A Management Strategy for Centralized Wireless Sensor Networks Applied to Small and Medium Sized Manufacturing Enterprises

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Abstract—The demand for Wireless Sensor Networks (WSN) applied to industrial process monitoring and control is increasing as the forth industrial revolution (Industry 4.0) gathers pace. Flexibility and low cost make WSN the perfect choice for these modern 21st century manufacturing plants. Small and Medium Sized Enterprises (SMEs) have an important role in the growth of developing economies as they account for approximately 60% of all private sector employment, but are currently finding it difficult to take advantage of new sensor technologies. This paper describes the tests carried out with a WSN in order to ascertain the relationship between the Received Signal Strength Indicator (RSSI) and the Packet Error Rate (PER). Subsequently, a new RSSI based network management strategy is presented; it includes two RSSI tracking indices that guarantee an early warning in case the radio signal deteriorates. Both indices are generated in real time; the first estimates the RSSI tendency allowing for the mapping of a sample position in the set and its value, while the second compares the current RSSI to a preconfigured reference value. This article ends with the implementation and testing of the strategy on the ScadaBR Supervisory System.

Keywords-Wireless Sensor Networks; WSN; PER; RSSI; Network Management.

I. INTRODUCTION

Small and Medium Sized Enterprises (SMEs) contribute decisively for the advancement of developing countries. Worldwide, SMEs account for about 52% of private sector value added, varying from 16% of the gross domestic product (GDP) in low-income countries to 51% of GDP in high-income ones. SMEs dominate the world business stage; estimates suggest that more than 95% of enterprises across the world are SMEs, accounting for approximately 60% of all private sector employment [1].

If compared to wired networks, Wireless Sensor Networks (WSN) can offer substantial advantages regarding deployment, commissioning, and maintenance [2]. These networks can cover areas that are out of reach for wired networks allowing for the improvement of the processes.

The WSN currently offered by large solution providers tend to be complex, non-centralized and expensive [3] putting these solutions out of the reach of most SMEs considering that, differently from large corporations, these companies have neither the capital to acquire nor the dedicated departments to manage these new communication technologies [4].

The *raison d'être* of a WSN is to monitor and control processes and environments. A manufacturing process can be defined as a systematic series of operations executed to produce something. The more critical the process is, the more reliable the link needs to be [5]. The management of a WSN must define a set of functions that will integrate configuration, monitoring, operation and maintenance of the network services and devices [6].

Table I compiles the service classes for industrial environments, according to the International Society of Automation (ISA) [z].

TABLE I. SERVICE CLASSES (ISA)

Use	Class	Description	Characteristic
Safety	0	Emergency Action	Always Critical
Control	1	Control (Closed Loop)	Usually Critical
	2	Supervision Control (Closed Loop)	Usually not Critical
	3	Open Control (Open Loop)	Human Action
Monitoring	4	Alert	Few Consequences
	5	*Logging, up* e *download*	No immediate Consequences

The processes criticality and the characterization of the signal and medium generate subsidies to the network management system. The International Organization for Standardization (ISO) divides the network management into five distinct areas. This classification was developed for the Open System Interconnection (OSI) model:

- Configuration management - controls, identifies and collects from and supplies data to managed objects.
- Performance management - evaluates the behaviour of managed objects and the effectiveness of the communication.
- Fault management - enables the detection, isolation and correction of abnormal operation of the OSI environment.

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- Security management - addresses aspects essential to the safe operation and protection of managed objects.
- Account management - enables charges to be established and costs to be identified [7].

In wireless communications, the received signal strength is media dependent [6]. A strategy that assists in estimating the Received Signal Strength Indicator (RSSI) tendency with relation to a threshold would be relevant to the performance and configuration management, as actions could be taken before that threshold is reached.

Supervisory Data Acquisition and Control Systems (SCADA) are industrial control systems used in the monitoring and control of remote devices. These systems collect data from remote sensor nodes in real time in order to monitor and control communication networks, including alarm monitoring, data processing, and equipment and conditions control. Based on the information from remote sensor nodes, manual or automatic commands can be executed on remote devices [8].

