Reliability in Wireless Sensor Networks for Environment Monitoring

Tran Thanh-Dien [1]; Herrera Carlos [2]; Egas Carlos [2]; Pereira Vasco [1], Sá Silva Jorge [1]

[1]*Universidad de Coimbra, Departamento de Ingeniería Informática, Coimbra, Portugal*
[2]*Escuela Politécnica Nacional, Facultad de Ingeniería Eléctrica y Electrónica, Quito, Ecuador*

Abstract: Wireless Sensor Networks (WSNs) have been increasingly used in society and industrial environments. However, there are still several challenges in developing applications as well as in guaranteeing their operation in critical environments. There are many factors that contribute to these challenges, including the constraints and limitations of the sensor nodes, the noisy and interference environments, and the differences between WSNs and traditional networks. The main objective of this paper is to describe the project developed in the Department of Electronics, Telecommunications and Information Networks of Escuela Politécnica Nacional in Ecuador to use reliable solutions of WSNs to environmental monitoring as an alternative to conventional solutions.

Keywords: Wireless Sensor networks; industrial environments; environment monitoring.

Confiabilidad en Redes Inalámbricas de Sensores para Entornos de Monitoreo

Resumen: Las Redes Inalámbricas de Sensores (WSNs) han incrementado cada vez más su uso tanto en la sociedad como en el entorno industrial. Sin embargo, aún hay varios retos en el desarrollo de aplicaciones, así como la de garantizar su funcionamiento en ambientes críticos. Hay muchos factores que contribuyen a esos retos, incluyendo las restricciones y limitaciones de los nodos sensores, los ambientes con interferencia y ruido y las diferencias entre las WSNs y redes tradicionales. El principal objetivo de este artículo es describir el proyecto desarrollado en el Departamento de Electrónica, Telecomunicaciones y Redes de Información de la Escuela Politécnica Nacional de Ecuador, en el uso de soluciones confiables de Redes Inalámbricas de Sensores (WSNs) para monitoreo ambiental, como una alternativa a las soluciones convencionales.

Palabras clave: Redes inalámbricas de sensores; entornos industriales; monitoreo ambiental.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have been emerging as promising systems for monitoring and actuating in the physical world. With ability to sense, process and disseminate the climate conditions of the physical environment as well as respond to their changes, WSNs have a diversity of applications in areas that include military strategy, security, transportation, industry, health-care and smart home. In recent years, WSNs have been increasingly employed in critical and industrial environments (e.g., oil refineries and chemical processing) in areas such as the monitoring and control of the environmental working conditions, production processes, monitoring workers' health and location. The specific needs of these critical environments, together with the constraints and limitations of sensor nodes (e.g. small memory, low computation capabilities, short distance communication, and limited power) bring many distinct challenges for developing, deploying and managing WSNs.

As sensor networks operate in the same radio frequencies with other wireless networks, e.g., Wireless Local Area Network (WLAN), Bluetooth, and microwave, their quality can be severely affected. A recent study presented in (Sikora 2005) showed that with the interference of IEEE 802.11 networks the Packet Error Rate (PER) of IEEE 802.15.4 might rise up to 95% when the interferer is in the distance of 1.5 meters. In the inverse, the throughput of IEEE 802.11 based networks can be reduced up to 30% when in presence of IEEE 802.15.4 networks in a short distance (Pollin 2008) addition, other noise sources, e.g., mechanical devices and heating, as well as their variability with time also affect the performance and reliability of WSNs. The study in (Oliveira, Fonseca, Bartolomeu, & Costa, 2008) showed that microwave generators severely affect the performance of IEEE 802.15.4 based sensor networks in terms of delay and packet loss. Moreover, our empirical study presented in (Tran, Silva, Nunes, & Silva, 2012) showed that the quality of different channels of IEEE 802.15.4-based sensor networks varies from place to place and from time to time.

carlos.herrera@epn.edu.ec

Another crucial requirement is that the sensed data needs to be collected, processed, and visualized by applications to make them understandable by the users. In addition, in some scenarios, the sensor nodes also need to be monitored and controlled by users via front-end applications. Therefore, interoperability between WSNs and external applications is desirable. Because of the limitations of sensor nodes, the common approach for integration between WSNs and external applications is to use a gateway (Dunkels, Alonso, Voigt, Ritter, & Schiller, 2004), (Emara, Abdeen, & Hashem, 2009) and (Kim, Kim, Kwak, & Byun, April 2007). The advantage of a gateway-based approach is that it makes the sensor network transparent to external environments. However, some works (Dunkels, Full tcp/ip for 8-bit architectures, 2003) and (Hui & Culler, Nov 2010) showed that it is possible to implement an IP protocol stack on sensor nodes. Although IP-based approach seems more natural for interoperating between WSNs and user applications, it is not a solution for all types of sensor networks. In fact, this approach has several problems such as energy efficiency, security, and compatibility. Consequently, gateway-based approach is still a common approach for integration between sensor networks and the Internet, and applications in foreseeable future.

