The Impact of Temperature on Outdoor Industrial WSN Applications

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Abstract

The industrial world is currently considering the adoption of Wireless Sensor Networks (WSN) for industrial process and control applications. However, when using wireless sensor networks in such application scenarios, network performance, reliability, and robustness must be ensured with high degrees of precision.

In this paper we study an outdoor deployment of a wireless sensor network in an oil refinery. We investigate the influence of temperature variations and mandatory ATEX casing on data delivery performance. Our experimental evaluation shows the impact that high temperature variations, such as the ones expected at the deployment location, have on network performance. We further show how the design and the deployment of wireless sensor networks in such application scenarios is influenced by temperature, and how less energy is needed to ensure reliable communications during night.

Index Terms

Temperature, Electrical equipment enclosures, Industrial control, Petroleum industry, Estimation, Wireless sensor networks

I. Introduction

Wireless Sensor Networks (WSN) are currently sucessfully used for applications such as precision agriculture, military surveillance and building monitoring. Recently, it has been investigated how WSNs could support new areas such as industrial process automation and control applications. There are a large number of process automation and control networks in use which would benefit from a wireless deployment. For example, it is desirable to reduce deployment costs and increase system flexibility.

To support this application domain, WSNs must provide performance assurances in terms of data transport delay and reliability. However, most WSN protocols and mechanisms are designed to preserve energy and not to meet performance targets. Hence, it is necessary to develop new protocols and mechanisms for WSNs that are able to give performance assurances while remaining reasonable energy efficient.

A WSN used for process automation and control must be able to deal with fluctuating channel and environmental characteristics. For example, a communication protocol should be able to maintain a set packet delivery rate when link reliability drops for a short period of time. To be able to construct protocols that can compensate for varying channel conditions, the expected level of fluctuations has to be known.

We investigate how temperature and weather conditions affect data delivery. We focus our study on the WSN deployment in an oil refinery in Portugal. For this application scenario, nodes are deployed outdoors and have to be encased in ATEX-compliant boxes to meet fire safety regulations. Consequently, we investigate the impact of:

- Ambient temperature on link quality and low-power wireless communication;
- ATEX-compliant casing on temperature and low-power wireless communication;
- Temperature and ATEX-compliant casing on energy consumption.

Our main contribution is to provide experimental results that show that the temperature fluctuations can create a variation of signal strength of up to $10dB$. We show how this may impact on the design of applications and protocols, the deployment of nodes and energy consumption. We further show how the use of ATEX casing [1], which is necessary to meet EU-regulations, may affect the temperature of the sensor nodes, and thus affect their performance.

Our results show that these impacts on communication are not negligible when deploying wireless sensor networks for industrial process automation and control applications in outdoor environments. Given the high degree of precision and reliability required in this application scenarios, particular care must be put when placing the sensor nodes in order to avoid link quality fluctuations.

This paper proceeds as follows: Section II provides a description of the application context of our case study. We quantify the impact of temperature on link quality in Section III. Thereafter, we analyze the impact of ATEX-compliant casing on temperature and the communication link quality in Section IV. Finally, in Section V we show how temperature has an influence on the necessary transmission power needed to maintain network connectivity. In Section VI we discuss how the temperature/link quality interdependencies should influence WSN design for our investigated application scenario. After an overview of the related work in Section VII, we conclude the paper in Section VIII.

II. Application Context

Process automation and control applications have stringent performance requirements in regards to data transport delay and reliability. In order to understand how such systems operate and the requirements they must meet, we carried out a case study: we investigate a WSN process control and automation deployment scenario in a petrochemical industry.

The GALP [2] oil refinery at Sines, Portugal (see Figure 1), is a complex industrial facility that includes a wide range of processing that needs careful monitoring and control of operations. High focus in this environment is put on health and safety. For example, fire prevention, safe operation of machinery and carful handling of products are absolutely important and have to be taken into account when designing a WSN for this scenario.

A. The Refinery Monitoring and Control System

There are currently 35,000 sensors and actuators in use in the refinery to perform real-time monitoring of industrial operations such as leakage detection, measurement of pressure in the pipes, fluid levels and of the overall environment. The monitoring of the environment in a refinery provides essential information to ensure the good health of the refinery and its production processes.

In the oil refinery three subsystems exist for the monitoring and control of the plant: the *indicator system*, the *control system*, and the *emergency system*, as shown in Figure 2.

