# Toward Interoperability of Heterogeneous Self-organizing (smart) Things

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PRESENTED BY

**VALERIA LOSCRÍ**

# Toward Interoperability of Heterogeneous Self-organizing (smart) Things

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And last but not least, I want to express my deep gratitude to the reviewers of my HDR thesis, Pr. Pietro Manzoni, Pr. Hakima Chaouchi, Pr. Nadjib Ait Saadi. I want to cordially thanks Pr. Martine Lienard and Prof. Isabelle Guérin Lassous for accepting to examine my thesis and attending my dissertation defense and again thanks to Nathalie.

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*To the memory of my lovely father Saverio.*
*To my best mother, Mariangela.*
*To my jewels, Gabriele and Elena.*
*To my love, Pietro.*
*I dedicate my HDR thesis.*

| | |
|---|---|
| **ANN** | Artificial Neural Networks |
| **BER** | Bit Error Rate |
| **BIA** | Bayesian Inference Approach |
| **BN** | Bayesian Network |
| **BP** | Belief Propagation |
| **CSONS** | Complex Self-Organized Network Systems |
| **EC** | Energy Consumption |
| **ER** | Estimation error |
| **FG** | Factor Graph |
| **GM** | Graphical Models |
| **GPS** | Global Positioning System |
| **IoRT** | Internet of Robotic Things |
| **IoT** | Internet of Things |
| **LPSN** | Low Power wireless Sensor Node |
| **MRF** | Markov Random Fields |
| **MRS** | Multi Robot Systems |
| **MSE** | Mean Squared Error |
| **NDS** | Neuro Dominating Set |
| **PIR** | Pyroelectric passive InfreRed nodes |
| **QoS** | Quality of Service |
| **RFID** | Radio Frequency Identification |
| **RSSI** | Received Signal Strength Indicator |
| **SINR** | Signal to Interference plus Noise Ratio |
| **VSC** | Video Surveillance Camera |
| **WSN** | Wireless Sensor Networks |

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# PART I

## ACTIVITIES REPORT

# Curriculum Vitae

## 0.1 Personal Data

NAME AND SURNAME: Valeria Loscrí
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## 0.2 Professional Career

| | |
|---|---|
| *Current* | CR1 Research Scientist INRIA LILLE - NORD EUROPE, Villeneuve d'Ascq<br>Member of Committee of Digital Transfer (CDT). Scientific European Responsible for Inria Lille. Holder of the Prime d'Excellence Scientifique (PEDR from 2015 |
| OCT. 2013 - OCT. 2015) | Research Scientist (CR2) INRIA LILLE - NORD EUROPE, Villeneuve d'Ascq |
| JAN. 2006-JULY 2006 | Visiting Research RICE UNIVERSITY, Houston, United States |
| OCT. 2006-OCT 2013 | Research Scientist Fellowship Universitá della Calabria, Italy |
| 2008-2013 | Lecturer (Contract Professor) Universitá della Calabria, Italy Faculty of Computer Science Engineer. |
| 2003-2008 | Assistant Professor Universitá della Calabria, Italy Faculty of Computer Science Engineer. |
| SEPT. 2003-JAN. 2004 | Computer Technician at NOTANGLE SNC, Cosenza, Italy |

## 0.3 Education

NOV. 2003-JAN.2007 **Ph.D.** in Computer Science and System Engineering
- Universitá della Calabria - Cosenza, Italy.
**Phd Thesis** on MAC and Routing Algorithms in Wireless Networks.
**Thesis**: *"Protocols architecture for Wireless Networks: issues, perspectives and enhancements"*
**Supervisor**: Salvatore Marano

MAY 2003 **M.sc.** in Computer Science Engineering
Telecommunication Specialization, Universitá della Calabria, Italy.
**Thesis**: *"Proposal of a multi-path routing algorithm over an E-TDMA MAC protocol to increase throughput and to reduce the delay in MANETs "*

JULY 2006 **Liceo Scientifico "G. Berto"**, Vibo Valentia | Final Grade: 60/60

## 0.4 Scholarships and Certificates

NOV.2003-NOV. 2006 Italian Ministry of Education and Research (M.I.U.R.) Scholarship

# Supervision Activity

## Ph.D. Supervision

- **Cristanel Razafindambimby**(Oct. 2014 – October 2017): financed by the Ministry of the Research and University. Tanel'work focuses on distributed cooperation and communication among mobile heterogeneous devices Supervision quota: 100 %
- **Riccardo Petrolo** (Oct.2013-Oct.2016): financed in the context of the FP7 European project VITAL. Riccardo's work focuses on application of IoT paradigm in the Smart City context. Supervision quota: 50 %
- **Rosario Surace** (Nov.2011-Jan.2014): financed by the Italian Ministry of Research and University (M.I.U.R.). Rosario's work focuses on "Unmanned Aerial Vehicle Routing Problems" and "Decentralized Approaches Swapping for Wireless Sensor Networks". Supervision quota: 95 %
- **Carmelo Costanzo** (Jan.2009-Jan.2012):financed by the Italian Ministry of Research and University (M.I.U.R.). Carmelo's work focuses on "Algorithms and Techniques towards the self-Organization of Mobile Wireless Sensor, Robot and UAV Networks". Supervision quota: 50 %

## Postdoc Supervision

**Arash Maskooki**(Jan.2015-Jan.2016), financed by the Ministry of the Research and University, worked n learning mechanisms and cognitive wireless networks. Supervision quota: 100 %

## Visiting Ph.D. Supervision

**Roberto Morabito** (cosupervised, Sept.2016-Dec.2016): Oy LM Ericsson Ab (Ericsson Finland) - PhD Candidate, Aalto University. Roberto's work focuses on (Lightweight) Virtualization Technologies.

## Engineer Supervision

### Engineer Supervision in progress

**Antonio Costanzo** (Since March 2017): Antonio's work focuses on implementation of communication systems based on Visible Ligth Communication in the context of the FUI project StoreConnect.

### Engineer Supervision completed

- **Salvatore Guzzo Bonifacio** (cosupervised, Jan. 2015-Jan. 2016): Salvatore's work focused on implementation of discovery mechnanisms in IoT platform for Smart City applications in the context of the FP7 European project VITAL.
- **Emilio Compagnone** (Sept.2014-Aug.2016): Emilio's work focused on a robotic platform based on the integration of WiFi robots and Arduino modules in the context of ADT program ARUNTA.

## Master Students Supervision

(Thesis from 6 to 9 months)

- **Tadeu Gyovany Goncalves Kusese** (2017): "Energy Transfer mechanisms based on phonons for nanocommunications". This work focused on the exploitation of specific mechanisms based on phonons in order to transfer information between two molecules.

- **Emilio Compagnone** (2013): “Design and implementation of an Arduino-based Rover: WebCam application based on OpenCV”. This work focused on the implementation of an Arduino-based Rover and development of Detection of object
- **Simone Fiorenza** (2013):“Design and implementation of an Arduino-based Rover: target localization in an unknwown environment”. This work focused on the implementation of an Arduino-based Rover and development of an algorithm to detect and reach a target based on Received Signal Strength (RSS).
- **Salvatore Guzzo Bonifacio** (2013): “Design and implementation of an Arduino-based Rover: communication and self-orientation based on MARG”. This work focused on the implementation of an Arduino-based Rover and the tools to make the devices able to communicate to each other and to self-orient in the environment.
- **Giuseppe Blotta** (2012): “Evolution of MPLS network for electrical energy systems supply”. Master’s degree in Telecommunications Engineering at the University of Calabria.
- **Davide Fabio** (2011): “Reactive coverage techniques for wireless sensor networks with dynamic events”, Master’s degree in Computer Engineering at the University of Calabria.
- **Rosario Surace** (2011): “Modeling and Simulation of optimal UAV’ camera Drones positioning techniques for Filming Sport Events”. Master’s degree in Telecommunications Engineering at the University of Calabria.
- **Valentina Mannara** (2011): “Nanobot swarm techniques for endogenous deseases”. Master’s degree in Computer Engineering at the University of Calabria.
- **Nunzia Paolí** (2010): “Cellular System reinvented through Open Software/Hardware”. Master’s Specialization in Open Source Software/Hardware in the framework of OPENKNOWTECH project at the University of Calabria.
- **Sabrina Nicosia**(2010): “New algorithms of coverage in wireless sensor networks based on Particle Swarm Optimization”. Master’s degree in Telecommunications Engineering at the University of Calabria.
- **Nunzia Paolí**(2009): “Broadcast Transmission Techniques based on users’ cooperation”. Master’s degree in Telecommunications Engineering at the University of Calabria.
- **Carmelo Costanzo** (2008): “Distributed algorithms for sensor placement through controlled mobility". Master’s degree in Computer Engineering at the University of Calabria.
- **Daniela Mauro** (2008): “Innovative methods for the localization of mobile terminals in a city environment". Master’s degree in Computer Engineering at the University of Calabria.
- **Giuseppe Morabito** (2005): “Proposal of an extension of a routing algorithm for Wireless Sensor Networks to increase the lifetime and reduce the energy consumption”. Master’s Degree in Computer Engineering at the University of Calabria.
- **Vincenzo Mantuano** (2005): “Proposal of a dynamic management algorithm for role assignment for wireless sensor networks”. Master’s Degree in Computer Engineering at the University of Calabria.
- **Salvatore Mascaro** (2005): “Introduction of an analytical framework to evaluate a tradeoff between energy consumption and schedule update for time-slotted ad-hoc and sensor networks”. Master’s degree in Computer Engineering at the University of Calabria.
- **Manuela Maria Giglio** (2004): “Validation of a simulator for a SmartPhone by considering GPRS/UMTS data traffic”. Master’s degree in Computer Engineering at the University of Calabria.
- **Serena Ardissone** (2004): “Analysis and verification of a videocalling in a bi-processor Smartphone”. Master’s degree in Computer Engineering at the University of Calabria.
- **Luca Puccinelli di Belsito** (2004): “Simulation of a serial channel between two processors in a bi-processor Smartphone”. Master’s degree in Computer Engineering at the University of Calabria.

## Internship Supervision

- **Thomas Armengaud** (June 2017-Aug. 2017): implementation of Visible Light Communication techniques on Raspberry PI devices.
- **Driss Aourir** (Apr. 2017-Sept. 2017): implementation of predictive algorithms for reduction of data sending in the IoT context based on Raspberry PI and FIT IoT platform.
- **Jonhathan Prin** (June 2016-July 2016): implementation of neuronal networks approaches on robotic platforms.
- **Sonja Nienaber**(Sept. 2014 – Dec. 2014): implementation of visual techniques on robotic platforms based on De Bruij graphs.
- **Basile Mona**(Jun. 2014-Sept.2014): on positioning techniques in mobile wireless sensor networks.

# Teaching Activities

I started my teaching experience at the Universitá della Calabria in 2003, as a teaching assistant while I was a Ph.D. student and I continued as assistant professor till 2008. In 2008 I become lecturer at the Faculty of Engineer of the Universitá della Calabria till spring 2013. I am currently taking a course as lecturer at the IMT Lille Douai concerning connected objects in the context of smart homes.

Since 2015: Lecturer of the Course "Connected Objects" at the IMT Lille Douai in the context of Smart Homes, a Master's course, 24 hours, $\approx$ 20 students.

2013 March to September: Contract professor of "Laboratorio di Progettazione di reti (Telecommunications Networks design Lab)", a Master's course in Telecommunication Engineering at the University of Calabria, 56 hours $\approx$ 30 students.

2012 October: Contract professor of "Telecomunicazioni 1", a Post-Master's course for "Expert in Prediction/Prevention Hydrogeological Risk – ESPRI" organized by University of Calabria, 10 hours.

2012 September to December: Contract professor of "KOM4T me: Knowledge Management 4 info Telematic in Mobile Environment", a Poster-Master's course for expert in knowledge management systems applied to the context of infotainment for vehicular environments, organized by University of Calabria, Infomobility.it Spa, Magneti Marelli Spa, Info Blu Spa and Kanso Srl, 100 hours.

2012 March to December: Contract professor of "Trasmissione Numerica (Digital Transmission)", a Master's course in Telecommunication Engineering at the University of Calabria, 36 hours.

2011 March to December: Contract professor of "Laboratorio di Progettazione di reti (Telecommunications Networks design Lab)", a Master's course in Telecommunication Engineering at the University of Calabria, 56 hours.

2010 February to April: Contract professor of "Open Source tools for Networking", a Post-Master's course for Open Source experts and researchers, in the framework of OPENKNOWTECH organized by University of Calabria and the Italian Ministry for Education, University and Research (MIUR), 40 hours.

2009 September to October: Contract professor of "Math and logic" at the Engineering Faculty for Introductory Universities Studies at the University of Calabria, 24 hours.

2008 March to September: Teaching assistant of "Laboratorio di Progettazione di reti (Telecommunications Networks design Lab)", a Master's course in Telecommunication Engineering at the University of Calabria, 20 hours.

2007 April to June: Teaching assistant of "Foundations of Telecommunications", an undergraduate course in the Computer Engineering degree course at the University of Calabria, 20 hours.

2007 April to June": Teaching assistant of "Foundations of Telecommunications", an undergraduate course in the Electrical Engineering degree course at the University of Calabria, 20 hours.

2007 March to May: Contract professor of "Wireless communication networks", a Post-Master's course for industrial researchers and technicians, in the framework of PILOT (Piattaforma di Interoperabilita' per la LOgistica ed i Trasporti) organized by Etnoteam, Universita' della Calabria and Universita' "Mediterranea" di Reggio Calabria and the Italian Ministry for Education, University and Research (MIUR), 24 hours.

2005 April to September: Teaching assistant of "Evoluzione di IP ed Internetworking" (IP Evolution and Internetworking) a Master' course at the Faculty of Engineering of Computer Science of University of Calabria, 26 hours.