While working with WSNs in outside and industrial environments (Energia, 2014) and (Soporcel, 2014) we found that these above-mentioned problems are critical for facilitating the design, development, and to fulfill the needs of a WSN in such restricted environments. The key technical contributions of the work presented in this paper are: (1) mechanisms to allow the WSNs to reliably operate in real, noisy and interference environments; (2) an adaptable integration framework for interoperating WSNs and external environments. All of the proposed models presented in this paper were implemented and tested in real scenarios, mainly in a project developed in Ecuador to monitor environment and air parameters.

The rest of the paper is organized as follows. Section 2 discusses the coexistence problem and reliable communications for WSNs. Section 3 presents a new adaptable approach for interoperability between sensor networks and external applications. Section 4 details the project developed at Escuela Politécnica Nacional (Ecuador) that uses WSNs to monitor the air quality. In this project, we used some of the reliable studies and interoperability mechanisms described in the previous sections. The final section presents conclusions and future works.

2. COEXISTENCE AND RELIABLE COMMUNICATION

WSNs are different from other types of networks in that the end users seldom interact directly with the nodes, but mainly with the applications at the control center. Thus, one of the crucial requirements of WSNs is to maintain its operation uninterruptedly for a long time. As a result, energy efficiency and high reliability are two main concerns when designing and deploying sensor networks. As wireless networks (e.g., Wi-fi, Bluetooth, cordless phone) are presented almost everywhere, the coexistence is critical. In addition, machinery and other devices also create noise that impacts in the communication of a sensor network. Moreover, because of the limitations of sensor nodes, their radios are more susceptible to noise and interference than those of other wireless technologies. Consequently, the effects of these factors on the quality and stability of the sensor networks are even more severe. The wireless communication standards usually consist of a set of discrete channels, allowing multiple wireless networks operating on the same frequency band, where each utilizes a single channel or a subset of them. However, current sensor networks do not have the ability to determine which channels are not in use, as well as they cannot detect the current conditions at the deployment environment, i.e., WSN cannot evaluate the quality of the different channels. This means that they do not have the mechanisms to deal with noisy environments and interferences. This section presents our studies and proposals for this problem. In particular, the next sub-section summarizes our empirical studies on the quality of different channels of IEEE802.15.4 compliant sensor networks in different environments.

2.1 Quality of Channels of IEEE 802.15.4 Compliant Sensor Networks

IEEE 802.15.4 standard (Hui & Chakrabarti, 6lowpan: Incorporating ieee 802.15.4 into the ip architecture - internet protocol for smart objects (ipso) alliance (white paper # 3), 2009) is intended to be the key enabler for low complexity, ultra-low power consumption, and low data rate wireless connectivity among inexpensive fixed, portable and moving devices. One of the Radio Frequency (RF) bands supported by IEEE 802.15.4 is 2400 - 2483.5 MHz, which is also referred to as the Industrial, Scientific and Medical (ISM) band. The channels in this band are numbered k = 11 .. 26 at frequencies 2405 + 5(k -- 11) MHz as shown in Figure 1.

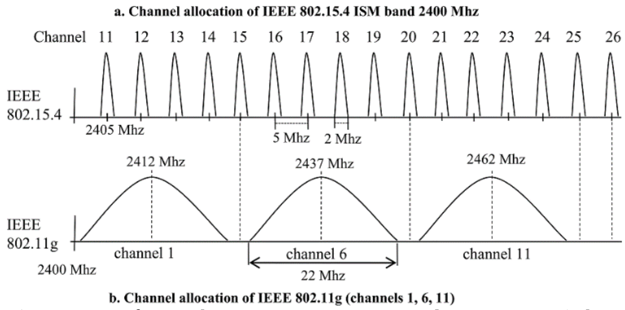
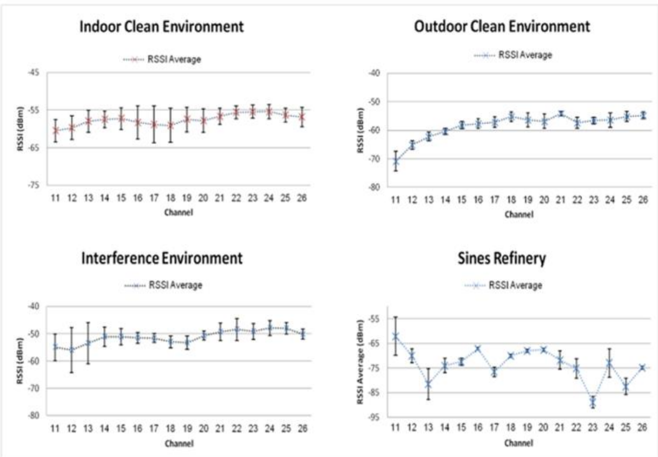


