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PII: S2452-414X(16)30095-4
DOI: 10.1016/j.jii.2017.02.003
Reference: JII 26

To appear in: *Journal of Industrial Information Integration*

Received date: 2 November 2016
Revised date: 4 January 2017
Accepted date: 9 February 2017

Please cite this article as: Federico Civerchia, Stefano Bocchino, Claudio Salvadori, Enrico Rossi, Luca Maggiani, Matteo Petracca, Industrial Internet of Things Monitoring Solution for Advanced Predictive Maintenance Applications, *Journal of Industrial Information Integration* (2017), doi: 10.1016/j.jii.2017.02.003

Industrial Internet of Things Monitoring Solution for Advanced Predictive Maintenance Applications

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Abstract

Internet of Things (IoT) solutions in industrial environments can lead nowadays to the development of innovative and efficient systems aiming at increasing operational efficiency in a new generation of smart factories. In this direction the article presents in detail an advanced Industrial IoT (IIoT) solution, the *NGS-PlantOne* system, specially designed to enable a pervasive monitoring of industrial machinery through battery-powered IoT sensing devices, thus allowing the development of advanced predictive maintenance applications in the considered scenario. To the end of evaluating the performance of the developed IIoT system in a real environment, the *NGS-PlantOne* solution has been first installed and then set in operation in a real electricity power plant. The deployed testbed, based on 33 IoT sensing devices performing advanced temperature and vibration monitoring tasks, has been kept in operation for two months while evaluating transmission delays and system operating life through power consumption measures. Performance results show as the developed IIoT solution benefits from all the advantages provided by the adopted IoT protocols, guaranteeing that each node is reachable through simple IP-based techniques with an acceptable delay, and showing an estimated average life of 1 year in case of each IoT smart device is configured to send collected and elaborated data every 30 minutes.

Keywords: Industrial Internet-of-Things, Smart Plants, Industrial monitoring.

1. Introduction

In the last several years the continuous advancements in the electronic field, as well as the development of new high performance and cost effective wireless

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communication systems, have fostered the so-called Internet of Things (IoT) vision [1]. The possibility of connecting devices or objects, while giving them the possibility to share information related to the surrounding environment, is a further step in the direction of creating effective Cyber-Physical Systems (CPSs) [2] in which monitoring and controlling tasks can be performed. Following such a vision, advanced applications based on IoT objects have been proposed in several application domains, thus laying the foundation for the creation of Smart Cities [3], Smart Homes [4], and more recently Smart Factories [5, 6].

Industrial Internet of Things (IIoT) systems can be successfully used to create effective smart factories in which higher levels of efficiency can be reached. IoT smart objects can be pervasively used to collect data on the field with the aim of improving productivity through advanced automatic processes [7], safety trough a deeper knowledge of workers position [8], and by reducing equipment faults through fast event detection capabilities [9]. By using wireless sensor devices to monitor equipment status, advanced and pervasive predictive maintenance applications can be developed, thus reducing maintenance costs and avoiding dangerous situations. Moreover, by considering IoT devices able to communicate and interoperate among them, possible delays due to human-in-the-loop interactions can be avoided, and a fast reaction to critical events can be achieved. To accomplish such a vision, and to create effective and smart wireless monitoring solutions in the IIoT scenario, several communication standards must be used to let devices to interoperate among them. When considering active wireless monitoring IoT nodes, the main standards to consider are [10]: (i) IEEE802.15.4 at physical and medium access control layers, (ii) 6LoWPAN and RPL at the network layer, and (iii) CoAP at the application layer. IEEE802.15.4 is the basic communication standard already used in well-known industrial wireless monitoring solutions such as WirelessHART and ISA100.11a [11]. 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) [12] provides IPv6 Internet-based communication capabilities on devices based on IEEE802.15.4, while RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [13] provides routing capabilities among nodes. The CoAP (Constrained Application Protocol) [14] standard, instead, provides RESTful-based capabilities [15], thus letting IoT objects to share monitoring information to be used for industrial analytic purposes according to the Internet paradigm. As a result, each node of the system can interoperate with all the other devices by exploiting IPv6-based capabilities and by offering or using data or other capabilities (i.e., the result of sensing activities or possible actuating capabilities).

Although the use of IoT-based solutions in the industrial environment is considered very promising by the research community and the industry, no real IIoT solutions aiming at improving reliability through advanced monitoring applications fully leveraging on the protocols reported above have been proposed and tested in an operational environment. As a consequence, no real information related to IoT system architecture components, devices design, and overall performance are available. Starting from these considerations, the paper presents a complete and fully operational IIoT solution, the *NGS-PlantOne* system, specially designed to support advanced predictive maintenance applications in the industrial environment, as well as extensive performance collected through a real deployment in an electricity power plant. In the paper, the system architecture is described before presenting all developed monitoring nodes with their on-board logic capabilities, and by highlighting all design choices, both hardware and software, oriented to the energy consumption reduction and communication latency, two main figures of merit to be considered for an operationally oriented system design. Regarding the deployed testbed, 33 IoT nodes have been installed in 3 areas where several industrial machinery are monitored, and performance concerning latency and power consumption evaluated over a period of 2 months starting from April 2016 when the whole system has been installed and commissioned, thus reporting an intensive and comprehensive study of the capabilities and performance of a complete IIoT system in real industrial environments.

