Department of Automation and Systems Technology

Application-Driven Data Processing in Wireless Sensor Networks

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Maurizio Bocca

Aalto University

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Abstract

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Abstract

Wireless sensor networks (WSNs) are composed of spatially distributed, low-cost, low-power, resource-constrained devices using sensors and actuators to cooperatively monitor and operate into the environment. These systems are being used in a wide range of applications. The design and implementation of an effective WSN requires dealing with several challenges involving multiple disciplines, such as wireless communications and networking, software engineering, embedded systems and signal processing. Besides, the technical solutions found to these issues are closely interconnected and determine the capability of the system to successfully fulfill the requirements posed by each application domain.

The large and heterogeneous amount of data collected in a WSN need to be efficiently processed in order to improve the end-user comprehension and control of the observed phenomena. The thesis focuses on a) the development of centralized and distributed data processing methods optimized for the requirements and characteristics of the considered application domains, and b) the design and implementation of suitable system architectures and protocols with respect to critical application-specific parameters.

The thesis comprehends a summary and nine publications, equally divided over three different application domains, i.e. wireless automation, structural health monitoring (SHM) and indoor situation awareness (InSitA). In the first one, a wireless joystick control system for human adaptive mechatronics is developed. Also, the effect of packet losses on the performance of a wireless control system is analyzed and validated with an unstable process. A remotely reconfigurable, time synchronized wireless system for SHM enables a precise estimation of the modal properties of the monitored structure. Furthermore, structural damages are detected and localized through a distributed data processing method based on the Goertzel algorithm. In the context of InSitA, the short-time, low quality acoustic signals collected by the nodes composing the network are processed in order to estimate the number of people located in the monitored indoor environment. In a second phase, text- and language-independent speaker identification is performed. Finally, device-free localization and tracking of the movements of people inside the monitored indoor environment is achieved by means of distributed processing of the radio signal strength indicator (RSSI) signals.

The results presented in the thesis demonstrate the adaptability of WSNs to different application domains and the importance of an optimal co-design of the system architecture and data processing methods.

Keywords Wireless sensor networks, wireless automation, structural health monitoring, indoor situation awareness, data processing

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To my parents

Preface

I landed in Helsinki at the beginning of October of 2005. The original plan was to stay in the Control Engineering Laboratory for the time required to complete my Master thesis. Things have turned out to be a bit different from what I had planned, but certainly for the better.

Throughout my doctoral studies, Prof. Heikki Koivo has been a patient and wise guide in the world of academic research. I want to thank him for giving me the opportunity to continue working in the Lab and for always supporting my decisions when these had to be made. Besides, I want to thank Heikki for being a very intuitive and sharp counterpart during our frequent basketball- and football-related conversations.

Prof. Mohammed Elmusrati (University of Vaasa, Finland) and Prof. Neal Patwari (University of Utah, USA) are warmly thanked for providing detailed comments that were extremely valuable for improving the overall quality of the manuscript. Also, I would like to express my gratitude to Prof. Patwari for inspiring our work on device-free localization and tracking.

I am thankful for the support I received from the “Finnish Foundation for Technology Promotion”, the “Jenny and Antti Wihuri Foundation”, and the “Ulla Tuominen Foundation”. I would also like to thank the “Finnish Funding Agency for Technology and Innovation” (TEKES) for funding the WISM (2008-09), GENSEN (2009-10) and WISMII (20011-12) projects in which I have worked. In addition, I am grateful to the “Multidisciplinary Institute of Digitalisation and Energy” (MIDE) of Aalto University for supporting the ISMO (2008-11) project. I here express my sincere gratitude to all the industrial and academic partners of these projects.

I would like to thank Dr. Lasse Eriksson heartily for three reasons: a) for setting a standard of high-quality research while instructing my doctoral studies, b) for his availability in organizing valuable experiments in industrial environment and c) for proofreading and commenting on the manuscript.

In all these years in the Control Engineering Lab and in our newly formed Wireless Sensor Systems group, I have had the pleasure to work with a bunch of very talented and enthusiastic colleagues. They have made this experience memorable not only from the professional point of view but also from the personal one. I am sincerely grateful to all these people for their inspiration.

During my stay in Helsinki, I was lucky enough to meet and become friend with some truly exceptional people with whom I share extravagant memories. You know who you are. Thanks! And to Harri and Teresa: this world would be a much better place with more people like you. Dziękuję bardzo! A big, fat, greek thanks goes to Emmanuel Chavredakis, especially for teaching me so well how to properly use the Finnish language. Finally, a special thanks goes also to "La Prof.", Luisa Sozio, a true italian whose size is proportional to her good heart: "*nullum vitium taetrius est quam ignorantia*".

Last but not least, my family: my parents Barbara and Edoardo, my cousins Alberto and Davide, my uncles Luigi and Marco, my aunts Luigia and Piera. No matter where I was, I always knew I could count on you at any moment, and this is probably the most important thing to know when you are living far from home. Thank you so much.

Ευχαριστώ για όλα. για πάντα μαζί.

Maurizio Bocca

List of Publications

[PUB 1] K. Tervo, *M. Bocca*, L. M. Eriksson, and A. Manninen.
"Wireless joystick control for human adaptive mechatronics applications: case trolley crane",
Proceedings of the IEEE International Conference on Networking, Sensing and Control (ICNSC'09), Okayama, Japan, March 26-29, 2009.

[PUB 2] K. Tervo, *M. Bocca*, L. M. Eriksson, and A. Manninen.
"Wireless manual control for human adaptive mechatronics",
International Journal of Advanced Mechatronic Systems (IJAMechS), Vol.2, No.4, pp. 254-270, 2010.

[PUB 3] O. Kaltiokallio, L. M. Eriksson, and *M. Bocca*.
"On the performance of the PIDPLUS controller in wireless control systems",
Proceedings of the 18th IEEE Mediterranean Conference on Control and Automation (MED'10), Marrakech, Morocco, June 23-25, 2010.

[PUB 4] *M. Bocca*, E. I. Cosar, L. M. Eriksson, and J. Salminen.
"A reconfigurable wireless sensor network for structural health monitoring",
Proceedings of the 4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4 2009), Zurich, Switzerland, July 22-24, 2009.

[PUB 5] *M. Bocca*, A. Mahmood, L. M. Eriksson, J. Kullaa, and R. Jäntti.
"A synchronized wireless sensor network for experimental modal analysis in structural health monitoring",
Computer-Aided Civil and Infrastructure Engineering (CACAIE), 2011, available on-line: DOI 10.1111/j.1467-8667.2011.00718.x.

[PUB 6] *M. Bocca*, J. Toivola, L. M. Eriksson, J. Hollmen, and H. Koivo.
"Structural health monitoring in wireless sensor networks by the embedded Goertzel algorithm",
Proceedings of the 2nd ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS 2011), Chicago, IL, USA, April 11-14, 2011.

[PUB 7] *M. Bocca*, C. Galperti, R. Virrankoski, and H. Koivo.
"Estimating the number of persons in an unknown indoor environment by applying wireless acoustic sensors and blind signal separation",
Proceedings of the IEEE Mobile Computing and Wireless Communications International Conference (MCWC'06), Amman, Jordan, September 17-20, 2006.

[PUB 8] *M. Bocca*, and H. Koivo.
"Real-time text and language independent speaker identification with a reconfigurable wireless network of acoustic sensors",
Proceedings of the 2008 IEEE International Conference on Technologies for Homeland Security (HST'08), Waltham, MA, USA, May 12-13, 2008.

[PUB 9] O. Kaltiokallio and *M. Bocca*.
"Real-time intrusion detection and tracking in indoor environment through distributed RSSI processing",
Proceedings of the 17th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA 2011), Toyama, Japan, August 28-31, 2011.

Author Contributions

[PUB 1] The author designed the wireless joystick control system and implemented the code. He participated to the development of the methods presented in Section 3 and contributed to its writing.

[PUB 2] The author participated to the design and validation of the methods embedded in the wireless joystick control system and was responsible for the implementation of the code. He wrote Section 2 of the manuscript.

[PUB 3] The author designed the implementation of the PIDPLUS wireless controller and contributed to its implementation and validation. He also commented on the manuscript.

[PUB 4] The author designed the application and implemented the code. He performed the tests and derived the results. Emre Cosar contributed to the implementation and validation of the application. Juho Salminen contributed to the development of the wireless platform used in the tests. Lasse Eriksson supervised the research. The author wrote the entire manuscript. All co-authors commented on the manuscript.

[PUB 5] The author developed and validated the ISMO-2 node used in the tests. He implemented the application code. Aamir Mahmood contributed to the implementation of the TS protocol and to the writing of Sections 2.6 and 2.7. Jyrki Kullaa developed the method to estimate the missing samples and performed the modal analysis. He contributed to the writing of Sections 2.4.1 and 3.2.2. Lasse Eriksson and Prof. Riku Jäntti supervised the research and commented on the manuscript.

[PUB 6] The author designed the application, implemented the code, performed the tests and derived the results. He also wrote the entire manuscript. Janne Toivola and Jaakko Hollmén contributed at the idea level. Lasse Eriksson and Prof. Heikki Koivo supervised the research. All co-authors commented on the manuscript.

[PUB 7] The author implemented the code of the application and derived the results. Reino Virrankoski contributed to the data analysis and to the writing of the manuscript. Prof. Heikki Koivo supervised the research.

[PUB 8] The author designed the application, implemented the code, and collected the database of voice samples used in the simulations. He also wrote the entire manuscript. Prof. Heikki Koivo supervised the research.

[PUB 9] The author instructed Ossi Kaltiokallio in developing the application and the data processing methods presented in the manuscript. In various phases, he also participated to the implementation of the code and to the writing of the manuscript.

Nomenclature

Symbols

α	Coefficient
ϕ	Complex mode shape
ΔC_{cep}, $\Delta\Delta C_{cep}$	First and second order derivatives of C_{cep}
ΔT	Time interval
ω_c	Carrier frequency
a, b, c	Parameters of the ellipsoid model
c_i	Goertzel algorithm coefficient
e	Control error
f	Frequency
f_i	Frequency of interest
f_n	Phase of the n-th received multipath component
f_s	Sampling frequency
h	Number of nodes equipped with microphones
k	Discrete-time index
k_d	Controller gain – derivative term
k_i	Bin corresponding to a frequency of interest
m	Mel-frequency
n	number of independent acoustic sources
q_0, q_1, q_2	Results of the Goertzel algorithm iterations
r_n	Amplitude of the n-th received multipath component
s	Last collected acceleration sample
$s(t)$	Transmitted sinusoidal carrier
s_i	Sensor node i
$s_i(k)$	Independent acoustic source i at time instant k
t	Continuous-time index
$v(t)$	Amplitude of the received radio signal
$w_{(x_p,y_p)}$	Weight of the pixel at coordinates (x_p,y_p)
$x(k)$	Original voice signal
$x_i(k)$	Acoustic signal recorded by sensor node i
$x_f(k)$	Enhanced voice signal
x_p	Pixel coordinate
y	Output of the peak filter
y_c	Output of the cubic curve mapping
y_f	Output of the exponential filter
y_p	Pixel coordinate
y_{range}	Pre-defined operating range of the joystick
y_0	Offset value
$z^e_{(x_p,y_p)}$	Value of ellipsoid e at coordinates (x_p,y_p)
A	Mixing matrix
C	Correlation matrix
C_{cep}	MFCCs vector
C_{sig}	MFCCs matrix
C_{sp}	Matrix of the MFCCs corresponding to speech
C_L	Amplitude of the line-of-sight component
C_N	Vector of the normalized means of C_{sig}
D	Derivative term of the PIDPLUS controller
$D^{s_j}_{s_i}$	Damage indicator between sensor nodes i and j
F	Filter for the PIDPLUS controller
$H(Z)$	Transfer function of the 2nd order IIR filter

M	Smoothening vector
N	Number of collected samples
N_{bins}	Number of bins used in the DFT
N_{cep}	Number of MFCCs
N_e	Number of ellipsoids overlapping a pixel
N_w	Number of windows in the voice signal
O	Actuator value
T_i	Integration time of the PIDPLUS controller
T_f	Time constant
$T_{s_i}^{s_j}$	Transmissibility function between sensor nodes i and j
V	Linear transformation
X	Squared magnitude of the frequency spectrum

Operations

µ( )	Mean of a vector
| |	Absolute value
H	Conjugate transpose
T	Transpose

Abbreviations

AoA	Angle of Arrival
BSS	Blind Signal Separation
CPS	Cyber-Physical System
DoS	Denial of Service
DAC	Digital-to-Analog Converter
DCT	Discrete Cosine Transform
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
GoeA	Goertzel Algorithm
HAM	Human Adaptive Mechatronics
InSitA	Indoor Situation Awareness
ICA	Independent Component Analysis
IIR	Infinite Impulse Response
ISM	Industrial, Scientific and Medical
LoS	Line-of-Sight
ModAC	Modal Assurance Criterion
MCU	Microcontroller Unit
MFCC	Mel-Frequency Cepstral Coefficient
OS	Operating System
QoS	Quality of Service
PCA	Principal Component Analysis
PCB	Printed Circuit Board
PDR	Packet Delivery Ratio
PID	Proportional-Integral-Derivative
PPM	Parts Per Million
RF	Radio Frequency
RSSI	Radio Signal Strength Indicator
SHM	Structural Health Monitoring
SNR	Signal-to-Noise Ratio
ToA	Time of Arrival
TDoA	Time Difference of Arrival
TF	Transmissibility Function
TS	Time Synchronization
WiNCS	Wireless Networked Control Systems
WAUT	Wireless Automation
WSN	Wireless Sensor Network

Contents

1 Introduction

This section briefly discusses the background of the thesis and summarizes the contributions of the author.

1.1 Background

The vast and heterogeneous amount of data wireless sensor networks (WSNs) are able to collect must be effectively processed in order to provide the end-user with a comprehensive understanding of the monitored ongoing phenomena and events.