Figure 1. Interference between IEEE 802.15.4 and IEEE 802.11 (Sikora 2005)

As the ISM band is also used by other wireless networks such as IEEE 802.11b, g, n and Bluetooth, IEEE 802.15.4 based sensor networks may co-exist with other wireless networks, affecting each other's quality and stability. In addition, the effects of the noise and interference on different channels may not be the same and it is difficult to predict. To study how the noise and interference affect the quality of different channels of IEEE 802.15.4 compliant sensor networks in ISM band, we conducted numerous experiments at four different places. The first two locations were considered "clean environments" because there were no interferences from other wireless networks, no obstacles, and no obvious noise sources. One is indoor and the other in an open space. The third environment is our laboratory at Informatics Department of the University of Coimbra, which has several IEEE 802.11g wireless networks that operate on the channels 1, 6 and 11. The last location is an industrial environment at the Sines refinery, Galp Energia, Portugal. Although there are no other wireless networks that interfere with the IEEE 802.15.4 within the refinery, there is a considerable amount of noise caused by several types of machines and pumps that work 24 hours a day.

The metrics used to evaluate the quality of each channel were Received Signal Strength Indication (RSSI), delay time (the time it takes to transfer a packet from sender to receiver), and packet loss rate. To get these metrics, we set up a simple testbed with two TelosB sensor nodes (MEMSIC, 2014) with Contiki Operating System (Contiki, 2014), and X-MAC protocol (Buettner, Yee, Anderson, & Han, 2006). The details of experimental results were presented in (Tran, Silva, Nunes, & Silva, 2012). Figure 2 presents a summary of these experimental results.

a. The RSSI of IEEE 802.15.4 channels at different environments



b. The packet loss rate of IEEE 802.15.4 channels on different environments

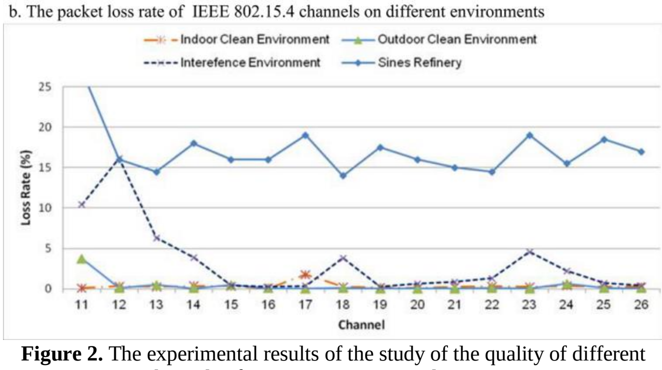


Figure 2. The experimental results of the study of the quality of different channels of IEEE 802.15.4 Compliant WSN

The experimental results show that the quality of channels in the IEEE 802.15.4 based sensor networks depends on the locations, noise and interference conditions. In addition, the effects of these factors depend on different channels. Moreover, the quality of a channel also varies with time, i.e., a good channel at a specific time may perform badly at some other time. By observing the signal strength, the impact on the performance and on the reliability of the wireless communication can be perceived. As a conclusion, in noisy and interference environments is very difficult to predict performance without an empirical study. As a result, when deploying a wireless network in such scenarios, it is necessary to have an experimental evaluation to select the most suitable channel(s).

3. AN ADAPTABLE INTEGRATION FRAMEWORK

The sensed data from WSNs should be collected, processed, and visualized by external applications to make it meaningful to the users. In addition, the users or controllers should also send commands to the sensor nodes through the external applications. Two common approaches for interoperability between WSNs and external applications are gateway-based and IP-based. The former approach requires one or more gateways to be deployed between the sensor networks and external networks, in order to translate and forward the traffic between them. The latter one tries to directly implement IP protocol stack and/or web services on sensor nodes.

The studies in (Dunkels, Full tcp/ip for 8-bit architectures, 2003) and Hui (2009) have proven that it is feasible to deploy IP protocol suite into sensor nodes. In addition, it is also possible to implement the web services on the constraint sensor nodes as explained in (Priyantha, Kansal, Goraczko, & Zhao, 2008), (Dawson-Haggerty, Jiang, Tolle, Ortiz, & Culler, 2010), (Guinard, Trifa, Pham, & Liechti, 2009) and (Shelby, Hartke, & Bormann, 2014). However, in order to fit IP protocol suite and web services into the sensor nodes, it is necessary to apply optimization mechanisms including IP header compression (Hui & Chakrabarti, 6lowpan: Incorporating ieee 802.15.4 into the ip architecture - internet protocol for smart objects (ipso) alliance (white paper # 3), 2009), Message Compression (Shelby, Hartke, & Bormann, 2014), EBHTTP (Tolle, 2010), packed JSON , UDP binding (Dawson-Haggerty, Jiang, Tolle, Ortiz, & Culler, 2010), which makes them incompatible with their counterpart standards.