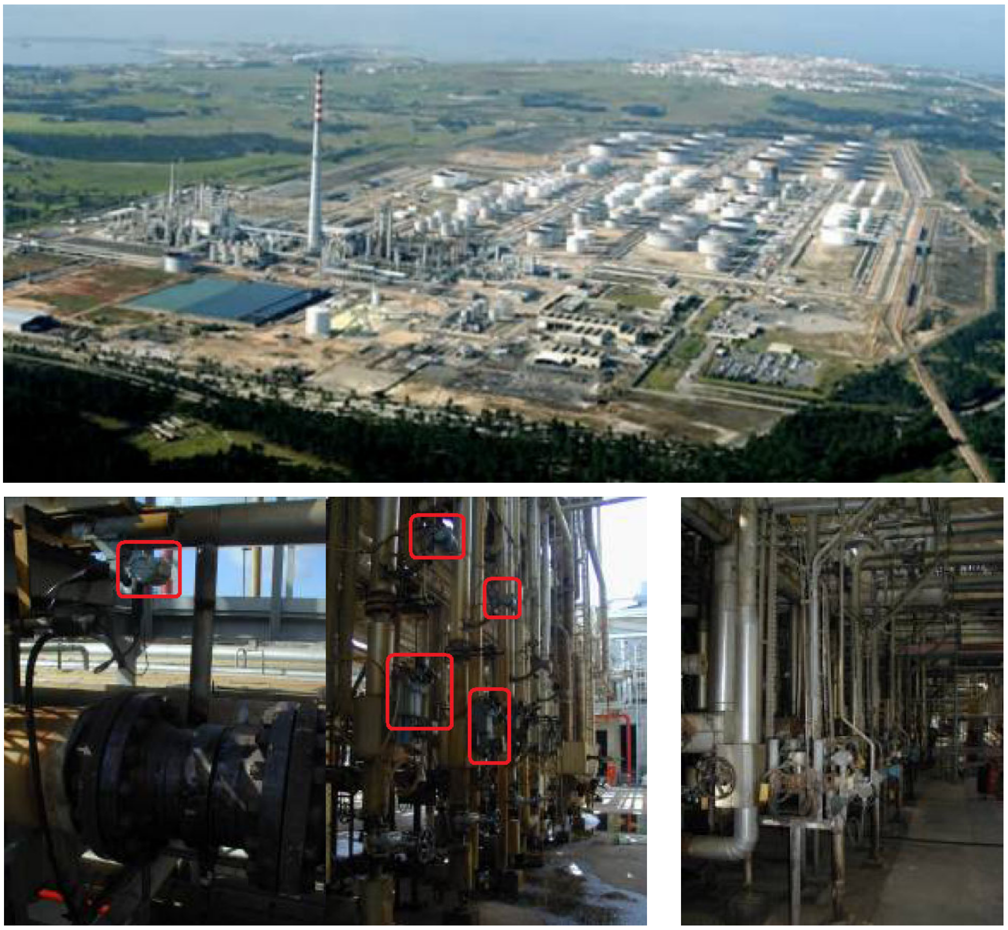

Fig. 1. The GALP oil refinery in Sines, Portugal, and some of the installed sensors.

The *indicatory system* is used purely to provide the control centre with information about status and faults of equipment and generic aspects of the environment. Within this system, information flows one way from the in-field sensors to the control centre. The data from such sensors is typically not as vital as those of the next two systems; however data should still arrive in a reliable and timely fashion to inform control centre operators of potential dangers.

The *control system* is used to control different aspects of the refinery. Information flows in both directions: from in-field sensors to the control centre, and from the control centre to actuators. In this system it is vital that data arrives at its intended destination in quick and reliable way. Operators require instant feedback from sensors as actuators are used to modify aspects of the environment.

The *emergency system* is used to monitor and control only mission critical systems, and trigger events to prevent an accident. Sensors and actuators in this system are part of a

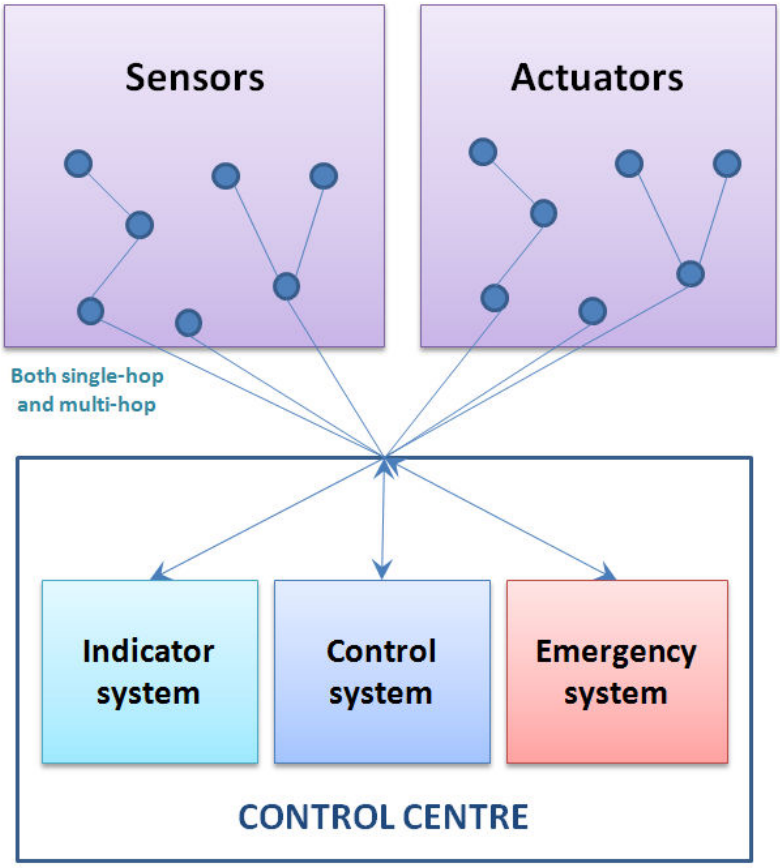

Fig. 2. Monitoring and control systems in the refinery.

closed loop system with no user intervention. The information flowing in these systems has the highest priority, and thus requires the highest levels of reliability and lowest delay bounds.