Several factors, such as the capability of the system to collect high quality data and to effectively process them despite the resource limitations of the nodes, determine the performance of a WSN. For this purpose, the characteristics and requirements specific to each application domain must be clearly comprehended and considered while developing the proper data processing methods and designing the architecture of the system. Due to this close relationship between the physical and the digital world, WSNs are nowadays often referred to as cyber-physical systems (Lee, 2006).

Over the last decade, WSNs have been successfully applied to a wide range of applications, e.g. environmental monitoring (Mainwaring et al., 2002, Hu et al., 2005, Werner-Allen et al., 2006, Corke et al., 2010), structural health monitoring (Lynch and Loh, 2004, Ceriotti et al., 2009), health monitoring and elderly care (Patel et al., 2009, Hegarty et al., 2010, Ko et al., 2010), wireless automation (Gungor and Hancke, 2009) and smart homes and surveillance (He et al, 2006, Shu et al., 2009), just to name a few.

The flexibility and adaptability of this technology are the main reasons for its success. The sensor nodes composing the system, equipped with different types of sensors and/or actuators, are rapidly deployable in large number over extended areas. This flexibility has often opened the way to applications

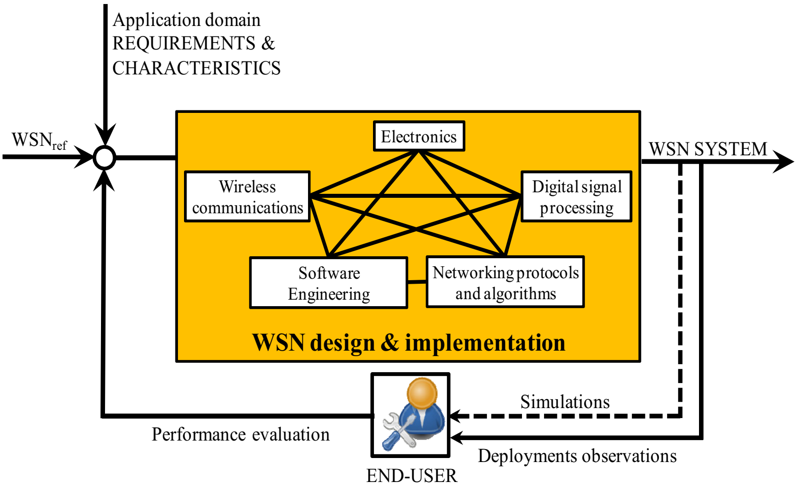


Fig. 1.1 WSN design and implementation process

e.g. underground (Silva and Vuran, 2010) and underwater (Alippi et al., 2011) monitoring, which would otherwise be too difficult and/or expensive to be realized with the traditional wired measurement systems.

1.2 Motivation and objectives

The design and implementation of an effective WSN requires dealing with several challenges involving multiple disciplines, such as embedded systems, wireless communications, software engineering, networking algorithms and protocols, and signal processing (Römer and Mattern, 2004). The technical solutions found to these issues are closely interconnected and determine the capability of the system to fulfill the requirements posed by each application domain (Figure 1.1).

The research presented in this thesis focuses on two aspects: on one side, the development of centralized and distributed data processing methods optimized for the requirements and characteristics of the considered WSN application domains. On the other, the design and implementation of suitable system architectures and protocols with respect to critical application-specific parameters, such as time-synchronization, latency, real-timeliness, energy efficiency, robustness (to measurement noise and packet losses), and quality of the measurements collected by the nodes composing the network.

In the thesis, three different application domains are considered: wireless automation (WAUT), structural health monitoring (SHM), and indoor situation awareness (InSitA). Time synchronization (TS) plays an important role throughout the entire thesis. It is used to keep a precise synchronicity of the samples collected by the nodes, which ultimately improves the accuracy of the results obtained through frequency-domain analysis techniques. Besides, it enables TDMA communication among the nodes, which activate their radio only in correspondence of packet transmissions and receptions, thus reducing their power consumption. In the thesis, signal noise and data loss represent two additional problems that are thoroughly considered. Depending on the specific requirements of the application domain, noisy signals are filtered and processed to remove potentially harmful effects. On the other hand, high-quality data can be lost due to packet drops or inability of the microcontroller to sample while performing other operations. In this case, the missing data are recovered by requesting the nodes to retransmit the lost packets, or by applying off-line missing data estimation algorithms.

1.3 Contributions

The main contributions of the thesis can be summarized as follows:

- In the context of WAUT, a novel wireless joystick control system for human adaptive mechatronics (HAM) applications was created. The system was tested in two laboratory-scale case studies, i.e. a trolley crane and a ball balancing system. It is composed of a receiving and a transmitting node. Dedicated algorithms have been designed and then embedded in the transmitting node to remove the potentially dangerous effects of measurement noise and bad control actions taken by the human operator. Other algorithms have been embedded in the receiving node in order to compensate for packets losses and to reduce the effects of the noise introduced by the actuators. The system allows performing small and high-precision, as well as fast and smooth adjustments of the position of the controlled item also in the presence of a faulty communication link. In the second case study, the PIDPLUS wireless controller was designed and implemented and new results are derived on its performance under various packet drop conditions.

- Two novel applications for SHM were developed and tested on a wooden model bridge. The system is remotely configurable through a Matlab® interface running on an external PC connected to the sink node. In the first application, all the vibration data collected by the sensor nodes are gathered at the sink node for off-line modal analysis. The system is able to recover the data packets originally lost during the transmission phase. A new wireless platform specifically designed for SHM improves the quality of the measurements. A high accuracy, low-power time synchronization protocol guarantees a precise synchronicity of the samples collected by the nodes composing the network. The proposed SHM system is able to accurately identify the modal properties of the monitored structure. In the second application, a distributed method to detection and localization of structural damages is proposed. In it, the nodes process the vibration signals in real-time by the Goertzel algorithm (GoeA). The results of their computations are exploited to derive transmissibility functions (TFs). This approach allows the system correctly detecting and localizing structural damages, reducing latency and energy consumption of the nodes.

- In the context of InSitA, the low-quality and short-time acoustic signals collected by the resource-constrained sensor nodes were at first exploited to estimate the number of people located inside an indoor environment, i.e. to solve the so called "cocktail-party problem". For this purpose, the whitening phase of independent component analysis (ICA) is employed. In the second phase, the acoustic signals were processed to achieve text- and language-independent speaker identification. The developed light-weight algorithm, based on cepstral analysis, achieves high identification accuracy with short-time and low quality signals. Furthermore, detection and tracking of a person moving in an indoor area surrounded by sensor nodes was obtained by means of distributed processing of the radio signal strength indicator (RSSI). For this purpose, a novel variance-based algorithm which does not rely on a pre-existing model of the radio signal propagation patterns was developed. The algorithm dynamically adapts to the changing conditions of the environment to trigger alerts related to significant events, i.e. people intrusions. This feature makes it suitable for emergency response scenarios. The system proved to be able to accurately track a person also in obstructed environments.

1.4 Summaries of the publications

The thesis consists of a short summary and nine publications, found in the appendices. This section introduces the content of each publication.

1.4.1 Wireless automation

PUB I. The paper describes the development of a wireless joystick control system for a laboratory-scale trolley crane system. The MoCoNet platform (Pohjola et al., 2005) is used for data logging and analysis. The aim of the study is to develop intelligent methods to support and improve the performance of the human operator, who is modeled as a PD controller with finite time delay. Preliminary tests for the identification of the characteristics of the human controller in performing pre-determined tasks, e.g. load swinging balancing, are carried out. In the system, the control signal is filtered in order to remove the effects of measurement noise and improve the precision and smoothness in the guidance of the trolley crane.

PUB II. The paper describes the design and implementation of a wireless joystick control system for HAM applications. In order to improve the control performance and the stability of the control system, packets losses in the controller-to-actuator link are compensated by identifying the characteristics of the PD human controller. During the interruptions of communication, the control effort is decreased by applying a PIDPLUS-type of algorithm (Song et al., 2006). The proposed compensation method considers the last known state of the system and the prediction of the state of the human operator made at the time the last packet was received. This method does not require a model of the controlled system. Advanced filtering algorithms, embedded in the transmitting and receiving nodes, remove the effects of measurement and actuators noise, and balance the consequences of bad control actions taken by the human operator. The wireless joystick control system is validated in two laboratory-scale case studies, i.e. a trolley crane and a ball balancing system.

PUB III. The paper investigates the performance of the PIDPLUS wireless controller with respect to the different packets loss rates and varying time-delays typically found in wireless networked control systems. First, by considering a simple process model, the performance of the event-based PIDPLUS wireless controller is compared to the one of the time-based PID. In a second phase, the PIDPLUS wireless controller is implemented and validated in a laboratory-scale, unstable ball balancing system. Through several tests, the effect on the control performance of a) the timing of occurrence of the packets drops and b) of the limited computation and communication resources of the wireless sensor nodes is analyzed.

1.4.2 Structural health monitoring

PUB IV. The paper presents a reconfigurable WSN for SHM. An interface running on the external PC connected to the sink nodes allows the end-user to remotely configure the key parameters of the application, i.e. the activated nodes, the sampling frequency, the length of the measurement period, the sensitivity of the accelerometer, and the vibration axis to be considered in the sampling. An automatic retransmission procedure successfully recovers those data packets originally lost during the transmission phase.

PUB V. The paper describes a time synchronized and remotely configurable WSN for SHM enabling an accurate identification of the modal properties of the monitored infrastructure. The sensor nodes used in the tests, specifically designed for the requirements of SHM, increase the signal-to-noise ratio of the vibration data. In the synchronization phase, the sink node broadcasts a series of beacons through which each sensor node estimates its own clock skew. The estimated value is then used during the sampling phase to ensure a highly accurate synchronicity among the collected measurements. The data collected during tests carried out on a wooden model bridge were exploited for modal analysis. The results obtained with the wireless system, compared to the ones derived from acceleration signals collected by high quality wired sensors, show a precise and reliable identification of the modal properties of the monitored structure. Power consumption and expected lifetime of the wireless monitoring system under different activation and packet loss rates are also evaluated.

PUB VI. The paper describes a WSN in which the sensor nodes process the acceleration measurements in real-time by applying the GoeA. This algorithm allows the nodes to perform a frequency-domain analysis of the acceleration signals in an efficient way. The results of the computations are shared in the network to derive TFs, whose changes indicate the presence and position of a structural damage. The real-time, distributed approach implemented in this application prevents the nodes from transmitting large amounts of data to the sink node for off-line modal analysis, reducing the latency and increasing the lifetime of the wireless monitoring system.

1.4.3 Indoor situation awareness

PUB VII. In the paper, the short-time and low signal-to-noise ratio acoustic signals recorded by wireless sensor nodes equipped with microphones are processed in order to estimate the number of people located in an unknown indoor environment. For this purpose, a BSS technique based on PCA is applied. Despite the resource limitations of the sensor nodes, i.e. the limited applicable sampling frequency, the system provides correct estimates. When the applied sampling frequency is lowered, TS errors among the nodes start decreasing the reliability of the final estimate.

PUB VIII. The paper describes a WSN in which the sensor nodes, equipped with microphones, record acoustic signals in typical indoor environments (e.g. offices, corridors, halls, etc.). These signals are then processed by means of a computationally light-weight algorithm to perform text- and language-independent speaker identification. The developed algorithm is based on cepstral analysis. In the feature vector extraction process, the portions of the acoustic signal corresponding to actual speech are effectively separated from the ones corresponding to silence or background noise. The tests are carried out by using a database composed of 200 acoustic signals recorded in typical indoor environments, including 60 individuals (45 men, 15 women) and 15 different languages. The effect on the identification accuracy of the applied sampling frequency and length of the measurement period, as well as the one of the key parameters of the feature extraction process is also analyzed.

PUB IX. The paper presents a WSN in which the sensor nodes, deployed in an indoor environment along a square perimeter, form a virtual grid of wireless links to detect the intrusion and then track the movements of a person inside the monitored area. This is achieved by distributed processing of the RSSI measurements. TS is exploited to establish a TDMA communication protocol among the nodes. This enables a consistent extension of the system lifetime. The embedded RSSI processing algorithm, which operates iteratively, triggers alerts in correspondence of interesting events, i.e. people intrusions. Through it, the volume of traffic towards the sink node is minimized. Moreover, the developed variance-based algorithm does not rely on a pre-existing model of the radio signal propagation patterns. The current position of the intruder is obtained from the spatial configuration of the alerts received at the sink node. The tracking accuracy and smoothness of the system are further improved by applying a Kalman filter. The application is tested in various obstacle-free and obstructed indoor environments.

1.5 Structure of the thesis

The thesis is organized as follows. Chapter 2 provides a brief overview of the fundamental features, main challenges and potential applications of WSNs. The specific requirements, characteristics and challenges of the considered application domains, i.e. WAUT, SHM, and InSitA, are presented in chapter 3. Chapter 4 summarizes and discusses the original contributions and main results of the thesis. In Chapter 5, some of the lessons learned from deploying wireless sensor systems in the real-world are discussed, and future research directions are considered. Finally, conclusions are drawn in Chapter 6.

2 Wireless Sensor Networks Overview

This section provides a brief overview of the fundamental characteristics of WSNs, describes the typical challenges to be faced in the design and implementation phases, and lists some of the most significant application domains.