There are several gateway-based works for integrating WSNs with external applications including (Dunkels, Alonso, Voigt, Ritter, & Schiller, 2004), (Aberer, Hauswirth, & Salehi, 2007), (Shu, Cho, Lee, Hauswirth, & Zhang, 2007), (Grosky, Kansal, Nath, Liu, & Zhao, 2007) and (Emara, Abdeen, & Hashem, 2009). The advantage of the gateway-based approach is that it makes the sensor networks transparent to external environments. In addition, the developers can use any protocols that are most suitable for sensor networks. However, the problem with current gateway-based approach is that it requires either sensor nodes to format the data according to the format required by the provided drivers of the gateway or to develop a software driver or analyzer for each sensor or data frame format. In addition, the gateway is also a single point of failure.

In order to make the sensors as plug and play components of the gateway, the IEEE 1451 family standards (Lee, 2000) have been proposed. One of the core components of this family standard are the definitions of Transducer Electronic Data Sheets (TEDS), which are embedded into the transducers (sensors or actuators), to make the sensed data analyzable. Although it provides a standard way to exchange data, TEDS documents need to be considered in every sensor. In addition, specific software drivers need to be developed for each TEDS. Recently, OGCs PUCK protocol (O'Reilly, 2012) was proposed to store and automatically retrieve metadata and other information to/from the sensor nodes. The information stored in the nodes memory is called PUCK memory, which may be the IEEE 1451 TEDS or SensorML (O'Reilly, 2012). The host computer, e.g. gateway, which supports PUCK protocol, can automatically retrieve and utilize the information from sensors when it is installed. The PUCK protocol brings another level of plug and play capability for sensor devices. However, it requires implementing PUCK documents on every sensor devices. In addition, to make a device as a plug and play component, the driver code has to be physically stored in the PUCK memory before deployment. The problem with current gateway-based approach is its adaptability, i.e., ability of the gateway or proxy to be reused for different protocols and data formats of sensor networks without reprogramming. The main cause of this problem is that it is difficult or even impossible to create a standard for the structures of data inside the frames of sensor networks because of innumerable many possible data frame formats. The following section presents our proposed approach to make the integration framework adaptable to the diversity of types of protocols and data formats of sensor networks, without reprogramming.

3.1 The Interoperability Mode

In order to create a system that is able to respond to a large number of concurrent requests, we employed a multilayered software architecture. As shown in Figure 3, the model uses the proxy and the gateway as an intermediate layer for interoperability between sensor networks and the front--end applications. The gateway provides an interface for the external applications to access the data and functionalities of sensor networks. The proxy interacts directly with the WSNs, getting and analyzing data frames from the sensor network and then sending them to the gateway for storage. It also delivers the commands from the control applications to the sensor network. Both proxy and gateway may also comprise some other facility services such as authentication and authorization.

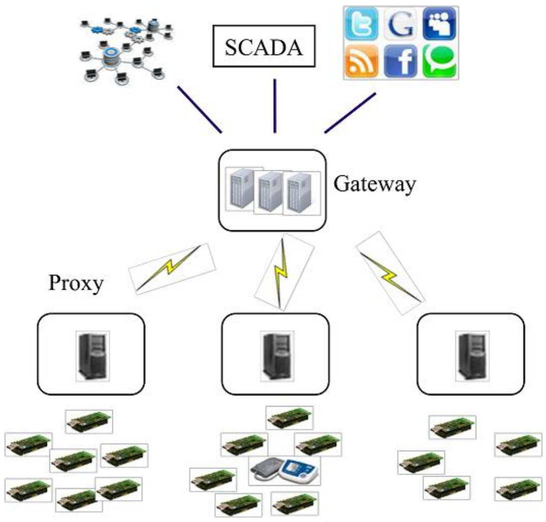


Figure 3. The General Model for Interoperability

3.2 Sensor Traffic Description Language (STDL)

In order to make the framework adaptable to different types of sensor network, we propose a language named Sensor Traffic Description Language (STDL), which is realized by the proxy. As shown in Figure 4**,** the STDL document acts as the brain of the engine, guiding it through the processing of a received raw frame. The STDL document maps the frames structure and allows the engine to extract the necessary data. When a raw frame is received from the Traffic Listener, the STDL engine translates it into one or more messages, and raises corresponding data events. The Data publisher component of the proxy is responsible for processing the data events raised by the engine, extracting data from event messages and forwarding them to the storage in the gateway. The Location Requester, a part of the localization system, registers the events of the STDL engine, composes and sends the requests to the localization engine on the gateway, which estimates the position of a device. When receiving the messages from the Request Receiver, STDL engine transforms messages into raw packets and send them to the sensor networks via the Command sender.