The rest of the paper is organized as follows. Section 2 reports main related works by discussing IIoT solutions devoted to monitoring purposes. In Section 3 the *NGS-PlantOne* architecture is presented by detailing its main components. Section 4 carefully presents the testbed design and its deployment in an electricity power plant by reporting main issues encountered. The performance of the system are presented and discussed in Section 5. Section 6 concludes the paper.

2. Related works

The use of IoT-based wireless monitoring solutions in the industrial environment is considered very promising by the research community and the industry, as they allow to merge the benefits provided by classical wireless sensor networks based on the well-known IEEE802.15.4 standard (i.e., low-cost, flexibility, ease of relocation) [16] with the benefits provided by the IPv6 protocol (i.e., global addressing, autoconfiguration, mobility management), and by the RESTful architecture (i.e., scalability, uniform interfaces, web services approach). Following the above mentioned vision several works focusing on Industrial IoT systems, and aiming at increasing interoperability and performance at various levels have been presented. In [17], for instance, the benefits of the IoT in the industrial environment are highlighted while proposing a solution able to solve interoperability issues in smart sensors. Since each physical sensor device connected to a microcontroller unit requires different sampling rate, and signal types, a reconfigurable standard interface based on a complex programmable logic device is proposed. In [18], [19] and [20], instead, radio propagation issues, error correction algorithms, and advanced routing techniques are analyzed and proposed to improve network reliability and nodes survival rate in wireless sensors deployed in an industrial environment.

Despite the great potential of such IoT-based systems, real IIoT solutions aiming at improving reliability through advanced monitoring applications, as well as their real experimentation through extensive testbeds deployed in industrial environments, have not fully exploited. In this direction, related works mainly present feasibility studies based on laboratory implementations, thus without providing real information related to IoT system architecture components, devices design, and overall performance in real industrial environments. For instance, in [21] an emulated IIoT solution monitoring welding station is proposed and the correctness of the implemented system evaluated in a laboratory testbed, thus without considering performance related to latency and energy consumption, considered of utmost importance for these applications [22]. Such a work mainly focuses on the correct integration of envisioned technologies, while considering sensor devices implementing the whole IoT protocol stack and a software middleware running at a gateway level. Thanks to the adopted IoT protocols the middleware can manage a set of monitoring and control functions. Looking at overall system performance, in [23] the communication latency of an implemented IIoT solution is evaluated as a function of the network topology and the number of communication hops in a laboratory testbed. Main results show as an IIoT system outperforms traditional WirelessHART systems in terms of latency while providing advantages thanks to the adopted IP-based protocols. The same experimental approach based on a laboratory testbed is followed in [24] where an IIoT monitoring solution for liquid containers is presented and performance related to the onboard logic algorithms evaluated without considering delay or energy consumption. In the work, a multi-agent based approach is detailed considering both sensor and actuator network applications, thus showing the potential of an IP-based approach in creating effective cyber-physical systems.

In all above mentioned works, the great benefits of an IIoT solution are underlined, while only a particular element of a wider monitoring system is presented, and performance evaluated only on that specific part considering a controlled environment, thus providing limited figures of merit for the real deployment of IoT-based monitoring solutions. This work presents a complete and fully operational IIoT solution specially designed to support advanced predictive maintenance applications in the industrial environment. All components of the systems are first presented by underlining their design choices oriented to an operationally oriented system design. Moreover, extensive performance collected through a real deployment in an electricity power plant are reported and discussed to show the feasibility and benefits of the proposed IoT monitoring solution in an industrial environment.

3. System architecture and components

The presented IIoT monitoring solution can be described in a nutshell as a distributed system based on battery powered low-cost devices able to pervasively measure temperature and vibrations from machinery already installed in a power plant. The proposed system fully applies the IoT paradigm in the power plant monitoring scenario by considering the reference communication stack briefly reported in Section 1. More in particular, all monitoring devices (i.e., IoT smart objects) are able to abstract monitored variables, and detected events, as resources provided by embedded web-services. As a consequence, each resource can be handled by using the CoAP protocol working on top of

6LoWPAN, thus enabling a RESTful paradigm in the constrained environment. From an architectural point of view, *NGS-PlantOne* is similar to other other traditional monitoring solutions, with significant differences in the role of its components, since they are not simple devices but real IoT smart objects. The *NGS-PlantOne* high-level architecture is reported in Fig. 1, and it is mainly based on four main components: (i) sensor devices, (ii) gateway, (iii) Remote Control and Service Room (RCSR), and (iv) Open Platform Communications (OPC) server. All components are discussed in the following by underlying their role in the system, adopted communication protocols, main features, and a high-level description of the embedded logic they implement to be considered real smart objects.