2.1 Fundamental characteristics

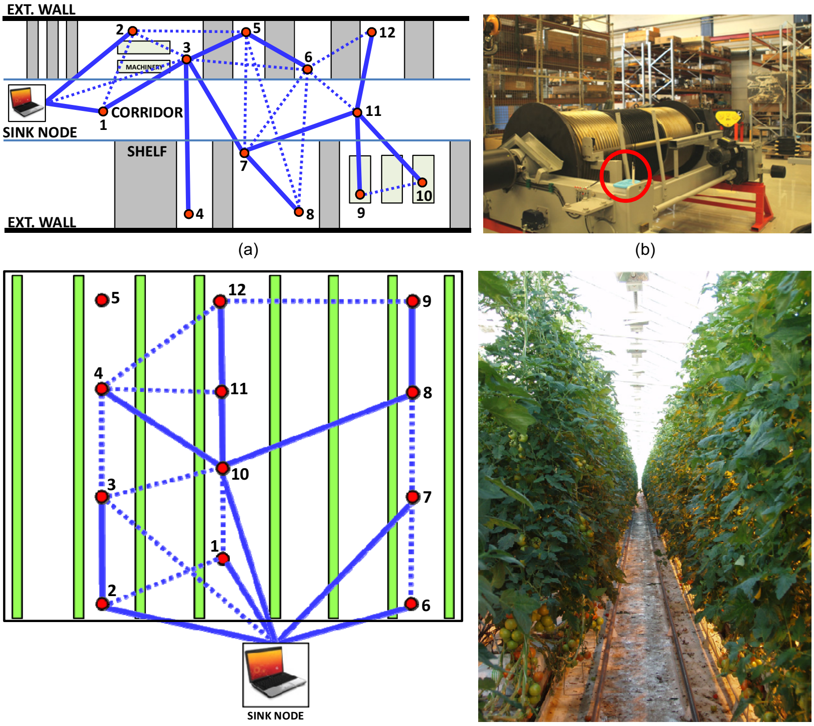
A WSN is formed by tens, potentially hundreds, of sensor nodes, low-power, resource-constrained, spatially distributed, autonomous devices connected wirelessly, using sensors and/or actuators to cooperatively monitor and/or operate into the environment.

The nodes are low cost, small-scale devices typically equipped with one or more types of sensors and/or actuators, a low-power radio transceiver and microcontroller unit (MCU), with limited computational power and memory space. The power source of the sensor nodes is usually a battery, which can eventually be recharged through a small-scale energy scavenging system, e.g. solar panels, piezos and radio frequency (Roundy et al., 2004). To guarantee the prolonged operation of the system, the nodes must be able to physically endure harsh and varying environmental conditions. For this purpose, a proper casing of the nodes' components is critical. Due to the limited cost of a single unit, WSNs were originally projected to be composed of a large number of nodes, i.e. hundreds, potentially thousands, and to cover extended areas (Akyildiz et al., 2002).

The nodes can be stationary, as in most of the applications, or mobile (Ali et al., 2006, Eriksson, J., et al., 2008, Kim et al., 2011). The network is denoted as homogeneous if all the sensor nodes are equipped with the same hardware components, or otherwise as heterogeneous. One or more data collection and processing units, or sink nodes, can be found in a WSN, inside or outside the deployment area. In some applications, these units are often equipped with radios capable of transmitting the collected data over long distances.

The network can be fully or partially connected, depending on the density and spatial configuration of the nodes in the deployment area. The network connectivity is also affected by the transmission range of the nodes, which depends on factors such as the (adjustable) transmitting power of the radio (Lin et al., 2006, Correia et al., 2007), the type and gain of the antenna, the characteristics of the surrounding environment (Zhao and Govindan, 2003), and the temperature and humidity conditions (Boano et al., 2010).

Energy is one of the nodes' most critical resources. Besides determining the lifetime of the single nodes and consequently of the entire network, energy consumption optimization is one of the fundamental issues driving the design of algorithms and protocols (Burri et al., 2007, Ferrari et al., 2011). However, a WSN must also be able to cope with nodes' failures, in terms of hardware breakdown, lack of energy and temporal/permanent inability to communicate with the neighboring nodes. To overcome these problems, efficient protocols must be designed in order to monitor the status of the nodes, in terms of energy level and connectivity with the other nodes, and dynamically adjust the network topology (Hou et al., 2005, Hackmann et al., 2008). In real-



(a) (b)

(c) (d)

Fig. 2.1. Results of the network initialization procedure (Bocca et al., 2011) in an industrial hall ((a) and (b)) and in a tomato greenhouse ((c) and (d)). The solid lines represent the links selected during the initialization, whereas the dashed lines represent the alternative available links.

world deployments, the discovery of the existing connectivity graph and the selection of the high quality wireless links over the low quality ones (Figure 2.1) guarantee a more reliable and timely collection of the data at the sink node. These issues become more challenging with mobile sensor nodes.

In the majority of the applications, the sensor nodes are usually activated in three ways:

- they periodically wake-up from a very low-power sleep state, collect one or more measurements, and then transmit these data to the next hop of the route to the sink node;
- they are triggered by the reception of a command from the sink node, requiring the acquisition and transmission of new measurements. In this case, the sink node can also modify some of the parameters of the application run by the sensor nodes.
- they autonomously activate themselves after detecting an event in the surrounding environment, e.g. when a sensor measurements exceeds a threshold.

In these scenarios, the nodes can function as repeaters, receiving data from other nodes which are topologically located more far away from the sink node and forwarding the received information to the closer ones. Also, the nodes along the path from the source to the final destination can perform data processing and/or aggregation in order to reduce the traffic volume and save energy. Data aggregation is often exploited in tree-like multihop networks composed of a large number of sensor nodes in which each unit is expected to transfer to the sink node a huge amount of data (Rajagopalan and Varshney, 2006).

The low-power MCUs found in the sensor nodes are resource-constrained, in terms of available memory space, computational power and clock speed. For this reasons, the operating systems (OSs) specifically developed for WSNs are much less complex than general-purpose OSs, not providing heavy-weight mechanisms such as e.g. file system and virtual memory. TinyOS (Hill et al., 2000), based on an event-based programming model, has been the first OS specifically designed for the development of WSNs applications. Other OSs, such as Contiki (Dunkels et al., 2004) and FreeRTOS (www.freertos.org), provide real-time support. Besides OSs development, the group of software-related issues in WSNs include middleware (Römer et al., 2002), i.e. the development of programming and data abstractions interfacing the end-user high level software with the sensor nodes low level software, security (Perrig et al., 2004), and macro-programming (Hnat et al., 2008).

2.2 WSN design space

The design and implementation of an effective WSN are hindered by three types of resource limitations found in the sensor nodes, i.e. available energy, MCU memory space and computational power, and wireless communication bandwidth. Depending on the particular characteristics and requirements of each application, protocols and algorithms can be designed and implemented so to e.g. consume a large portion of one (or more) of these resources, and save the other(s). Several trade-offs, e.g. energy-latency (Moscibroda et al., 2006) and lifetime-performance (Zhu et al., 2008), must be considered in the design phase. The final performance of the system is often the result of the compromise choices done in the design phase.

Similarly, each application domain poses different quality-of-service (QoS) requirements. The concept of QoS refers to the quality of the data collected by the sensor nodes and transferred to the sink node, i.e. the nodes' capability to depict reliably and with high accuracy the ongoing monitored phenomena. QoS involves all the layers of the protocol stack. Packet delivery ratio (PDR), latency and jitter, i.e. the packet delay variation, play an important role, since in several applications it is fundamental to reliably and timely receive the data at the sink node (Chen and Varshney, 2004). However, intensive computations executed locally in the nodes and temporary communication failures can increase latency and jitter, and can make the data received at the sink node outdated.

In the sensor nodes, embedded computations require a very small amount of power compared to the one consumed for communication. For this reason, distributed and/or collaborative data processing methods, which reduce the volume of traffic in the network, guarantee a consistent power consumption reduction and a consequent extension of the lifetime of the system. When the number of nodes in the network is large and their data production rate is high, the use of such data processing methods prevents from the emergence of traffic hot spots in those nodes topologically located close to the sink node(s), which would quickly run out of energy. On the other hand, the low-power MCUs typically found in the sensor nodes limit the complexity of the embedded data processing algorithms and the speed of execution of the operations, particularly when floating point precision is required. If needed, the nodes can be equipped with a more performing MCU. However, enhanced performances come at the cost of higher power consumption.

In order to save energy, a node should spend most of its lifetime in a very low-power sleep mode, the radio being off, and then activate itself at the right time to perform specific tasks. Consequently, a node in deep sleep mode is not able to e.g. forward packets and collect new sensor measurements. In this case, network connectivity and physical coverage of the monitored area can be guaranteed by deploying redundant nodes and by coordinating their deep sleep schedules. However, the setup of the required coordination among the nodes inevitably consumes energy and affects the design and implementation of the routing protocol, which would have to deal with time-varying topologies. TS (Ganeriwal et al., 2003, Maro'ti et al., 2004, Schmid et al., 2010) represents a potential solution to this issue, allowing the sensor nodes to turn on the radio in correspondence of scheduled communications.

In several applications, sensor measurements are meaningful only when time and position of the observations are known. For this reason, TS and localization protocols are required. For nodes localization, the use of GPS receivers often does not represent a feasible option, due to the high cost, form factor, large energy consumption and to the impossibility of use in particular scenarios (e.g. indoor and underwater environments) (Patwari et al., 2005). Other techniques used to estimate the positions of the nodes include ranging based on the received signal strength, time-of-arrival (ToA), time-difference-of-arrival (TDoA), and angle of arrival (AoA) (Mao et al., 2007).

The wireless communication among the nodes is the backbone for the correct functioning of a WSN. However, compared to the wired systems, in which the communication among the devices is reliable and immediate, the low-power wireless links found in WSNs have heavily varying characteristics and performance over time and space. Several factors contribute to this, e.g. the presence of another interfering wireless network (e.g. WLAN) operating in the same frequency band (Angrisani et al., 2008, Hauer et al., 2009) or physical obstructions affecting the propagation of the radio signal (Chipara et al., 2010). As a consequence, the unpredictability of the quality and reliability of the existing wireless links makes QoS provisioning a very challenging task. Thus, a critical factor to be considered in the design of the networking protocol is the value of the transmitted information: if the packet contains e.g. the results of local computations, obtained by processing a large number of data collected by other nodes, the value of the packet is higher than the one of e.g. packets containing only individual sensor measurements. Therefore, critical data packets must be protected from losses due to communication failures. This can be achieved through acknowledgements or retransmission procedures, at the expense of higher power consumption and latency.

Due to the key role played by wireless communication, security represents an important issue in the design of a WSN, especially in e.g. critical military applications. Security mechanisms are required to protect communications from external denial-of-service (DoS) attacks and intrusions (Sen, 2009). Passive attacks can be carried out by eavesdropping nodes' transmissions, in order to perform various operations, such as traffic analysis, node localization and disclosure of the contents of the packets. Examples of active attacks are routing attacks, flooding, or node capturing (Karlof and Wagner, 2003, Khokhar et al., 2008).

2.3 Applications

Due to the flexibility provided by the integration of sensing, computing and communicating capabilities into miniaturized hardware, WSNs have been used in variety of applications. The deployment of these systems in real-world scenarios requires to analyze and identify effective technical solutions to issues spread over multiple disciplines, such as embedded systems software and electronics, programming abstractions, signal processing, networking protocols and wireless communications. The performance of a WSN depends also on the knowledge and accurate description of the monitored phenomena provided by experts of the application domain, e.g. civil engineers in SHM, biologists in environmental monitoring applications, etc.

Some of the advantages of the use of WSNs over wired systems are:

- The possibility to deploy, with no spatial restrictions, a high number of sensors and/or actuators at a reduced cost;
- The improved screening capability on the monitored phenomena;
- The reduction of the installation and maintenance time and costs;

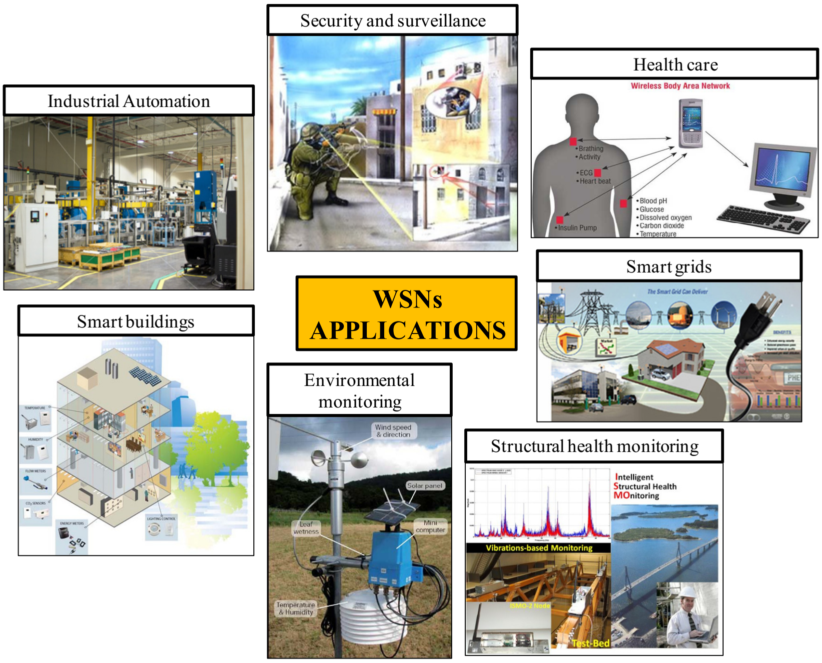


Fig. 2.2. WSNs applications.

- The possibility to easily modify the existing setup of the network, e.g. adding or removing nodes, in order to adapt to the ongoing physical phenomena;
- Because of the absence of wires, mobility and the capability to operate also in very harsh environments.

Figure 2.2 depicts some of the most popular applications of WSNs. Among these, applications like surveillance and environmental monitoring (including cattle/wildlife monitoring and precision agriculture), have been very popular since the early days of research in the area. Other applications, e.g. smart grids and smart buildings, have only recently started to be investigated, attracting more and more the attention of industries and governments. For industrial process measurement and control, other networking technologies operating in the 2.4 GHz industrial, scientific and medical (ISM) radio band, such as WirelessHART (Song et al., 2008) and ISA100.11a, already have millions of units installed and running around the world.

3 Applications Requirements and Challenges

This section describes requirements and challenges of the three application domains considered in the thesis.