B. Challanges of a Wireless Monitoring and Control System

The vast majority of sensors and actuators in the oil refinery use wired-based technologies such as $4 - 20mA$ system. The cost in time and finance to deploy new sensors in such industrial environments can be huge and in lesser cases sensors are simply not deployed for this reason. In this context, wireless sensor networks could be employed to ease and reduce the cost of deployment and increase flexibility. These WSN must maintain and match the performance assurance given from their wired counterparts.

When deploying senors in any industrial setting it is very important to consider the environment in which they will be deployed. In the context of the refinery, the sensors will be deployment mostly outdoors and they must meet a number of regulations which are common across many industries.

As nodes are deployed outdoors they are exposed to changing weather conditions. As weather conditions change over time the link quality is changing as well. Especially temperature has an impact on the link quality that can be achieved and, thus, it is important for the design of a WSN to take these effects into account.

In the potentially explosive refinery, it is mandatory that the equipment is ATEX compliant. The ATEX directives are regulations regarding the use of equipment in explosive atmospheres valid within the European Union, and thus, wireless sensor nodes deployed in such an industrial context must adhere to such standards. It is possible to obtain ATEX certification for a wireless sensor node. However, this is a costly and time consuming process which needs to be repeated whenever the sensor node is modified, for example, by changing the sensor.

An alternative to obtaining ATEX certification for the sensor node is to obtain it for the enclosure that will house the node, as shown in Figure 3. This is the industries prefered way of obtaining ATEX compliancy as it provides greater flexibility. Obviously, there is the danger that the ATEX enclosure has an impact on the communication links as the sensor nodes antenna is located within the enclosure. Furthermore, the casing has as well an influence on how weather conditions influence the node. For example, the casing can create a greenhouse effect that increases the temperature.

All three outlined subsystems require that data is transported timely and reliable. Hence, for this type of application it is necessary that the used communication protocols are capable to achieve the required data transport performance even if wireless channel quality is fluctuating. To enable an efficient design of the communication protocols it is necessary to quantify the range and dynamics of link quality fluctuation. For the outlined application scenario in the oil refinery we see that ambient temperature and ATEX casing contribute to link quality fluctuation. Hence, it is the aim of our study to quantify these impacts.

III. Impact of Temperature on Low-power Communication

The outdoor deployment in the refinery is affected by frequent temperature changes and different weather conditions. Hardware components for outdoor deployments are usually designed for an operating temperature range from $-40°C$ to $+85°C$. However, temperature changes cause crystal frequency to shift, thermal noise level of the transceiver to increase,

Fig. 3. ATEX enclosures.

and amplifiers to saturate [3], resulting in performance degradation of the radio device [4], [5].

A. Sentilla Tmote Sky Platform

To quantify the impact of temperature on a communication link, an experiment involving two Tmote Sky nodes was carried out. The Sentilla Tmote Sky [6] uses the Chipcon 2420 radio chip [7] that operates at 2,4 GHz. The nodes run the Contiki operating system [8] with a customized application for the experiment. One node is used as transmitter, the other node as receiver. 256 packets of 12 bytes payload are transmitted every 4 seconds. The receiver averages the Received Signal Strength Indicator (RSSI), the Link Quality Indicator (LQI), the Packet Reception Rate (PRR), local temperature, and sender temperature (contained in the received packets), and logs all this information. During the experiment duration of approximately 90 minutes, the temperature is increased from $-10°C$ to $50°C$. The results of this experiment are shown in Figure 4.

In the same experiments, the receiver measured also the impact of temperature on the noise floor. Such values were recorded immediately after getting a packet, and averaged every 4 seconds following the same procedure explained above. The results are shown in Figure 5.

The impact of temperature on the radio chip is non negligible, and influences the design choices since the higher the temperature, the lower the the signal strength. Figure 4 shows a signal strength drop of approximately $9dB$ over the investigated temperature range. Hence, high temperatures might lead to a loss of connectivity within the sensor network.

Figure 5 shows that the noise floor decreases as well with temperature. This is an important observation as the RSSI value is used by the medium access control (MAC) layer to determine

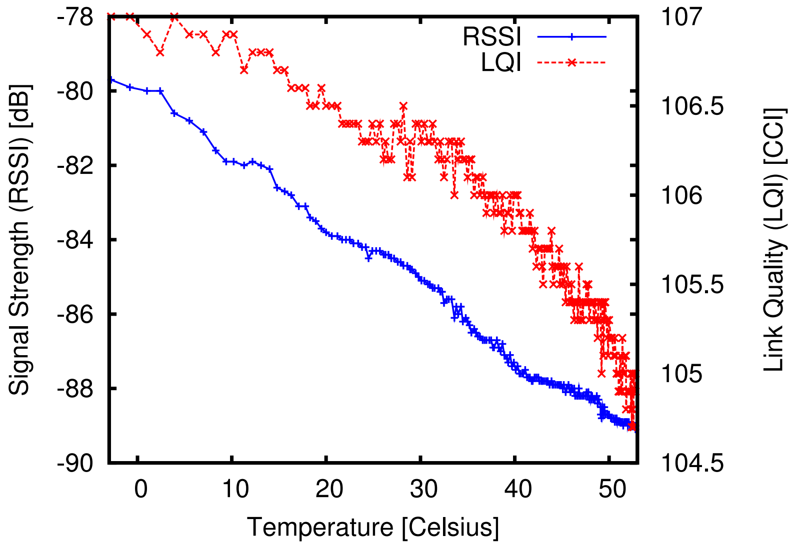

Fig. 4. Temperature impact on the RSSI and LQI indicators of the CC2420 radio chip, measured experimentally using the Sentilla Tmote Sky platform.