Big WSN suppliers tend to offer solutions for the needs of large enterprisers, with prices that can reach millions of dollars. These suppliers offer large, noncentralized networks that grant the routing decisions to the nodes [9][10][11], effectively rendering the network hostage of the topology, impacting in its control. This reality does not really attend the necessities of SMEs regarding cost, control and complexity, as, usually, these plants are small in area, demanding cheaper, less complex network solutions. Centralized solutions also allow for full network control.

For the tests in this paper, we use a low cost, centralized WSN approach geared towards SMEs, where the network manager has total control over its running.

We also identified a shortage of low-complexity network summarization solutions that can be used by non-technical operators working in SMEs. For that reason, in this paper, we present a management strategy that uses the RSSI as the main metric.

This paper is organized into eleven sections: in Section II we compare different WSN solutions, in Section III we explain the relation between RSSI and Packet Error Rate (PER), in Section IV we present the Radiuino Platform, in Section V we specify the testing set up, in Section VI we show the benchmarking test results, in Section VII we introduce the indices management strategy, in Section VIII we describe the tests done with the strategy, in Section IX we show the strategy implementation on a supervisory system, in Section X we show the tests done and in Section XI we present our conclusions and future work.

II. WSN IN THE INDUSTRIAL ENVIRONMENT

Since WLANs, Bluetooth, WiFi, WirelessHart and Zigbee, to mention just some, were introduced, a lot of the effort was focused on the non-licensed Industrial, Scientific and Medical (ISM) band of 2.4 GHz as some systems can require higher data rates. However, in some cases, this band may get overcrowded, degrading the signal. There are, however, other non-licensed bands reserved for ISM applications that can be used for wireless communication [12].

The 915 MHz ISM band is narrow and limits the maximum data rates. Applications such as SCADA, where the data requirements are lower than applications found in the 2.4 GHz frequency band, can use the 915 MHz band.

In this paper, we use a platform which operates on the 915 MHz band as there are no restrictions for the use of this ISM band regarding the application type [12].

III. THE RSSI-PER RELATION

The RSSI is chosen as the main metric in this study since link quality monitoring methods based on hardware, e.g., Link Quality Indicator (LQI), Signal to Noise Ratio (SNR) and RSSI, make use of basic metrics provided by the chip that, if compared to software solutions, require far less overhead allowing for a better response to changes on the link [13].

As indicated by [14], for a given scenario, there is a clear relation between the RSSI and the PER as the latter tends to go up as the RSSI goes down. In this paper, we propose a strategy that takes advantage of this relation.

IV. THE RADIUINO PLATFORM

All measurements in this work are done using the low cost, open software, open hardware Radiuino platform [15]. The firmware used in the transceivers was developed using the Radiuino Integrated Development Environment (IDE). The Radiuino platform is structured in layers of protocol akin to the Transmission Control Protocol/Internet Protocol (TCP/IP).

The RSSI and PER monitoring applications were developed in Python 2.6 [16] and the supervisory system used for the management was the open software ScadaBR [17].

V. BENCHMARKING AND TEST SET UP

Benchmarking tests were carried out on all modules before any tests with the strategy were carried out.

The module BE990 was the transceiver used in all nodes. All were configured with a data rate of 38.38 Kbps, operating in the ISM band of 915 MHz and using frequency shift keying (FSK) modulation. The BE990 complies with the Brazilian National Telecommunications Agency (ANATEL) regulations; it carries an Atmega 328 micro controller, a Texas CC1101 transceiver and a Texas CC1190 radio frequency (RF) amplifier [18].

Each sensor node was constituted of a module BE990 mounted on a DK104 development board. The module on the sink node was mounted on a UartSBee board [15]. We used 12 volts batteries to power the nodes during tests.

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For the benchmarking tests, the wireless communication link between the sink node and each remote sensor node was emulated using a coaxial cable.

