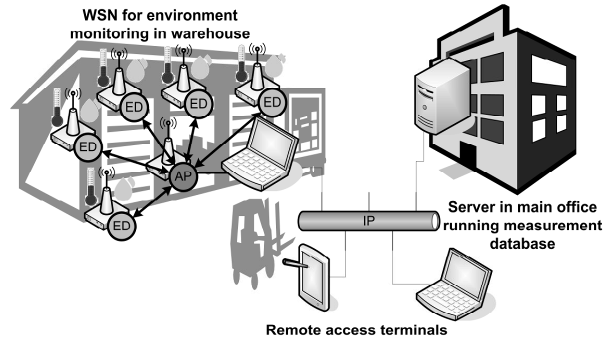

Figure 10. Architechture of application for remote environment monitoring inside the warehouse

using Equation 1, where x_i and y_i are the measurement Equation 1, where x_i and y_i are the measurement samples and n - number of measurements) for the measurements from two different sensors is on average 0.71 (the minimum sample correlation coefficient between two sensors was below 0.2) for temperature values and 0.63 (with -0.05 minimum value) for relative humidity values. The average sample correlation coefficients calculated over shorter periods of time were even lower.

$$r_{xy} = \frac{n \cdot \sum x_i \cdot y_i - \sum x_i \cdot \sum y_i}{\sqrt{n \cdot \sum x_i^2 - \left(\sum x_i\right)^2} \cdot \sqrt{n \cdot \sum y_i^2 - \left(\sum y_i\right)^2}} \qquad (1)$$

Also, based on the presented in Fig. 11 results it can be noted that although most of the time the environment in the warehouse was static, the RSSI of signals from different nodes over that time had some fluctuations. For some nodes, those fluctuations were very significant.

V. Discussion and Conclusions

The industrial environment is very challenging for wireless networks overall and Wireless Sensor Networks (WSNs) in particular. The main objective of the RealFusion project was to evaluate different WSN radio options to be used in real-life industrial environment and to evaluate in practice several real-life Industrial WSN applications.

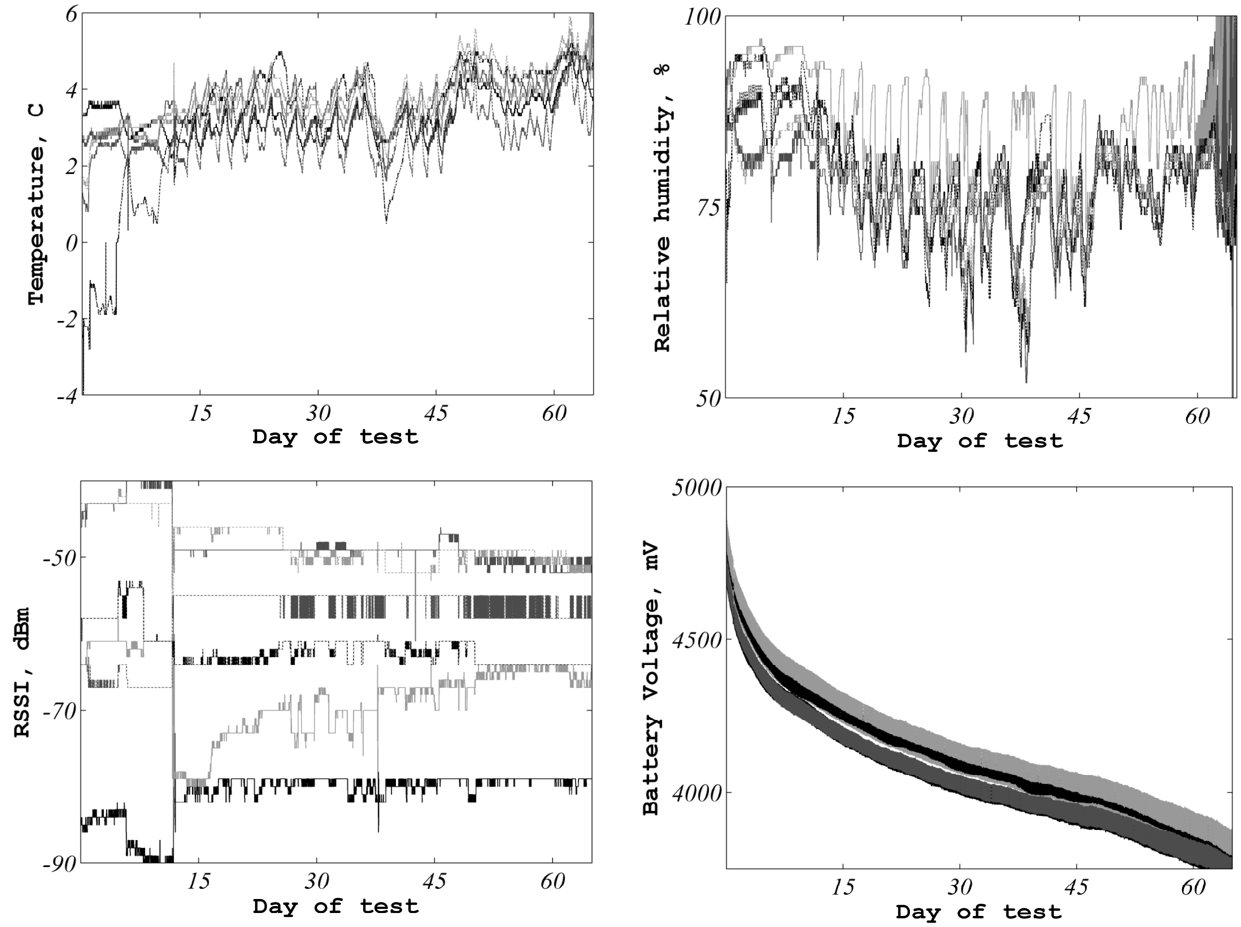

Figure 11. Data obtained from sensor nodes during the evaluation.

As reveal the presented in the paper results although the low radio frequency bands (433 and 868 MHz) allow to get better coverage and longer communication distances, the links implemented by those radios in industrial environment are very unreliable and the achieved maximum datarate is quite low. Although the radios at 2.4 GHz provide lower coverage, their usage in the tested environment allowed to increase the average communication datarate comparing to 433 MHz and 868 MHz radios. Meanwhile, as revealed in the presented measurement data and proved by results of the first application deployment, the radio propagation conditions in industrial environment can vary significantly over time in accordance with nontrivial laws. For real-life applications those variations can result in periodic losses of significant amount of data packets or, as it happened e.g., for tested application with 868 MHz radios, in the collapse of the whole WSN. Meanwhile, as has been shown during the evaluation of the second application, even if the site is not attended and is not subject to frequent changes, the radio communication conditions have some minor fluctuations over time.

An interesting result that was obtained during the evaluation of second application is that the correlation between both the temperature and humidity values within the same compartment can be rather low even in the case that the environment in the compartment was not a subject of frequent changes.

Although the use of WSN provides many benefits for industry and there are many various potential application areas for Industrial WSN, the problem of implementing reliable wireless communication in real-life industrial environment is still very complicated and requires further research. The presented paper has provided some initial evaluation results for different ISM radios in real-life industrial environment that can be valuable for developing the new IWSN applications and have revealed some real-life problems to be solved in future.

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