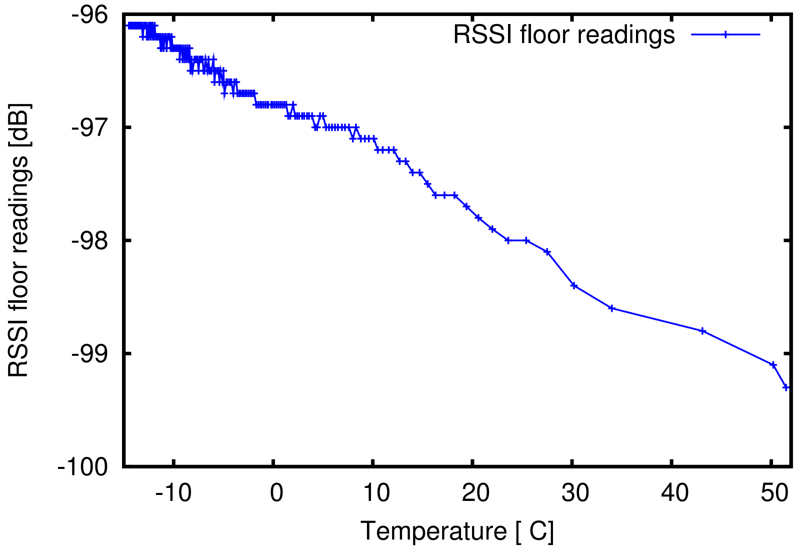

Fig. 5. Noise floor readings of the Tmote Sky at different temperatures.

if the channel is currently busy or not. As Figure 5 shows, the noise floor is temperature dependant and, thus, temperature must be taken into account when determining the RSSI value at which the channel is considered to be busy.

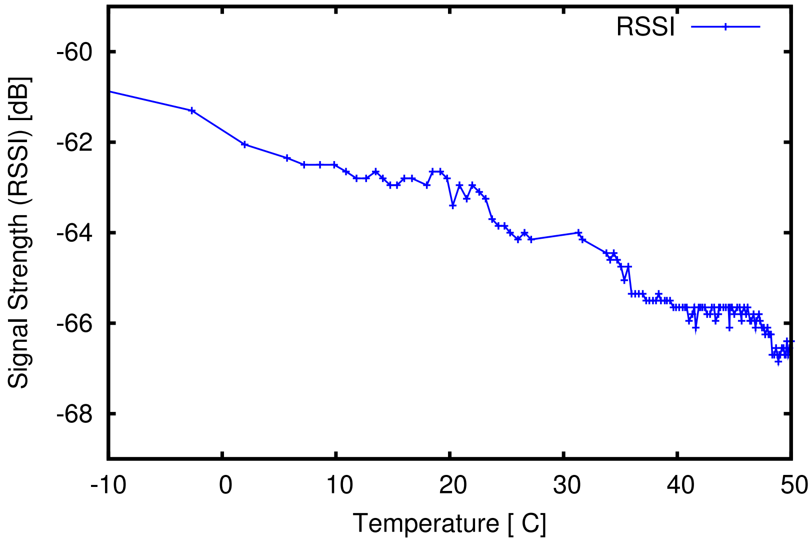

Fig. 6. Temperature impact on the signal strength in the CC1020 radio chip, measured experimentally using the Scatterweb MSB430 platform.

B. Scatterweb MSB-430 Platform

In a second experiment we used the Scatterweb Modular Sensor Boards (MSB430) [9], [10] platform. This platform uses a CC1020 [11] running at $868MHz$. The experimental setup was similar to the setup used for the previously described experiment. However, only the RSSI was recorded as the LQI is not available in the MSB430 platform. The results are shown in Figure 6.

As with the Tmote Sky platform, also the noise floor on the MSB430 platform is measured, and its relationship with the temperature is shown in Figure 7.

The results show a similar dependency of temperature and RSSI as in the previous experiment. Thus, it can be concluded that the observed temperature dependance is most likely independent on the node platform used, as well as the radio frequency. Figure 6 shows a signal strength drop of approximately $6dB$ over the investigated temperature range.

IV. Specific Implementation Requirements and Certifications: ATEX Enclosures

In order to achieve ATEX compliancy, sensor nodes can be enclosed in ATEX complient casings. This procedure avoids costly certification procedures, especially when small changes