In order to avoid saturation, Mini-Circuit attenuators [19] were placed between the module in the sink node and the modules in each sensor node, as indicated in Figure 1.

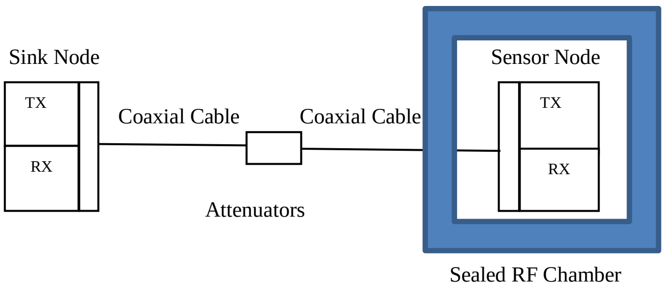

Figure 1. Emulation Setup Diagram.

The modules in each sensor node were placed in a sealed RF test chamber to check their normalization and assess their PER and RSSI results with minimum electromagnetic interference (EMI).

VI. BENCHMARKING AND CORRELATION TESTS RESULTS

The results of the benchmarking tests are summarized in Table II. It shows that all modules were conforming, returning very similar values of RSSI and PER for the same attenuation scenario, in this case 90 dB. The highest standard deviation was just 0.13 dBm and the highest PER only 1.6%, indicating good stability of all modules. We concluded that the modules could be considered normalized and could be used in the correlation tests.

TABLE II. BENCHMARKING RESULTS

Sensor	RSSI (average)	S.D. (dBm)	PER (%)
S1	- 42.50 dBm	0	0
S2	- 42.50 dBm	0.13	1.6
S3	- 42.00 dBm	0	0

The same set up shown in Figure 1 was used again to collect the information that allowed correlating the RSSI to the PER. This time, the attenuation was gradually increased, thus reducing the RSSI level at the sensor node and consequently increasing the PER, so to find the RSSI level corresponding to the 5% PER reference level suggested by [20]. In order to guarantee the reliability of the results, three series of 200 packets each were sent to each sensor node. The data presented in Table III shows the average results of the three test series.

TABLE III. CORRELATION RSSI - PER

RSSI Average (dBm)	PER (%)	RSSI SD (dBm)
-45.0	0	0.11
-52.0	0	0.31
-63.0	0	0.38
-69.5	0	0.64
-70.0	2.0	0.57
-71.5	2.5	0.69
-72.0	4.5	0.76
-75.0	5.0	0.57
-77.5	12.5	1.15
-80.0	38	4.41

The results indicate that -72 dBm is the maximum RSSI before the PER reaches the 5% reference level.

VII. INDICES ZR AND ZT

Indices aid in the monitoring work since they simplify the comparison of a current state with a past or predefined one.

This paper presents a management strategy that includes two indices, both generated in real time. The first estimates the trend of RSSI allowing for the mapping of a sample position in the set and its value, while the second compares the current RSSI to a preconfigured reference one.

These indices are loosely based on the Box Plot diagram and therefore present benefits such as the low complexity calculations required to obtain them, thus ensuring their easy implementation in supervisory systems.

In order to evaluate the trend of the RSSI based on the signal dispersion, we propose the index Zr composed by the ratio of the average RSSI values of a large, configurable, sliding time window (Zb) expressed by (1), which can also be understood as the historical average, by the average of the RSSI values of a small, configurable, sliding time window (Zs) expressed by (2).

$$Zb = \overline{x} = \frac{x1+x2+\cdots+xm}{m} \tag{1}$$

$$Zs = \overline{x} = \frac{x1+x2+\cdots+xn}{n} \tag{2}$$

Where $m > n$.

The index Zr, expressed by (3), shows how far Zs departs from the historical average Zb indicating the dispersion and, more importantly, the RSSI trend, with the advantage of returning values around 1. This index is independent of the signal strength in which the sensor node operates. This feature allows for its easy implementation in the monitoring of wireless sensor networks; since these sensor nodes are usually positioned in different areas, they tend to present different RSSI levels.