2005 March to June: I have taught in a course for "Expert in Telecommunications Networks and Satellite Telecommunications " at the higher school IFTS. The courses were entitled:

- Data Networks and routers
- Communications Protocols
- Windows NT and Linux server Configuration

2004 September to 2005 March: Teaching assistant of "Reti Radiomobili I" (Radiomobile Networks) a Master' course at the Faculty of Telecommunications Enegineering of University of Calabria, 26 hours.

# Administrative Responsibilities and Collective Interests

## Leadership within the Scientific Community

- I have been elevated to the IEEE Senior Membership degree
- Member of Social Network Technical Committee
- Member of Emerging Technologies Initiatives for Molecular, Biological and Multi-Scale Communications (ETI-MBMC)
- Member of Social Network Technical Committee
- Involved as digital communication expert in the activities of "Convergences du Droit et du Numerique" - Bordeaux, February and September 2017.

## Proposal Refereeing

- (2017) - Referee for an (European Research Council) ERC Consolidator project
- (2017) - Referee for a project in the framework of COPECUB-CAPES
- (2017) evaluator of projects in the context of STIC/MATH AMSUD.
- (2017) follow-up evaluator for the projects in the context of the program Equipes Associés.
- (2017) referee for 7 project in the context of the program Equipes Associés.
- (2016) referee of a project in the framework program Air Force Office of Scientific Research (AFOSR) - Air Force Young Investigator Research Program (YIP).
- (2009-2012) evaluator of Research Project Proposal under the Framework Programme for Research, Technological development and Innovation of the Research Promotion Foundation.
- From 2015 Scientific European Responsible for the Inria Lille center.
- From 2014 member of the committee for Inria Lille of Technological Transfer Development (CDT)

## Participation in Doctoral Dissertation Committees

- (2017) Member of the dissertation committee of **Riad Mazloum**, UPMC Laboratoire LIP6.
- (2017) Evaluator of the dissertation of **Jorge Herrera**, UPV, Universidade Politécnica Valencia.
- (2016) Reviewer of the dissertation of **Orazio Briante**, Universitá Mediterranea di Reggio Calabria.

# Invited Talks

- (December 2017): invited speaker at IoT Week, Lille, France.
- (November 2017) I gave a talk in the context of Nuneriqu'elle - Euratechnologies.
- (July 2017): invited speaker at Workshop on Retrofitting London and Paris via the Internet of Things - London.
- (May 2017): invited speaker at FET-European CIRCLE Workshop, Dublin.
- (January 2017): invited speaker at Smart City Communication day in Sophia-Antipolis .
- (2015): I was involved in the ICT2B event in Frankfurt - Germany (February 2015) and Thessaloniki - Greece (June 2015).

# Projects

## Projects proposed as Coordinator:

(2014-2016) ARUNTA - ADT (Technological Development Actions) Arduino-based Robots for Ubiquitous Network Applications

## Projects participated as a member:

(2016-2018) FUI project StoreConnect: (a 2-year project, Sept. 2016 – Aug 2018). The main objective of StoreConnect is to develop a standard middleware for connected stores.

(2013-2016) VITAL FP/-ICT-2013-SMARTCITIES: this project focuses on Smart Cities and one of the key objective is to propose a prototype application platform that will be very revolutionary in terms of offered services, by allowing the integration and interaction of several Internet of Things data sources and systems.

(2011-2013) STEM-NET: “STEM" devices for self-organizing wireless Networks; Funded by Italian Ministry of Education and Research in July 2011 under the framework of National research project (PRIN), 203.801 euro. Partners: University of Calabria, University of Bologna, University “Mediterranea” of ReggioCalabria. PON01-02149 - "KOM4T me" Knowledge Management 4 infoTelematic in Mobility Environment.

(2006-2009) MASCOT: was a Specific Targeted Research Project (STREP) supported within the Sixth Framework Program of the European Commission (Project No. IST-26905).

(2007-2008) GITA: New Architectures for Interactive Fruition of Historical and Artistic Contents on Wireless Multi-Technology Platform 2006-2008 (P.N.R. (National Government Support Grant))

(2000-2006) LOGICA (ICT Technologies for Logistics) 2000-2006 (P.O.R. (Regional Government Support Grant))

# Editorial Activities and Technical Committees

## Member of the Editorial Boards

- Eitorial board member of IEEE Transactions on Nanobioscience journal since 2017.
- Editorial board member of Elsevier Computer Networks journal since 2016.
- Editorial board member of Robotics Software Design and Engineering of the International Journal of Advanced Robotic Systems since 2016.
- Editorial board member of Elsevier Journal of Networks and Computer Applications (JNCA) journal since 2016.

## Chair of Conference Program Committees

- (Co)-Program chair for [IoT and SmartCities] MMSys 2017 and 2018, CITS 2018, Globecom 2017, NDIDO 2017 (Nouveaux Defis de l'Internet des Objets - 2017).
- Member of the Scientific Committee for the Conference Challenges of IoT in Digital Tools & Uses Congress

## Member of the Conference Program Committees

Member in the Technical Program Committees (TPC) of CoRES 2018, IoT Global Innovation Forum 2017, ICNSC 2017, NTMS 2017 and 2018, GIoTS 2017 and 2018, WF-5G'18 (2018 IEEE 1st 5G World Forum 2018), CSCN 2017, MoWNet 2017, VTC 2017, VTC 2018 - Spring, WPMC 2017, NEW2AN WSMART 2017, WiMob 2017, WPMC 2017, IoTGIF 2017

## Guest editorial activities

- Co-editor of MMTC COM-SOC letter of issue on Visible Light Communications, May 2017.
- Member of the 'Research Group on IoT Communications and Networking Infrastructure' at ComSoc Communities.
- co-editor of IEEE Access journal special issue on Body Area Networks.
- editor of the book "Vehicular Social Networks," Taylor and Francis Group, 2017
- participation to the revue "Internet des Objets" iSTE OpenScience.

# PART II
## SCIENTIFIC REPORT

# Abstract (English version)

In this manuscript, I will summarize my research activities carried out during the last 7 years. The context of my research activity is represented by networked systems constituted by elementary units (nodes) communicating to each other wirelessly. The main objective of my research work is to exploit the features of heterogeneous devices in order to increase the interoperability to enable the self-organization of these devices to accomplish several different tasks. The term heterogeneity is referring to several aspects of the devices such as 1) equipped or not with motion capabilities; 2) communication technology; 3) resources in terms of memory, battery, etc. The heterogeneity of the devices and also of the network technologies, is perceived, in this manuscript, as a potential to increase the connectivity in complex systems such as cities, swarm of robots and sensors for indoor/outdoor monitoring, smart cars, etc.

In particular, I investigate on the self-configuration and self-management concepts of the systems by starting from the idea of the nodes as elementary units of the systems showing a dynamic and adaptable nature to make them suitable in different conditions and for different main objectives.

Self-Organization is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of a system. The rules specifying interactions among the systems components are executed using only local information, without reference to the global pattern [15].

The network issues have been addressed using different approaches from the theoretical studies aimed at finding the maximum achievable performance benchmarks, through the introduction of appropriate optimization models, the use of biology-inspired mechanisms, such as genetic algorithms (GA), neural networks (NN) and Fuzzy-Logic. The purpose of this type of approach is to move in the direction of networks that are able to self-organize by adapting to different environmental conditions and dynamic as well as hard scenarios (*i.e.* environment disasters). In particular, we have considered network simulation tools and also developed from scratch some simulation tools. More importantly, we have realized several test-bed as proof-of-concepts of the solutions implemented, in order to test them in real conditions.

The rest of this manuscript is organized as follows. There are two main parts. Part I is focused on my CV and and my activity report. The second part is dedicated to the technical research propositions. In Chapter 1 is the Introduction of the thesis to define the context, the motivation and challenges and the main contributions. Background on Self-Organizing Systems is given in Chapter 2. In Chapter 4 we investigate on different learning approaches exploited to accomplish different tasks, both at node-level and network/system-level; In Chapter 5 real experiments of outdoor and indoor applications will be explained. Finally, Chapter 6 will conclude the manuscript and develop the perspectives.

# Abstract (French version)

Dans ce manuscrit, je vais résumer mes activités de recherche menées au cours des 7 dernières années. L'objectif principal de mon travail de recherche est d'exploiter les caractéristiques des dispositifs hétérogènes afin d'augmenter l'interopérabilité pour permettre l'auto-organisation de ces dispositifs pour accomplir plusieurs tâches différentes. Le terme hétérogénéité fait référence à plusieurs aspects des dispositifs tels que 1) équipés ou non avec de capacités de mouvement; 2) la technologie de communication; 3) les ressources en termes de mémoire, batterie, etc. L'hétérogénéité des dispositifs et aussi des technologies de réseau, est perçue, dans ce manuscrit, comme un potentiel pour augmenter la connectivité dans des systèmes complexes tels que les villes, essaims de robots et de capteurs pour surveillance intérieure / extérieure, voitures intelligentes, etc.

En particulier, j'étudie les concepts d'autoconfiguration et d'autogestion des systèmes en partant de l'idée que les nœuds sont des unités élémentaires des systèmes montrant une nature dynamique et adaptable pour les adapter dans différentes conditions et pour différents objectifs principaux.

L'auto-organisation est un processus dans lequel le modèle au niveau global d'un système émerge uniquement de nombreuses intéractions entre les composants de niveau inférieur d'un système. Les règles spécifiant les interactions entre les composants du système sont exécutées en utilisant uniquement des informations locales, sans référence au modèle global [15].

Les problèmes de réseau ont été abordés en utilisant différentes approches à partir des études théoriques visant à trouver le maximum de repères de performance réalisables, à travers l'introduction de modèles d'optimisation appropriés, l'utilisation de mécanismes d'inspiration biologique, tels que les algorithmes génétiques (GA), les réseaux de neurones (NN) et Fuzzy-Logic. Le but de ce type d'approche est de se diriger vers des réseaux capables de s'auto-organiser en s'adaptant aux différentes conditions environnementales et aux scénarios dynamiques et difficiles (*i.e.* catastrophes environnementales).

Le reste de ce manuscrit est organisé comme suit: il y a une première partie qui résume mon CV et mon rapport d activités'. La seconde partie est sur les contributions de recherche. Dans le chapitre 1 est l'introduction de la thèse pour définir le contexte, la motivation, les défis et les contributions principales. Le contexte des systèmes complexes est donné au chapitre 2. Au chapitre 3 decrit la funcionalié de decouverte soit intérieure au reseaux, soit extérieure. Au chapitre 4, nous étudions différentes approches d'apprentissage utilisées pour accomplir différentes tâches, tant au niveau du nœud qu'au niveau du réseau/du système; Les principaux résultats des différentes solutions basées sur les passerelles seront présentés au chapitre 5. Enfin, le chapitre 6 conclura le manuscrit et développera les perspectives.

# 1

# Introduction

In this manuscript I will summarize my research activity that has been carried out during the last seven years. The main objective of my research work is to deal with complex network systems by leveraging features and properties of singular basic units (nodes) in order to achieve global objectives such as coverage of target area, connectivity among nodes by trying to reduce the impact in terms of data traffic sent in the networks and energy consumption.

I have had the opportunity to address wireless networks from resource and service discovery functionalities in order to get the needed state information to self-organize the nodes among them and to exploit mobility and other intrinsic features of nodes as primitives of the network in order to design and implement high performant systems. Some of the theoretical models elaborated have been implemented in test-beds by leveraging real devices (e.g. wireless sensors, Raspberry Pi, Arduino, Wi-Fi bots, etc.) in order to show proof-of-concepts and validate simulated or theoretical results.

It is worth noting that the contributions presented in this document are the fruit of deep collaboration with several PhD students, engineers and colleagues. In particular, in terms of PhD students, it is worth to me to mention Mr. Rosario Surace, Mr. Riccardo Petrolo and Mr Cristanel Razafimandimby. The support of engineers, Emilio Compagnone, Salvatore Guzzo Bonifacio, Antonio Costanzo, has been really precious in order to implement realistic scenarios to validate the various approaches.

## 1.1 Context

Recently, the concept of complex systems or complex infrastructures of "System of Systems" has emerged in the ICT context, above all due to the rapid deployment of billions of "communicating" (smart) objects that have led to the birth of the Internet of Things (IoT) paradigm. In this direction, Cisco "coined" the term Internet of Everything (IoE) [1] to characterize the creation of a *networks of networks* of billions of connections with potential unprecedented opportunities.

IoT paradigm has been envisaged as a powerful enabler for new applications, both for daily-life and for industry. By 2018, the IoT market will overcome the ones of PC, phones and tablets [1] and applications based on IoT will be a consistent part of the business of the companies. In order to make the proliferation of objects feasible and effective, efficient solutions have to be proposed ranging from intelligent exploitation of heterogeneity of the devices, smart approaches to manage mobility by controlling or predicting it where possible, etc. Most of the today's larger-scale IoT systems and platforms are mainly based on sensing-oriented devices and networks, and therefore focused on monitoring activities mainly providing data collection and analysis. However, the development of next generation IoT applications and services will strongly depend on the availability of full-fledged platforms for smart objects, distributed edge and embedded intelligence, and cognitive networks, whose key aspects will support decentralized actuation and smart behavior.

A global complex system encompasses: 1) IoT Platforms; 2) Cloud and Services; 3) Stakeholders or final users;

[1] BI Intelligence Estimates

An example of such a type of complex system is represented in Figure 1.1 where we can observe sveral types of sub-systems such as Smart City, Smart Highway, Smart Hospitals, etc. Each subsystem can be characterized with several IoT platforms. Each platform associated wto a sub-system can interoperate or not with the other platforms of the same sub-system and with the platforms of the other subsystems. One of the big issue related to the IoT paradigm has been that the IoT architectures have been designed and evolued independently and the most of times are not interoperable to each other.