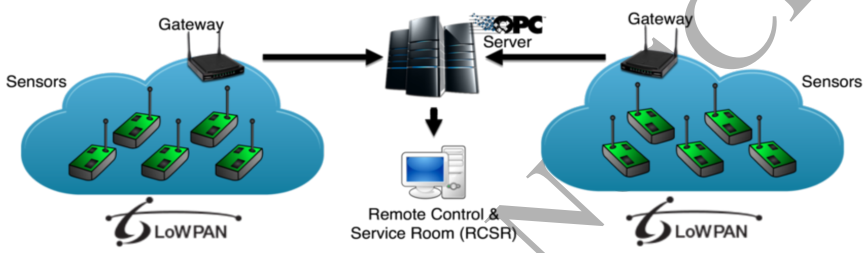


Figure 1: *NGS-PlantOne* architecture.

Sensor devices constitute at the same time the lowest and the most important part of the system. In fact, they directly interact with the environment by measuring variables of interest and by processing acquired data to perform onboard analysis tasks. As previously briefly introduced two main sensor devices have been developed for monitoring purposes: (i) a temperature node able to measure machinery temperature, and (ii) an accelerometer node able to perform vibration analysis tasks. Both nodes are depicted in Fig. 2, they mainly embed a System-on-Chip (SoC) able to run dedicated applications and manage the whole network communication stack based on IEEE802.15.4, 6LoWPAN and CoAP protocols. More in particular, the CC2538 [25] from Texas Instruments (TI) has been selected as the main component of the system because its low-power oriented design, while a battery fuel gauge, the TI BQ27441-G1 [26], has been installed. Such a component is directly connected to the selected battery [27], thus controlling the battery recharge when the device is connected to the conventional power source. The fuel gauge is able to provide information on the battery status (remaining battery capacity (mAh), state-of-charge (%), battery voltage (mV)) during the operation of the system. A picture of the base board on which the two sensor nodes have been developed is reported in Fig. 3. Regarding the temperature node (Fig. 2a), such a component installs a probe which at one end mount an analog temperature sensor to be installed in contact with the machinery. The analog to digital conversion is performed by a very performant converter, thus letting to reach a precision of 0.55℃ in the range between -50℃ and 200℃. The accelerometer node (Fig. 2b), instead, is connected

(a) Temperature monitoring node.

(b) Vibration monitoring node.

Figure 2: *NGS-PlantOne* monitoring nodes.

to a probe in which a digital three-axis accelerometer has been installed inside a housing made of epoxy resin. The selected accelerometer has a sampling rate of 800 Hz with a resolution of 12 bits. According to the IoT vision, both nodes can be considered real smart objects since they do not merely sense and send data, but onboard analyses are performed. More in particular, the temperature node is able to send both raw data and events about critical situations. When the detected temperature is bigger than remotely programmable thresholds the sampling rate is automatically increased, and all events are sent towards upper layers of the system. To this end, programmable thresholds, acquired data, and critical events are variables that are exposed as network resources by the embedded web-service and then managed through CoAP methods. In the accelerometer node, a basic vibration analysis is performed by evaluating, on each axis, Peak-2-Peak (P2P) and Root-Mean-Square (RMS) parameters on windows of time. When such values result bigger than programmable thresholds, a fault event is reported. Also in this case, programmable thresholds and fault events are exposed variables that can be managed through CoAP methods. As re-

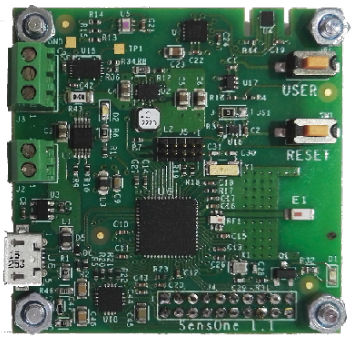


Figure 3: Base board for *NGS-PlantOne* monitoring nodes.