The index Zr will tend to 1 as Zs approaches Zb.

$$Zr = Zb / Zs \quad (3)$$

The second index, Zt, expressed by (4) tracks the value of Zs in relation to a reference value Rv correlated to a PER threshold and tends to 1 as Zs approaches this reference value. This index is dependent on the signal strength at which the sensor node operates.

$$Zt = Rv / Zs \quad (4)$$

The observation of these two indices gives the operative in charge of the network a clear vision of the sensor nodes current situation with respect to the RSSI and, consequently, the PER.

VIII. Indices Testing

For the preliminary tests of the strategy, a WSN as specified in Section V, comprising a sink node and a single sensor node was setup with the sensor node operating with a RSSI above the reference level of -72dBm, as established in Section VI, allowing for the mapping of the RSSI variation to the increase of the PER. From this data, the indices Zr and Zt were extracted and compared to the RSSI behavior. The choice of the sliding time window for the tests was based on the Quality of Service (QoS) we expect industrial processes will demand from a WSN, so the sliding time window used for Zb was 60 minutes and for Zs it was 1 minute. However, these values are still subject of research.

To validate the results, graphical comparisons between the variation of RSSI and Zr, RSSI and Zt and Zr and PER were done.

Figure 2 shows the RSSI with values in dBm on the primary vertical axis against the index Zr with values on the secondary vertical axis and the number of packets on the horizontal axis.

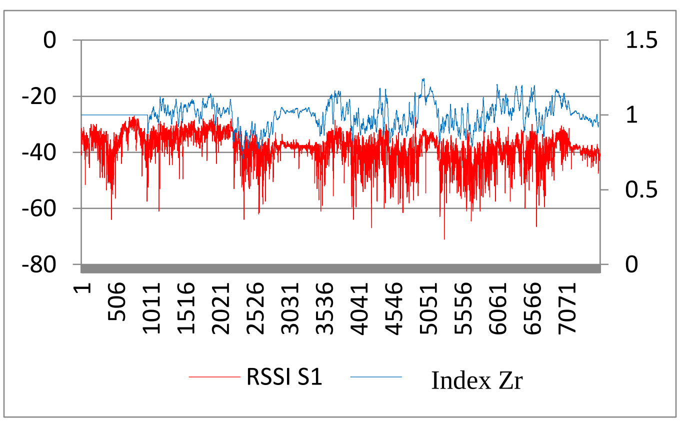

Figure 2. RSSI x Index Zr.

The graph shows that the index Zr was equal to 1 up to approximately the packet 1000, which is equivalent to the 60 minutes required for Zb to be established. From that point on, the index tracks the variation of RSSI, always centred on 1 and differs from the RSSI as it considers the averages of the last 1 and 60 minutes sliding windows. This feature dilutes the impact of possible extreme and discrepant samples.

The graphs in Figure 3 show the RSSI with values in dBm on the primary vertical axis against the index Zt with values on the secondary vertical axis, and the number of packets on the horizontal axis. The index Zt tracked the RSSI variation with respect to the reference level of -72 dBm that was never reached.

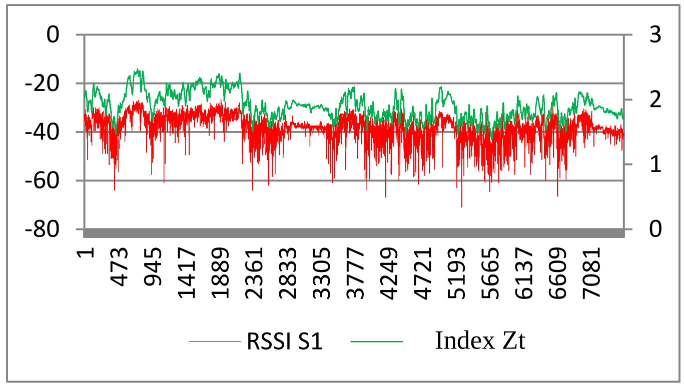

Figure 3. RSSI x Index Zt.