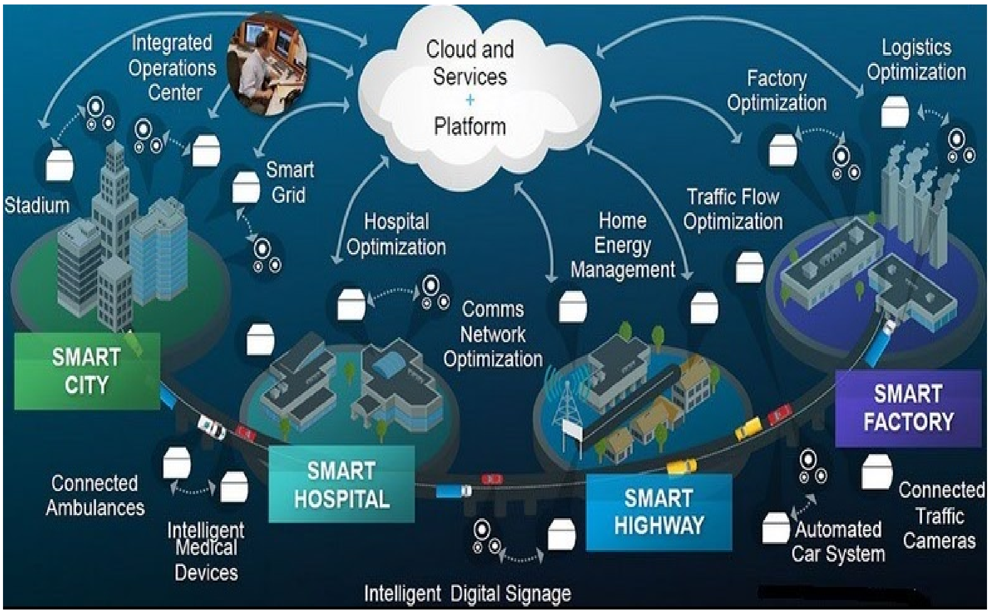



Fig. 1.1: Global Complex System as System of Systems

In terms of IoT contributions, I will address sensor and robotic networks by also introducing the concept of Internet of Robotic Things [8] and by leveraging on embedded devices such as Raspberry Pi and Arduino. Sensors and robots can be deployed in all the sub-systems considered in **??**. I will showe examples of full-edged platforms in different domains, ranging from building monitoring (indoor applications) to smart agriculture applications and smart car evolution.

## 1.2 Motivations and Challenges

As illustrated in Figure 1.1, the global complex system is composed of several stand-alone systems that can be simple systems (e.g. automated car system) or more complex systems such as Smart City.

Such systems (more or less complex) can be characterized with different types of heterogeneous networks, where there exist heterogeneous communicating objects/things.

In order to ensure effective services with a certain level of quality, many challenges have to be identified and must be tackled in every system and also in each network.

To the follow, I will illustrate the main motivations and challenges addressed in this manuscript.

1. **Resource and Service discovery in wireless networks**: One of the most important challenges when complex network systems are considered, is the discovery of pertinent data-sources that satisfy user requirements. Indeed, given business criteria defined by users, are fundamental to have effective mechanisms providing resources that better suit these criteria.
   The community refers to this challenge as "service discovery" [77]. The "discovery" of direct neighbors defined as "1-hop" communication neighbors is considered as an *in-network* operation. This *in-network* process is important for the maintenance of the network itself and to introduce new services and new devices.

Protocols as Universal Plug and Play (UPnP) by Microsoft and Service Location Protocol (SLP) by IETF have been proposed for TCP/IP networks, but effective solutions are needed for resource-constrained networks in order to ensure high scalability in terms of adding new devices. All that suggests that new distributed and "simple" solutions have to be conceived.
Another kind of *discovery* is the *out-network* discovery, based on a middleware for discovering heterogeneous resources of different IoT platforms, systems and networks. The main challenge is about how representing the data-sources in order to provide the users with easy access to the resources and the associated services.

2. **Interconnection of heterogeneous devices and their interoperability**: IoT landscape is evolving towards a constant enrichment of different technologies, that makes mandatory having devices capable to present the *things* to the users and applications by keeping in mind the scalability issue.
Based on these considerations, the European Telecommunications Standards Institute (ETSI) proposed a new network architecture model, Mobile Edge Computation [3] enabling cloud-computing capabilities at the edge of the cellular network, closer to the device.
A similar concept has been also proposed by CISCO through the FOG computing paradigm [4]. FOG computing allows a distributed implementation of services that in a cloud-based network are normally centralized.
The solutions considered right now, normally limit the gateway functionalities in terms of protocol conversion or data forwarding. Enriching the gateway with additional functionalities could have an important impact on the performances of a system/network. That said, it is important to find criteria to define which functionalities are important to move to which node in order to improve the reaction time of the systems and keep the global solution scalable.

3. **Proof-of-Concepts to validate theoretical and simulation results**: Complex Systems as the name well explains, are "complex" in their nature and global behavior is often difficult to predict, depending on several inputs, different variable states, etc. In the Internet of Things, Internet of Everything, Cloud of Things, Internet of Robotic Things landscapes, test-beds as a proof-of-concepts play a key role in order to make the convergence between the research and real-world. Test-beds deployed have twofold purposes: a) to allow real-world experimentation on IoT related technologies; b) trying to infer the services of complex systems aimed at ensuring a final user QoS.
Real experiments are never easy to realize, since they are really time-expensive and often the output results do not match with expected results, requiring updates on the algorithms and re-verification of the test-beds.

Based on the above concepts, in this thesis I will focus on effective mechanisms to discover *things* and *services*. After that, I will focus on how these *objects* can communicate in order to interoperate and can "smartly" change their roles to adapt to external and internal evolutions. Finally, I will leverage the current technologies in order to validate the proposed approaches and with a *loop-wise* based logic, I will re-exploit the results of the real implementation as input for the theroretical and simulated algorithms.

## 1.3 Contributions

Hereafter, I summarize my main contributions towards the challenges identified. Note that the contributions are classified with respect to the type of challenge and systems as represented in Figure 1.1.

### 1.3.1 "How to discover data-sources that better suit business criteria?"

In order to face the challenges related with the discovery of appropriate data-sources based on user requirements, two different types of approaches have been investigated in this manuscript.

The first one is on *in-network* discovery mechanism CACHACA implemented in the context of the VITAL project (http://vital-iot.eu), standing for Confident-based Adaptable Connected objects discovery to Harmonize smart City Applications [11].

CACHACA has the main objective to allow user the discovery of available services in a certain IoT platform based on two kinds of confidence paramaters, a physical one and a service confidence.

The second type of discovery has also been implemented in the context of VITAL and specifically as part of the Discoverer module horizontally integrated in the platform (see Figure 3.10), responsible for discovering Inter-Connected Objects (ICOs), Systems and Services. Discovery functionality plays a fundamental rule in the VITAL platform since all the "relevant" resources of different IoT platforms and systems are discovered through this functionality.

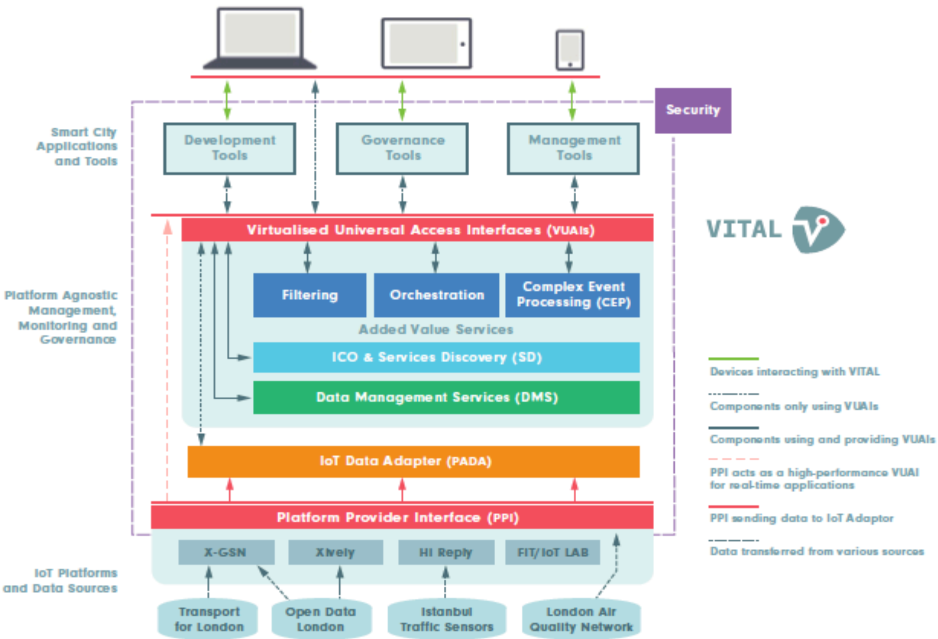



Fig. 1.2: VITAL architecture

### 1.3.2 "How to interconnect heterogeneous devices and make them interoperable?"

In order to address the challenges deriving from interconnection of heterogeneous devices and with the goal to improve the global performances of a complex system by leveraging on concepts as interoperability of the single components of the system, we focused on different components and aspects of the network.

A first fundamental aspect we have considered is that, in order to have devices that are interconnected and interoperable, we need to keep connectivity among the devices and at the same time they need to cover "interesting" areas, namely areas or zones where ther are events occuring. Based on these considerations, we focused on *connectivity maintenance* and *collective coverage*.

A second important aspect has been the possibility to dynamically change the roles of the nodes based on external/internal changes. External changes may refer to lower link quality due to adding of noise on a channel. Internal changes may refer to a low level of battery and then a node would prefer to reconfigure its working state to a lower energy consumption state.

The idea of designing new communication devices, capable to adapt their operation roles in a self-organized fashion to rapidly face the changes within the working environment, has gained a very high attention from the wireless network research community [109, 110]; similarly, the availability of novel general purpose and powerful hardware platforms able to be dynamically reconfigured via software, has paved the way for new research directions in which it is possible to deploy extremely challenging communication scenarios [111, 112].

By taking into account the unique features offered by the recent Software Defined Radio (SDR) paradigm, we considered the design of a self-adapting deployment strategy for a communication network in which several wireless devices, scattered all around in a specific area, can carry out a common task according to specific network requirements in terms of coverage and/or connectivity.

*A contribution regarding evolutionary and adaptive devices with connectivity and coverage constraints* has been realized through the design of Artificial Intelligence (AI) approaches. In particular, a combination of genetic/neural network algorithms has been developed on nodes equipped with Software Defined Radio capabilities, in order to make these nodes smarter and allow them the selection of a specific and opportunistic modulation technique based on both external environmental conditions and internal consitions. Furthermore, motion capability of some nodes has also been exploited with a sinergic approach in order to improve the general performance of the global complex system in terms of connectivity and coverage.

### 1.3.3 "How to validate theoretical and simulation results?"

A major feature of the Future Internet is represented by the federation of resources based on different technologies as shown above. In order to be able to establish the criticism of the different solutions developed, as network scientists, we have realized that we need to validate theoretical and simulation results in distributed systems and above all under real environment conditions. Bearing that in mind we have mainly investigated the most of our solutions through the design and implementation on real test-beds in order to give a proof of concept of the approaches developed.

In particular, we have taken a loop-wise approach by examining the test-bed output results and re-using them in the theoretical formulation or in the simulation tools to improve their reliability.

The *first contribution in terms of test-beds* implementation has been for smart building monitoring through CACHACA algorithm. In order to prove the scalability potentiality of the approach, the large-scale platform FIT-IoTLab (https://www.iot-lab.info) has also been exploited in order to perform some experiments.

An important contribution in this direction has been realized in the context of vehicular technology with the implementation of the *Future Smart Car based on a lightweight virtualization as enabling technology* [12, 13].

This represents a sort of gateway-based architecture, since a specific central device has been equipped with intelligence to perform different kinds of processes originated by different sensors and devices (e.g. cameras) deployed inside the car.

We have designed an efficient spatio-temporal correlation technique based on a Bayesian Inference Approach (BIA), to avoid transmission of high spatio-temporal correlated data. We have applied this technique both in *indoor* [10] and *outdoor* [14] applications. In particular, in [10] a hierarchical architecture composed with simple nodes, a smart gateway and data centers has been considered nd th eapproach has been validated in the Berkeley laboratory equipped with 54 sensors collecting temperature, humidity, light and voltage readings as well as the network connectivity information in order to reconstruct the network topology. In [14] the BIA approach has been applied to the monitoring of peach trees.

By focusing on solutions addressing these three main questions, we have elaborated "global" solutions for having complex self-organized networked systems responding to the user requirements.

The rest of tha thesis is organized as follows. The Chapter 2 is to describe the Complex Self-Organized Network Systems (CSONS). In the third Chapter I will detail the different types of discovery mechanisms *in-network* and *out-network*. Chapter 4 will be on the mechanisms to make heterogeneous devices able to interact and interoperate. In Chapter 5 I will present some real architectures to implement some of the solutions developed in the previous chapters. Finally I will conclude and give my research directions in Chapter 6.

# 2

# Complex Self-Organized Network Systems

A Complex Network System (CNS) can be defined as a fragile equilibrium achieved through several basic heterogeneous spatio-temporal evolving components that interact through each other. The interaction activity implies interoperability and coexistence in order to self-organize CNS and allow their evolution to keep their equilibrium.

CNSs have to accomplish specific actions and tasks in order to globally achieve specific objectives (e.g. provide final users with specific services, monitoring, event detection, etc.).

Self-organization is a great concept for building scalable systems consisting of a large number of subsystems and elementary units. Fundamental aspects in such a kind of environments are coordination and collaboration of subsystems and elementary units (nodes) for achieving a common objective. Principles of self-organization have evolved in nature and in the last few years, the concept of self-organization has been applied to technical systems and finally to wireless networks. Also, in this context the self-organization concept can be summarized as the interaction of multiple components in order to achieve the same goal. This collaborative work may be without any central control and key desirable features of similar networks are scalability, reliability, resilience and availability [16].

Complex Self-Organized Network Systems (CSONSs) need to meet specific conditions in order to be effective and advantageous in real applications. We have identified four main features that have to be met by CSONSs: a) **Resilience**, as the capability of the system to react to unexpected and also hostile external conditions; b) **Reliability**, as the ability to perform in a consistent way; c) **Scalability**, as the ability to handle with growing of the system in terms of components or with a growing amount of load; c)**Availability**, as the possibility to use the network whenever is needed.