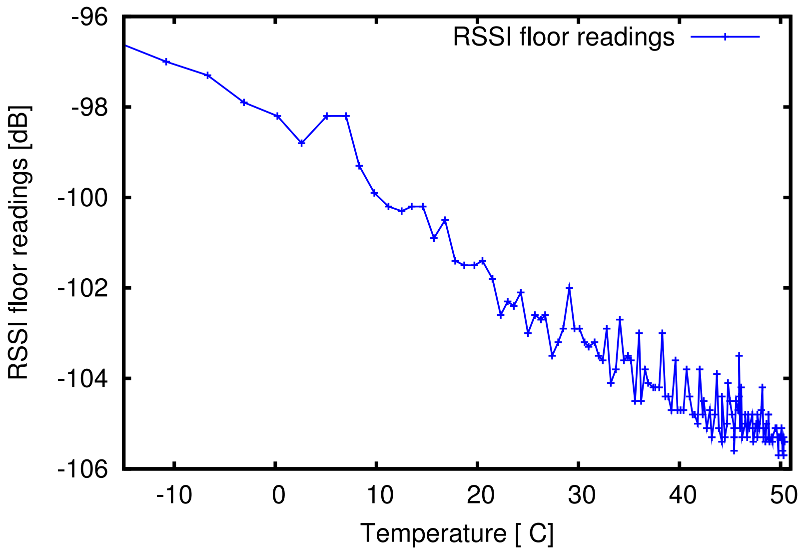

Fig. 7. Noise floor readings of the Scatterweb MSB430 at different temperatures.

are applied to the sensor node hardware.

A. ATEX Enclosures

When the sensor nodes are enclosed into the ATEX cases, the radio propagation is affected by both node orientation and casing. There is no trend established to know how orientation affects the measured Received Signal Stength Indicator (RSSI) at the receiver nodes. Depending on the environment, on the presence of objects or obstacles, as well as on the environmental interference and the rotation of the sensor node or casing, the signal strength can be higher when the nodes are inside the case. Viceversa, for other conditions, the signal strength may be higher when the nodes are outside the case.

Figure 8 shows the behaviour of the RSSI with respect to the orientation of the sensor node both inside and outside the ATEX case. Our experiments show that there is no particular effect due to the ATEX casing, rather the effect is due to other environmental issues.

B. ATEX Enclosures and Temperature

The temperature impact inside the ATEX cases follows the same behaviour shown in Section III. A high temperature inside the ATEX case can cause a worsening effect on the recorded RSSI. The temperature impact is maximum when the temperature inside the ATEX cases of both sender and receiver is high. Our experiments show in fact that when

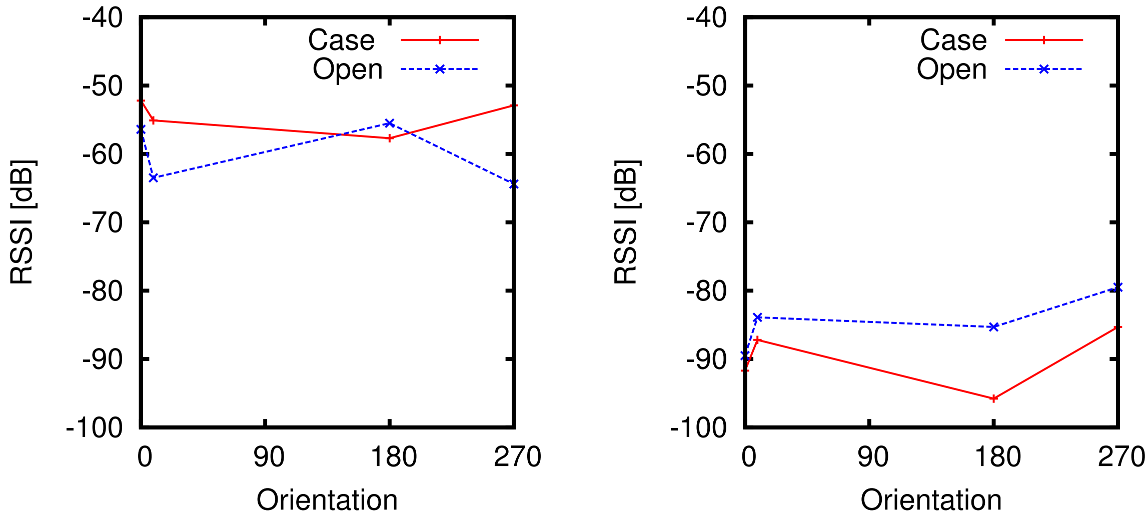

Fig. 8. Received Signal Strength Indicator (RSSI) on sensor nodes inside and outside the ATEX casing. The difference depends more on the orientation of the node than on the casing, hinting that there is no particular trend inside or outside the case.

the receiver is cooled from $45°C$ to approximately $-10°C$, the RSSI rises by approximately $5dB$. Likewise, when we cool the temperature of the transmitting device from $45°C$ to $0°C$, RSSI rises again by $5dB$. When the temperature of both the sender and receiver is cooled, there effects are summed to $10dB$. Figure 9 shows the worst case, when the ATEX cases of both receiver and sender are cooled. We carried out the experiments using the Tmote Sky platform, using the same procedure and software described in Section III.

The experimental results show that temprature changes have a significant impact on the RSSI. In the investigated oil refinery application scenario it might be useful to place nodes in ”cool spots” in order to ensure stable communication links. In particular, in the refinery scenario, the deployment is highly controlled and sensor nodes are not deployed in a random fashion. Hence, it is possible to take temprature into account when nodes are deployed.

The airtight ATEX casing creates a greenhouse effect that increases the inner temperature. In our application case, the temperature inside the ATEX cases may follow dangerous patterns, with respect to our discussion in Section III, and may degrade the performance of the network or cause the disruption of connectivity between sensors. A high temperature inside the ATEX case can cause a worsening effect on the recorded RSSI, and the greenhouse effect may accelerate this effect.