The index Zt acts as an alarm that is triggered whenever the RSSI reaches the pre-defined reference value, since its permanence at or below this threshold indicates an increase in the PER.

Figure 4 presents the index Zr with values on the primary vertical axis against the PER with values on the secondary vertical axis and the number of packets on the horizontal axis.

The graphs show that although the PER was consistently very low, it was higher at the times when the index Zr was below 1, that is, when the RSSI was below its historical average. It is important to observe that the graph of the PER is shown as the hourly average of its values.

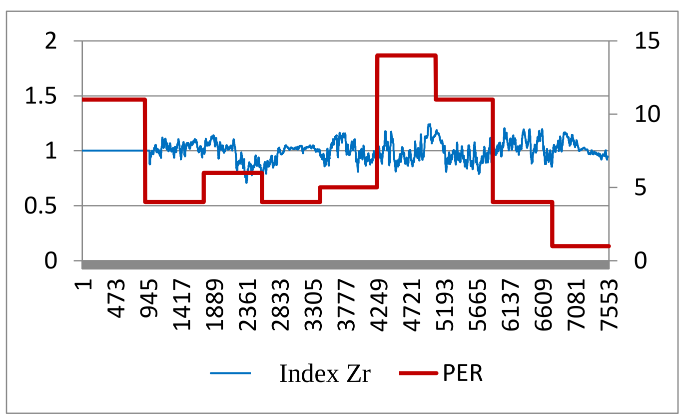

Figure 4. Index Zr x PER.

The results shown on the graphs confirm the robustness of the indices Zr and Zt and their applicability as a wireless network management strategy.

IX. IMPLEMENTATION ON SUPERVISORY SYSTEM

The strategy was implemented on the ScadaBR Supervisory System. For the tests, a WSN as specified in Section V, consisting of a sink node and three sensor nodes using a point-to-multipoint topology was set up, as shown in Figure 5. The supervisory system was configured to collect the downlink RSSI data from each sensor node, calculate Zs for the last minute and Zb for the last 60 minutes.

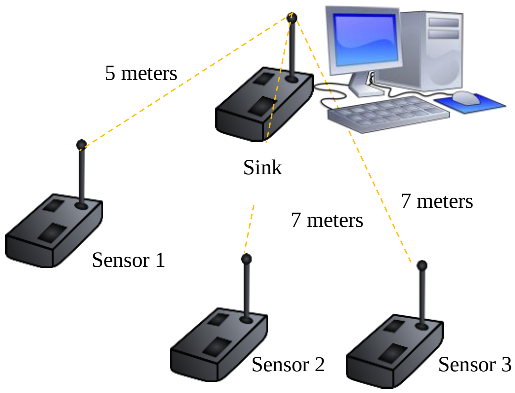

Figure 5. Point-to-Multipoint Topology.

Monitoring via supervisory system allows the construction of graphical interfaces in which different levels of information can be presented, contemplating different levels of knowledge. Figures 6, 7, 8 and 9 show the ScadaBR screen. In each figure, the bottom chart on the right, "RSSI Sensors 1,2 and 3" brings information that will be appreciated by a technically qualified person, the network manager, for example. The upper chart on the right, "Indices Sensors 1, 2 and 3" will be of great value for a person that is interested in the network but not necessarily technical, such as the production manager. The most concise information appears on the left side of the dashboard, with the Limit and Tendency light emitting diodes (LEDs) that are intended to alert a person that is not necessarily interested in the network, but dependent on it, such as a machine operator. Figure 6 shows a snapshot of the graphs obtained with sensor nodes 1, 2 and 3.