One of the most important challenge in designing Wireless Self-organizing Networks is the achievement of self-* properties as:

- *Self-management* - capability to maintain nodes and/or networks based on the parameters of the system;
- *Self-configuration* - allows networks applications to configure their own operational parameters (*e.g.* routing decision parameters or sleep periods) depending on the current situation in terms of environmental circumstances, *e.g.* connectivity, quality of service parameters and self-organize into desirable structures and patterns (*e.g.* routing tables or duty cycling patterns);
- *Self-healing* - allows wireless networks applications to autonomously detect, localize and recover automatically from failures in the network (*e.g.* node or link failures).
- *Self-optimization* - allows networks applications to constantly seek for enhancements by adapting to network dynamics with minimal human intervention;

The self-* properties are important in this kind of systems, since they are often required to operate in physically unreachable areas (*e.g.* inside a building wall) or in unattended areas (*e.g.* forest or ocean) or potentially harsh/hostile areas (*e.g.* nuclear power plants, emergency situations). The design of self-organizing systems is not top down as in traditional systems which are typically built starting considering the overall system and then approach the single components and modules. Typically to design Self-Organizing systems the approach starts from thinking at the local interaction among components that, if they are properly modeled, could led to some kind of organization even if there is no guarantee about that [19].

Self-organization can be realized through different approaches [18]:

- *Location-based mechanisms*: geographical positions or affiliation to a group of surrounding nodes such as clustering mechanisms, are used to reduce necessary state information to perform routing decisions or synchronizations. Usually, similar methods known for global state operations can be employed in this context. Depending on the size of active clusters or the complexity to perform localization methods, such location-based mechanisms vary in communication and processing overhead;
- *Neighborhood information*: further state reduction can be achieved by decreasing the size of previously mentioned clusters to a one-hop diameter. In this case, only neighborhood information is available to perform necessary decisions. Usually, hello messages are exchanged in regular time periods. This keeps the neighborhood information up-to-date and allows the exchange of performance measures such as the current load of a system;
- *Probabilistic/Predictive algorithms*: in some cases for examples if messages are very infrequently exchanged or in case of high mobility or in case of reduction of data to send, pure probabilistic methods and inference approaches can lead to very good results without any use of state information. Statistical measures can be used to describe the behavior of the overall system or the behavior of single components in terms of next action to perform. Obviously, no guarantee can be given that a desired goal will be reached;
- *Bio-inspired methods*: biologically inspired methods build a category that is composed of neighborhood-depending operations very similar to behavior of some species present in nature as ants or fishes and birds. All objectives are addressed by using positive and negative feedbacks often using learning approaches (e.g. neural networks mechanisms, fuzzy logic, etc.) allowing a complex organization among the single components of the system with same objective to be pursued.

These concepts have been deeply applied in the design and development of STEM-Net architecture [109] an *evloutionary* approach to deploy, extend and manage the network in a complex system. One of the specific complex system considered in [109] has been a Smart City context.

The "stemness" concept includes the main self-* properties, but it pushes these features even farther until including the concept of mutation and evolution. These latter components have been considered together with "mobility" as intrinsic primitives of the network. In fact, with miniaturization of computing elements many mobile devices appeared in the market that can collaborate in an ad hoc fashion without requiring any previous infrastructure control; Consequently mobility has a large impact on the behavior of ad hoc networks [20]. This latter consideration allows us to consider the mobility as a fundamental aspect of the self-organizing networks, by also integrating it as a primitive component in the network design.

## 2.1 Wireless Sensor Networks

In the Internet of Things (IoT) landscape, the everyday objects surrounding us have become proactive actors of the Internet, generating and consuming information.

One of the most important components in the IoT paradigm is represented by wireless sensor nodes. The benefits of connecting wireless sensor networks (WSNs) and IoT elements go beyond remote access. Indeed, heterogeneous information systems can be able to collaborate and provide common services.

This envisaged integration and the remark that IoT is based on WSNs, is not mere speculation, but something that has been supported and encouraged by different companies and technologies such as $6LowPAN$ standard, defined by IETF [25]. Currently, wireless sensor data can be linked through different ways (e.g. web-service based on REST, social networks based on twitter, etc.).

A Wireless Sensor Network (WSN) consists of low-cost, low-power, multifunctional, autonomous sensor nodes deployed either randomly or according to some predefined statistical distribution, over a geographic region of interest to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants and to cooperatively pass their data through the network to a main location usually a sink node with more energy and processing and communication capabilities. The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in many industrial and consumer applications, such as industrial process monitoring and control, machine health monitoring, transportation, entertainment, crisis management, homeland defense, home automation and smart spaces. The WSN is built of nodes, from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors.

Every node is equipped with a radio transceiver with an antenna in order to have communication capabilities, a micro-controller in order to perform processing activities, different types of memories in order to store data, an energy source (e.g. a battery or an energy harvesting component). There exist several types of sensors varying in size (size ranges can vary from nano-meters to several centimeters), costs (from few dollars to several thousand of dollars) depending on the complexity and singular components present in each device, computational and memory resources, mobility capacity, communication interfaces, etc. Generally, sensor nodes are resource and energy constrained with limited computational and communication capacities and they are able to monitor a limited amount of their surrounding. However, when several "simple" nodes form a network, nodes can cooperate and collaborate to each other and complex tasks can be accomplished that are not possible to be realized by a single device.

One of the primary advantages of deploying a wireless sensor network is its low deployment cost and freedom from requiring a messy wired communication backbone, which is often unfeasible or economically inconvenient. Due to these constraints, resource management is of critical importance to these networks. Sensor nodes are scattered in a sensing field with varying node densities. Each node has a sensing radius within which it can sense data, and a communication radius within which it can communicate with another node. Each of these nodes will collect raw data from the environment, do local processing, possibly communicate with each other in an optimal fashion to perform neighborhood data or decision fusion (aggregation), and then route back those aggregated data in a multi-hop fashion to data sinks, usually called the base-stations, which link to the outside world via the Internet or satellites. Since an individual node measurement is often erroneous because of several factors, the need for collaborative signal and information processing is critical.

Bearing that in mind, in order to have efficient sensor networks, it is extremely important to efficiently deploy nodes through (quasi)-optimal topology control strategies. This is possible when nodes are placed manually in pre-defined and pre-determined locations. Often nodes are too numerous or locations are not directly accessible by human to manually deploy them. In these cases, sensors can be dropped from an aircraft.

Once the nodes are deployed in the sensing field, they form a communication network, which can dynamically change over time, depending on the topology of the geographic region, inter-node separations, residual battery power, static and moving obstacles, presence of noise, and other factors. Routing protocols and node scheduling are two other important aspects of wireless sensor networks because they significantly impact the overall energy dissipation. Routing protocols involve primarily discovery of the best routing paths from source to destination, considering latency, energy consumption, robustness, and cost of communication. Conventional approaches such as flooding and gossiping waste valuable communication and energy resources, sending redundant information throughout the network. In addition, these protocols are neither resource-aware nor resource-adaptive. Design of efficient data dissemination algorithms represents an important challenge that needs to be addressed and has been a hot research topic for several years.

In order to better characterize a WSN, we can summarize their main features as follows:

- heterogeneity of nodes;
- energy computation and memory constraints;
- dynamic spatio-temporal topology;
- mobility of nodes;
- scalability to large scale of deployment;
- ability to cope with node failures;

- resilience vs harsh environmental conditions.

In the last few years the scenario of WSN has been enriched with different devices equipped not only with computational and memory capacities but also with actuation features, such as motion capabilities.

In literature such networks with more intelligence and abilities are reported as Wireless Sensor and Actuator Networks (WSANs) [21]. More specific details about these networks will be given in the followings subsections.

## 2.2 Robot Networks

Recent technological advances in robotic and communication fields have contributed to advances in design of automation and robotic systems composed by several types of devices as vehicles, sensors, actuators, etc. New robotic systems have been designed and implemented, able to interact with other robots, with human beings, etc. Ad-hoc cooperation protocols and Artificial Intelligence (AI) mechanisms have been conceived to cope with this type of systems, named "Network Robot Systems (NRSs)" [22] that gives origin to the Internet of Robotic Things (IoRTs) paradigm, defined for the first time by ABI research [8].

NRSs have to meet specific features in order to be considered as NRSs:

- **Cooperation**: in this specific case the cooperation is envisaged as network-based cooperation, where human being, robots, sensors and any other IoT object communicate by the means of a network;
- **Autonomous Capabilities**: as an element of a NRS, a robot has to be able to perform autonomous actions such as move towards a "better" position to ensure connectivity or to cover an "interesting" area;
- **Human-robot interaction**: a system can be classified as NRS if there is an interaction between robots and human;
- **Environment sensors and actuators**: besides the sensors of the robots, the environment must include other sensors, such as vision cameras and laser range finders, and other actuators, such as speakers and flickers;

An effective summary of what a Network Robot System is, has been provided by the European study group Research Atelier on Network Robot Systems inside of $EURONII$ as:

> *A Network Robot System is a group of artificial autonomous systems that are mobile and that make important use of wireless communications among them or with the environment and living systems in order to fulfill their tasks.*

NRSs can be considered as an interesting convergence of several research fields beyond robotics.

In particular Artificial Intelligence (AI) research, ubiquitous computing, network communications. Some of the key issues that must be addressed in the design of Network Robot Systems are cooperative localization and navigation, cooperative environment perception, cooperative map building, task allocation, cooperative task execution, human-robot interaction, network operation, and communications. The topic Network Robot Systems transcends conventional robotics, in the sense that there exists, for these types of distributed heterogeneous systems, an interrelation among a community of robots, environment sensors and humans. Applications include network robot teams (for example to play soccer), human-robot networked teams (for example a community of robots that assist people), robots networked with the environment (for example for tasks on urban settings or in space applications) or geminoid robots (a replication of a human with own autonomy and being partially tele-operated through the network).

The evolution from conventional robotics and NRSs has been effectively captured by ABI research [8] by the means of Internet of Robotic Things (IoRT) concept.

In [26], the authors provide a complete definition of IoRT as:

*A global infrastructure for the information society enabling advanced robotic services by interconnecting robotic things based on, existing and evolving, interoperable information and communication technologies where cloud computing, cloud storage, and other* *existing Internet technologies are centered around the benefits of the converged cloud infrastructure and shared services that allows robots to take benefit from the powerful computational, storage, and communications resources of modern data centers attached with the clouds, while removing overheads for maintenance and updates, and enhancing independence on the custom cloud based middleware platforms, entailing additional power requirements which may reduce the operating duration and constrain robot mobility by covering cloud data transfer rates to tasks without hard real time requirements.*

This characterization places IoRT in respect of Cloud Robotics (CR) as a kind of evolution of CR. In fact, IoRT leverages some specific characteristics of CR such as virtualization technology by exploiting the enabling technologies of IoT to empower flexibility in designing and implementing of new network robotics applications in order to be able to provide distributed computing resources as a core utility.

Complex Heterogeneous Network Systems represent the core of this thesis, where different communicating objects ranging from the simplest sensing devices to the more complex robots have been considered in order to implement and validate the resource discovery approaches, the AI algorithms to make the units to cooperate and evolve in an autonomous fashion.

## 2.3 Conclusions

In this chapter I have presented the fundamental vision of what a Complex Self-Organized Network System is. A deep comprehension of the main components of a similar system has been of paramount importance in order to identify the main research directions. Firstly, I have learned that all the complex systems are composed by elementary, basic units and when the system is self-organized without any central controller, it is necessary to leverage all the single units based on the specific capacities and capabilities. This suggests that heterogeneity needs to be not only identified but also integrated in the system and treated as a control primitive in order to properly find its right role in a complex system. That said, all the complex systems I have treated were IoT-based systems and then I have dealt with the main actors of IoT platforms in terms of hardware components, wireless sensors and wireless robots. I have then analyzed Wireless Sensors Networks and Network Robot Systems in order to identify their main features and how they can be exploited for "smart" applications.

# 3

# Resources and Services Discovery

One of the most important challenges, common to all the complex systems, is the discovery of pertinent sources in order to meet user requirements. Effective and efficient discovery mechanisms are fundamental in order to provide users with resources fitting their business criteria. We have distinguished onto two main types of *discovery services*, a) *in-network* and b) *out-network*.

The first one refers to the "classical" discovery as an operation that can be performed directly *in-network* (i.e., the detection of neighbors) and/or *out-network* (i.e., a middleware that aims to discover resources that belong to different networks). The first case is something more related with the building and maintenance of the network itself, especially in order to introduce new services and devices; a variety of protocols exists and is used nowadays for TCP/IP networks [34]; to name the most well known, Service Location Protocol (SLP), developed by IETF and Universal Plug and Play (UPnP) developed by Microsoft. A lot of effort has also been done for resource-constraint networks; in [35], Shelby et al. present COAP; in this case, services are published into a register - which can be queried by users - stored at the gateway. In order to overcome the limitations of a centralized solution, in [31] we proposed a ranking mechanism for Sensor Networks that facilitates the discovery of services; thanks to our proposal indeed, sensor nodes can discover the neighborhood and, at the same time, the services offered just by adding few bytes of overhead (10 bytes for each service) to their discovery protocol.

The second one is referring to tools able to discover resources belonging to different networks. In particular, when we consider *out-network* discovery, the challenge concerns more the representation of different data-sources and how users can easily access those resources and the provided services. In this context, many middleware solutions have been proposed; in the following, we present the most representative.

It is worth to notice that the research activities regarding discovery presented in this work are of general application for any type of complex system. Anyway, we have developed them in the context of an European project on Smart City and for that, we have contextualized them, where not otherwise specified, to a city context.

*Global Sensor Networks* (GSN) [1] is a middleware that aims to address the challenges of sensor data integration and distributed query processing. The main purpose is to make applications hardware-independent. GSN lacks semantics to model meta-data.