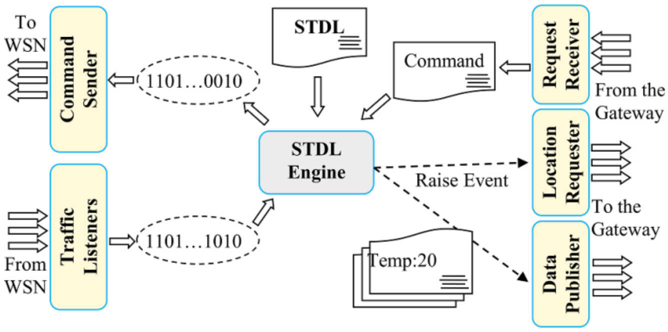


Figure 4. The Components of the Proxy

The STDL is an XML-based language, which adds adaptability to the infrastructure for interoperability between sensor networks and external applications. It is used to describe the structures of the raw frames in sensor networks. It guides STDL engine on how to extract the data from the raw frames thus making the gateway to be adaptable with different types of WSNs. The traffic in WSNs can be described as a set of frames (frames element), each described by three components: (1) attributes; (2) header; (3) content. The detail description of STDL is presented in (Tran, Nunes, Herrera, & Silva, 2014).

To illustrate how to use STDL to describe the raw frames, let us assume a sensor network that creates a raw frame as the one showed in Figure 5.The STDL description of this frame is shown in Figure 6. In this example, it is assumed that the only information needed is the sending node identification and the light and temperature values. Consequently, the content element of the frame description only comprises three elements: senderId, light and temperature, respectively.

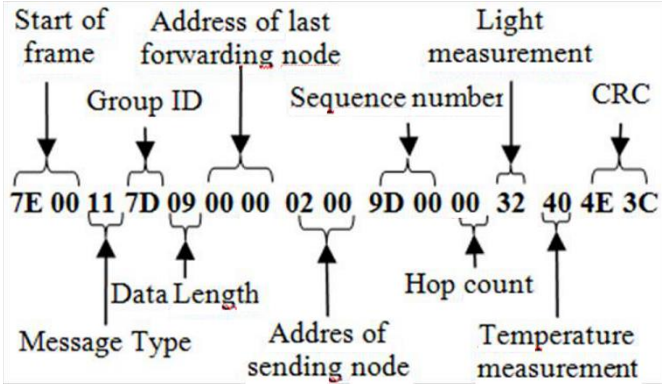


Figure 5. An example of a Simple Raw Frame

```
<?xml<?xml version="1.0" ?>
<frames>
  <frame id="1" name="light temperature"
                      tvpe="11" length="9" lengthTvpe="0">
   <header>
      <startOfFrame numberOfBit="16">0x7E 0x00
      </startOfFrame>
      <tvpeField startPosition="2" numberOfBit="8"
                                    dataTvpe="uint8"/>
      <lengthFieldstartPosition="4" umberOfBit="8"
                                    dataType="uint8"/>
   </header>
    <content>
     <simpleFrame>
      <field name="senderId" dataType="uint16"
         startPosition="7" numberOfBit="16" unit="none"/>
      <field name="light" dataType="uint8" tartPosition="12"
                          numberOfBit="8" unit="lux"/>
      <field name="temperature" dataType="int8"
            startPosition="13" numberOfBit="8" unit="F"/>
     </simpleFrame>
    </content>
  </frame>
    ...
</frames>
```

Figure 6. The frame description for the raw frame in Figure 5

The work in this section showed that a hybrid Proxy/Gateway is a suitable solution for mashing up physical resources with virtual environments. It preserves the major concepts of current research on sensor networks while providing an adaptable infrastructure for seamless interoperability between wireless sensors with external applications.

4. AIR MONITORING IN QUITO

All of the previous sections described the initial work that we have done to build a reliable solution based on WSNs to monitor the air quality of Quito, Ecuador. Although there are already several commercial systems, most of them are based on wired and complex equipment to environment monitoring. The objective of our system is to use common equipment based on WSNs to do that task. In addition, the proposed approach based on WSN should be at least as reliable as wired and traditional solutions. If we can provide such level of reliability, we can take advantage of other properties of WSNs like low cost and flexibility.