For this reason we inspect the behaviour of the temperature inside the ATEX casing with

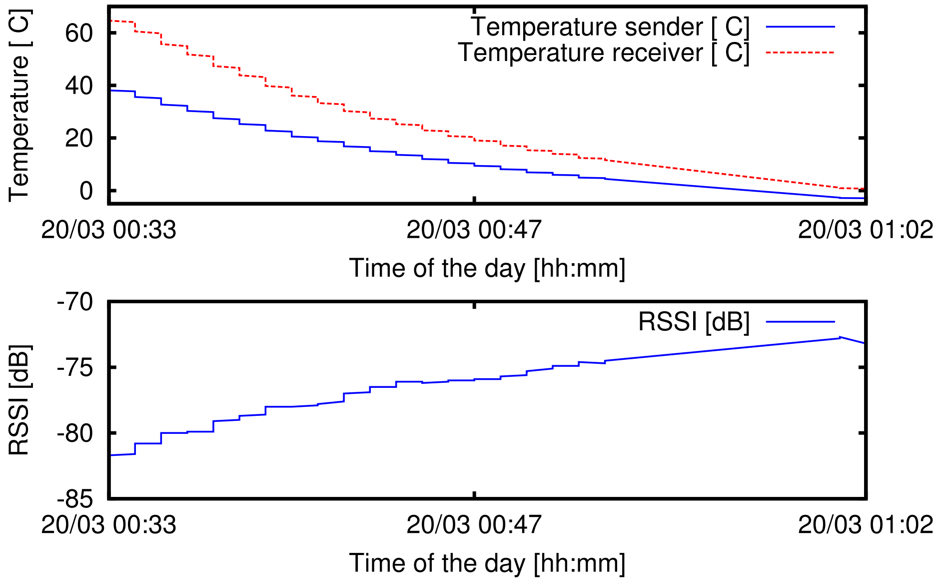

Fig. 9. Effects of the temperature on communication when the ATEX cases of both receiver and sender are cooled.

different weather conditions at different hours of the day. We use Contiki [8] and the Sentilla Tmote Sky nodes and their Sensirion SHT11 temperature sensors [12] to perform such outdoor experiments. We compare the behaviour of nodes enclosed in ATEX boxes with nodes at free-air.

Figures 10 and 11 show the behaviour of temperature inside and outside the ATEX case in both daytime and nighttime. The greenhouse effect is visible especially in the nighttime, where the nodes are actually kept at a higher temperature than the ones outside the case (Figure 10). However, when the sun shines directly on the sensor nodes, the nodes outside the ATEX cases will be influenced in a much faster way, and temperature will rise quickly.

Figure 11 shows that the ATEX case slows down the increase of temperature, which avoids sudden temperature changes. This may imply that sensor nodes have enough time to modify the routing schemes or their behaviour in case that temperature reaches values dangerous for communication.

In the case of refinery for example, the informative system may switch the behaviour from real-time data communication to data collection (i.e. waiting the temperature to decrease again before transmitting). This would avoid retransmissions and a consequent waste of energy, and can be done since the data of the informative system is not urgent.

The deployments for the control and emergency systems should be instead carried out in

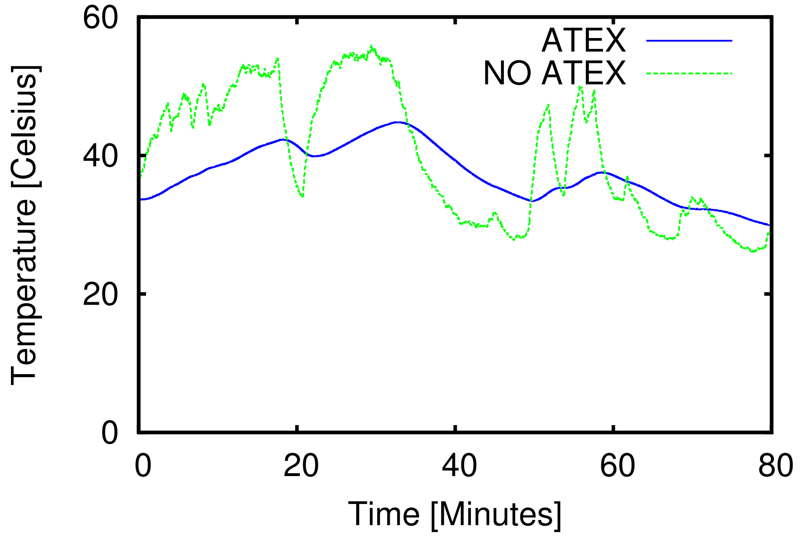

Fig. 10. Temperature registered on Tmote Sky nodes inside and outside ATEX enclosures during daytime. When the sun shines directly on the sensor motes, the ATEX case shields the nodes, and slows down the increase of temperature inside the case.