*OpenIoT* [2] concentrates on providing a cloud-based middleware infrastructure in order to deliver on-demand access to IoT services, which could be formulated over multiple platforms. Anyway, it is not designed to deal with Smart City scenarios, since it does not consider the fundamental aspect of data layer as a transveral module of the protocols layer in order to be able to be able to capture specific features of Smart City as complex system.

*Sensor-Cloud* [36] aims at managing physical sensors by connecting them to the cloud; sensor devices should be described by using SensorML. It does not take the management of entire systems and/or services into account. This represents a fundamental aspect to be able to realize Smart City applications.

From the above solutions, it is evident that using semantic technologies is recognized as a good enabler in order to describe resources across different IoT plat-

[1] `https://github.com/LSIR/gsn`
[2] `http://www.openiot.eu`

forms and data-sources. Once modeled, the users should easily access to those resources, select the one that most suits his/her specific business context. In some circumstances, indeed, the user is just interested about a generic Inter-Connected Object (ICO) that can observe, in an Area of Interest, a defined property (e.g., Speed and/or Temperature); therefore it is important to provide the "best" candidate resource. Among other functionalities, this is what our Discovery module achieves.

## 3.1 *In-network* Discovery

An efficient maintenance allows the introduction of new services and management of adding devices. In Internet, already there exist different protocols for discovery process, such as Service Location Protocol (SLP) [90]. Another example of discovery protocol can be considered CoAP [91], where services are published in a register and can be queried by the users and stored at the gateway.

In this work we focused on an additional layer, namely a *data exchange layer* that can be very beneficial to manage an increasing number of connected devices in the system. This additional data layer has been introduced for the first time in [74]. Through this additional layer we consider a semantic annotation whose benefits have been largely discussed in [92] and span from a) resilience in case of failure; b) data that can be re-used; c) "write-once run-anywhere" applications. This *data exchange layer* may influence discovery and routing approaches and it will be crucial to enable scalability from an application's point of view. Technologies at the basis of this layer are Linked Data [75] and Resource Description Format [76], accepted as standards in the Web and providing a reference model. The main goal in terms of "*In-network* Discovery, was to discover the resources/services/nodes more suitable for the specific application considered, by taking into account that there are a huge amount of available sources that can be considered.

More specifically, we proposed a Confidential-based Adaptable Connected objects discovery to HArmonize smart City Applications (CACHACA), a ranking mechanism for Sensor Networks that facilitates the discovery of services provided by each network element. By running CACHACA, it is possible to evaluate and classify the neighborhood and the available services for each node. In order to estimate the pertinence of neighbors and services, we leverage on the flexibility of the fuzzy logic and on its capacity to handle imprecise and incomplete data. CACHACA can be used in order to obtain:

- a **complete** information, by combining different data sources that offer different services;
- an **accurate** information, by combining different data sources that offer the same services.

The main novelties introduced by CACHACA rely on the adoption of the Sensing-as-a-Service model [77], which allows each network element to be seen as a service provider and the possibility to rank those services. Performances of CACHACA have been first evaluated through extensive simulations and then stressed when facing a realistic environment through experiments run on the FIT IoT-LAB testbed. Achieved results demonstrate its effectiveness in the discovery of services process with regards to traditional approaches.

### 3.1.1 System Model

In our system we can distinguish three different entities as shown in Figure 3.1

Each node $u$ runs a Neighbor Discovery process in order to discover any other neighbor nodes $v$. A node $v$ is said a neighbor of node $u$ if they are in communication range to each other. A Neighbor Table (NT) of each node is refreshed at a frequency $f$ with information related to the neighborhood.

Based on [78], NT contains at least the following elements:
- *numTx*: number of transmitted packets to $v$;
- *numTxAck*: number of packets acknowledged by $v$;
- *numRx*: number of packets received from $v$;
- *Timestamp* of the last frame received from $v$;
- *Connectivity statistics* (e.g., RSSI, LQI), which can be used to determine the quality of the link.

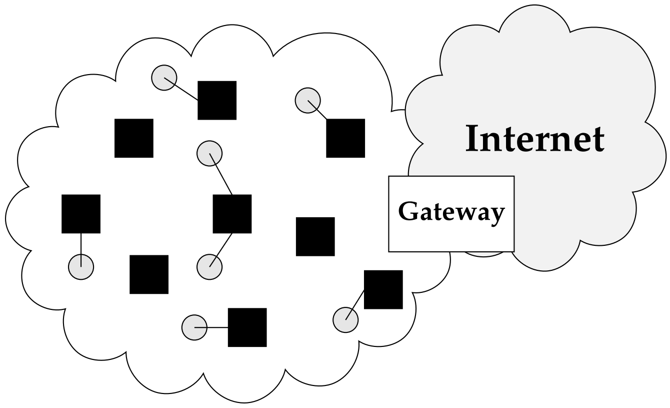



Fig. 3.1: Network elements: *Node* (square), *sensor* (circle), and *gateway* (rectangle).

All the nodes are based on a standardized format (such as IPSO [79]) for describing the services. Services (e.g. humidity, temperature, etc.) are combined with other information such as:
- *freshness* of the information; can be real-time or temporized;
- *provider*: to specify whether the service is directly provided by the node itself or by a neighbor.
The above parameters can be used in order to define relationship of a node with the neighborhood. In this sense, in this work, we use some of the above parameters in order to introduce two additional functions, the PHYSICAL CONFIDENCE ($\varphi$) - based on the *RSSI* and *Timestamp* - and the SERVICE CONFIDENCE ($\omega$) that is computed based on the service information.

RSSI stands for Received Signal Strength Indicator and is a measure of received power. According to [80], the RSSI is reported as an integer ranging from $-100\ dBm$ to $0\ dBm$; in this work, we normalize it as a value from $0$ to $100$.

### 3.1.2 Fuzzy logic

In order to compute the physical confidence, we use a rule-based fuzzy inference system [27]. A fuzzy logic system can be developed in three steps:
- **Definition of fuzzy sets (fuzzification).** In this first round non-fuzzy inputs (i.e., numbers) are converted into fuzzy sets by using membership functions (e.g., triangular, trapezoid, singleton, bell, or some other type of function).
- **Definition of fuzzy rules.** Expressed as statements like “IF ... THEN ...", the fuzzy rules summarize the relationship between the fuzzy sets and the output variable.
- **Defuzzification.** This stage consists into conversion of the fuzzy output in a fruitful value to be used for making a decision.

### 3.1.3 Physical confidence computation

Phyical confidence $\varphi$ computation is based on the rules defined above. In particular, we consider "physical" metrics as timestamp and the RSSI acquired during the neighbor discovery protocol. It is worth recalling that this protocol is totally distributed and only based on local exchange of information (between nodes $u$ and its neighbor $v$). Three fuzzy sets have been then considered : BAD, GOOD, and EXCELLENT as displayed in Figure 3.2. In particular, in Figure 3.2 we show the diagrammatic representation of the RSSI that is computed using a trapezoidal membership function. Equation 3.1 shows how $\mu(x)$ is computed for the set BAD.

$$\mu_{bad}(x) = \begin{cases} 0 & \text{if } x > 35 \\ 1 & \text{if } 0 < x < 25 \\ 3.5 - 0.1\,x & \text{if } 25 \le x \le 35 \end{cases} \tag{3.1}$$

The estimation of $\varphi$ is also based on the Timestamp. in this case, we consider the difference $\Delta$t (Eq. 3.2) between the instant at which the computation process is executed ($t_{now}$) and the Timestamp $t_{timestamp}$ stored into the NT. Timestamp will

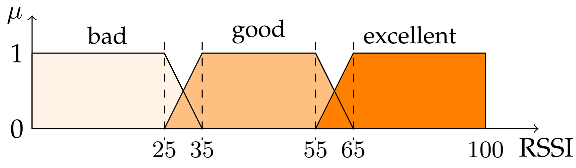



Fig. 3.2: Diagrammatic representation of RSSI.

give us information about the "freshness" of the data and is then considered as priority metric.

$$\Delta t = t_{now} - t_{timestamp} \tag{3.2}$$

Once Δt is obtained, we consider again three fuzzy sets: BAD, GOOD, and EXCELLENT. Since we supposed that the application is time-constrained, we favor small values of Δt (Fig. 3.3); therefore a node that provides services in real-time will be highly compared to one with higher values of Δt.

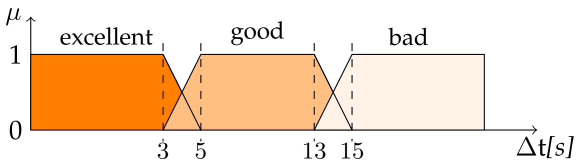



Fig. 3.3: Diagrammatic representation of Δt.

Fuzzy logic will be applied after the fuzzification process in order to compute the physical confidence.

Table 3.1 shows the definition of the rules in CACHACA. An example can be observed as: "**IF** RSSI is *Excellent* **AND** Δt is *Excellent* **THEN** $\varphi$ is *Excellent*". As already noticed before, this Timestamp gives us "freshness" information on the nodes and data and it is for that reason that we have considered it as more important than the link quality in the definition of our fuzzy rules. Indeed, when the RSSI is *Good* and Δt is *Excellent*, neighbors are still noted as *Excellent*; this is because a communication can be completed even with a low RSSI, on the other end, if the neighbor is not often active, it is important to classify it as *Bad*.

Table 3.1: Rule based fuzzy inference.

| $RSSI$ | $\Delta t$ | $\varphi$ |
|---|---|---|
| Excellent | Excellent | Excellent |
| Good | Excellent | Excellent |
| Excellent | Good | Good |
| Good | Good | Good |
| Bad | Excellent | Good |
| Excellent | Bad | Bad |
| Good | Bad | Bad |
| Bad | Good | Bad |
| Bad | Bad | Bad |

### 3.1.4 Service confidence computation

The service confidence ($\omega$) is computed by each node considering one of its mono-modal services per time (e.g., temperature); in this case we use just the *Freshness* feature. As shown in Table 3.2, $\omega$ is considered *Excellent* when it is possible to access in real-time to the values of the services.

Table 3.2: Service confidence computation for a Full node.

| $Provider$ | $Freshness$ | $\omega$ |
|---|---|---|
| sensor | real-time | Excellent |
| sensor | temporized | Bad |

### 3.1.5 CACHACA

Each node is now able to compute confidence values of its neighborhood in a periodic way. Algo. 1 describes how the physical confidence is updated by $u$ upon reception of a new packet from $v$.

$u$ checks whether $v$ is already stored into its NT, if so, it updates its NT with the *RSSI* and the *Timestamp* and then it computes $\varphi$ for each node present in its NT. If not, a new entry will be added, with the ID of $v$, the *RSSI* and the *Timestamp*; at this point $u$ computes $\varphi$ for each neighbor by applying the fuzzy logic rules above presented.

**Algorithm 1** Physical confidence update - Run on node $u$ upon reception of packet from node $v$.

**if** $v \in$ NT **then**
    update RSSI and Timestamp values for $v$ in NT;
**else**
    add $v$ in NT with associated RSSI and Timestamp;
**end if**
$\forall$ $w$ in NT, update $\varphi(w)$ following Table 3.1.

All the nodes periodically advertise their services. This mechanism allows an update of potential "new" services and makes feasible the concept of scalability we have had in mind as a main objective to be pursued.

The format of the frame is shown in Fig. 3.4; the $Service$ uses $10$ bytes, while the confidence can be transmitted by using only $1$ byte. Considering that the length of the MAC frame of IEEE 802.15.4 can be maximum $127$ bytes, and subtracting $31$ bytes of header and $2$ bytes of footer, in one message we could advertise up to $7$ services.

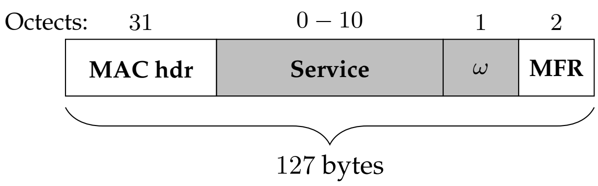



Fig. 3.4: Frame format with *Service* and *Service confidence*.

Upon reception of such a message from a neighbor $v$, a node $u$ can thus upgrade entry of $v$ in its NT with these values as shown in Table 3.3; for each neighbor, the information stored will be: the offered *Service*, the *ID*, the two *confidences* (physical and service), the *RSSI*, and the *Timestamp*. This Neighbor Table is used to evaluate the neighborhood and to rank the neighbors. Furthermore, the NT can be cleaned by removing deprecated entries for space saving purposes.

When the information about a service is relayed, the $\omega$ confidence is also function of the physical confidence. Table 3.4 shows how $\omega$ transmitted by the relay node is influenced by $\varphi$ and $\omega$ of the Neighbor that provides the service; the best value that we can obtain is *Good* and it is verified when the $\omega_{Neighbor}$ is *Excellent* and $\varphi_{Neighbor}$ is *Excellent* or, at least, *Good*; while, even when the $\omega_{Neighbor}$ is *Excellent*, $\omega$ will be *Bad* if the $\varphi_{Neighbor}$ is *Bad*. Algo. 2 shows the process of advertisement of a service by a relay node; this can be done just when the $\omega$ is *Good*.