The proposed system should monitor and control the parameters shown in Table 1. It also uses rules according to the Ecuadorian legislation. These rules describe the common pollutant concentration levels that define alerts, alarms and emergencies as shown in
Table 2. (Note: All values in micrograms per cubic meter with the air at 25°C and 760 mmHg.)

Table 1. Maximum environmental allowed values (Ecuador 2014), (Municipio Del Distrito 2005)

Pollutant emitted	Fuel used	Units	Max. values
Particles	Solid	mg/Nm3	200
	Bunker	mg/Nm3	200
	Diesel	mg/Nm3	150
	Gaseous	not applicable	not applicable
Nitrogen oxide	Solid	mg/Nm3	900
	Bunker	mg/Nm3	700
	Diesel	mg/Nm3	500
	Gaseous	mg/Nm3	140
Sulfur dioxide	Solid	mg/Nm3	not applicable
	Bunker	mg/Nm3	1650
	Diesel	mg/Nm3	1650
	Gaseous	not applicable	not applicable
Carbon Monoxide	Solid	mg/Nm3	1800
	Bunker	mg/Nm3	300
	Diesel	mg/Nm3	250
	Gaseous	mg/Nm3	100

Table 2. Common pollutant concentration levels defining alerts, alarms and emergency messages (Municipio Del Distrito 2015)

Pollutant and time	Alert	Alarm	Emergency
Carbon Monoxide (Average concentration in eight hours)	15000	30000	40000
Photochemical oxidants, ozone (Average concentration in one hour)	300	600	800
Nitrogen oxides as NO2 (Average concentration in one hour)	1200	2300	3000
Sulphur dioxide (Average concentration in twenty four hours)	800	1600	2100
Particles PM10 (Average concentration in eight hours)	250	400	500

Our initial work was to measure and select a good channel that supports good metrics of quality. According to our empirical study at the deployment environment, channel 16 was selected for WSN because of its quality and reliability in terms of signal strength and packet loss.

We also implemented a web-based application based on the framework described in section 3 to visualize the air parameters. The STDL is used to describe WSN data frames in order to extract needed data. Figure 7 shows the web interface of our application.

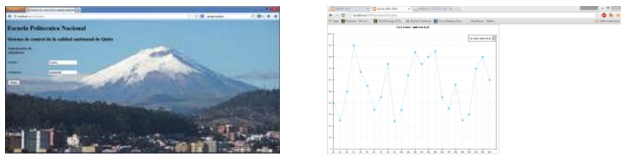


Figure 7. The Web Interface for the air monitoring application

According to this approach, we are now integrating different types of sensors. Initially we were only using TelosB. As we can see in Figure 8, currently we are also using Libellium nodes in our proposed solution. This is a heterogeneous solution composed by TelosB and Libellium nodes.

At this stage to, improve the reliability of WSNs, we developed a new MAC protocol for WSNs named Dynamic Channel Allocation MAC (DynMAC) (Correia 2015), which is based on non-coordinate mechanisms for coexistence. DynMAC employs Cognitive Radio (CR) techniques such as spectrum sensing, channel assessment and decision, information sharing and networks parameters reconfiguration to deal with noise and interference. These techniques allow DynMAC to deal with environments with noise and interferences and take into account their variations along operation time. Consequently, DynMAC adds an additional reliable layer for WSNs.

To validate our proposed mechanisms in DynMAC, we set up a testbed using TelosB sensor motes and Contiki operating system. The topology of the testbed is depicted in Figure 9, using a sink-3-3-6 structure. There were several IEEE 802.11g nodes working on channel 1, 6, and 11.

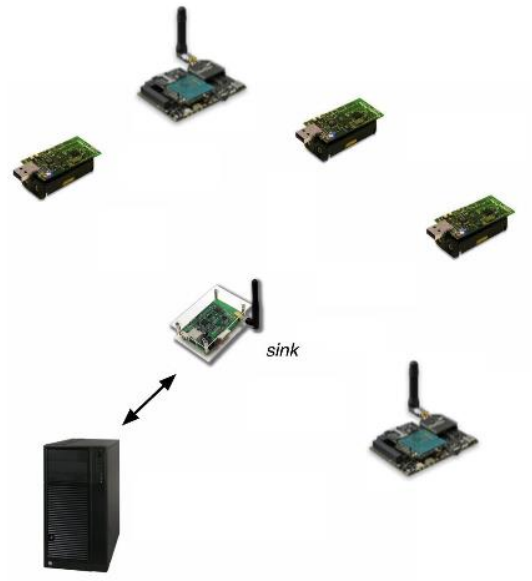


Figure 7. Heterogeneous environment

The first experiment we did was to evaluate the initial best channel select process. This test was done by repeatedly rebooting the sink and counting the numbers of times each channel appeared as best and worst one. Out of 1500 tests, channel 26 has appeared as the best channel for 833 times (55.53%). Other channels that also appeared as good channels with a high frequency were 25 (9.07%), 16 (6.4%), 17 (6.07%). On the other hand, channels 23, 24, and 11 appeared as the worst ones with the rate of 42.8 21.13%, and 13.73%, respectively. This result is reasonable because the WSN was interfered with the IEEE 802.11g networks operating on channel 1, 6, and 11. In addition, the access point operates on channel 11 was very near the sink.