ported above, in this case, the sensor device perform a basic three-axes based vibrational monitoring analysis based on parameters evaluated in the time domain. Enhanced algorithms performing analysis in the frequency domain (e.g., Fast Fourier Transform evaluation) have not been implemented because of their complexity. Since the whole monitoring network is required to work without external power supply, thus enabling retrofitting capabilities of already installed machinery, all sensor devices are battery equipped. To save energy not only the whole hardware design has been targeted to low-power consumption, but all applications have been developed accordingly, and radio duty cycling policies have been adopted while reducing the number of packets to be sent over the wireless channel. For the whole application design the Contiki Operating System [28] with the Erbium REST engine [29] has been used, and the low-power features provided by the TI CC2538 have been exploited, thus reducing the SoC consumption. From a network point of view, a basic radio duty cycling policy has been implemented on sensor devices. By leveraging on IEEE802.15.4 medium access control layer features, provided in hardware by the TI CC2538, a custom radio duty cycling layer acting with the same principles of the default Contiki radio duty cycling mechanism (namely ContikiMAC) has been used. The check rate of the radio duty cycling mechanism has been imposed equal to 8 Hz, thus following the suggestions of other works focusing on radio duty cycling approaches. In the current firmware implementation of the sensor nodes no network security algorithms have been considered. Even though in its actual implementation two type of sensor devices have been considered, new devices embedding other sensors or actuators, and compliant with IoT protocols can be easily added in the monitoring segment. In fact, thanks to the main features introduced by the IPv6 protocol, they can be recognized in a plug&play manner and exposed resources made available to upper layers.

The gateway of the system is a multi-MAC network node placed at the border of the monitoring network and able to interact on one side with the sensor nodes, and, on the other side, with the backbone network. From a communication point of view the gateway translate 6LoWPAN messages coming from end devices to IPv4 or IPv6 data packets to be sent towards a remote control and service room. From a hardware point of view, the gateway is an embedded system based on a microprocessor, no battery powered, and able to host IEEE802.15.4 and Ethernet communication modules, a picture of an installed gateway is reported in Fig. 4. The developed gateway does not realize simple network translation tasks, but it embeds network management and data storage capabilities. By leveraging on IoT protocols on the monitoring network side, the gateway is able to manage and optimize data requests and event notification policies, to check node connectivity and perform system integrity tests. The embedded local database permits to store a large amount of data, thus addressing remote connection problems, and avoiding the loss of useful data that could be used for offline analysis aiming at improving predictive maintenance applications. Thanks to its software design the gateway could host, in the near future, onboard understanding capabilities to be used to take local decisions on acquired data and detected events, thus fully exploiting distributed processing capabilities in the IoT scenario.

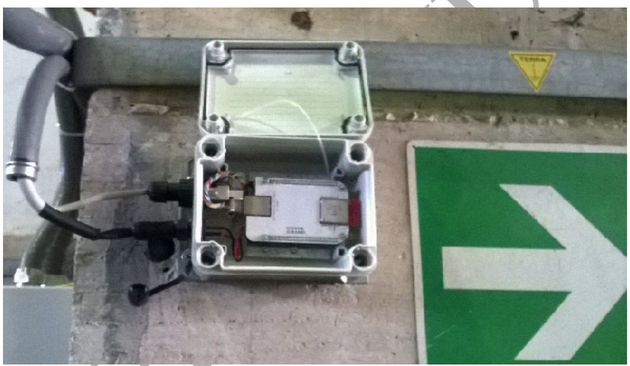


Figure 4: *NGS-PlantOne* gateway.

The RCSR is a remotely located computer which provides several features. Since it is meant to be installed in the main control room of an industrial plant, the RCSR provides a visual tool showing the behavior of monitored parameters for each machinery, as well as all possible alarms based on detected events. From the RCSR it is possible to perform on-demand queries to specific sensor nodes (through the dedicated gateway), to know their status or other useful management parameters such as the residual percentage of the battery and the transmission latency. Moreover, the RCSR hosts a database to store all collected data to be used for big-data analysis purposes, and connectors towards an OPC server, a necessary component to interoperate with standard industrial systems.

The OPC server is the last component of the system. It is in charge to store all data acquired from all monitoring segments in order to let industrial systems embedding OPC clients to gather on-the-field acquired information in a standard way. For instance, data in OPC servers can be retrieved by Supervisory Control And Data Acquisition (SCADA) systems or other Human-Machine Interface

(HMI) tools to be shown in industrial visualization tools. The OPC server has been developed as part of *NGS-PlantOne* while enabling its interaction with the RCSR.

4. Testbed design and deployment

To the end of evaluating the performance of the presented system in real conditions, an extended testbed has been installed in an electricity power plant. In particular, 3 monitoring networks have been installed in 3 selected areas and connected to the RCSR through system gateways. Each area has been chosen in accordance with the plant personnel, thus selecting systems in operation in which a pervasive monitoring of temperature and vibrations can improve maintenance policies. The 3 selected areas are: (i) Area 1 - Evacuation heavy ashes, (ii) Area 2 - Seawater pumps, and (iii) Area 3 - Evaporators. All areas are detailed in the following by reporting the number of installed devices, monitored machinery, and on-the-field activities. Overall considerations on the system deployment, as well as main problems encountered during the installation are reported at the end of the section.