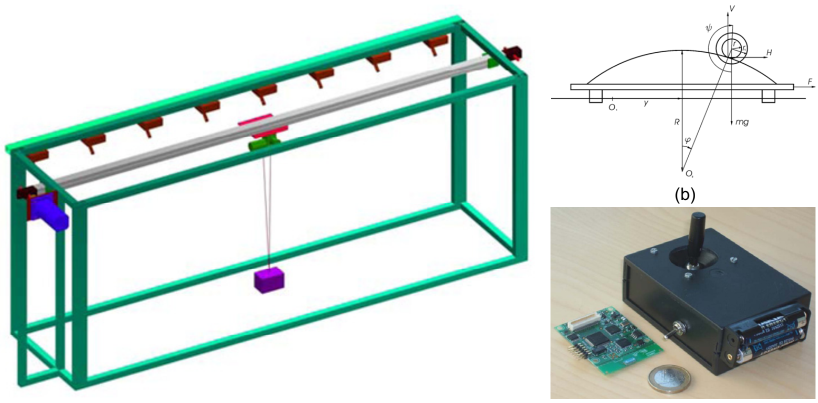
3.1 Wireless automation

Until now, WSNs have been used in several industrial applications, such as wireless automation, wireless process control and real-time monitoring. The applications are expected to increase significantly in number over the next years (Embedded WiSeNTs Consortium, 2011).

Unlike other application domains, e.g. environmental monitoring, in which data delivery reliability and timeliness are not explicitly required, industrial applications pose strict and critical requirements in terms of reliability, timeliness, system scalability and energy efficiency (Willig, 2008). This is particularly true for HAM applications (Suzuki et al., 2005, 2010): when a human operator remotely controls a machine through a wireless link, the encountered requirements and challenges are similar to those which are observed and tackled in the context of wireless networked control systems (WiNCS) (Hespanha et al., 2007, Eriksson, 2008, Park et al., 2011).

In first place, an effective real-time control of an industrial process requires the existence of reliable wireless links between the controlling, sensing and actuating units. On one hand, the unreliability of wireless communications in industrial environments manifests itself in terms of random packet losses. On the other, the fulfillment of the strict timeliness requirements of WAUT applications is challenged by the jitter introduced by TS errors, MAC layer, multihop routing and MCU scheduling.

Furthermore, the developed networking protocols must be able to cope with a network composed of a large and potentially varying number of nodes. This feature involves several challenging issues, such as nodes and connectivity



(b)

(a)

(c)

Fig. 3.1. The trolley-crane system (a) and the ball balancing system (b) used in the tests. In (c), the wireless joystick device used to control them.

graph discovery, TS, link quality estimation, network topology definition and control, dynamic communication scheduling adjustment, etc. (Freris et al., 2010, Puccinelli et al., 2011).

To extend the lifetime of the system and reduce the maintenance costs, the battery-powered nodes, which can eventually be equipped with a small-scale energy harvesting system, require an optimized power management scheme. However, the adoption of such a scheme should not degrade the control performance, i.e. the system must still meet the application requirements of reliable and timely packets delivery.

In industrial applications, the deployed sensor nodes must be robust to extreme environmental conditions, e.g. temperature and humidity, vibration, dust and dirt. Also, they must be able to correctly operate in the presence of high levels of electromagnetic noise. Moreover, both the data collected by the sensor nodes and the control commands received in the actuating nodes must be accurate and acquired/delivered in a timely manner. This is particularly important in HAM applications, such as the trolley-crane and ball balancing systems depicted in Figure 3.1, where the fundamental goals are e.g. control accuracy, the possibility to perform various tasks with very high precision, and the capability of the control system to filter and/or compensate for wrong control actions taken by the human operator.

3.2 Structural health monitoring

The aim of SHM is to provide an accurate diagnosis of the structural health of civil infrastructures, e.g. bridges, tunnels, dams, pipes, heritage buildings, etc., by processing the data collected by sensors deployed on them. A SHM system should be able to accurately perform four tasks (Rytter, 1993):

- Damage detection;
- Damage localization;
- Damage quantification;
- Assessment of the remaining lifetime of the monitored infrastructure.

Traditionally, the sensors deployed on the structure are connected through coaxial wires with a central data repository system. However, cabling implies high installation and maintenance costs (Celebi, 2002). Moreover, cables are subjected to wear or breakage. WSNs consistently reduce the installation and maintenance costs. Furthermore, the compact size and low cost of a single wireless sensor node enables the deployment of a large number of units on the monitored structure, especially in those locations difficult to be reached by wires, increasing the screening resolution of the system.

SHM presents special requirements to WSNs. First, the quality of the data collected by the sensor nodes must be as high as possible in terms of signal-to-noise ratio (SNR). This fact requires minimizing the floor noise level of the acceleration signals. Moreover, a very high sensitivity is necessary, since the system must be able to accurately measure peaks as low as e.g. 500 μg. Secondly, in order to capture the spatial characteristics of the vibration of the monitored infrastructures, the sampling procedure must be as synchronous as possible throughout the network. This fact requires minimizing the jitter of each node, i.e. the random variations of the sampling interval, and the time synchronization error among the sensor nodes.

From the point of view of wireless communications, the shape, size and materials of which structures are normally composed of, primarily concrete, force the establishment of chain-type multi-hop networks (Chen and Wang, 2008). In SHM, all the data collected by the sensor nodes need to be reliably transferred back to the sink node. Similarly, also the commands and the requests to change application-specific parameters issued by the end-user operating at the sink node have to reach in a timely fashion all the targeted sensor nodes.

A WSN for SHM is supposed to operate for an extended period of time, e.g. few years, requiring minimal maintenance. For this purpose, the creation of a wireless sensing platform capable of collecting high-quality data requires a consistent engineering effort. The casing hosting the components must resist to enduring harsh environmental conditions, e.g. humidity, rain, frost, wind, temperature variations, etc. Furthermore, the attachment of the platform to the monitored structure must be practical, so to reduce the installation time, and provide the required rigidity, so to minimize the damping and spurious vibrations which would decrease the quality of the collected measurements, as shown in Figure 3.2.

(a) (b)

Fig. 3.2. The ISMO-2 node (a) used in the tests carried out at the wooden truss structure (b). The wireless platform includes a Sensinode's U100 Micro.2420 unit, a LIS3LV02DQ 3-axis digital accelerometer by STMicroelectronics, and a SHT71 temperature and humidity sensor by Sensirion.

In WSNs, TS is hampered by the poor quality of the crystal oscillators found in the nodes. The consequent drift and clock skew differ from node to node and can vary depending on the age, ambient and operating temperature of the device. Moreover, the TS accuracy required by the data processing methods applied in SHM to obtain reliable results and estimates, i.e. modal analysis, is in the order of few tens of microseconds (Krishnamurthy et al., 2008).

The TS challenge is double-faced: on one side, despite the existence of a multi-hop network, the TS error among the nodes must be minimized, in particular in the sampling phase. On the other, the communication overhead inevitably introduced by a TS protocol must be limited, in order to avoid shortening the lifetime of the system.

Due to the unreliable nature and varying performance of the wireless links, the sensor nodes have to autonomously detect if (and which) data packet went lost during the transmission. In this situation, they have to retrieve the lost data and successfully forward them to the sink node. In case of failure of this recovery procedure, the samples missing from the acceleration signals can be estimated by exploiting the received ones and the redundancy of the sensor nodes deployed on the structure.

Given the huge amount of acceleration data collected by the sensor nodes and the power consumed to transfer them to the sink node, distributed data processing techniques for e.g. damage detection and localization have been proposed (Lynch et al., 2004). In these applications, the collected data are processed locally in the sensor nodes. Subsequently, the final results of the computations, contained in a small number of packets, are transferred to the sink node. The embedded processing algorithms can trigger the collection of a larger amount of data upon detection of anomalous or dangerous situation. Embedding such data processing techniques in the nodes is made challenging by the bounded amount of available RAM memory (e.g. 10 kB) and by the limited computational power and speed of the low-power MCU. Moreover, the adopted algorithm must be able to accurately detect and possibly localize the onset of small damages without generating false alarms.

3.3 Indoor situation awareness

Soldiers, fire fighters and emergency responders refer to situation awareness as being keenly aware of the environment in which they are operating in to gain a tactical advantage and to maximize the effectiveness of their actions. Situation awareness is achieved by combining in a unified real-time model the information coming from various sources, e.g. sensors' data, GPS systems and pre-existing maps and pictures of the environment (Figure 3.3). WSNs, composed of tiny, wearable and/or rapidly deployable sensor nodes, represent an attractive technology to achieve these goals, which include:

- the estimation of the number and of the identities of people located inside the target building;
- the localization and tracking of the individuals, with the aim to detect potentially anomalous behaviors;
- the understanding of the actions and of the roles played by each person located in the monitored area, e.g. in a hostage situation, the identification of the hostage(s) and of the kidnapper(s);
- the detection of dangerous chemicals (e.g. flammable gases, weapons, explosives), and of extreme environmental conditions (e.g. very high temperatures indicating the onset of a fire);
- the monitoring of the vital signs of the blue forces, i.e. soldiers, fire fighters, emergency responders, etc.

Typical sensors used in InSitA applications are microphones, miniaturized cameras, accelerometers, RSSI measurements, etc. The acquisition, storage and processing of the large amount of data collected with these sensor types is made even more difficult by the high sampling rates required to collect high quality and useful information (Guo and Hazas, 2011). Also, the information collected by the nodes located inside the target building must be transferred to the sink node located outside as quickly and reliably as possible. These critical requirements clash with the limited resources of the nodes in terms of communication bandwidth and hardware capabilities. Moreover, in the case in which the sensor nodes were randomly scattered throughout the target building, a crucial issue becomes the time required to setup the network, i.e. to discover the existing links among the nodes and define a reliable tree-like topology, to localize the nodes, to time synchronize the network, etc.

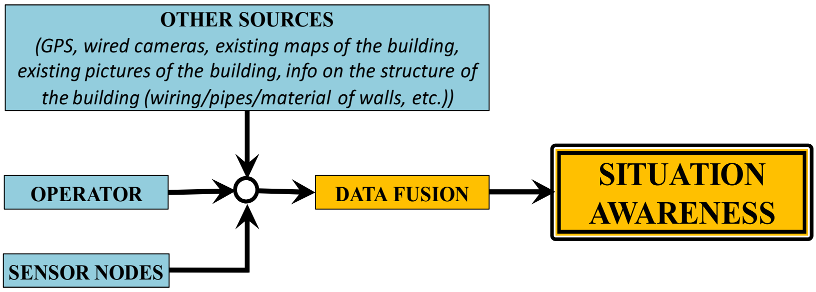


Fig. 3.3. InSitA with WSNs (derived from Endsley's situation awareness model (Endsley, 1995)).

One of the feasible approaches to achieve the main objectives of InSitA is represented by a wireless network of acoustic sensors: the feature vectors extracted from the voice signals recorded by small and unnoticeable sensor nodes equipped with microphones can be matched against an already existing database to perform speaker identification. Similarly, the acoustic signals can be exploited to estimate the number of people found in an unknown indoor environment, solving the first step of the so-called “cocktail party problem” (Haykin and Chen, 2005).

Throughout the last decades, speaker identification has been widely studied and applied in a variety of contexts. However, the conditions in which it has been carried out have almost always been fairly idealistic and stationary, i.e. with very high sampling frequency and SNR. On the contrary, in WSNs the limited resources of the nodes strictly constrain the applicable sampling frequency, as well as the length of the measurement period. Moreover, because of the strict real-time requirements of InSitA, traditionally efficient but computationally intensive methods, based on a priori information about the acoustic features of the monitored environment, cannot be applied. Thus, in the case of WSNs, the applied methods must be able to deal with noisy and short-time signals. Similarly to what is required in SHM, also in InSitA TS among the nodes is required to be able to correctly fuse the data and obtain reliable estimates of the number of individuals found in the monitored area.

WSNs provide also the means to localize people and track their movements by processing the variations of the RSSI. In this case, the nodes composing the network can be considered as radio frequency (RF) sensors (Patwari and Wilson, 2010). For this particular application, the transmission of all the raw RSSI measurements collected by the nodes to the sink node for off-line data analysis, though effective for tracking, is not power efficient. Furthermore, this approach would increase the latency of the system, especially in multi-hop networks, restricting its utility in typical emergency response scenarios, where real-timeliness is a critical requirement. In addition, training a radio signal propagation model of the monitored environment in static conditions, i.e. with no object in it, would require time, e.g. minutes, and waste the power of the nodes. Moreover, this approach would be sensitive to marginal changes of the radio signal propagation patterns. This would make it prone to generate false alarms in the highly dynamic emergency response scenarios (Chen et al., 2011).

4 Results

The main results of the thesis are related to the design and development of optimized solutions and data processing methods to fulfill the requirements posed by the three considered application domains, i.e. WAUT, SHM and InSitA. This section summarizes the results presented in the publications.

4.1 Wireless automation

This section describes the design and implementation of a manual wireless joystick control system for HAM applications. Furthermore, the performance of the PIDPLUS algorithm in controlling an unstable process is evaluated under different packet drop conditions.

4.1.1 Experimental setup

The laboratory-scale trolley crane system (2.5 x 0.8 x 0.6 m) used in the tests of *PUB 1* and *PUB 2* is equipped with two electric motors, controlling the movement of the load vertically (hoist) and along one horizontal direction (trolley). The trolley position and length of the rope which connects the hoist motor to the load are measured with two potentiometers.

The data collected on the trolley crane system, e.g. trolley position and rope length, raw and filtered control commands, etc., were logged in real-time on an external database accessible through the Internet by using the MoCoNet platform (Pohjola et al., 2005). The developed wireless joystick control system for HAM applications is composed of two sensor nodes (Figure 4.1): the transmitting one measures the displacement of the joystick in the two directions provided by two analog potentiometers. The receiving one converts the received information of the displacement of the joystick into voltages through two DACs. These control commands are then filtered and processed before reaching the electric motors.