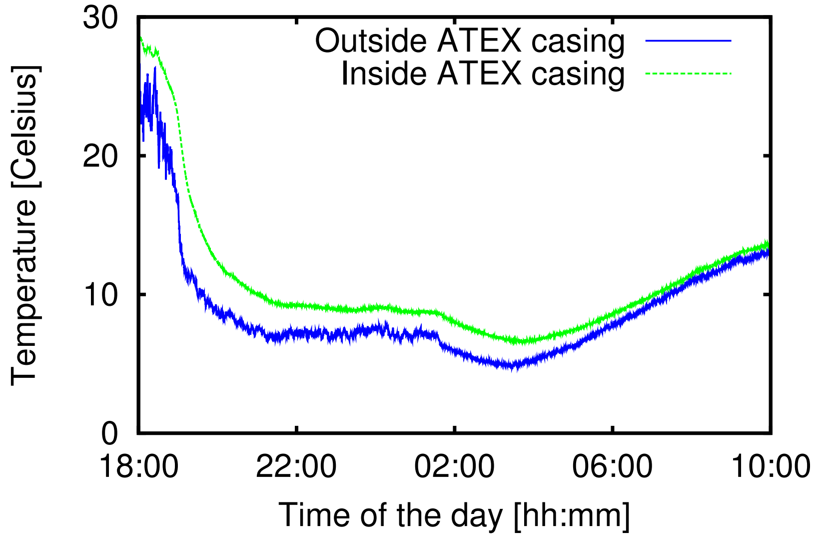

Fig. 11. Temperature registered on Tmote Sky nodes inside and outside ATEX enclosures during nighttime. The ATEX casing creates a greenhouse effect on the sensor nodes, and the temperature inside the case is higher than outside.

such a way that even the highest temperature combined with the greenhouse effect does not affect the latency of the real-time data communication.

V. The Impact of Temperature on Transmission Power

Sections III and IV describe the influence of temperature and ATEX enclosures on transmission links in industrial outdoor deployments. The experimental results show that an increase in temperature leads to a reduction of the received signal strength. Therefore, it can be expected that, with an increase in temperature, a higher transmission power is required to ensure successful data transmission.

To investigate this effect, we carried out a preliminary outdoor experiment during daytime. The aim of this experiment was to determine the minimum level of transmission power necessary to ensure successfull data transmission between two Tmote Sky nodes.

To determine the minimal power needed for a successful communication, we implemented a sender and a receiver using the Contiki operating system. The sender transmits a test packet periodically to the receiver. The receiver confirms reception of the test packet by transmitting an acknowledgement packet to the sender. When an acknowledgement is received, the sender decreases transmission power. If a packet is lost, a timeout will occur, and a new transmission will take place using the same transmission power setting. If the test packet is not acknowledged within $K = 10$ tranmissions, the previous power setting of the transmitter is recorded as the minimum power level necessary to maintain communication on the link.

The experiment was repeated using different distances between the two nodes (the distance was gradually increased from $50cm$ to $20m$). The set of measurements was carried out twice; first, with sender and receiver at a temperature of $18°C$ and second, with both nodes at $38°C$. Figure 12 shows the results of the experiments, where PA_POWER represents the transmission power level used in Contiki.

As expected, significantly less transmission power is required at low temperatures. For example, at a communication distance of $20m$, approximately 20% less transmission power is required at lower temperatures. This translates according to the CC2420 data sheet to $1.5mA/s$ that can be saved during times the node is operated at $18°C$. Thus, the creation of a control loop algorithm that adapts the transmission power to the temperature sensed by the sensor nodes may help to increase the overall network lifetime.

The experiments shown in Figure 12 were carried out during daytime by cooling the sensor nodes before the experiment to $18°C$. Then the nodes were deployed and the first measurement was carried out. The nodes were then left in position to warm to $38°C$ and then the second measurement was taken.

In addition, we carried out experiments leaving the motes communicating over day and

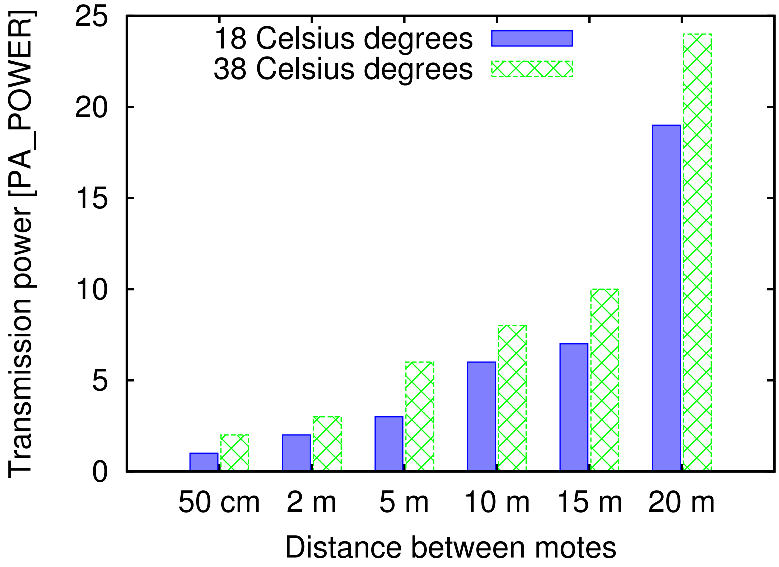

Fig. 12. Minimum transmission power required for a successful communication between two sensor nodes with warm and cold temperature. Higher temperature requires higher transmission power to mantain a reliable communication between nodes.

night and we observed similar trends. However, during nighttime there is not only a decrease in temperature but also the ambient noise is reduced as generally fewer electric devices are operated at night times. It was not possible from these experiments to seperate clearly temperature effects and ambient noise effects. However, it should be noted that this effect even increases the differences between necessary transmission power between night and day time operation of a WSN.