4.1. Area 1 - Evacuation heavy ashes

In the first selected area, 7 sensor devices have been mounted to monitor temperature and vibrations in several points of an ashes water pump. Since the selected machine is considered of particular importance, and it is quite large in size, 4 nodes for the vibration monitoring and 3 nodes for the temperature have been installed close to critical parts. A picture of several installed nodes is reported in Fig. 5. The whole monitoring area is managed by a single gateway, which position has been experimentally defined trough Packet Loss Rate (PLR) measures considering the farthest sensor. For all selected positions the PLR is

Figure 5: Sensor devices installed in Area 1.

lower than 10%. Since all devices are battery powered, the whole area has been installed in half day, with the greatest loss of time due to the installation of the gateway. Such a component is not battery equipped, and moreover, it is connected to the main network of the power plant through a wired connection. No time overhead was required for the sensor probes installation on top of the machine since all magnetic solutions have been selected by the plant personnel involved in monitoring tasks.

4.2. Area 2 - Seawater pumps

In the second area, two machinery to be monitored have been selected, in particular, a feed pump and a lubricating oil exchanger. The feed pump has been equipped with 4 sensors, a picture is reported in Fig. 6, while 3 more sensors have been installed to monitor the lubricating oil exchanger. A total of

Figure 6: Sensor devices installed in Area 2.

7 sensor devices has been installed in the second area. Since the two machinery are located at a distance of around 10 meters with several obstacles in the middle, and the only possible position of the gateway was unable to guarantee acceptable PLR values, 3 router nodes have been installed. A router is basically a sensor device without sensing capabilities (no probes are installed on the

device) and connected to the power supply. Its primary role is to forward data packets according to routing paths established by the RPL protocol, thus fully exploiting multi-hop communications in industrial IoT systems. Thanks to the use of the 3 routers, the final PLR in the whole area results lower than 5%. The whole area has been installed in one day and a half with delays due by the necessary electrical wiring to power the routers. Also in this case, magnetic probes have been used because of their ease of installation.

4.3. Area 3 - Evaporators

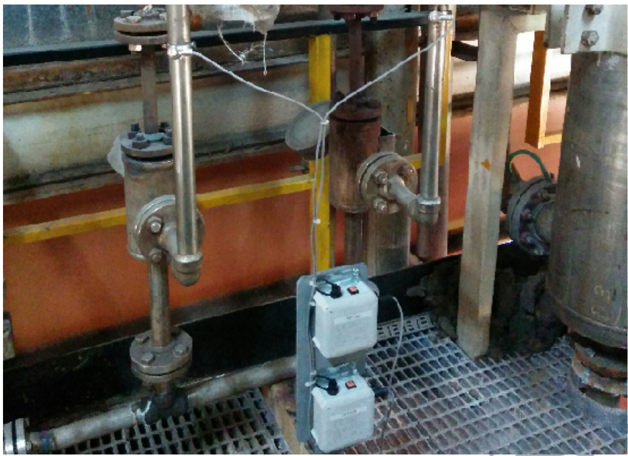
The last area is the biggest in the number of installed devices among the 3 selected. In this area several pumps have been equipped with both temperature and vibration sensors, for a total of 4 machinery (ejector, condensate, distilled and recirculation pumps) monitored with 19 wireless sensors. All monitoring devices plus one gateway have been installed in this area during one day and a half of work. The position of the gateway has been evaluated through several tests conducted on the field and based on the PLR evaluation, thus requiring additional time for the complete deployment of the area. As a result of the conducted tests the gateway has been installed in a position able to guarantee a maximum PLR lower than 10%. Some sensor devices installed in the third area can be noticed in Fig. 7 where two monitored pumps are depicted: the ejector (Fig. 7a) and condensate (Fig. 7b) pumps. In this case, both magnetic and clamp mounted sensors have been used.

4.4. Overall considerations on system deployment

From an architectural point of view, the deployed system is equal to the reference high-level architecture reported in Fig. 1, with the addition of one more monitoring area. Since the gateway associated with a monitoring area embeds network management and data storage capabilities, the system results highly scalable, and other areas can be easily added for further extensions. The whole commissioning of the 3 areas has required less than one week with delays mainly due to the installation of gateways and routers, which are devices regularly powered by the electricity network. The installation of a single sensor requires a very little amount of time, moreover, thanks to the IPv6 protocol features it is automatically recognized by the system (i.e., plug&play capabilities) and all information related to the sensor itself (e.g., IPv6 address, exposed resources, etc.) appear on the graphical interface of the remote control and service room. The only necessary configuration step during the installation phase is the association of the sensor with the monitored machinery, a step that can be easily done in the RCSR by associating an human-readable label to the IPv6 address of the device. An image of the RCSR showing the output of a temperature node, as well as an indication of possible dangerous events, is reported in Fig. 8.