Table 3.3: Neighbor Table.

| $ID$ | $Service$ | $\omega$ | $\varphi$ | $RSSI$ | $Timestamp$ |
|---|---|---|---|---|---|
| 1 | temp | excellent | good | 80 | 1431108000 |
| 30 | light | good | good | 50 | 1431108008 |
| 2 | temp | excellent | excellent | 90 | 1431108007 |
| ... | | | | | |

Table 3.4: Service confidence computation for a Relay node.

| $\varphi_{Neighbor}$ | $\omega_{Neighbor}$ | $\omega$ |
|---|---|---|
| Excellent | Excellent | Good |
| Good | Excellent | Good |
| Good | Bad | Bad |
| Bad | Bad | Bad |
| Bad | Excellent | Bad |

**Algorithm 2** Service confidence computation for a Node. - Run at node $u$ upon reception of a packet from $v$

**if** $v \in$ NT **then**
  update NT(*RSSI, Timestamp*) for NT.*ID*;
**else**
  store $v$ in NT with associated RSSI and Timestamp;
**end if**
$\forall w \in$ NT **do** update $\varphi(w)$ with Table 3.1
**if** (($\varphi(w)$) = (*Excellent*)) || (($\varphi(w)$) = (*Good*)) **then**
  compute $\omega(w)$;
  **if** ($\omega$ = (*Good*)) **then**
    broadcast (Service, $\omega$);
  **end if**
**end if**

### 3.1.6 Performance Evaluation

To evaluate the performance of CACHACA, we first use Contiki-OS[3] and its simulation tool Cooja; Table 3.5 summarizes the principal parameters. Among the others (e.g., TinyOS, Riot[4]) we choose Contiki because its good assessment by the community, its completeness and re-usability; with Contiki indeed, it is possible to run simulations and then re-use the code to flash real devices. We consider an area of 200x200 $m^2$, in which $M$ network elements are randomly positioned; $M$ is the sum of $R$ relays and $N$ full nodes equipped with 1 sensor. Values of $M, R$ and $N$ and what they stand for depend of the scenario under evaluation as detailed later.

Table 3.5: Simulator parameters.

| $Parameter$ | $Value$ |
|---|---|
| Nodes radio chip | CC 2420 |
| Nodes flash memory | 1 MB |
| Simulation seed | random |
| Simulation runs $\forall$ scenario | 10 |

We use the following metrics to assess the performances of CACHACA:

- *service*$_{avg}$ represents the average number of services discovered by each node;
- *neighbor*$_{avg}$ is the average number of neighbors discovered by each node;

[3] http://www.contiki-os.org
[4] http://tinyos.net, http://www.riot-os.org

- $packets_{avg}$ is the average number of packets transmitted by each node;
- $\omega_{avg}$ is the average value of the service confidence $\omega$ computed by each node;
- $\varphi_{avg}$ is the average value of the physical confidence $\varphi$ computed by each node.

We performed the simulations in five different scenarios (Table 3.6). In all scenarios, $N$ is set to 5; each node advertises its own service periodically. In the first Scenario, we have just the 5 nodes running, while in the second and third scenarios we introduce some relay nodes. In the latter 2 Scenarios, we consider that relay nodes can randomly move inside the area with an average speed of $1\ m/s$. This set of Scenarios can be used to describe a generic smart city use case (e.g., smart building). A number of different sensors is available in distinct rooms; those sensors can offer services like temperature, luminosity, and so on; other devices (attached for instance to the smart-phones of employed) act as relay for the sensors' services. We chose to use only 5 Full nodes and evaluate the number of relays necessary to discover all the potential services. Moreover, we vary the number of relays between 10 and 15 because we want to study the behavior when the network is not highly dense and therefore avoiding to compare CACHACA with the *Broadcast scenario* that suffers from crowded cases.

Table 3.6: Simulator scenarios.

| | $N$ | $Services$ | $R_{fix}$ | $R_{mobile}$ | $M$ |
|---|---|---|---|---|---|
| **Scenario1** | 5 | 5 | 0 | 0 | 5 |
| **Scenario2** | 5 | 5 | 5 | 0 | 10 |
| **Scenario3** | 5 | 5 | 10 | 0 | 15 |
| **Scenario4** | 5 | 5 | 0 | 5 | 10 |
| **Scenario5** | 5 | 5 | 0 | 10 | 15 |

### 3.1.7 Simulation results

Fig. 3.5 shows the average number of packets sent per node. We can observe that the $Packet_{avg}$ is higher in the first Scenario; while this number decreases with relay nodes. This is because relay nodes broadcast packets only if the service offered by the neighbor has $\omega = Excellent$ and the $\varphi$ of the neighbor is at least *Good*. Introducing mobility makes $Packets_{avg}$ increase because of the higher possibility to meet nodes and therefore for relay to broadcast services. For the sake of equity and fairness, we have also considered that relay nodes broadcast a service immediately when it is discovered, without taking account of the quality (dashed lines in the Figure). In this case, we can observe that the number of messages increases intensely and so also the quality of the channel and the energy consumption will be negatively affected.

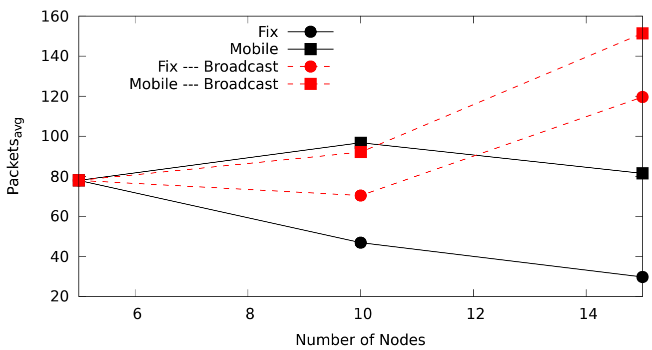



Fig. 3.5: Number of Elements vs. Packets$_{avg}$ sent.

Fig. 3.6 indicates the average number of Neighbors and Services discovered by each element network in function of the Number of Nodes. In the first Scenario, and in general when there is no mobility, the performance are bad, this is because nodes and relays are randomly deployed on the field and therefore it is possible that they are not in communication range. With mobility (Scenario5), the performance improves; each node is capable to discover about $40\%$ of the available services and more than $50\%$ of neighbors.

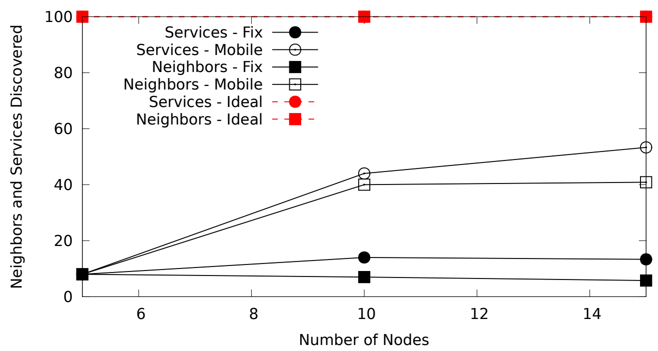



Fig. 3.6: Number of Nodes vs. Services and Neighbors Discovered.

In the last investigation (Figure 3.7), we consider the behavior of $\varphi$ and $\omega$ in function of the Number of Nodes. We can observe that the average $\omega$ computed by each node for the discovered services is *Good*; this means that each node can discover more than $40\%$ of the services provided with *Good* confidence. Regarding the Physical Confidence, we can note that it increases when mobility comes in play, but at the same time, $\varphi$ decreases with a higher number of nodes, because of possible interference. Anyway, it is important to highlight that even when $\varphi$ is *Bad*, a communication can happen.

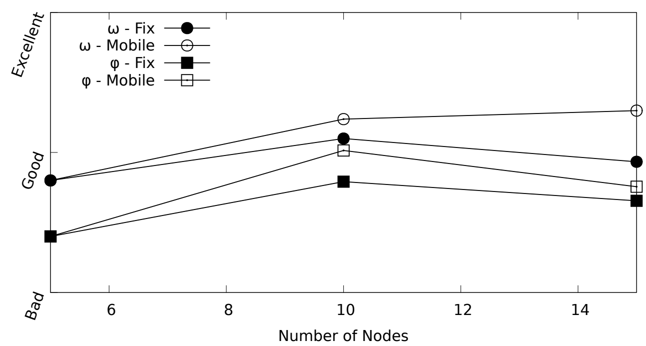



Fig. 3.7: Number of Nodes vs. Physical and Service Confidence.

### 3.1.8 Experimentation results

In order to face CACHACA to a realistic environment, we ran experimentation on FIT (Future Internet of Things) IoT-LAB[5]; a very large scale infrastructure facility suitable for testing small wireless sensor devices and heterogeneous communicating objects over large scale. We used the Rennes site, and we performed experimentation (parameters available in Table 3.7) using Scenarios $1, 2$ and $3$ (no mobility).

Figure 3.8 shows the Services and the Neighbors discovered. We can observe that in this case, CACHACA has performance similar to the ideal scenario (dashed lines); when the Number of Nodes is $10$, each network element discovers almost all the Services and about $70\%$ of the neighbors; the same trend is maintained when

[5] `https://www.iot-lab.info`

Table 3.7: Experimentation parameters.

| *Parameter* | *Value* |
|---|---|
| Nodes type | WSN 430 |
| Nodes radio chip | TI CC 2420 @ 2.4 GHz |
| Nodes flash memory | 1 MB |

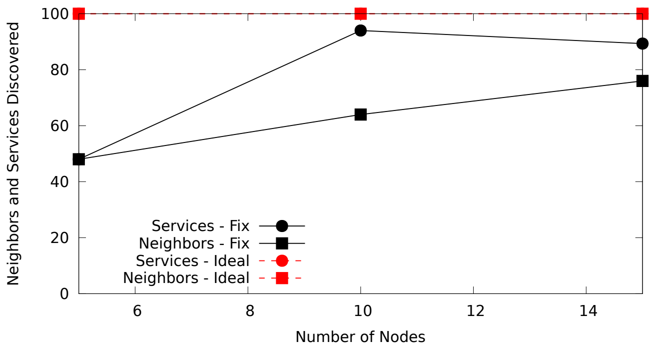



Fig. 3.8: Number of Nodes vs. Service and Neighbor Discovered (FIT IoT-lab).

the Number of Nodes is 15. Those results are in line with the ones obtained running simulation with Cooja; therefore we can conclude that when we increase the Number of Nodes the efficiency of our proposal is higher.

Regarding the Physical and Service confidences (Fig. 3.9), we can observe that both parameters have better performance when the network is sparse; this is because, the services are directly provided by the direct neighbor, without the intervention of relay; $\varphi$ decreases with the Number of Nodes, because of more interference. The trend obtained in this analysis is once again complementary to the one obtained with the simulator.

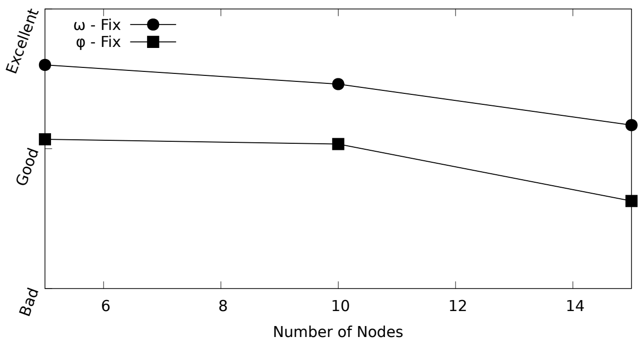



Fig. 3.9: Number of Nodes vs. Physical and Service Confidence (FIT IoT-lab).

## 3.2 *Out-network* Discovery

*Out-network* Discovery consists in the discovery of services and resources associated with different data-sources and their representation. Usually this type of resources is available as end-points of IoT platforms. In our work we have investigated the *Out-network* Discovery in the context of Smart City as a complex system, Vital [41] as architecture to manage the complex system in Figure 3.10. The module we have contributed to develop is the Discoverer module within Vital-OS (as operating system for Smart City). This component is horizontally integrated in the platform as shown in 3.10 and is in charge to discover Internet-Connected Objects

(ICOs), Systems/IoT Platforms and Services. In this part we will only focus on ICO Discovery.

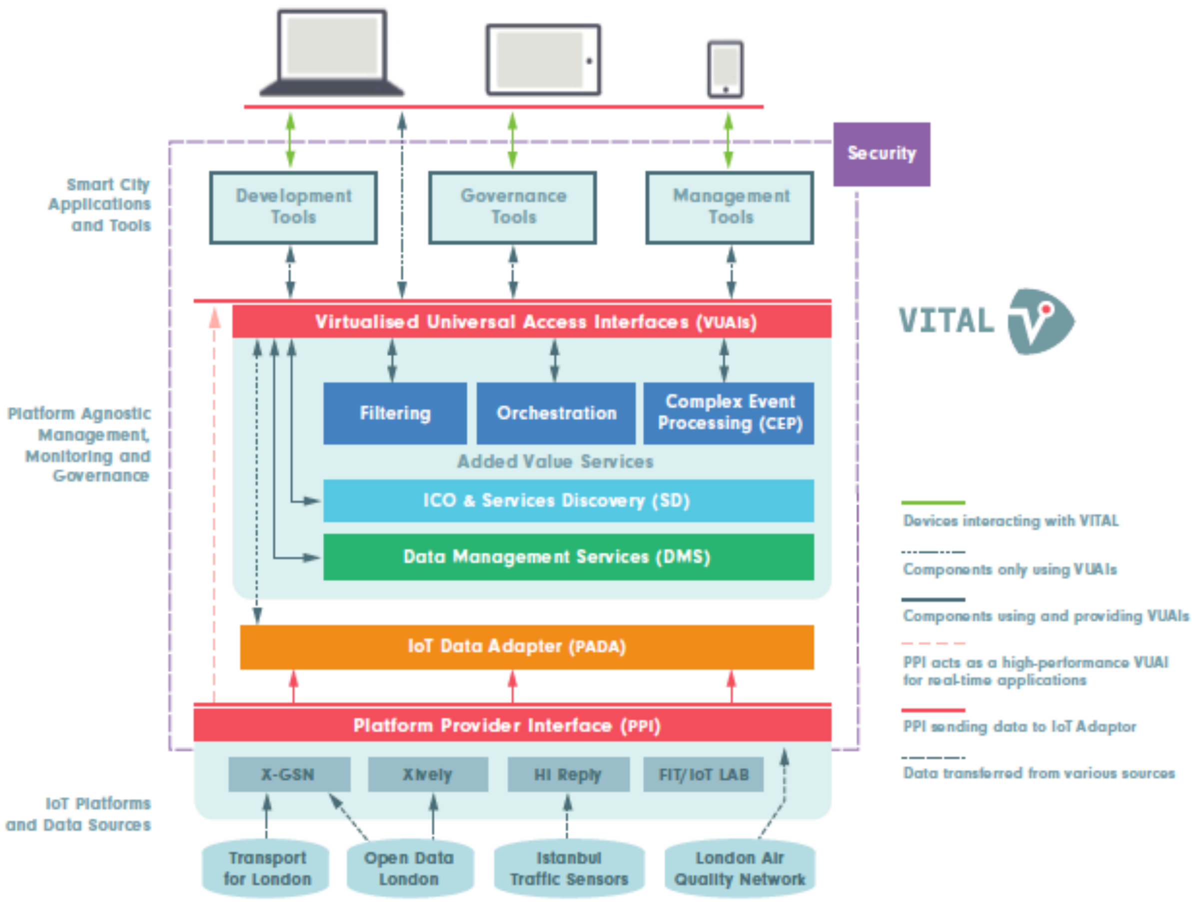



Fig. 3.10: VITAL architecture

A very key factor, in this context, is represented by the virtualization of interfaces in combination with cross-context tools that enable the access and management of heterogeneous objects supported by different platforms and managed by different administrative stakeholders.