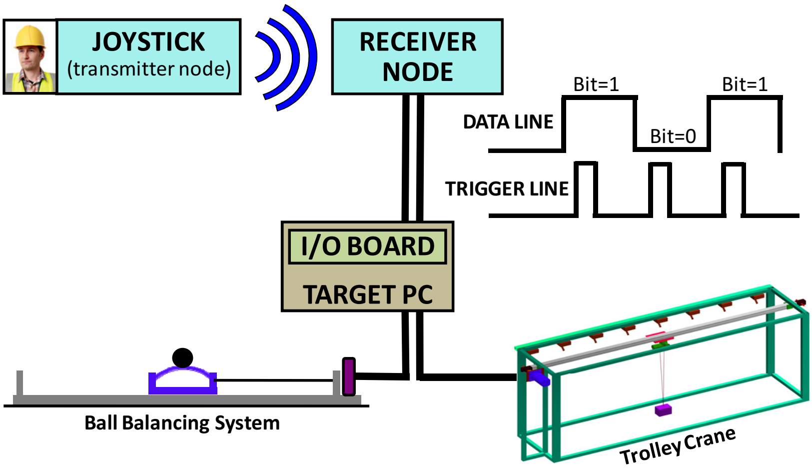


Fig. 4.1. Block diagram of the wireless joystick control system developed in *PUB 1*, *PUB 2* and *PUB 3*.

In *PUB 2* and *PUB 3* the developed wireless joystick control is also used in a ball balancing system. In it, a cart, on the top of which there are two convex rails on which a ball is free to roll, is moved along two tracks through an electric motor. The main control objective is to keep the ball in the middle of the rails by continuously moving the cart back and forward. The secondary control objective is to keep the cart as close as possible to the horizontal middle position of the tracks.

4.1.2 Embedded filtering and signal processing

In *PUB 1*, the filtering and signal processing functions are implemented in Simulink (Matlab®). Several operations, including scaling, peak filtering, exponential smoothing, cubic curve mapping and dead-zone compensation were developed. The two values obtained by sampling the potentiometers of the joystick are passed through these stages before being provided to the actuators. The MoCoNet platform offered the possibility to log a huge amount of measurements, corresponding to different operational conditions of the system, for off-line analysis and improvement of the processing functions.

In *PUB 2*, the filtering and signal processing functions are embedded in the transmitting node. First, the values obtained from the potentiometers are limited into the pre-defined operating range of the joystick. The displacement range is divided in two areas, corresponding to the situations in which the operator is changing or not the position of the load, respectively. The rate at which the potentiometers are sampled depends on the current state of the joystick. Two states are defined: the *moving* state corresponds to when the operator is changing the position of the load; the *idle* state corresponds to when no action is undertaken by the operator. The sampling rate is increased when the operator is moving the load in order to make the control sufficiently fast and smooth.

If the joystick has not changed state in the time interval required to collect five measurements, the median value is calculated. This reduces the effect of the noise of the acquisition process. Otherwise, each time the joystick changes state, the median value is calculated taking into consideration only those measurements corresponding to the state from which the joystick is moving out. This guarantees the receiving node to receive updated information also in the case the joystick is frequently changing state, e.g. in the case of small adjustments of the position of the load.

The computed median values, one per direction, are passed through a peak filter in order to remove those peaks introduced by the measurement noise. This stage prevents the motors from dangerously running as a result of noise, thus introducing unnecessary swinging of the load. The peak filter is also able to follow the commands of the operator when performing rapid adjustments of the position of the load. The output of the peak filter is passed through an exponential filter, which further reduces the effect of the measurement noise:

$$y_f(k) = \alpha\, y_f(k-1) + (1-\alpha)\, y(k), \tag{4.1}$$

where $y_f(k)$ is the output of the exponential filter, $y_f(k\text{-}1)$ its previous value, $y(k)$ the input signal, i.e. the output of the previous peak filter, and $\alpha \in [0,1]$ is the coefficient of the exponential filter. The value set for the filter coefficient α affects the lag of the control actuated by the operator.

Before transmitting the filtered control signals to the receiving node, a cubic curve mapping, formulated as:

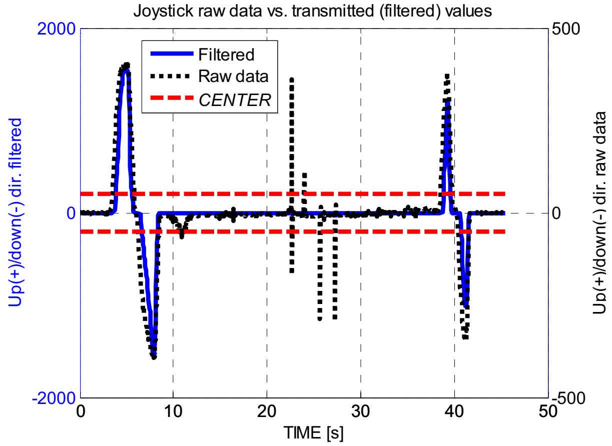


Fig. 4.2. Raw potentiometer values (dotted line) and processed control signal (solid line) of the wireless joystick. The dashed line represents the boundaries between the two states of the joystick, i.e. moving or stationary.

$$y_c(k) = \frac{(y_f(k)-y_0)^3}{(y_{range}/2-y_0)^2} + y_0 \tag{4.2}$$

is applied to the output of the exponential filter. In it, $y_c(k)$ is the output, $y_f(k)$ is the input, i.e. the output of the exponential filter, y_o an offset, i.e. the raw potentiometer values corresponding to a stationary joystick, and y_{range} is the difference between the maximum and minimum values of the pre-defined operating range of the joystick. This type of mapping is applied to allow the operator performing both small, high precision adjustments of the position of the load, requiring a low velocity, and large, smooth and fast adjustments.

The developed embedded filtering and signal processing functions improve the guidance of the wireless joystick control system from two points of view:

- they enable the operator to smoothly perform small adjustments of the position of the load with high precision, avoiding undesirable and potentially dangerous sudden bursts of the actuators;
- they make the acceleration/deceleration of the actuators smoother, a particularly important feature in control systems, which e.g. prevents from generating structural fatigue and stress on an industrial crane used to move heavy loads.

Before being provided to the electric motors moving the load, the processed control values received at the receiving node are transferred to the control system, which in turn scales them into suitable voltages. The received values are transferred through a digital serial communication scheme. In this way, the usual connection between the DACs of the node (one for each direction of movement) and the ADCs of the control system interface is avoided, since this would considerably introduce additional noise.

4.1.3 Wireless PIDPLUS control

Unlike wired networks, wireless networked control systems are characterized by intermittent packet losses. For these systems, the standard, time-based PID algorithms have poor dynamic response. The effect of packet losses on the control of an unstable process is evaluated in *PUB 3*, in which the manual wireless joystick control system is substituted with a wireless PIDPLUS controller (Song et al., 2006) composed of three nodes: one for measuring the current position of the cart on the tracks and of the ball on the rails, one for computing the control signal and one for actuating the electric motor. The event-based PIDPLUS controller overcomes the problems caused by packets losses and asynchronous communications encountered in the time-based PID algorithm, such as spikes in the control signal and windup situations. In the PIDPLUS controller, the integral and derivative terms are updated only upon reception of a new measurement packet:

$$D(k) = k_d \frac{e(k)-e(k-1)}{\Delta T} \tag{4.3}$$

$$F(k) = F(k-1) + [O(k-1) - F(k-1)] \cdot \left(1 - e^{-\frac{\Delta T}{T_i}}\right). \tag{4.4}$$

In (4.3), e is the process output error at time instant k and ΔT the time elapsed between the receptions of the last two measurement packets. The integral term is replaced by the filter F as in (4.4), in which $O(k\text{-}1)$ is the previous actuator value and T_i is the integration time of the controller.

In *PUB 3*, in order to reduce the measurement noise, a first-order, event-based filter with time-constant T_f is applied:

$$e_f(k) = \frac{T_f}{\Delta T + T_f} e_f(k-1) + \frac{\Delta T}{\Delta T + T_f} e(k) \tag{4.5}$$

The filtered error signal e_f is used in (4.3). For long communication outages (large ΔT), the filter weights the up-to-date raw data more than the outdated filtered value.

The measuring node obtains the current position of the cart and of the ball by sampling two analog potentiometers. These values are first passed through the same peak filter used in the trolley crane case and then transmitted to the controller node. In it, the instants of reception of the measurement packets are time-stamped so to be able to estimate the value of ΔT. The control value is calculated by applying the PIDPLUS algorithm and then transmitted to the actuator node. The electric motor is actuated through the DACs of the node. The actuator node transmits back an ACK packet including the latest applied control value.

In each cycle, the computations involving floating point variables and the radio transmissions and receptions are the most time-consuming operations. The MCU found in the nodes would execute the algorithm computations at a much higher speed by using integer type variables only. However, this would inevitably affect the control signal precision. The cycle time can vary due to the undeterministic CSMA/CA MAC protocol implemented in the nodes. For this reason, if the chosen sampling interval h is close to the cycle time, the possibility of losing measurement packets increases. This would potentially push the ball balancing system towards instability.

In the case of an unstable process, such as the ball balancing system, the state of the process at the moments in which packets are lost, either from the measuring node to the controller or from the controller to the actuating node, plays a key role in defining the capability of the system to achieve the control task. When consecutive packets are lost, the controlled process might have already entered the instability region before communication is re-established.

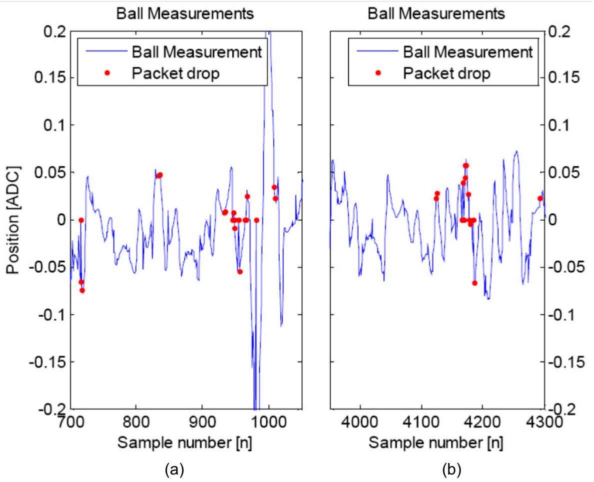


Fig. 4.3. In the case of an unstable process, the moments in which packets are lost, either from the measuring node to the controller or from the controller to the actuating node, define the instability (a) or stability (b) of the process.

Also, upon reception of a measurement packet after consecutive losses, the controller might produce a very large control value in order to compensate. This can lead the process towards instability. This situation is illustrated in Figure 4.3. In (a), consecutive packet losses make the controller produce a large control value, which drives the process unstable. In (b), despite packet losses, the controller is able to keep on balancing the ball.

4.1.4 Summary of the findings

The results obtained in the area of WAUT can be summarized as follows:

- The signal processing and filtering methods embedded in the wireless joystick control system a) remove the effects of the sensors' noise and b) improve the accuracy and smoothness of the control performed by the human operator;
- In identifying the control characteristic of the human operator, a PD-type model can be used to capture general features, i.e. time constants and delays, but does not account for other critical features, e.g. such as the typical intermittence and saturation of the human controller;
- Despite the computational limitations of the nodes, smart algorithms can be implemented to compensate for the intermittent packet losses encountered in wireless networked control systems and to improve the effectiveness of the performed control tasks and the stability of the controlled systems.

4.2 Structural health monitoring

In the context of SHM, a wireless system was developed, implemented and tested on a wooden truss structure to perform experimental modal analysis and damage detection and localization.

4.2.1 Experimental setup

The wooden model bridge used in the tests is 420 cm long, 65 cm wide and 34 cm high. It is equipped with 16 high quality and perfectly synchronous wired accelerometers whose data provide the reference for the evaluation of the results obtained with the developed wireless system. The model bridge, weighting approximately 37 kg, is connected to a programmable electro-dynamic shaker, which can be set to generate different types of excitation.

4.2.2 Platform development

One of the main research efforts carried out in *PUB 4* and *PUB 5* focused on the design and development of a wireless sensor node capable of resisting extreme environmental conditions and of minimizing the floor noise level of the collected vibration measurements. Both characteristics are required in typical SHM applications. The ISMO-2 (named after Intelligent Structural health MOnitoring) node is equipped with a 3-axis MEMS accelerometer and a high-precision temperature and humidity sensor. The accelerometer has a selectable full scale of ±2g or ±6g, and a selectable 12 or 16 bit representation. The ADCs integrated in the sensor, which convert the acceleration samples into a digital bit stream, are coupled with dedicated reconstruction filters that remove the high frequency components of the quantization noise. The temperature and humidity sensor has 0.05% RH and 0.01°C resolutions, and low power consumption, i.e. 0.55 mA in active mode, less than 1 μA in sleep mode.

The three components of the ISMO-2 node, i.e. Sensinode's Micro.2420 platform (Sensinode Ltd.), accelerometer and temperature and humidity sensor, are contained in a 22 x 6 x 3.5 cm aluminum case. A WLAN antenna with a 5.0 dBi gain is used to increase the transmission range of the node. The Micro.2420 platform and the PCB containing the accelerometer are tightly screwed to an aluminum bar that provides the rigidity required to minimize both noise and damping. The node can be magnetically attached to the structures. The two magnets are placed at the two ends of the aluminum bar, since their proximity to the accelerometer consistently increases the floor noise level of the acceleration measurements.

4.2.3 System reconfiguration and data collection procedure

In *PUB 4*, a simple Matlab® interface is developed to enable the end-user operating at the sink node to remotely configure the key parameters of the SHM application. The parameters list includes the IDs of the selected ISMO-2 nodes, the radio channel to be used for data transmission, the monitored axis of vibration, the sampling frequency, and the length of the measurement period. The sink node is connected via USB to an external laptop running the Matlab® interface. The parameters set by the end-user are transferred to the sink node through the serial port of the laptop.

