Computers, Environment and Urban Systems 65 (2017) 41–52

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

Enhancing reliability in Wireless Sensor Networks for adaptive river monitoring systems: Reflections on their long-term deployment in Brazil

Jó Ueyama[a, d, *], Bruno S. Faiçal[a, b], Leandro Y. Mano[a], Guilherme Bayer[a], Gustavo Pessin[c], Pedro H. Gomes[d]

[a] *University of São Paulo (USP), São Carlos, São Paulo, Brazil*
[b] *State University of Northern Paraná (UENP), Bandeirantes, Paraná, Brazil*
[c] *Instituto Tecnológico Vale (ITV), Belém, Pará, Brazil*
[d] *University of Southern California (USC), Los Angeles, CA, USA*

ARTICLE INFO

Article history:
Received 22 July 2016
Received in revised form 11 April 2017
Accepted 15 May 2017
Available online xxxx

Keywords:
Wireless Sensor Network
Smart cities
Sensing critical environments
Public safety
Disaster resilience
Communications networks

ABSTRACT

Several adaptive systems have been proposed that are based on the concepts of smart cities, which can be successfully adapted to natural disasters or other public safety concerns. Since these systems are embedded in a critical and dynamic environment, it is really important to have an infrastructure that is capable of providing real-time environmental information. This paper discusses two research questions that arise from adaptive ubicomp systems: (*i*) *what* are the key requirements to provide a reliable WSN-based system (e.g. a river monitoring system)? and (*ii*) *how* can an adaptable and reliable WSN-based system be developed? This paper seeks to respond to the former question with the aid of the RESS standard platform. The latter question is answered by employing a generic approach for adaptation. The term "critical systems", means that any error may result in the loss of human life. We devised the RESS standard after deploying the WSN-based river monitoring system in Brazil for five years. Our prototype underwent several trials, sometimes leading to failure or damage, before we came up with a more reliable solution, which is outlined in this article. Finally, while our RESS platform is policy-free, it is extensible/adaptable and hence can naturally be adapted to new policies.

1. Introduction

More than half of the world's population is currently located in urban areas, with a concentration of up to about 80.2% in countries with higher income levels, and forecasts suggest that this proportion will increase (United Nations, 2014). The unbridled growth of cities has caused an increase in the number of natural disasters and the use of technology to overcome these problems has been investigated by many researchers (Araujo, Duarte-Figueiredo, Tostes, & Loureiro, 2014; Neto, Guidoni, & Villas, 2014; Ueyama et al., 2014). These studies adhere closely to the concept of smart cities, which allows the resources and services of an urban city to be managed in an optimal manner (Komninos, 2011).

Wireless Sensor Network (WSN) have been used in a large number of applications that range from health-care, structural monitoring, asset tracking to environment monitoring and disaster and emergency response (Rashid & Rehmani, 2016; Rehmani & Pathan, 2016; Yick, Mukherjee, & Ghosal, 2008). In the particular case of disasters and emergency response, WSNs are used to monitor natural phenomena, such as storms, hurricanes or volcanos and supply computing systems with information to assist in decision-making (Baggio, 2005; Kim, Jabro, & Evans, 2011; Ueyama et al., 2014). One example of an application that is exploited in this paper is rain monitoring in urban areas that are prone to flooding.

It should be pointed out that many WSN applications are not affected by single-supply sensing error at any given time (such as failing to measure a data reading used to generate an average). In contrast, in environments that are dynamically critical (like those addressed in this paper) the reliability of the WSN is a factor of extreme importance. In these scenarios there is a need for information to be available in real time so that it can be used for immediate action. In addition, even small errors may result from the unavailability of information, which may cause systems or sectors that use this information to make wrong decisions, and increase the odds of the loss of human life.

---

[*] Corresponding author at: University of São Paulo, Av. Trab. São-Carlense, 400, São Carlos - SP, 13566-590, Brazil.

E-mail addresses: joueyama@icmc.usp.br (J. Ueyama), bsfaical@uenp.edu.br (B.S. Faiçal), leandroyukiomano@usp.br (L.Y. Mano), guilherme.bayer@usp.br (G. Bayer), gustavo.pessin@itv.org (G. Pessin), pdasilva@usc.edu (P.H. Gomes).

http://dx.doi.org/10.1016/j.compenvurbsys.2017.05.001
0198-9715/

With this in mind, this paper discusses two research questions: (*i*) *what* are the key factors to take into account while striving to provide a reliable WSN-based critical systems, such as a flood monitoring system? and (*ii*) *how* can we develop an adaptable and reliable WSN-based critical system? The first question is answered by means of our proposed RESS standard platform. The second is answered by employing our generic approach for adaptation. We devised a reliable WSN/IoT-based river monitoring system that is policy-free and accepts new policies in a plug & play fashion. Our system has been successfully deployed in the city of São Carlos/Brazil and has been running for over five years. Our approach has been adopted for several systems, including mobile phone software and follows our generic approach for adaptation.

The rest of the paper is structured as follows. Section 2 outlines the existing guidelines for WSN. Section 3 provides an overview of our current WSN implementation used for river monitoring and examines its long-term deployment. Our proposal is set out in Section 4. In Section 5, there is an explanation about how the data on the behavior of the sensor nodes were gathered and analyzed. Finally, in Section 6 we conclude this work, and point out areas that need to be explored in further studies.