As shown in Figure 3.10, the VITAL architecture is organized in three main layers: *IoT Platforms and Data Sources*, *Platform Agnostic Management*, *Monitoring and Governance*, and *Smart City Applications and Tools*. In the following, we present the features of fundamental modules:

- **IoT Platforms and Data Sources**. It is the first layer of the architecture, where different data-sources stand. In order to be virtualized and integrated into VITAL, those systems have to expose a well defined PPI (Platform Provider Interface).
- **Platforms Access and Data Acquisition (PADA)**. The role of this layer is to access the low-level capabilities of the IoT Systems (through PPI) and to transform the acquired data and meta-data into a common data model (i.e., VITAL ontology).
- **Data Management Services (DMS)**. This layer provides cloud-based functionality for managing data and meta-data. The offered services include data and meta-data persistence, creation of new data, and more. The DMS communicates, via REST interfaces, directly with PADA, Added Value Services and the VUAIs (Virtualized Unified Access Interfaces).
- **ICOs and Services Discovery (SD)**. This layer provides the means for discovering ICOs in the scope of horizontal integrated IoT applications spanning multi-

ple platforms and business contexts. It directly interacts with the DMS in order to discover the “appropriate" resources for a particular business context.

- **Added Value Functionalities**. It involves a set of complete services and tools:
  - *Filtering*. It provides the means for reducing the information associated with individual data streams persisted in the platform agnostic data management layer. Therefore, it reduces unwanted information, thereby optimizing processing performance and economizing on network bandwidth.
  - *Complex Event Processing (CEP)*. It enables the processing of data-streams for multiple sources in order to identify patterns and/or infer events.
  - *Orchestration*. Its role is to combine and manage multiple services from the above-listed modules, in order to deliver new added-value services.
- **Smart City Applications and Tools**. At this layer, we support the development, integration, deployment, and operation of Smart City applications. This goes for instance with a complete environment to assist in the easy deployment and development of Smart City application [30].

### 3.2.1 Discovery of “relevant" resources

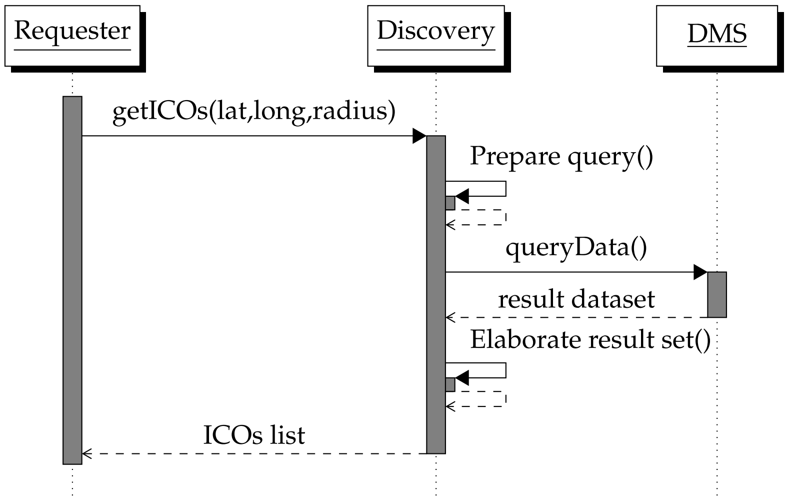



Fig. 3.11: SD - Example of interactions.

The Discoverer module - horizontally integrated in the platform itself as shown in Figure 3.10 - is responsible for discovering ICOs, Systems, and Services inside VITAL. Although the discovery of Systems and Services represents an important business for the whole architecture, in this paper, we only focus on the ICOs.

The SD offers its functionality to other modules, via a RESTful web service [37]; queries are embedded in the body of an HTTP request and represented using JavaScript Object Notation (JSON) Standard. In the following, we describe the main interfaces exposed by the SD and their features.

The discovery process is performed on data stored in the DMS; this operation is achieved without regard to the underlying platform handling the ICOs. This represents, therefore, a key feature as the platform agnostic property is one of the goals proposed by the architecture. Internet-Connected Objects being part of VITAL, are described by a set of meta-data that characterizes the nature of an element. Thanks to this information, ICOs can be classified according to their properties. Such a classification is essential for the later discovery of all the elements stored in the system and that suit the criteria defined by users. The main properties that can drive a discovery process are:

- **Position**. It represents the last known position of an ICO - expressed in latitude and longitude coordinates -. Such values can be immutable in the case of a *stationary node* or it can change over time for a *mobile node*.
- **Mobility**. It describes the mobility type of an Internet-Connected Object. Every node can be configured as being *Stationary*, *Mobile*, or *Predicted* - in this latter case the mobility pattern is known -.

Table 3.8: SD - ICOs request parameters.

| NAME | TYPE | DESCRIPTION |
|---|---|---|
| *type* | String | Category assigned to ICO |
| *position* | Object | Keys to perform discovery over spatial region |
| *latitude* | Number | Latitude's value expressed in WGS84 standard |
| *longitude* | Number | Longitude's value expressed in WGS84 standard |
| *radius* | Number | Distance in Kilometers from the center or the Area of Interest |
| *observes* | String | Measuring properties provided by an ICO |
| *movementPattern* | String | Select ICO registered with a specific movement pattern |
| *connectionStability* | String | Select a specific level of connection stability |
| *hasLocalizer* | Boolean | Select ICO with localizer services (i.e., GPS) |
| *timeWindow* | Number | Time in minutes; represents the time window for position estimation |

- **Connectivity**. It provides information about the capability of a node to be connected over the Internet and a description of the connection stability.
- **Observation capability**. It describes all the properties that a node can observe (e.g. Speed, Footfall).

All the above parameters are modelled according to the VITAL ontology; a detailed list of those properties is available in Table 3.8.

Listing 3.1: SD - Example of request.

```
{
  "position": {
    "radius": 10,
    "longitude": 3.147887,
    "latitude": 50.605792
  },
  "observes": "vital:Speed",
  "type": "vital:VitalSensor"
}
```

Figure 3.11 shows how the SD interacts with other modules in order to execute an assigned task. Listing 3.1 describes an example of a request in JSON; the target, in this case, is the discovery of ICOs that can observe *Speed*, in the Area of Interest defined by the *position* properties.

Upon reception of a request, the DISCOVERY re-formulates the query. In order to perform a geographical search, it is necessary to compute latitude and longitude boundaries. Given a centre position (*lat - long*) and a distance (*radius*) in kilometers, the conversion process aims to compute minimum and maximum values for both latitude and longitude. This computation is performed using the law of haversine [38] defined in spherical trigonometry, which relates sides and angles of spherical triangles. Once the query is ready and modelled according to the VITAL ontology, it is sent to the DMS, which will respond with a data-set of available ICOs matching the request parameters. At this point, the SD applies its rules - giving priority to ICOs that are closer to the Point of Interest, have good connection, etc. - in order to provide back to the REQUESTER an organized list of ICOs.

In order to have a time estimation about the above operations, we deployed the Discoverer on WildFly [6] - an application server written in Java, which implements JAVA EE specifications -. WildFly is executed on a machine with 8 GB of RAM and a processor Intel Core i5 (2.6 GHz). Figure 3.12 resumes the main results; we can observe that the SD takes, in average, 2 seconds in order to discover a generic ICO, System, or Service registered in the VITAL's DMS. To avoid time out issues, we implemented a timer of 5 seconds, after which the SD returns with an error to the REQUESTER. Regarding the CPU, each query is performed in 32 milliseconds.

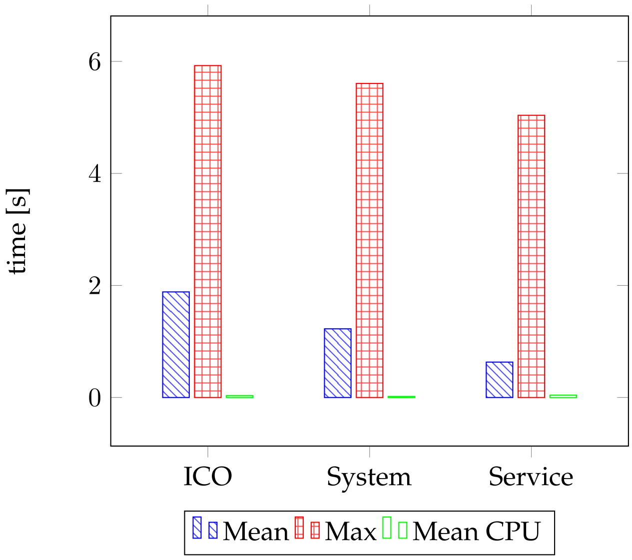



Fig. 3.12: SD - Performance.

## 3.3 Conclusions

In this chapter I have presented *in-network* and *out-network* discovery approaches both in the context of Vital project.

By working on these approaches we have tried to give an answer to the fundamental question around IoT paradigm: Why Discovery?

An inherent characteristic of the IoT is "heterogeneity" introduced by a plethora of things with different data communication capabilities (protocols and hardware, data rates, reliability, etc.); computational, storage and energy capabilities; diversity in the types and formats of data (audio, video, text, numeric, and streams); and IoT standards (device standards, standards to represent data, IEEE projects on IoT standards, ITU and ISO IoT standards, etc.). The diversity in things and the data produced by them pose significant challenges in fulfilling the ambitious dream of a truly interconnected smart world of things.

Further, it is expected the IoT will be a major source of big data driven by its velocity, variety, value and volume. The diverse IoT data will be in high demand by business and end-user applications and hence will have to be stored in widely distributed, heterogeneous information systems to ensure global availability. However, retrieving the data from these heterogeneous data stores is a non-trivial task without a common machine-readable data representation framework. Moreover, when dealing with large volumes of distributed and heterogeneous data, issues related to interoperability will need to be addressed. It is widely recognized that efficient mechanisms for discovering available resources and capabilities in the IoT is essential.

[6] `http://wildfly.org`

Even if our approaches have been developed in the specific context of Smart City as part of the Vital project, they have been designed in such a way to respond to the key challenge of the IoT paradigm: how to find a "thing" in the Internet of Things haystack? Indeed, the sine qua non condition we have considered has been that the approaches have to be "horizontal" approaches. More specifically, a fuzzy-logic based solution has been performed to address the first type of discovery, by implementing an *network element as a service* paradigm. One of the main objectives we have considered when we have implemeted this discovery algorithm, was the scalability, meant as the possibility to add not only new nodes to the network but also to conceive new services. The second part of the chapter is about the *out-network* discovery. This type of functionality has become fundamental with the advent of IoT paradigm and the several vertical Silos, in order to try to effectively "horizontilize" the IoT based solutions. The specific module proposed in this work has been developed in the context of the Vital project and then for a Smart City system. It is worth recalling that from the beginning of this manuscript, we have referred to Smart City as a Complex Self-Organized Network System (CSNOS) and then the discovery solutions conceived in this context, can be generically extended to all the types of systems that can be categorized as CSONSs.

Indeed, both *in-network* and *out-network* discovery have been conceived with an agnostic approach in respect of the specific CSONS. This research activity has played an important role for the type of adopted approach, since from one side it is important to be able to "filter" data form the too many available sources of data and the other side it is possbile to "infer" ne type of information.

We have exploited this acquired expertise for the scenario of Smart Car as I will explain in Chapter 5.

**Publications**
[J8][J16][J17][C4][C8][C12][C13][C16][C18][C21]

# 4

# Interoperability approaches for heterogeneous devices

In the last few years, several different types of communication devices featured with different communication interfaces, resources, storage capabilities, motion ability have appeared in the IoT landscape, making it fragmented and paving the way for developing vertical IoT silos. In this chapter, our main objective is to show how the heterogeneity, if opportunistically addressed by explicitly integrating it in the system design, can play a fundamental role in the context of challenging communication scenarios.

Different types of heterogeneity can be envisaged. Devices can be static or supporting mobility, they can be equipped with capability to implement different modulation schemes or not, they can be energy-constrained or not, they can be resources limited or not, etc.

This chapter is constituted by two main parts.

In the first part I will describe different theoretic tools that can be efficiently exploited to conceive connectivity and coverage techniques and assign different roles to different nodes.

In the second part of this chapter, I will show a practical aplication of some of the tools presented. I will focus on new kinds of advanced communication devices, able to adapt their operation roles in a self-organized fashion to rapidly face the changes within the working environment as considered in [109], [110]. In this context, a primary role has been also played by powerful hardware platforms able to be dynamically reconfigured via software [111], [112].

Specifically, different reconfiguration and dynamic self-adaptation levels have been integrated directly in the network system design in order to achieve high communication performance in very different communication scenarios by directly integrating Software Defined Radio (SDR) paradigm and *controlled mobility* as control primitives of the network.

SDR paradigm offers unique features that allowed the design of a self-adapting deployment strategy for a communication network in which several wireless devices, scattered all around in a specific area, can carry out a common task according to specific network requirements in terms of coverage or connectivity.