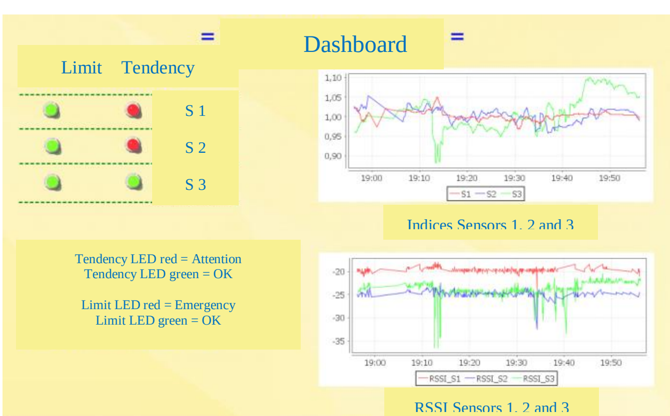

Figure 6. Supervisory System Dashboard.

The chart "Indices Sensors 1, 2 and 3" shows the variation of the index Zr for each sensor node while the chart "RSSI Sensors 1,2 and 3" brings the variation of RSSI. On the left, the Limit LEDs flash green while the index Zt is above the reference value, in this case -72 dBm, and red when Zt is at or below it, and the Tendency LEDs that indicate the position of the index Zr, flashing green while it is above 1 or red when it's below. For the sake of screen simplicity, we chose not to present graphs with the Zt index variation. It can be seen that the Tendency LEDs for sensor nodes 1 and 2 were red indicating that RSSI on these two nodes were in a downward trend. This fact can be confirmed by the graph "Indices Sensor nodes 1, 2 and 3" as the trend lines for sensor nodes 1 and 2 (red and blue lines) end below 1.

X. STRESS TESTING

To validate the use of the indices strategy on the ScadaBR Supervisory System, we extended the use of the test setup described in Section VIII. Tests introducing unexpected situations of use were carried out. These tests were useful to reveal any potential problems with the strategy on the supervisory system, such as performance or behavior issues, errors on startup, shutdown or on the interface.

The first test, shown in Figure 7, was done in order to ascertain what would be the supervisory system behavior in case one of the sensor nodes became unavailable.

The network was started and the 60 minutes needed for Zb to be established were observed. To simulate unavailability, the sensor node 3 was purposely disconnected from power.

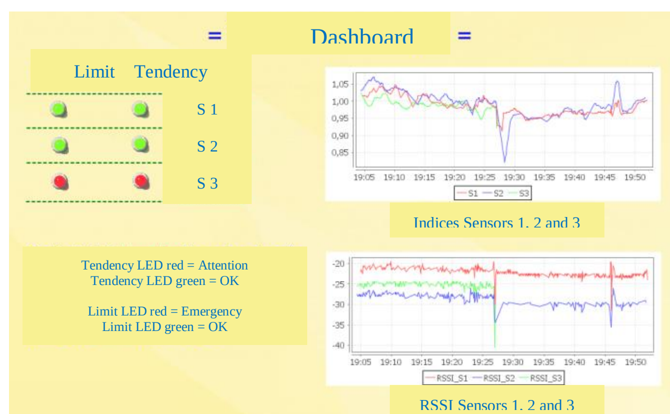

Figure 7. Supervisory System Dashboard - First Test.

The Limit and Tendency LEDs for the sensor node 3 immediately lit up in red and the green trend lines for the sensor node 3 on graphs "Indices Sensors 1,2 and 3" and "RSSI Sensors 1,2 and 3" disappear. We conclude that the strategy in the supervisory system behaved as expected.

The second test, shown in Figure 8, investigated the behavior of the indices strategy on a supervisory system in case of sudden signal deterioration. For this test, the sensor node 3 was distanced from the sink node, simulating signal deterioration. Again, it can be seen that the Tendency LED for sensor node 3 lights up in red and the green line in the "RSSI Sensors 1,2 and 3" graph reaches values below -40 dBm, reflecting accurately the node situation.