The sink node is responsible for activating the selected sensor nodes and for reliably distributing the parameters set by the end-user. After the sampling, it also takes care of requesting the collected acceleration measurements from all the sensor nodes. If the transmission of the data from one sensor node stops, e.g. because of battery depletion or of physical obstruction of the wireless link (Mottola et al., 2010), the sink node proceeds by requesting the data from another previously activated sensor node. Otherwise, if some packets went lost during the data transmission, the sink node transmits a retransmission request including the sequential numbers of the lost data packets. The sensor node retrieves the corresponding data from its external flash memory and retransmits them to the sink node. This procedure stops only when all the acceleration data have been successfully transferred to the sink node or when the number of lost data packets does not decrease after a pre-defined number of retransmission requests from the sink. In the tests carried out in *PUB 5*, the implemented lost packets recovery procedure contributed to the final 99.95% PDR.

4.2.4 Time synchronization and sampling procedure

The typical skew and drift of the clocks of the sensor nodes is due to the poor quality of the crystal oscillators found in the Micro.2420 platforms, which have a ±40 parts-per-million (PPM) accuracy. However, to obtain accurate and reliable estimates of the modal properties of the monitored structures, high-precision TS is required to avoid phase difference in the data collected by the sensor nodes.

In the system described in *PUB 5*, the sink node broadcasts a series of TS beacons at regular intervals (e.g. one per second). The first beacon is used by the sensor nodes to adjust the offset of their clocks. Nevertheless, due to the clock skew, the nodes keep on deviating from the global time provided by the sink node. At the reception of the following TS beacons, each sensor node measures a specific TS error, which represents an estimate of its clock skew. The measures exceeding a pre-defined threshold, e.g. 20 µs, being caused by the instability of the crystal oscillator, are discarded. The final estimate of the clock skew, i.e. the one used in the skew compensation performed during the sampling, is obtained as the median of the other measures of the TS error.

The TS task, including the reception and processing of the TS beacons and the computation of the clock skew estimate, runs at the MAC layer. In the sensor node, at the reception of the sampling command transmitted by the sink node, the interrupts of the synchronized timer are activated, triggering the synchronous toggling of a port of the MCU. The sampling task, running at the application layer, collects an acceleration sample at each transient of the toggled MCU port. The measured absolute average TS error is 1.74 µs/hop. Despite the crystal oscillator instability, the error is below 5 µs for 98.57% of the time.

The acceleration signals collected by the ISMO-2 nodes are processed to identify the modal properties, i.e. natural frequencies, damping ratios and mode shapes, of the wooden model bridge. In *PUB 5*, the results obtained with the time synchronized wireless SHM system are compared to the ones obtained with the high-quality wired accelerometers. Both wired and wireless data sets are processed by applying a covariance-based stochastic subspace method (Van Overschee and De Moor, 1996, Peeters 2000). In the wooden truss structure used in the tests, fourteen modes were identified in the frequency range [0, 40] Hz. The absolute average relative difference between the natural frequencies identified with the wireless and wired measurements was 0.422%.

Given two complex mode shapes, ϕ_r and ϕ_t, the modal assurance criterion (ModAC) can be computed as:

$$ModAC = \frac{|\phi_r^H \phi_t|}{\phi_r^H \phi_r \phi_t^H \phi_t}, \tag{4.6}$$

where H is a conjugate transpose. The ModAC measures the consistency of the two mode shapes (Allemang, 2003). The average ModAC value was 0.943.

Concerning the damping ratios, their variability is typically very high, e.g. 200%, also when different wired measurement sets are compared. However, the maximum relative difference between the damping ratios estimated with the wireless and wired systems was 42.2%.

4.2.5 Embedded data processing

Despite being an effective approach to assess with precision the structural health of the monitored structure, transmitting all the data collected by the sensor nodes to the sink node for off-line modal analysis drains a consistent amount of energy and requires a long time, particularly in the case of a tree-like multi-hop network.

A feasible approach to overcome these problems is one in which the sensor nodes locally process the acceleration data in real-time, and then share the results of their computations in the network, collaborating to the detection and localization of eventual structural damages (Hackmann et al., 2008, Mizuno et al. 2008). This approach is implemented and tested in *PUB 6*. By applying the GoeA (Goertzel, 1958), the sensor nodes perform a frequency-domain analysis of the acceleration signals, closely monitoring those ranges of frequencies known to show significant changes due to damages.

Compared to the often used fast Fourier transform (FFT), which calculates the frequency spectrum of a *N*-sample signal in *O(N log(N))* steps, the GoeA calculates a single bin of the spectrum in *O(N)* steps. Thus, if fewer bins than *log(N)* are required, the GoeA becomes computationally more efficient. As an additional advantage, the GoeA works iteratively, updating the results after the acquisition of a new sample. Because of this, the acceleration signals do not need to be stored in e.g. the RAM memory of the nodes, saving memory space, or in an external flash memory, saving power. Furthermore, the final results of the computations can be transmitted soon after the completion of the sampling phase, reducing the latency of the system.

The GoeA implements a second order infinite impulse response (IIR) filter centered on each frequency of interest f_i. Its transfer function *H(Z)* is:

$$H(Z) = \frac{1-e^{-2\pi\frac{f_i}{f_s}}Z^{-1}}{1-2\cos\left(2\pi\frac{f_i}{f_s}\right)Z^{-1}+Z^{-2}}, \tag{4.7}$$

where f_s is the applied sampling frequency. For each frequency of interest f_i, the equations iteratively executed by the nodes during the sampling are:

$$\begin{cases} q_0^i = c_i \cdot q_1^i - q_2^i + s \\ \qquad q_2^i = q_1^i \\ \qquad q_1^i = q_0^i \end{cases}, \tag{4.8}$$

where s is the last collected acceleration measurement, and q_1 and q_2 store the results of the two previous iterations. The coefficients c_i and the bins k_i which correspond to the selected frequencies of interest are computed as:

$$c_i = 2\cos\left(2\pi\frac{k_i}{N}\right), \tag{4.9}$$

$$k_i = \left\lfloor 0.5 + \frac{N \cdot f_i}{f_s} \right\rfloor, \tag{4.10}$$

where N is the number of collected samples. After the N-th iteration, the sensor nodes can calculate the squared magnitude of the frequency spectrum X at each frequency of interest f_i as:

$$|X_i(N)|^2 = q_{1_i}^2 + q_{2_i}^2 - q_{1_i} \cdot q_{2_i} \cdot c_i. \tag{4.11}$$

The filter in (4.7) has a single Z-domain zero located at:

$$Z = e^{-2\pi \frac{f_i}{f_s}}, \tag{4.12}$$

and conjugate poles at:

$$Z = e^{\pm 2\pi \frac{f_i}{f_s}}. \tag{4.13}$$

The pole/zero pair at $Z = e^{-2\pi \frac{f_i}{f_s}}$ cancel each other. A limitation of the GoeA derives from the fact that, when implemented in MCUs with a limited word length, as the one used in the tests (Texas Instruments MSP430F1611), the filter coefficients in (4.9) are represented with an accuracy defined by a fixed number of binary bits. As a consequence, the filter poles might not lie exactly on the unit circle, ultimately introducing an error in the estimation of X_i. The numerical properties of the floating-point implementation were analyzed by Gentleman, 1969. The conclusion was that the cumulative effect of rounding errors could severely affect the accuracy of the results for frequency bins close to zero. The theoretical bounds found in Gentleman are very conservative, as they are several orders of magnitude bigger than the real errors measured in practical situations (Barrio and Berges, 1998). On the other hand, a fixed-point implementation of the GoeA has been proven to be prone to overflows (Beraldin and Steenaart, 1989).

From the structural point of view, significant changes in the frequency spectrums of the acceleration signals collected by the sensor nodes can be caused not only by the onset of damages, but also by variations of the environmental conditions, e.g. temperature and humidity, or by a different magnitude, type and position of the excitation to which the structure is subjected. For these reasons, it is fundamental to extract from the vibration data a feature that guarantees environmental invariability. In *PUB 6*, transmissibility functions (TFs), representing the result of the interference of vibrations propagating and reflecting along the structure, are considered.

Given a pair of sensor nodes, s_i and s_j, with $i \neq j$, deployed at different locations, and a range of frequencies of interest $[f_1, f_2]$, the transmissibility function T is defined as:

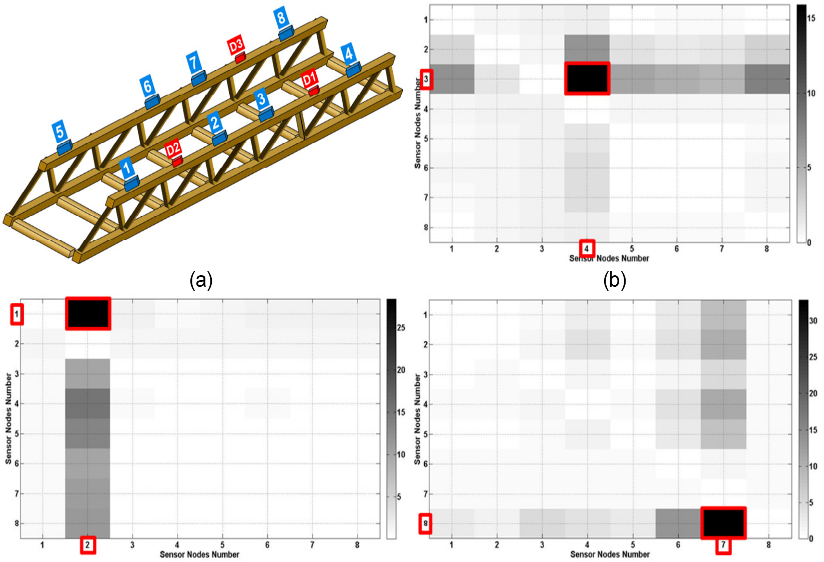
$$T_{s_i}^{s_j}(f_1,f_2)=\frac{\sum_{f=f_1}^{f_2}\left(X_{s_j}(f)\right)^2}{\sum_{f=f_1}^{f_2}\left(X_{s_i}(f)\right)^2}, \tag{4.14}$$

in which X is the frequency spectrum of the acceleration signal collected by a sensor node. The relative difference between the TFs obtained during a test and the ones corresponding to the monitored structure in undamaged conditions can be exploited to correctly detect and localize the onset of a structural damage. The damage indicator feature is calculated as:

$$D_{s_i}^{s_j}(f_1,f_2)=\frac{\left|T_{s_i}^{s_j}(f_1,f_2)^{TEST}-T_{s_i}^{s_j}(f_1,f_2)^{REF}\right|}{T_{s_i}^{s_j}(f_1,f_2)^{REF}}, \tag{4.15}$$

where the indices *REF* and *TEST* correspond to the reference and current condition of the monitored structure. By comparing the values of the damage indicator among all the pairs of sensor nodes, it is possible to correctly locate the damage, as shown in Figure 4.4.

In particular, during the tests it was observed that some frequency intervals show significant changes of the TFs between several pairs of nodes. Other frequency intervals show changes only in those pairs of nodes which are in the proximity of the real position of the damage, allowing its accurate localization. In the developed application, the end-user can adjust the



(a) (b)

(c) (d)

Fig. 4.4. The damage indicator features obtained during tests with a simulated damage located in different positions on the wooden model bridge (a): in (b), D1 (between nodes 3 and 4); in (c), D2 (between nodes 1 and 2); in (d), D3 (between nodes 7 and 8).

resolution of the GoeA in order to e.g. first perform a low resolution scan of the entire frequency spectrum to locate these signature frequency intervals, then eventually increase the resolution to monitor significant changes due to the presence of damages.

4.2.6 Summary of the findings

The results obtained in the area of SHM can be summarized as follows:

- WSNs can be successfully applied in SHM to obtain accurate estimates of the modal properties of the monitored structures;
- An accurate time synchronization of the clocks of the sensor nodes is crucial for the reliability of the modal analysis results. This is obtained by means of a low-power protocol based on clock skew estimation.
- Due to the specific hardware limitations of the sensor nodes (e.g. slow Flash memory writing) and communication unreliability, the collected acceleration signals can contain missing samples. However, these data can be estimated from the available ones and a correlation model of the monitored structure, or retrieved by means of retransmission.
- Distributed data processing techniques, as the Goertzel algorithm and the transmissibility functions, can be exploited to correctly detect and localize a structural damage. Compared to a centralized architecture, the distributed approach consistently reduces the overall latency of the system and increases its lifetime.

4.3 Indoor situation awareness

This section describes the main results obtained in the context of InSitA. The research focused on processing the acoustic signals collected by the sensor nodes to estimate the number of people located in the monitored area and to perform speaker identification. Moreover, people detection, localization and tracking is performed through distributed RSSI processing.

4.3.1 Blind signal separation by ICA

One of the feasible ways to estimate the number of people located inside an unknown indoor environment, e.g. a room, an office, a hall, etc., is to record and then process acoustic signals. When more than one person is found in the monitored area, the collected signals can be a mixture of several overlapping voices. In this case, the problem is double-sided: at first, it is required to correctly estimate the number of independent components, i.e. voices, found in the recorded acoustic signals. In the second phase, this estimate can be exploited for reconstructing the independent components, i.e. for separating each voice from the initial mixture. The achievement of these goals would give the blue forces a significant tactical advantage and would provide them very useful information for an effective planning of their intervention.

The scenario can be modeled as a BSS problem, in which the ultimate goal is to find a linear representation of the data, i.e. the observed mixed signals, in which the various components are as statistically independent as possible. Independent component analysis (ICA, Hyvarinen and Oja, 2000, Hyvarinen et al., 2001) assumes that the components are nongaussian. Over the years, ICA has also been applied in several different applications, e.g. brain imaging (Vigario, 1997), econometrics (Back and Weigend, 1997), and image feature extraction (Hoyer and Hyvarinen, 2000).