VI. Impact on Application Scenario

The influence of temperature variations on communication link quality must be taken into account when deploying a WSN in the application context outlined in Section II. In particular, the following aspects should be considered when designing and deploying a WSN for the oil refinery context:

Deployment Time: The time chosen to deploy and test the equipment in the refinery is crucial. New devices within the refinery are typically deployed and tested during the evening or night when the refinery is at its quietest. In the south of Portugal at Sines, temperatures can vary in the summer between 35°C during the day and 20°C during night times. In addition, some of the nodes will be exposed to direct sunlight which will increase the temperature even further (see Figure 11). Thus, temperature variations between 18°C and 38°C as used to derive results shown in Figure 12 have to be expected. The graph shows that two devices can communicate over a greater distance when environmental temperature is lower than at times of higher temperature. For example, a communication link configured with a transmission power level 3 to span $5m$ distance at night will only be able to cover a distance of $2m$ during day time which may well result in a disconnected network. Hence, devices deployed and tested during the usual refinery maintenance period (which coincides with the coolest time) may not be able to communicate during daytime, when temperatures are higher. Therefore, it is important that the communications of nodes are tested at the hottest times during the day, similarly at the hottest time of the year.

Maintenance: Wireless sensor nodes within the refinery will be battery powered and therefore only have a finite lifetime. Continued operations can only be ensured when batteries are replaced before depletion. The maintenance costs of replacing batteries of 35,000 nodes within the refinery are very high and cannot be neglected. Maintenance personal must be employed to ensure that batteries are replaced at the right time, which accounts for the largest part of maintenance cost, while actual material cost for batteries can be neglected. Hence, it is important to achieve a long node lifetime in order to reduce the maintenance frequency. It is not advisable to use the maximum transmission power a node provides. To conserve energy, the transmission power should be set to the minimum required to bridge the required distance. Given the results shown in Figure 12 the temperature dependencies of transmission power should taken into account as well. For example, for a communication distance of $20m$ an additional 20% transmission power can be saved if the transmission power is reduced with the lower temperatures. Assuming for a simplified calculation night time temperature during $8h$ of the day and day time temperatures during $16h$ and that a battery lasts normally one year and that communication is the dominant energy consumer. In this case, the nodes lifetime can be prolonged by 24 days. Furthermore, we may even consider the difference between the seasons during the year, prolonging even further the battery duration. Therefore it is worth to consider to adapt transmission power to ambient temperature.

Protocol Design: As pointed out in the previous pragraph it is necessary to take temperature into account also when deciding which transmission power should be used. Ideally, a node should adapt automatically to the proper transmission power setting. Generally, it is difficult to construct a stable adaptive algorithm if the temperature is fluctuating heavily over a short time span. However, as shown in Figure 10 the ATEX casing shields the sensor node from erratic temperature changes. Hence, we believe it is possible for the investigated refinery scenario to devise a stable and efficient algorithm for transmission power adaptation.

VII. Related Work

Several researchers have shown that outdoor sensor networks are affected by weather conditions and temperature.

Thelen et al. [13] have described how radio waves propagate better under weather conditions with high humidity in their potato field deployment. The results of Anastasi et al. [14], Sun et al. [15], and Capsuto et al. [16] suggest that weather effects, specifically fog and rain, may have a severe impact on the transmission range of sensor nodes, in particular with respect to the Packet Reception Rate (PRR). Boano et al. [4] quantified the impact on rain and fog with respect to the signal strength and the link quality under different platforms, showing that rainfall not heavier than 2-3 mm/hour do not affect the signal strength that much. On the contrary, when the rainfall is heavier, the connectivity may be disrupted.

Bannister et al. have shown that high temperatures negatively affect communication between sensor nodes [5]. In their deployment in the Sonoran Desert of the southwestern United States, the reduction of the signal strength was largest during the hottest time of the day.

We quantified the impact of temperature also at lower temperatures, and using different platforms and radio frequencies. We show how that the Link Quality Indicator (LQI), in addition to the Received Signal Strength Indicator (RSSI) is affected. This is very important, since RSSI and LQI are used often to estimate the future Packet Reception Rate (PRR) of the communication [17], [18], [19].

Most sensor networks for industrial control and automation applications must comply with the ATEX 95 equipment directive 94/9/EC for equipment and protective systems intended for use in potentially explosive atmospheres. To the best of our knowledge, however, there are no studies that assess if compliance with this particular standard has an impact on wireless sensor networks performance. Our measurements aim to close this knowledge gap.

VIII. Conclusion

Wireless sensor networks will be widely used in the future for outdoor industrial process and control applications. In these scenarios, the network must provide high and stable data transport reliability. Given the channel quality fluctuations present on wireless links, it is difficult to achieve this goal. However, if the nature of channel quality dynamics is properly understood, it is possible to construct network protocols that are able to adapt the network to the current conditions.

In this paper we investigated the temperature influence on low-power communications. We have used the deployment of an outdoor wireless sensor network in an oil refinery in which ATEX compliancy must be obeyed as our case study. Our experimental results have shown that temprature has a major effect on signal strength and link quality, and that operations at lower temperatures such as nighttime may require up to 20% less transmission power to maintain a reliable communication. We further have discussed how this impact affects the deployment and the design of the WSN in the refinery.

We believe that the findings presented in this paper can help to dimension general wireless sensor network deployments of industrial process and control applications. Furthermore, the presented results can be used to construct protocols that adapt transmission power to the measured ambient temperature.

Acknowledgments

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