5. Performance evaluation

The performance of the system have been measured in terms of latency and power consumption over a period of 2 months starting from April 2016. The



(a) Ejector pump.

(b) Condensate pump.

Figure 7: Sensor devices installed in Area 3.

first performance parameter, the latency, has been selected to measure the delay which affects the communication in the monitoring segment, thus considering sensor to gateway transmissions only. The latency parameter has been measured for each node in each area by performing several tests during the data collection period. To this end the ping command (available thanks to the adoption of the 6LoWPAN protocol) has been used, thus measuring the average connection Round Trip Time (RTT). All results reported in the following have been averaged among all measured values by indicating the number of hops between the device and the gateway. The second parameter, the power consumption, has

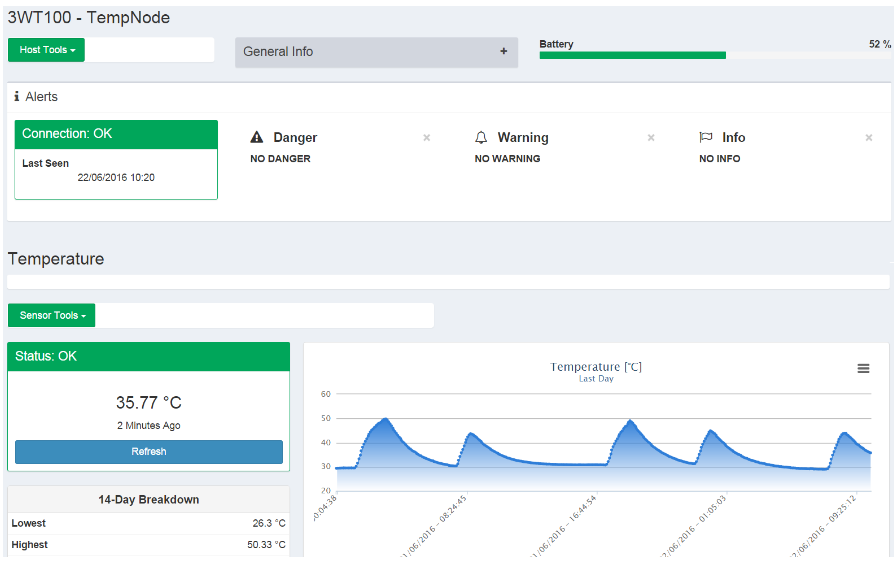


Figure 8: Graphical view of temperature node output in the RCSR.

been selected to evaluate the operating life of the system. Although an IIoT system can be designed to be low-power by using radio duty cycling techniques, event-based communications based on CoAP, and applications specially developed to save energy, the use of the IoT stack requires to enable 6LoWPAN and RPL packet exchanges that result in energy wasting. To reduce the impact of such background traffic, the number of background messages have been reduced to 1 every two hours once the routing path is established. Such a design choice does not limit the potentiality of the system and take into account the very low mobility of the nodes. On the other hand, to have significant power consumption values in the considered data collection period all devices have been configured to acquire many times the monitored variables in order to send periodically the output of their related exposed resources in short intervals of time, while no power saving schemes avoiding the transmission of similar data have been adopted. In particular, the temperature node has been configured with an internal sampling period of 10 seconds, then every 5 minutes all measured values are averaged and the resulting value sent to the gateway. The vibration monitoring sensor device, instead, has been configured to acquire every 5 minutes an acceleration burst of 10 seconds on all three axes, then P2P and RMS values for each axis are evaluated and sent to the gateway. Although such sampling and transmission rates have been imposed to have significant power consumption values in the considered data collection period, their choice has been discussed with monitoring systems experts, thus following their recommendations and requirements. Regarding the power consumption, this has been evaluated in terms of residual battery charge, which is a value that each sensor node can measure thanks to the embedded battery gauge component, the TI BQ27441-G1 briefly described in Section 3. The battery charge level reported by the gauge is a percentage value evaluated with respect to the whole charge of the battery and then exposed as a network resource, thus being accessible from the RCSR through an appropriate CoAP request. The battery of each device has been charged to a value of 100% before putting the system in operation. All batteries have a capacity of 5000 mAh. In the following the residual battery level after 15 days, 1 month and 2 months are reported for each sensor in each area. Performance results for each area are presented separately before overall considerations. In the 2 months of the experimentation no critical events related to the exceeding of imposed thresholds have been registered, as well as no faults have been experienced.

5.1. Area 1 - Evacuation heavy ashes

Performance results related to the first area are reported in Table 1, where the second letter of the sensor identifier clarify whether the device is able to sense temperature (T) or to perform vibration analysis tasks (V). For the latency, it is reported the average RTT and the number of communication hops from the sensor to the gateway. The battery charge level is reported at beginning of the experimentation (T0), after 15 days (T1), 1 month (T2) and 2 months (T3).