Given a set of recorded acoustic signals ($x_1(k), x_2(k), \ldots, x_h(k)$), where k is the sample index, it can be assumed that they originate from a linear mixture of independent components:

$$\begin{pmatrix} x_1(k) \\ x_2(k) \\ \vdots \\ x_h(k) \end{pmatrix} = A \begin{pmatrix} s_1(k) \\ s_2(k) \\ \vdots \\ s_n(k) \end{pmatrix}, \tag{4.16}$$

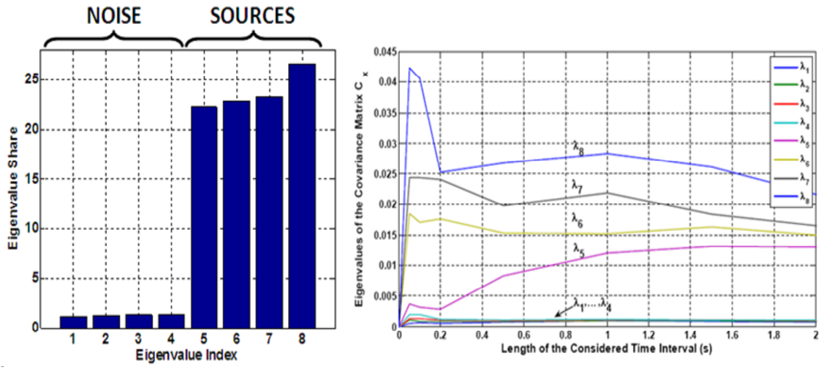
where A is an unknown mixing matrix and n, i.e. the number of sources, is smaller or equal to h, i.e. the number of nodes equipped with microphones. The target of ICA is to estimate the mixing matrix A and the independent components ($s_1(k), s_2(k), \ldots, s_n(k)$) from the available mixed signals.

ICA can be divided into a pre-processing phase and a separation phase. In the first one, the mixed signals are centered, i.e. each signal is subtracted its own mean, and whitened, i.e. the data are forced to be uncorrelated. The aim is to find a linear transformation V such that when $Y = VX$, $E\{Y\,Y^T\} = \boldsymbol{I}$. This can be achieved by setting $V = C^{-1/2}$, where C is the correlation matrix of the data matrix X:

$$E\{YY^T\} = E\{VX\,X^TV^T\} = C^{-1/2}\,C\,C^{-1/2} = \boldsymbol{I}. \tag{4.17}$$

In *PUB 7*, the whitening is achieved by means of PCA. First, the set of mixed acoustic signals is centered, creating the matrix $\tilde{X}(k) = [\tilde{x}_1(k), \ldots, \tilde{x}_h(k)]^T$. The covariance matrix of $\tilde{X}(k)$ becomes:

$$C_{\tilde{X}} = \frac{1}{k}\,\tilde{X}(k)\,\tilde{X}(k)^T, \tag{4.18}$$



(a) (b)

Fig. 4.5. The estimation of the number of independent acoustic sources from the original mixed signals, sampled at 8 kHz. In (a), for each eigenvalue λ, the eigenvalue share is calculated as $\lambda/\Sigma\lambda$. If the SNR of the recorded mixed signals and the sampling frequency are sufficiently high, the eigenvalues separation shows up after few seconds.

where k is the number of collected samples. If q is the number of independent source signals and $q \leq h$, i.e. the number of recorded mixed signals, then the q largest eigenvalues of $C_{\tilde{X}}$ represent a combination of the power of the source signals added to the noise power, while the remaining $h - q$ eigenvalues are related to noise only (Ham et al., 2000). If the SNR of the recorded mixed acoustic signals is sufficiently high, the difference of magnitude between the eigenvalues related to the independent source signals and the ones related to background noise is remarkable. This makes the estimation of the number of source signals q, i.e. voices, possible (Figure 4.5).

In *PUB 7*, the acoustic signals are recorded by using Mica2 motes equipped with a low power microphone. Unlike wired systems, in which the acoustic sensors can sample at very high frequencies, e.g. 48 kHz, the used wireless sensor nodes limit the applicable sampling frequency to 6.67 kHz. Moreover, storing the samples in the EEPROM memory introduces a periodic noise component in the signals. This type of non-volatile memory can be erased and written to by applying a higher than normal voltage, which in turn creates a disturbance in the low-power microphone circuitry.

By setting a lower sampling frequency, e.g. 3 kHz, the amount of data to be wirelessly transmitted at the base station is consistently reduced. However, by doing this, the separation among the eigenvalues of the correlation matrix becomes less defined, decreasing the reliability of the estimate of the number of voices originally found in the recorded mixed signals. An additional factor defining the accuracy of the final estimate is the synchronicity of the sampling performed by the sensor nodes. A consistent TS error irremediably corrupts the model in (4.16).

4.3.2 Speaker identification

Over the last decades, speaker authentication and identification have been widely studied. The proposed techniques include neural networks (Farell et al., 1994), hidden Markov models (Tishby, 1991) and cepstral analysis (Furui, 1981). Whereas in speaker authentication the speaker claims to be of a certain identity and the voice is used to verify this claim, speaker identification aims at correctly determining the identity of an unknown speaker. Thus, speaker authentication corresponds to a 1-to-1 match between the voice of the speaker and an already existing model of the voice, whereas speaker identification corresponds to a 1-to-many match in which the voice of the unknown speaker is compared to *N* already existing voice templates. In speaker identification, an optimal characterizing feature vector must have maximal inter-speaker, i.e. with signals of different individuals, and minimal intra-speaker, i.e. with signals of the same person, variation. It must also be robust against voice disguise and mimicry, and against distortion and noise.

In *PUB 8*, a feature vector is extracted from a recording of the voice of the speaker by applying a method based on cepstral analysis (Bogert et al., 1963, Noll, 1964). Its phases are depicted in Figure 4.6. In the pre-emphasis phase, the high frequencies of the spectrum, which are normally absorbed in the human speech production process, are enhanced by applying a filter as:

$$x_f(k) = x(k) - \alpha x(k-1), \tag{4.19}$$

where $\alpha \in [0.95, 0.98]$, k is the sample index, x the original voice signal and xf is the enhanced one. The signal is then windowed by applying a Hamming window.

The two key parameters of the feature vector extraction process are N_{bins}, the number of bins used in the discrete Fourier transform (DFT), and N_{cep}, the number of mel-frequency cepstral coefficients (MFCCs) considered in the discrete cosine transform (DCT), with $N_{bins} \leq N_{cep}/2$. The DCT converts

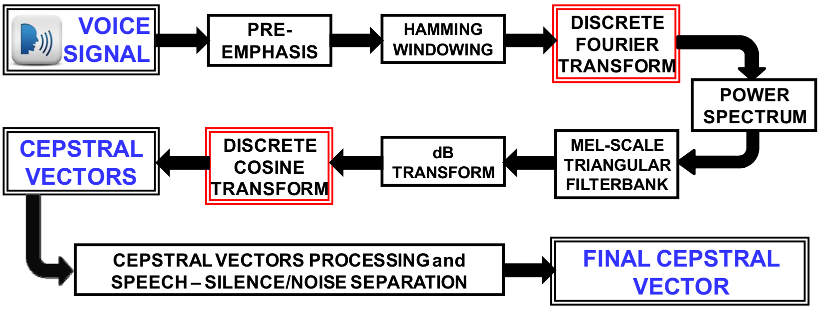


Fig. 4.6. The feature vector extraction process.

statistically dependent spectral coefficients into statistically independent cepstral coefficients.

The frequency spectrum of the voice signal is transformed by using the mel scale (Stevens et al., 1937), a perceptual scale of pitches judged by listeners to be equal in distance from one another. The conversion from a frequency f (in Hz) to a mel-frequency m (in mel) is:

$$m = 2595 \, log_{10}\left(1 + \frac{f}{700}\right). \tag{4.20}$$

In this scale, a 1000 mel perceptual pitch is assigned to a 1000 Hz tone. Above this reference point, larger frequency intervals are judged by listeners to produce equal pitch increments. A mel-scale triangular filterbank, which is composed of filters whose central frequencies are equally spaced on the mel-scale, is applied to the power spectrum. The filterbank reduces the random variation in the high frequencies region of the spectrum by progressively increasing the bandwidth of the triangular filters.

The first MFCC of each window of the signal is ignored since it represents only the overall energy contained in the spectrum. The remaining MFCCs are centered. Then, the lowest and highest order coefficients are de-emphasized by applying a smoothening vector M as:

$$M(i) = 1 + \frac{N_{cep}-1}{2} sin\left(\frac{\pi i}{N_{cep}-1}\right), \tag{4.21}$$

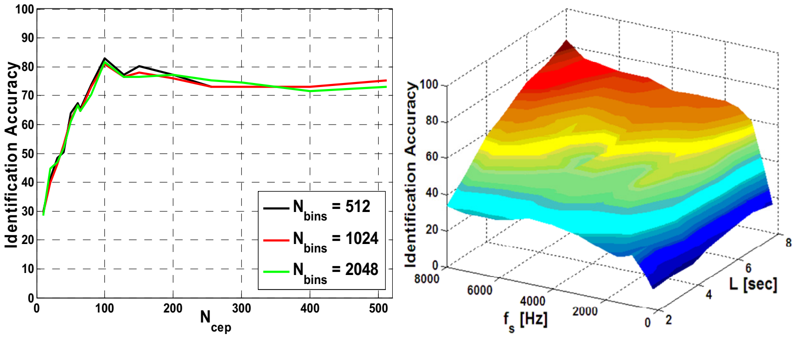
where i=1,…,(N_{cep} – 1).

If C_{sig} is the matrix containing all the MFCCs, with dimensions N_{cep} x N_w, where N_w is the number of windows, a vector C_N is formed by the mean of the respective columns of C_{sig}, normalized in the range [0,1]. The threshold used to separate the MFCCs vectors corresponding to actual speech portions of the signal from the ones corresponding to silence and/or background noise is the mean of C_N. The matrix C_{sp}, containing the useful mel-cepstral vectors, is:

$$C_{sp} = \left[C_{sig}(j) | C_N(j) \geq \mu(C_N)\right] \qquad j = 1, \ldots, N_W, \tag{4.22}$$

where j denotes the jth mel-cepstral vector of C_{sig} and $\mu(C_N)$ is the average of the vector C_N. The final MFCCs vector C_{cep} is computed by taking the row-wise average of the matrix C_{sp}. The feature vector characterizing the speaker comprehends also the vectors ΔC_{cep} and $\Delta\Delta C_{cep}$, derived respectively from the first and second order derivatives of C_{sig}.

The effect of N_{bins} and N_{cep} on the identification performance is analyzed while keeping the length of the recorded signal and the sampling frequency to



(a) (b)

Fig. 4.7. In (a), the effect of the number of considered MFCCs on the identification accuracy. In (b), the combined effect of the applied sampling frequency and length of the acoustic signal. The results are obtained from a database including 60 individuals (45 men, 15 women) and 15 languages. The recordings were performed in noisy indoor environments, e.g. offices and meeting rooms, corridors, halls, etc.

the maximum values obtainable with the used Micro.2420 nodes, i.e. 8 s and 8 kHz, respectively. The 83% maximum accuracy is achieved when N_{bins} = 512 and N_{cep} =100. For any fixed value of N_{cep}, N_{bins} affects only marginally the identification accuracy, generating a 2-3% variation. On the other hand, N_{cep}, which defines the precision of the feature vector in modeling the spectral characteristics of the speaker, plays a key role in setting the identification accuracy. Since the lower order MFCCs are heavily influenced by the random spectral variations and slowly varying additive noise distortions found in the signals, when N_{cep} goes below its optimal value, the identification accuracy rapidly decreases. When N_{cep} goes beyond the optimal value, the accuracy at first slightly decreases (5-8% reduction), and then levels off. By including a larger number of MFCCs, the final feature vector includes also information on the high-frequency additive noise distortions of the signals. These results are illustrated in Figure 4.7.

Given the derived feature vector of the speaker, the identification decision is based on the similarity with the feature vectors related to the individuals already included in the database. In *PUB 8*, the similarity is computed by means of the 1-norm distance. The most similar feature vector found in the database defines the identity of the speaker. This similarity measure was chosen due to its limited computational complexity in order to minimize the latency of the algorithm.

4.3.3 RF sensor network for intrusion detection and tracking

Over the years, the RSSI provided by the radio module of the nodes has been exploited for localization, ranging and link quality assessment (Srinivisan and Lewis, 2006, Tang et al., 2007). However, due to the fact that approximately 60% of the human body is composed of water, when a person enters the area

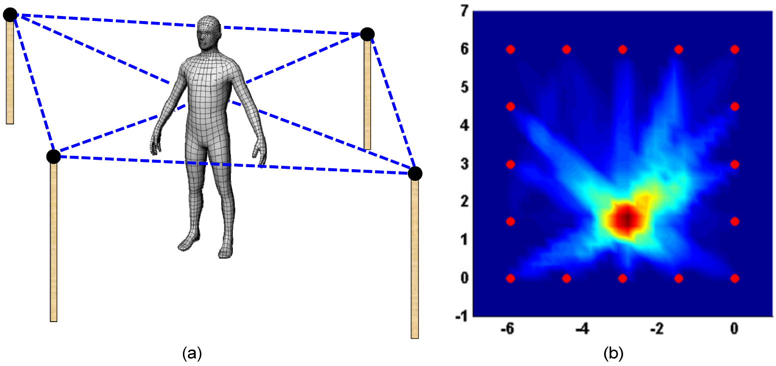


Fig. 4.8. A representation of the setup of the RF sensor network for intrusion detection and tracking (a). In (b), the estimation of the current position of the person moving inside the monitored area from the aggregation of the alerts received at the sink node.

of propagation of the radio signals transmitted by two communicating nodes, the RSSI data collected by both the devices show a consistent variation. Thus, by deploying multiple nodes around an area to be monitored, so establishing a virtual 3D grid of wireless links, this phenomenon can be exploited for detecting, localizing and tracking people (Figure 4.8). Furthermore, the RSSI-based approach does not require the monitored people to wear or carry any device, and does not suffer from the typical limitations of other technologies, e.g. ultrasound (Hazas and Hopper, 2006) and laser (Cui et al., 2007), which are very sensitive to the presence of occlusions in the monitored area (Gu et al., 2009).