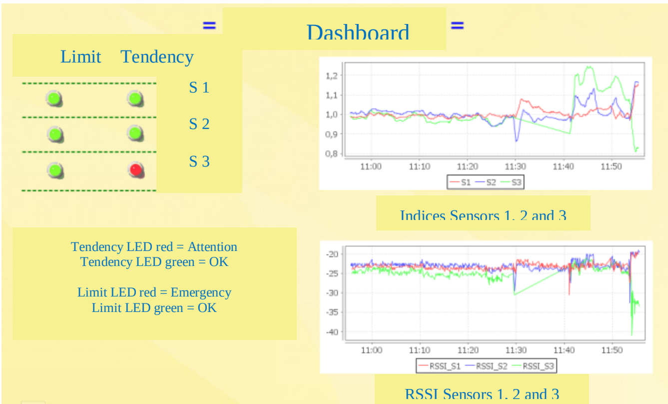

Figure 8. Supervisory System Dashboard - Second Test.

The third test, shown in Figure 9, investigated the supervisory system behavior in case of acute signal deterioration. For this test, the sensor node 3 was moved even further away from the sink node to a point where the RSSI reached and exceeded the reference value of -72 dBm, established in Section VI.

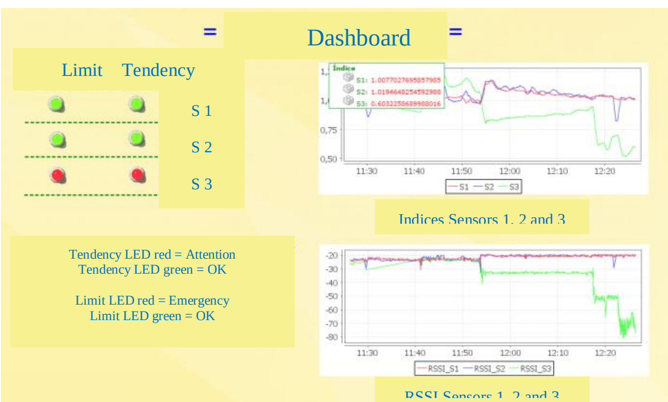

Figure 9. Supervisory System Dashboard - Third Test.

In this test, the dashboard shows the sensor node 3 Limit LED in red, indicating that the RSSI on that sensor node was below the reference value, which can lead to a PER above 5%. This condition was confirmed by the graph "RSSI Sensors 1, 2 and 3" as the green trend line for sensor node 3 reaches values below -80 dBm. The Tendency LED for that node also lights up in red indicating a RSSI deterioration which can be confirmed by the graph "Indices Sensors 1, 2 and 3" where the sensor node 3 green trend line shows the drop of the index Zr.

In order to carry out the last and most extensive test, all nodes were connected to mains power, in order to guarantee the uninterrupted supply of power. The test consisted of a continuous and uninterrupted use of the indices strategy on the ScadaBR for a whole week, in order to ascertain any possible system locking. At the end of that period, the tests pointed out that the system did not present any faults. The tests results with the indices strategy on the ScadaBR Supervisory System confirm the robustness of the solution.

XI. CONCLUSION AND FUTURE WORK

This paper objective was to demonstrate the feasibility of employing a new network management strategy based on indices that use the RSSI as the only metric, as this solution requires far less overhead allowing for a better response to changes on the link. For that, a testing set up using the Radiuino platform was assembled so data could be collected.

The preliminary tests with the indices strategy indicated that, when compared to the RSSI readings, the strategy presents an easier interpretation of the data as the impact of extreme and discrepant samples were diluted by it.

The strategy was also implemented on the ScadaBR Supervisory System where an interface that attended the needs of different levels of network expertise was created. The stress tests carried out then returned results that also confirmed that the strategy was stable and robust enough to be employed in the monitoring of WSN in SMEs and thus help these companies to take full advantage of the Industry 4.0 possibilities.

There are still a number of topics following from our findings that would benefit from more research, including the further development of the supervisory system, as other open source network and application monitoring software like the Zabbix could be tested and evaluated, and the development of a methodology for the choice of the sliding time window for the indices Zb and Zs, according to the different industrial plant environments and requirement settings.

Also, the deployment of the indices strategy in a real SME environment with sensors distributed across the plant, where adverse conditions like propagation issues and interferences in the spectrum are the norm, would allow for a better understanding of the real capabilities of the strategy.

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