2. Existing guidelines for implementing a WSN

Since WSNs are widely employed for monitoring environments with different features, works can be found in the literature that set out guidelines for implementing this technology. These studies address the challenges raised by the real deployment of WSNs (e.g. uninterrupted monitoring under stochastic conditions in different environments).

Gomez, Laube, and Sorniotti (2008) highlight the importance of WSNs in different fields, such as defense, healthcare, and traffic control. Furthermore, their ability to monitor the physical environment has led to their use in industrial and commercial applications, where information is obtained and processed in accordance with the needs of customers. The paper discusses the design guidelines that have been drawn up to integrate WSNs with Enterprise Systems (Enterprise Resource Planning System - ERP System). This involves combining a top-down approach of context-aware middleware with the bottom-up approach of WSNs middleware, for the design of a SOA-based architecture. This architecture provides a standardized, secure and reliable way for companies to use processed and/or raw data acquired by the sensor nodes for their business purposes.

However, the guidelines relied on by Gomez et al. (2008) fail to look at the implementation of WSNs from an architectural standpoint, but instead the WSNs are implemented in accordance with business regulations, to ensure they meet the conditions required to be integrated with Enterprise Systems. Thus, it can be assumed that the architecture implemented for the WSN is robust enough to prevent any failure during the operation. In addition, this study does not take into account the complexity of the environment to be monitored, although these features exert a strong influence on the architectural implementation of WSN projects.

In Giannopoulos, Goumopoulos, and Kameas (2009), there is a description of the design of a WSN to monitor environmental variables such as temperature, humidity, light and soil moisture. Their paper shows how to deal with problems that arise during the implementation of a real WSN, such as network synchronization, data consistency, data aggregation and energy saving. On the basis of their experience it is possible to draw up some guidelines for building similar systems, which share the objective of monitoring environments for long periods.

However, the experience of Giannopoulos et al. (2009) was based on the implementation of two sensor nodes in a controlled environment (a laboratory) and the expansion of the network (which involved more nodes) and the analysis was only conducted in a simulated way. Thus, although this was a valuable study, the difficulties and obstacles of implementing a WSN in a real-world environment are not addressed, since in real environments there are countless external factors that can influence the design of the system.

Mampentzidou, Karapistoli, and Economides (2012) prepared a set of guidelines to implement WSNs in agriculture, particularly in applications for monitoring crops. First, the authors categorize some key applications of WSN in Precision Agriculture - PA and summarize the components used in the WSN. Following this, there is a description of, the general guidelines that show how to deploy a WSN for agricultural applications. The paper makes a significant contribution to the field by addressing questions regarding hardware and software, communication, sensing, power supply, maintenance, and the importance of interacting with farmers.

However, there was a lack of a dynamic or critical environment for the proposed guidelines. Moreover, it is not essential to sense a possible disaster (which depends entirely on non-deterministic factors) to act as a monitoring platform for adaptive systems. Thus, the proposal does not aim at keeping the WSN working when there are natural disasters; in these situations, it is acceptable for failures to occur as a result of these phenomena.

The guidelines set out by Mampentzidou et al. (2012) cannot be regarded as appropriate for a WSN when they are implemented in critical environments. These scenarios – clarification needed here – are cited in future work, where the authors state that the proposed guidelines can be improved to provide support for other applications such as the environmental monitoring of natural disasters (e.g., volcanoes, landslides, wild fires).

With regard to the use of WSN technology for flood monitoring, there are several works that are worth citing. These include the work in Castillo-Effer, Quintela, Moreno, Jordan, and Westhoff (2004) that adopts WSNs for flash-flood warnings. This work was conducted in the Andean region of Venezuela and was designed to monitor the environment and track the disaster while it was taking place. However, the project was not concerned with assessing the nature of the environment, but rather in how monitoring was carried out with WSNs. Moreover, the aim of the experiment was not to provide an adaptive and tailorable WSN-based system.

Another similar work called RTFMS (a Real-Time Flood Monitoring System) (Sunkpho & Ootamakorn, 2011) was conducted in the island of Mauritius. This is also WSN-based and involves carrying out a real deployment in the field. The main value of this work is that it deals with forecasting and not only detection. It incurs small overhead in real-time, and is able to estimate the extent of the flooding very fast. The work made use of SunSPOT and MicaZ technologies, which are not very robust. Moreover, it does not include an evaluation for a long-term deployment and again is not designed to show how a reliable and runtime adaptable WSN-based system can be built.

Finally, the work in Seal et al. (2012) is also a WSN-based system that deals with flood monitoring. Similar to the work in Sunkpho and Ootamakorn (2011), it is mainly concerned with providing a model for predicting floods. This study has a prediction model based on multiple robust linear regressions. However, the authors are more concerned with displaying the algorithm itself rather than the WSN system. In other words, it is theoretical rather than an attempt to examine the system itself. Hence, this work does not include a field test and can only operate in simulated environments. As a result, it does not target long-term evaluation through a real deployment in the field.

The papers cited in this section represent the state-of-the-art recommendations for the implementation of WSNs in real applications. It should be noted that there is an absence of guidelines for the implementation of WSN in dynamic or critical environments to allow natural disasters to be monitored without interruption, or for