In the test setup depicted in Figure 4.8, the communication channel can be modeled as a Rician fading channel. In it, a transmitted sinusoidal carrier:

$$s(t) = cos(\omega_c t), \tag{4.23}$$

is received at destination as:

$$v(t) = C_L\, cos(\omega_c t) + \sum_{n=1}^{N} r_n\, cos(\omega_c t + f_n), \tag{4.24}$$

where C_L is the amplitude of the LoS component of the radio signal, N is the number of multipath components, r_n is the amplitude of the n-th multipath component, and f_n its phase. In a Rician fading channel, the LoS component is stronger than the others, and its amplitude is determined by path loss.

In *PUB 9*, each node processes the RSSI measurements locally in real-time. The detection of the intrusion of a person in the monitored area does not rely on a pre-existing model of the radio signal propagation patterns obtained in static conditions. Instead, the developed embedded algorithm is based on the observation that when one individual moves inside the monitored area, he alters the LoS and multipath components of the wireless links. Consequently, the variance in the RSSI measurements increases. The developed algorithm works iteratively and triggers in real-time the transmission to the sink node of alerts related to significant events, i.e. people intrusions.

The time synchronized nodes communicate in TDMA fashion following a pre-established schedule. The applied TS protocol enables the nodes turning their radio off whenever broadcasts are not scheduled, reducing their power consumption. Moreover, the TDMA communication scheme is robust against packet losses and node failures. As a result, when the slot length is set to 10 ms, the lifetime of the time synchronized network is approximately 80% more than the one of an unsynchronized system communicating with e.g. a token-passing protocol. By increasing the slot length, this improvement becomes larger, e.g. 200% at 50 ms.

The sensitivity area of a wireless link, i.e. the area around the LoS in which the presence and/or motion of a person affects the RSSI measurements, is modeled with an ellipsoid. By considering a receiver located at coordinates (x_r,0,0) and a transmitter located at (x_t,0,0), an ellipsoid passing by the two nodes is expressed as:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1, \tag{4.25}$$

where a is the LoS distance between the nodes, b is the perpendicular radius and c is the polar radius (set to unity). The exact value of b, which defines the size of the sensitivity area, was determined experimentally by measuring the relationship between the mean attenuation of the radio signal strength and the distance of the person from the LoS link.

To estimate the current position of the person, each ellipsoid is weighted by the magnitude of the corresponding generated alert. The monitored area is divided into 0.125 x 0.125 m pixels. The weight of each pixel is calculated as:

$$w_{(x_p,y_p)}=\sum_{N_e} z^{e}_{(x_p,y_p)}, \tag{4.26}$$

where N_e is the number of ellipsoid overlapping the pixel at (x_p,y_p) and $z^{e}_{(x_p,y_p)}$ is the value of each ellipsoid at those coordinates, derived from (4.25), in which c, i.e. the polar radius of the ellipsoid, has been multiplied by the magnitude of the corresponding raised alert. The coordinates of the pixel having the largest weight are used as estimate of the current position of the person found in the monitored area. To increase both the accuracy and smoothness of the tracking, and to further reduce the effect of the measurement noise, a Kalman filter (Kalman, 1960) is applied to the calculated position estimates.

In the tests carried out in *PUB 9*, 16 nodes are placed at regular intervals around a square perimeter. To decrease the measurement noise caused by the reflecting action of the floor, the nodes are elevated 1 m through podiums. The worst tracking error, which is observed in the test in which obstructions and objects are located inside the monitored area, is 0.24 m. The tracking accuracy of the system slightly decreases as the size of the monitored area increases. This is due to the fact that in larger areas the virtual 3D grid of wireless links becomes less dense and the amplitude of the received LoS component smaller. Also, as the nodes distance grows, the person obstructing the links does not generate the same significant attenuation and variance in the RSSI data. Compared to the case in which all the raw RSSI measurements need to be transmitted, the embedded algorithm reduces by 80% the volume of traffic towards the sink.

4.3.4 Summary of the findings

The results obtained in the area of InSitA can be summarized as follows:

- Despite the less strict requirement on time synchronization accuracy, the solution of the “cocktail-party problem” by principal component analysis is hindered by the hardware limitations of the sensor nodes, in terms of low signal-to-noise ratio of the recorded acoustic signals, limited applicable sampling frequency and coarse quantization of the ADC of the MCU;
- Accurate text- and language-independent speaker identification can be achieved also with short-time and low quality acoustic signals. The operations performed for the extraction of the speaker feature vector require a more powerful digital signal processing unit;
- Time synchronization of the nodes composing the RF sensor network consistently extends the life time of the system and makes it robust to nodes failures;
- The embedded RSSI processing algorithm reduces the total volume of traffic to the sink node, decreasing further the power consumption of the system;
- The localization and tracking accuracy is enhanced by normalizing the raised alerts to a ratio of the short-term over the long-term variance of the RSSI signal.

5 Discussion

This section discusses some of the lessons learned from deploying wireless sensor systems in real-world scenarios. Ideas for future research in the field of WSNs are also outlined.

5.1 Lessons learned from real-world deployments

The research that led to the results presented in this thesis, though starting from the analytical study of the theoretical foundations of WSNs, has been also guided by the experiences and observations collected during real-world deployments. The development of wireless sensor systems for use in real-world scenarios has not only given a rigorous testing environment, but it has also suggested novel approaches and theories in ways not possible otherwise.

5.1.1 Collaboration with application domain experts

The collaboration with scientists of other technical fields was fundamental for understanding the application requirements. However, not all requirements are equal: among them, some can be defined as “hard”, i.e. the ones the field experts consider indispensable, some others as “soft”, i.e. the ones the field experts are willing to negotiate in order to accommodate for the limitations of WSNs. For example, in SHM, TS accuracy and data transfer reliability belong to the first group; the improvement of the SNR of the vibration data collected by the sensor nodes, though appreciated, was considered as belonging to the second family. About this issue, the field experts were originally interested in developing novel data processing methods capable of dealing with data with a higher noise level than the one found in the data collected with the traditional wired systems. The same can be said regarding the estimation of the missing samples of the acceleration signals.

The task of the WSN developer is to find the appropriate technical solutions to totally fulfill the “hard” requirements. In the case of the “soft” ones, a close collaboration with the domain experts can pave the way to new, interesting modifications of their scientific routines that can accommodate the typical constraints of WSNs and fully exploit their several advantages.

5.1.2 Data validation

Since the decision-making process of the end-user is based on the outcomes of the algorithms employed to process the data collected by the sensor nodes, data validation is a fundamental issue. In order for the system to be a real support to the end-user, the data must be accurate, reliable and consistent, i.e. their quality has to be the same over extended periods of time.

Data validation includes multiple tasks, such as understanding the features of the sensors, calibrating them in varying conditions and comparing the data collected by the wireless nodes to the ones collected by high-quality wired instruments providing the reference. Data validation often turned into a time consuming activity. However, its importance in defining the performance and reliability of the system cannot be overlooked.

5.1.3 The effect of communication black-spots

In real-world environments, e.g. industrial halls and building interiors, cattle houses and greenhouses, etc., after the initial deployment, connectivity with one or more sensor nodes can be suddenly lost. This was frequently observed in environments where objects and people were moving around during the tests. In fact, due to the nondeterministic propagation of the low-power radio signals transmitted by the nodes, even small variations in the configuration of the surrounding environment can cause a specific node to temporarily enter a communication black-spot, i.e. a region in which the node is neither capable to successfully transmit to or receive from the other nodes of the network.

The difficulty arises from the fact that this phenomenon is hardly replicable in laboratory-scale tests, in which the conditions are fairly static. From the data processing point of view, the presence of time-varying communication black-spots affects the total amount and latency of the data processed by the algorithms. Thus, the applied methods need to be robust against this time-varying limitation. Similarly, flexibility and adaptability are demanded from the researchers in the system development phase and in the evaluation of the unexpected problems encountered during the deployment.

5.1.4 Wireless sensor networks, “the art of compromise”

As reported in Langendoen et al., 2006, the difference between simulations and real-world deployments can be huge and dramatic: Murphy’s law has one of its best playgrounds in the area of WSNs.

Besides keeping in mind two fundamental paradigms, “keep it simple!” and “first: make it work!”, the work of a WSNs developer turns into individuating the optimal set of compromises among the several trade-offs characterizing the behavior of these complex systems. This applies to the development of both hardware and software, and is a consequence of the multidisciplinary nature of sensor networks. The choices made to solve a specific problem (i.e. communication reliability) can impact other important aspects of the system (i.e. power consumption, latency, real-timeliness, etc.). Implementing more effective and resource-demanding solutions for tackling a single problem can jeopardize the functioning of other, previously validated operating blocks of the application code, compromising the overall performance of the system.

5.2 Future research directions

The research on WSNs has started approximately ten years ago. Researchers belonging to different communities, e.g. systems engineering, networking and wireless communications, artificial intelligence and machine learning, signal processing, embedded systems, software engineering, etc., have contributed to reach close-to-optimal solutions for several issues. Despite the advances in this area, opportunities for applying WSNs in new emerging applications abound, and new challenging issues will arise from them.

Looking back at the initial definition of WSNs, these systems were thought to be composed of hundreds, potentially thousands, of nodes. At the moment, the community is still very far from reaching this goal. Efficiently managing large-scale systems will be more and more required in the future, when low-power, low-cost wireless nodes will be embedded in most of our everyday life objects. Moreover, most of these devices will have mobility capabilities. Thus, standard protocols, e.g. TS, MAC, routing, etc., will have to be thought again in order to efficiently cope with this new, much more complex scenario.

Recently, more and more attention has been dedicated to the definition of cyber-physical systems (CPSs). A CPS is a system combining both sensing and actuating, where computation and actuation are both embedded into the environment. In these systems, the capability to act in real-time will become a critical requirement. Thus, on the software side, OSs and application codes will have to support real-time operation. On the networking side, reliable and timely multi-hop communication among the sensing and actuating nodes will have to be guaranteed.

In particular, in applications involving humans, e.g. assisted living, health care, situation awareness, etc., new, intelligent ways to interface them to the wireless systems will have to be developed. The human-to-system interaction will be bi-directional. Accordingly, the sensor systems will require flexibility and intelligence to correctly interpret the changing behavior of humans and machines. Thus, CPSs will necessarily become self-adaptive.

Nowadays, the level of flexibility and self-adaptation of these systems is still quiet far from what was originally thought and from what is actually needed in real-world scenarios. The next-generation CPSs will intelligently react to internal and external changes in real-time, and will be capable of interacting with people, animals, and machines, learning about their characteristics and their goals as they interact with them, and collaborating with them to achieve these goals.

6 Conclusions

By collecting a large and potentially heterogeneous amount of data, wireless sensor networks are capable of changing the way we observe, measure and interact with the phenomena and objects of the world we live in. In the thesis, three distinct application domains, i.e. wireless automation, structural health monitoring and indoor situation awareness, have been considered. The aim of the research has been the development of various centralized and distributed data processing methods that could optimize the overall performance of the developed applications. These algorithms have been designed to adapt to the characteristics and requirements specific to each application, as e.g. quality of the data collected by the nodes, system latency and reliability in collecting the data at the sink node, real-timeliness and energy-efficiency.

The research carried out in the area of wireless automation focused on the design of a wireless joystick control system for human adaptive mechatronics. The embedded signal processing and filtering methods remove the negative effects of measurement noise and of the high electrical noise introduced by the actuators. They also compensate for bad control actions taken by the human operator while performing certain tasks, and for the eventual packet losses. At first, tests were carried out in a laboratory-scale trolley crane: the wireless joystick control system allowed performing small and high-precision, as well as fast and smooth adjustments of the position of the load, also in the presence of a faulty communication link. In the second phase, the wireless joystick was applied to an unstable ball balancing system. For this case study, a PIDPLUS wireless controller was implemented to analyze further the effect of the timing of occurrence of the packet losses on the control performance.

In structural health monitoring, a wireless system must be able to reliably transfer the vibration data collected by the nodes to the sink. To achieve this, an automatic retransmission procedure was developed to successfully recover the lost data packets. A Matlab® GUI enables the remote reconfiguration of the key parameters of the monitoring application. A double-sided effort was made to enhance the quality of the data collected by the nodes deployed on the monitored structure: at first, a wireless platform specifically designed for the requirements of structural health monitoring was conceived. Moreover, a low-power time synchronization protocol was implemented to guarantee an accurate synchronicity among the samples collected by the sensor nodes. The vibration data collected by the developed wireless monitoring system enabled a precise identification of the modal properties of the wooden model bridge used for the tests.

In the second application, damage detection and localization were obtained through distributed data processing. The computationally efficient Goertzel algorithm was embedded in the nodes to detect the changes in the frequency spectrum of the vibration signals caused by the onset of a structural damage. By sharing the results of their local computations, the sensor nodes are then able to calculate transmissibility functions. These features are lastly exploited to correctly detect and localize the damage. The distributed approach, which does not require transmitting all the raw vibration data to the sink node for off-line analysis, reduces the latency of the system and increases its lifetime.

In the domain of indoor situation awareness, the research focused at first on processing the short-time and low-quality acoustic signals recorded by the nodes. Principal component analysis was applied to estimate the number of people located in the monitored indoor environment. Furthermore, a lightweight speech parameterization method based on cepstral analysis was used to perform text- and language-independent speaker identification. Later, the radio signal strength was exploited to localize and track a person in an area surrounded by sensor nodes. The developed embedded processing algorithm does not require a pre-existing model of the radio signal propagation patterns created with static conditions. Instead, it dynamically adapts to the current conditions to transmit alerts only in correspondence of intrusions of people inside the monitored area. The estimate of the position of the moving person is calculated by aggregating the alerts received at the sink node. The tracking accuracy and smoothness are further improved by means of a Kalman filter.

The results presented in the thesis represent an additional evidence of the fact that wireless sensor networks can be successfully utilized in a variety of application domains to improve our comprehension of and control over the observed phenomena. However, an optimal system performance can only be achieved by targeting an effective co-design of the system architecture and of the applied data processing methods.

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