Table 1: Performance results Area 1.

SensorID	**Latency**		**Battery charge**			
	Hops	RTT [ms]	T0 [%]	T1 [%]	T2 [%]	T3 [%]
A1T1	1	242.89	100	98	93	78
A1T2	1	228.11	100	99	93	78
A1T3	1	224.42	100	100	95	80
A1V4	1	232.59	100	90	79	58
A1V5	1	213.71	100	84	69	40
A1V6	1	216.67	100	89	78	56
A1V7	1	215.52	100	89	77	55

Since in the area the gateway has been installed close to the sensor devices, and no routers have been added, all devices are able to reach the gateway in one hop with a maximum average RTT equal to 242.89 ms. It must be underlined that such a delay is affected by the adopted radio duty cycling policy which turns on the devices every 125 ms. The status of the residual battery charge has a behavior which is not linear, thus reflecting the discharge curve of the adopted battery. It is interesting to note that temperature nodes consume less than vibration analysis nodes since the number of acquisitions and the application tasks they perform are less. After 2 months of operation, temperature nodes have in average a residual charge level of 79% against an average residual charge level of 52% for vibration analysis nodes.

5.2. Area 2 - Seawater pumps

Considered performance parameters are reported in Table 2 for the second area. Since router devices are used, multi-hop communications have been enabled, thus letting the sensor devices to reach the gateway in 4 and 3 hops. Such a multi-hop communication affects the RTT with a maximum average value of 327.62 ms in case of a 4 hops communication and 282.01 ms in case 3 hops are necessaries. Because routers are not battery powered, they do not implement radio duty cycling policies. The residual battery charge level has the same trend of the previous area for both types of sensors with slightly better average performance for the vibration monitoring node because of the lack of a node with very low charge levels (i.e., A1V5 in Area 1). After 2 months of operation, temperature nodes have an average residual charge level of 81% against an average residual charge level of 58% for vibration analysis nodes.

Table 2: Performance results Area 2.

SensorID	**Latency**		**Battery charge**			
	Hops	RTT [ms]	T0 [%]	T1 [%]	T2 [%]	T3 [%]
A2T1	4	303.16	100	97	90	79
A2T2	4	299.48	100	98	93	82
A2V3	4	311.76	100	92	81	58
A2V4	4	327.62	100	92	82	59
A2V5	4	326.67	100	90	81	57
A2T6	3	282.01	100	98	92	80
A2T7	3	277.67	100	100	94	83

5.3. Area 3 - Evaporators

Performance results related to the third area are reported in Table 3. In the table two nodes are missing, A3T8 and A3V14. Since such nodes have experienced hardware problems they have been removed and installed again after 15 days, thus their performance are not in line with those of all other nodes. Because all sensors are in line-of-sight with the gateway, the communication is direct (one hop based transmission) with a maximum average RTT equal to 243.89 ms. Regarding the battery level, at the end of the 2 months, the temperature nodes have an average a residual charge level of 76% against an average residual charge level of 59% for vibration analysis nodes.

5.4. Overall considerations on system performance

From a latency time perspective, all nodes of the IIoT monitoring system are reachable with acceptable delays, with bigger average RTT values in case multi-hop communications are necessary. For the deployed system the maximum experienced average RTT is equal to 327.62 ms. Since the latency depends on

Table 3: Performance results Area 3.

SensorID	**Latency**		**Battery charge**			
	Hops	RTT [ms]	T0 [%]	T1 [%]	T2 [%]	T3 [%]
A3T1	1	185.17	100	92	83	70
A3T2	1	194.23	100	99	91	79
A3T3	1	227.73	100	93	85	73
A3V4	1	219.52	100	92	84	62
A3V5	1	204.42	100	89	79	58
A3T6	1	243.89	100	94	84	72
A3T7	1	203.19	100	100	94	80
A3V9	1	207.81	100	94	83	60
A3V10	1	221.12	100	92	82	59
A3T11	1	197.31	100	95	84	71
A3T12	1	232.16	100	100	94	78
A3T13	1	209.57	100	100	95	80
A3V15	1	212.31	100	91	80	57
A3T16	1	229.41	100	96	92	80
A3T17	1	235.33	100	94	87	75
A3T18	1	226.67	100	94	88	76
A3T19	1	232.66	100	95	97	75