The second experiment was to test the time it took the normal nodes to join network. We did numerous tests to measure this time. From the experiment, it is very fast for a node to scan and detect the channel of its parent. In most cases the nodes only take 1 super-frame (less than 1 second) to find out on which channel the sink is running. However, in some cases, it takes up to 3 super-frames (2120 ms) to scan the operation channel of the sink node, a situation that occurs mainly from nodes at a level far away from the sink. This is reasonable because nodes at lower levels must wait for their parents to join the network before they can detect them.

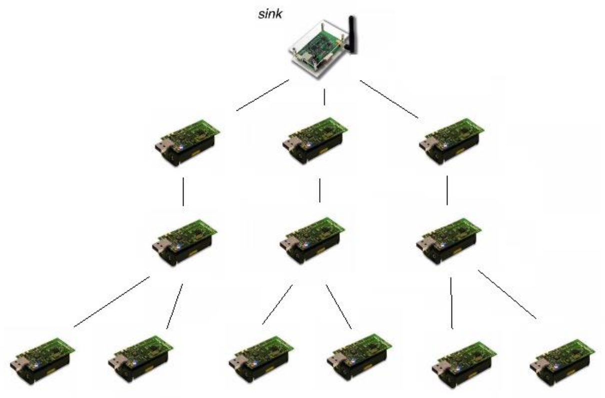


Figure 8. Topology of the testbed

With these experiments, we could conclude that our proposed mechanisms can help the WSNs to deal with the noise and interference environments. This adds another reliable level for WSNs to operate in critical environments.

5. CONCLUSION

This paper presents our set of infrastructure proposals for supporting WSNs in critical environments, more specifically to monitor air quality of Quito. In particular, we proposed an integration framework that can adapt to different types of sensor networks, like TelosB and Libellium.

The framework also helps the interaction between external applications and WSNs to become easier. In addition, we proposed methods to study the quality of different radio channels to select a best one for deploying a sensor network.

All the proposed services were implemented and evaluated using real testbeds. The supporting services proposed in this paper proved to be very efficient in the process of developing sensor networks in real scenarios. As a future work, we will continue proposing new methods to improve the reliability of WSNs and to integrate other supporting services in the WSNs (e.g., encryption).

ACKNOWLEDGMENT

The research leading to these results has received funding from SENESCYT - Secretaría Nacional de Educación Superior, Ciencia, Tecnología e Innovación de Ecuador.

REFERENCES

Aberer, K., Hauswirth, M., and Salehi, A., (2007), "Infrastructure for data processing in large-scale interconnected sensor networks", in Proceedings of the 2007 International Conference on Mobile Data Management, MDM ’07, Washington, pp. 198–205.

Buettner, M., Yee, G., Anderson, E., and Han, R., (2006), "X-MAC: A short preamble MAC protocol for duty-cycled wireless sensor networks", in Proceedings of the 4th International Conference on Embedded Networked Sensor Systems, SenSys '06, New York.

Contiki. (2014) Contiki: The open source os for the Internet of Things. [Online]. HYPERLINK "http://www.contiki-os.org"

Correia, L., Tran, T., Pereira, V., Giacomin, J., and Sá Silva, J., (2015), "DynMAC: A resistant MAC protocol to coexistence in wireless sensor networks", Computer Networks, vol. 76, pp. 1-16.

Dawson-Haggerty, S., Jiang, X., Tolle, G., Ortiz, J., and Culler, D., (2010), "SMAP – a simple measurement and actuation profile for physical information", in Proceedings of the Eighth ACM Conference on Embedded Networked Sensor Systems (SenSys '10), SenSys'10, New York, pp. 197-210.

Dunkels, A., Alonso, J., Voigt, T., Ritter, H., and Schiller, J., (2004), "Connecting wireless sensornets with TCP/IP networks" in Lecture Notes in Computer Science. Berlin - Heidelberg in Wired/Wireless Internet Communications, Springer, vol. 2957, pp. 143–152.

Dunkels, A., (2003), "Full TCP/IP for 8-bit architectures", in Proceedings of the 1st International Conference on Mobile Systems, Applications and Services, MobiSys '03, New York, pp. 85–98.