the check rate of the implemented radio duty cycling mechanism, lower check rates will reduce the RTT, at the cost of a higher power consumption. Regarding the power consumption, there is a difference between temperature and vibration analysis nodes. The average behavior of such nodes is reported in Fig. 9. Vibration analysis nodes present lower battery levels with respect to temperature nodes, showing in average a residual charge level of 57% against 77% after 2 months of operation. By fitting both battery discharging curves with a second order polynomial function, the temperature nodes show an average life of 150 days, while vibration monitoring nodes can operate in average for 124 days. It must be underlined that such values have been evaluated considering that each device sense, elaborate and periodically send a value every 5 minutes. The whole power consumption contains not only the effect due to the acquisition, processing and transmission (including processor quiescent times, and wake consumptions for radio listening), but it includes the effect of the background traffic (e.g., 6LoWPAN, RPL messages), as well as the self-discharging of the battery. In mathematical terms the battery discharging percentage is due by:

$$P_{total} = P_{data} + P_{background} + P_{self} \tag{1}$$

While P_{self} strictly depends on the type of battery (values lower than 5% for month are real values for LiPo batteries [30]), P_{data} and $P_{background}$ depend

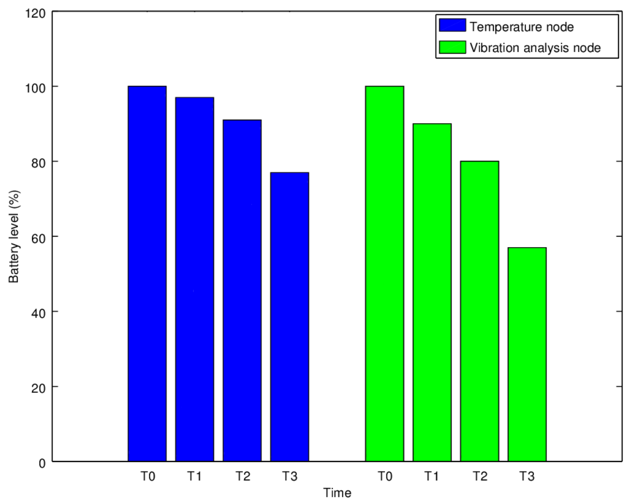


Figure 9: Average battery level for temperature and vibration analysis nodes.

on the configuration of the system. Considering the configuration used during the data collection (data every 5 minutes and 1 background packet every two hours), the percentage of power consumption related to background packets proportional to packet transmission consumption values reported in the data sheet, and a self-discharging percentage of 4% per month, the total discharging percentage during the estimated life can be divided as reported in Table 4.

Table 4: Battery discharge percentage breakdown.

Sensor	P_{data} (%)	$P_{background}$ (%)	P_{self} (%)	P_{total} (%)
Temperature	77	3	20	100
Vibration	81	3	16	100

Considering a configuration in which each device perform the same actions every 30 and 60 minutes, the life of both sensors can be approximately evaluated by considering a linear reduction of P_{data}, while taking the same discharging rate for both $P_{background}$ and P_{data}. As a result of such evaluation, reported in Table 5, the life of the whole system is little more than 1 year with a working period of 30 minutes, and 1 year and 4 months with a working period of 60 minutes.

Without considering the discharging percentage related to the battery factor, which is something related to the battery technology and capacity, the life of the system can be further extended by leveraging on the adopted IoT protocols. In fact, since all data provided by sensor nodes are exposed as resources that can be handled by using CoAP methods, a particular resource can be *observed* [31]

Table 5: Sensor devices lifetime.

Sensor	Lifetime - 30 minutes (days)	Lifetime - 60 minutes (days)
Temperature	418	510
Vibration	375	470

over several windows of time in order to send an update of the value only if a change is detected (i.e., event detection approach). This possibility represents an enhanced capacity of IIoT systems with respect to traditional monitoring solutions, thus resulting more appealing not only for the complete interoperability guaranteed by the IoT protocols but also for the advanced features provided by them.

6. Conclusions

In this paper an advanced IIoT monitoring solution, the *NGS-PlantOne* system, specially designed to support advanced predictive maintenance applications is presented, as well as its performance evaluated through a real testbed based on real IoT sensor devices installed in an electricity power plant. The proposed system fully apply the IoT paradigm in the industrial environment, letting each node to be globally reachable through its IPv6 address. Moreover, each sensing device can be considered a real IoT smart object, since it implements application logics able to extract additional knowledge from acquired values (i.e., detection and signaling of possible dangerous events) while exposing all available information as network resources according to the RESTful paradigm. The whole system has been deployed in an electricity power plant where 33 battery-powered IoT sensing devices have been installed in 3 separate areas where several machinery are monitored. Performance results evaluated in terms of latency and power consumption show as the proposed IIoT solution guarantee that each node is reachable through pure IP-based techniques with an acceptable delay while showing an estimated average life of 4 months with a transmission rate of 5 minutes. Considering a most appropriate transmission rate for a battery power monitoring system the operation time of the proposed solution can be increased to several years (e.g., 1 year with a transmission rate of 30 minutes), thus showing the feasibility and benefits of the proposed IoT monitoring solution in an industrial environment.

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