"Ecuador - Ecology, Nature Protection, Laws and Regulations Handbook", Volume 1, Strategic Information and Basic Laws, International Business Publications, USA, 2014 Edition.

Emara, K., Abdeen, M., and Hashem, M., (2009), "A gateway-based framework for transparent interconnection between WSN and IP network", in IEEE EUROCON'09, pp. 1775–1780.

G. Energia. (2014) Galp energia. [Online]. HYPERLINK "http://www.galpenergia.com" http://www.galpenergia.com

G. P. Soporcel. (2014) Grupo portucel soporcel. [Online]. HYPERLINK "%20http://www.portucelsoporcel.com" http://www.portucelsoporcel.com

Grosky, W., Kansal, A., Nath, S., and Zhao, F., (2007), "Senseweb: An infrastructure for shared sensing", MultiMedia, IEEE, vol. 14, no. 4, pp. 8–13.

Guinard, D., Trifa, V., Pham, T., and Liechti, O., (2009), "Towards physical mashups in the web of things", in Proceedings of the 6th International Conference on Networked Sensing Systems, INSS'09, Piscataway, pp. 196–199.

Hui, J., and Chakrabarti, S., (2009) 6lowpan: Incorporating IEEE 802.15.4 into the IP architecture - Internet protocol for smart objects (ipso) alliance (white paper # 3). [Online]. HYPERLINK "%20http://www.ipso-alliance.org/wp-content/media/6lowpan.pdf"

Hui, J., and Culler, D., (2010), "IPv6 in low-power wireless networks", in Proceedings of the IEEE, vol. 98, Nov 2010, pp. 1865–1878.

Kim, J., Kim, D., Kwak, H., and Byun, Y., (2007), "Address internetworking between WSNs and Internet supporting web services", in International Conference on Multimedia and Ubiquitous Engineering MUE'07, April 2007, pp. 232–240.

Lee, K., (2000), "IEEE 1451: A standard in support of smart transducer networking", in Proceedings of the 17th IEEE Instrumentation and Measurement Technology Conference. IMTC 2000, vol. 2, pp. 525–528.

MEMSIC. (2014) Memsic – powerful sensing solutions: Wireless sensor networks. [Online]. HYPERLINK "http://www.memsic.com/wireless-sensor-networks/"

Municipio Del Distrito Metropolitano de Quito, La Direccion Metropolitana De Medioambiente, http://www.ecuadorambiental.com/doc/normas_tecnicas.pdf, 2005.

O'Reilly, T., (2012) Ogc puck protocol standard version 1.4. [Online]. HYPERLINK "http://www.opengeospatial.org/standards/puck"

Oliveira, J., Fonseca, J., Bartolomeu, P. and Costa, L., (2008), "Evaluating severe noise interference in IEEE 802.15.4 based location systems", in IEEE International Conference on Emerging Technologies and Factory Automation, pp. 893–898.

Pollin, S., Tan, I., Hodge, B., Chun, C., and Bahai, A., (2008), "Harmful coexistence between 802.15.4 and 802.11: A measurement-based study", in 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, pp. 1-6.

Priyantha, N., Kansal, A., Goraczko, M., and Zhao, F., (2008), "Tiny web services: Design and implementation of interoperable and evolvable sensor networks", in Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems, SenSys '08, New York, 2008.

Shelby, Z., Hartke, K., and Bormann, C., (2014) Constrained application protocol (coap) draft-ietf-core-coap-18. [Online]. HYPERLINK "https://tools.ietf.org/html/draft-ietf-core-coap-18"

Shu, L., Cho, J., Lee, S., Hauswirth, M., and Zhang, L., (2007), "Vip bridge: Leading ubiquitous sensor networks to the next generation", Journal of Internet Technology, vol. 8, no. 3.

Sikora, A., and Groza, V., (2005), "Coexistence of IEEE802.15.4 with other systems in the 2.4 GHz-ISM-band", in Proceedings of the IEEE Instrumentation and Measurement Technology Conference. IMTC 2005, vol. 3, pp. 1786–1791.

Tolle, G., (2010) Embedded binary http (ebhttp) draft-tolle-core-ebhttp-00. [Online]. HYPERLINK "http://tools.ietf.org/html/draft-tolle-core-ebhttp-00"

Tran, T., Silva, R., Nunes, D., and Sa Silva, J., (2012), "Characteristics of channels of IEEE 802.15.4 compliant sensor networks", Wireless Personal Communications, vol. 67, no. 3, pp. 541–556, 2012.

Tran, T., Nunes, D., Herrera, C., and Sa Silva, J., (2014), "An adaptable framework for interoperating between wireless sensor networks and external applications", in SENSORNETS, pp. 95–102.