The specific context considers transmitter-receiver pairs and relay nodes (that we have considered as wireless sensors or connected robots as in the IoRT paradigm) equipped or not with motion capabilities. Specific Quality of Service (QoS) levels can be defined based on different scenarios and contexts. In order to guarantee a pre-defined QoS level, a totally distributed *Neural/Genetic* algorithm able to compute the best final positions and the most suitable modulation schemes for each transmitter-receiver pair, is proposed.

In particular, by considering a generic SDR architecture [113], the major advantages consisting into the ability of automatically selecting the more suitable modulation scheme to be used for an unknown received signal, can be effectively achieved. Thus, as a channel capacity varies, modulation scheme switching enables the baud rate to be increased or decreased in order to maximize the channel capacity usage. In addition, as demonstrated in our preliminary studies [115], SDR capabilities supported by a wireless node, coupled with the controlled mobility functionality, can improve the overall system performances in terms of connectivity. Therefore, such mobile SDR nodes turn out to be very useful for communication scenarios in which, the requirements on constrained QoS connectivity, are more stringent respect to the ones on the maximum coverage.

Several real-world applications where a good level of communication has to be guaranteed between a transmitter and a receiver can be considered. In [114] we focused on emergence situations, with rescue teams that need to effectively and efficiently communicate.

We can summarize our contributions as follows:

- different theoretical tools are presented that can be exploited for design interoperability approaches and emphasize the heterogeneity of the nodes;
- we consider reconfigurable devices, able to re-define their role in a global context based on neighborhood and environmental conditions;
- the role played by each node is redesigned both in terms of modulation scheme (where supported) and definition of a new position (where motion capability is supported) in order to ensure global connectivity and guarantee a certain level of communication QoS;
- in order to validate the proposed Neural/Genetic approach algorithm, we define a theoretical optimal solution as benchmark;
- we validated, throughout a self developed simulator based on a widely used open source framework for evolutionary design, the proposed strategy in different communication scenarios by varying both the amount of mobile and SDR nodes to measure the impact of a larger number of Mobile/SDR nodes on the overall system performances;

## 4.1 Background of Theoretical Tools

In this section, I will present some of the main theoretical tools I have exploited to design interconnectivity and interoperable solutions for self-organized wireless networks.

### 4.1.1 Bayesian Network

Bayesian Network (BN) is a graphical model which contains only directed edges and without directed cycles. Its directed property makes it suitable when modeling the dependency relationships between random variables. Hence, the main goal of BN is to graphically represent a set of $N$ random variables in $X = \{x_1, x_2, ..., x_N\}$, and the independencies structure between the variables in $X$. From the BN's independencies structure, the form of the joint probability distribution over the variables in $X$ will be extracted. To sum up, a BN for a set of N random variables $X = \{x_1, x_2, ..., x_N\}$ consists of two things :

- a set of N nodes
- a set of directed edges between the nodes that encode the conditional independence statements associated with the variables in $X$

The notation $x_i$ is used to represent both the variable and its corresponding node. Throughout this thesis, the words *'variable'* and *'node'* will be used interchangeably. Figure 4.1 shows an example of a Bayesian network with six random variables $\{x_1, x_2, x_3, x_4, x_5, x_6\}$.

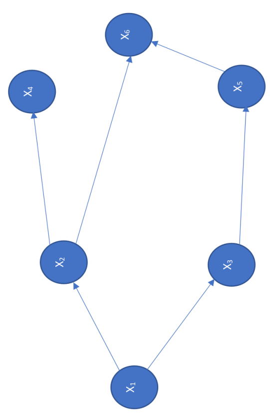


Fig. 4.1: An example of a Bayesian network

By using this example, the joint probability $p(X) \equiv p(x_1, x_2, x_3, x_4, x_5, x_6)$ is just the product of all the probabilities of the parent nodes and all the local conditional probabilities :

$$p(X) = p(x_1)p(x_2 \mid x_1)p(x_3 \mid x_1)p(x_4 \mid x_2)p(x_5 \mid x_3)p(x_6 \mid x_2, x_5) \quad (4.1)$$

In more general, the factorized equation for a Bayesian network with $N$ random variables $x_i$ is

$$p(x_1, x_2, ..., x_N) = \prod_{i=1}^{N} p(x_i \mid \Gamma_i) \quad (4.2)$$

where $\Gamma_i$ is the set of parent nodes of the node $x_i$.

### 4.1.2 Artificial Neural Network (ANN)

An artificial neural network (ANN) was inspired by the human brain and was designed as a computational model to solve specific problems. Its architecture is defined by (*i*) basic processing elements called artificial neurons and (*ii*) the way in which they are interconnected. The output value of a neuron is given by:

$$output = f(\sum_i w_i x_i + b) = f(W^T X + b) \quad (4.3)$$

where

- $x_i$: the inputs
- $w_i$: connections' weights between $x_i$ and the neuron
- $W$: weights' vector
- $X$: inputs' vector
- $b$: the bias
- $f$: the activation function

The basic architecture of ANN contains three neuron layers: input layer, hidden layer and output layer. In this case, the outputs of one layer become the inputs of next layer [106]. A typical artificial neuron and a basic ANN are illustrated in Fig. 4.2.

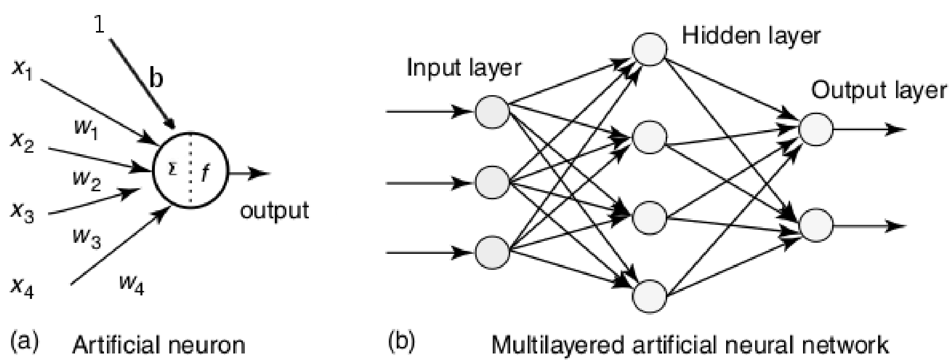



Fig. 4.2: Architecture of an Artificial Neural Network

A key element of an artificial neural network is its ability to learn. This means that ANN has to learn from a data set in order to match the inputs to the desired output. During the learning process, weights and biases are adjusted till the desired output is reached. There are several learning algorithms but backpropagation algorithm [107] is one of the most used.

### 4.1.3 Genetic Algorithm

The Genetic Algorithm (GA) is a bio-inspired metaheuristic belonging to the class of evolutionary algorithms. GA are characterized by a *population* of candidate solutions to a problem in order to find the optimal solution. *Chromosomes* are considered as a kind of properties characterizing each solution and as it happens in nature, they can be subject to the *mutation* operator.

Typically a GA requires:

- a fitness function that has to be evaluated at each iteration in order to find the optimal solution;
- a genetic representation of the solution domain.

The main operators that can be applied are as in nature, Selection, Crossover and Mutation as represented in Fig. 4.3.

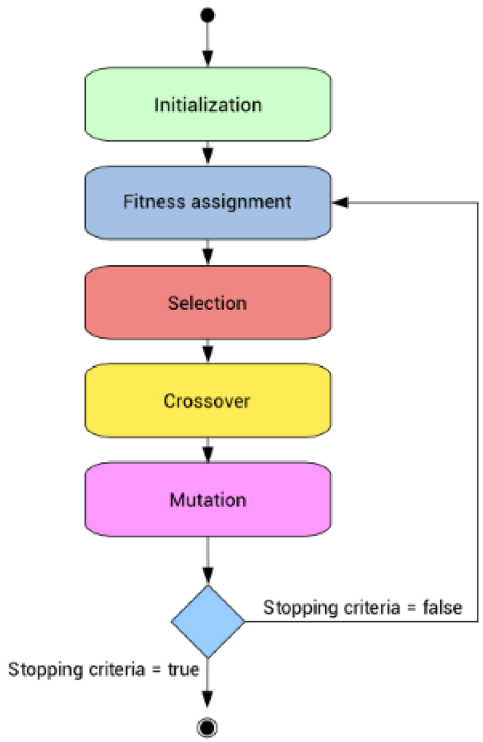



Fig. 4.3: Genetic Algorithm Working

### 4.1.4 Software Defined Radio paradigm

The term software-defined radio was coined by Joe Mitola in 1991 to refer to the class of reconfigurable radios. A radio that defines in software its modulation, error correction, and encryption processes, exhibits some control over the RF hardware, and can be reprogrammed is clearly a software-defined radio. Thus, it is a radio that is substantially defined in software and whose physical layer behavior can be significantly altered through changes to its software. The functionality of conventional radio architectures is usually determined primarily by hardware with minimal configurability through software. The hardware consists of the amplifiers, filters, mixers (probably several stages), and oscillators. The software is confined to controlling the interface with the network, stripping the headers and error correction codes from the data packets, and determining where the data packets need to be routed based on the header information. Because the hardware dominates the design, upgrading a conventional radio design essentially means completely abandoning the old design and starting over again. In upgrading a software-defined radio design, the vast majority of the new content is software and the rest is improvements in hardware component design. In short, software-defined radios represent a paradigm shift from fixed, hardware-intensive radios to multiband, multimode, software-intensive radios.

In Fig. 4.4, there is the representation of a typical model of a Software Defined Radio.

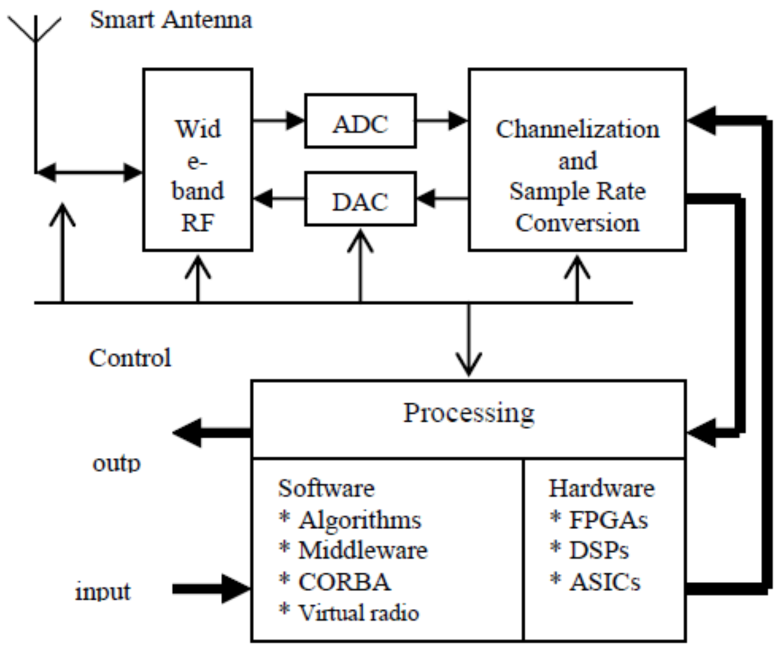



Fig. 4.4: Model of a Software Defined Radio [108]

## 4.2 A combined neural/genetic and Software Defined Radio (SDR) approach

In this section I will present how we have combined some of the different tools presented in the previous section to manage a Self-organized Complex Network where heterogeneous devices have been considered. Indeed, our system is composed by *simple* devices as wireless sensors and more powerful nodes as robots that give rise to the Internet of Robotic Things (IoRT) paradigm. Specifically, I will give some details on the combined neural and genetic approach and then I will present how we have exploited the SDR paradigm to equip some nodes with more capabilities to compute adaptive modulation schemes. The Bayesian approach will be exploited in a contribution explained in the next chapter dedicated to the implementation of real experiments.

### 4.2.1 Neural/genetic Algorithm

The main objective of the Neural/Genetic approach considered here is the computation of a suitable position of wireless nodes in order to meet specific network requirements. The approach is totally distributed and is based on local information, since each node moves towards a new position based on its own neural network and exploits its genetic algorithm to perform a new better solution. The two algorithms, are then completely distributed: a node computes the neural algorithm by knowing the positions of its (communication) neighbors and the genetic algorithm manages its own genes without global information.

Specifically, the two objectives considered in this work, namely, the coverage area and the number of sensor devices having a path toward a sink with a certain quality of service, are in contrast one to each other. Therefore we designed a wise strategy, based on the approach presented in [121], able to take into account both the requirements in a dynamic and re-configurable fashion.

#### 4.2.1.1 The Neural Network

The neural network determines the movements of each wireless node; it is fully connected, recurrent and time-discrete. The neural network consists in input, output and hidden neurons. Inputs are subdivided as follows:

- $4$ inputs to detect overlapping of sensing zone with neighborhood' sensing zone ($1$ for each direction);
- $4$ inputs to detect missing of sink connection ($1$ for each direction);
- $1$ to detect nodes in the same position.

The output is the new position. Each neuron "activates" a real-valued function and a time-varying real-valued connection with every other neuron of the network to map input (n-dim) in output (m-dim). We indicate with $out_j$ the output of neuron $j$ towards all other neurons of the network. The output of neuron $j$ is computed as shown in Equation (4.4).

$$out_j(k) = F\left(\sum_{i \in N} w_{ij} \cdot out_i(k-1) + b_j\right) \tag{4.4}$$

where $N$ is the set of neurons, $w_{ij}$ is the weight of the connection between neuron $i$ and neuron $j$ and $b_j$ is the bias of neuron $j$. Weights can produce both excitatory or inhibitory effect. The activation function $F$ is the following linear threshold function:

$$F(x) = \begin{cases} -1.0 & \text{if} \quad x \leq -1.0 \\ x & \text{if} \; -1.0 < x < 1.0 \\ 1.0 & \text{if} \quad x \geq 1.0 \end{cases} \tag{4.5}$$

For each node the output of the neural network is given from the two output neurons and it consists of two real numbers that vary in the range $[1, -1]$, as it is clear from (4.5) and Fig. 4.5. Based on these two values, the node chooses the action to do. Assuming a square field of $n \times n$ cells, the node can move in one of the four allowed directions or remain in the current cell.

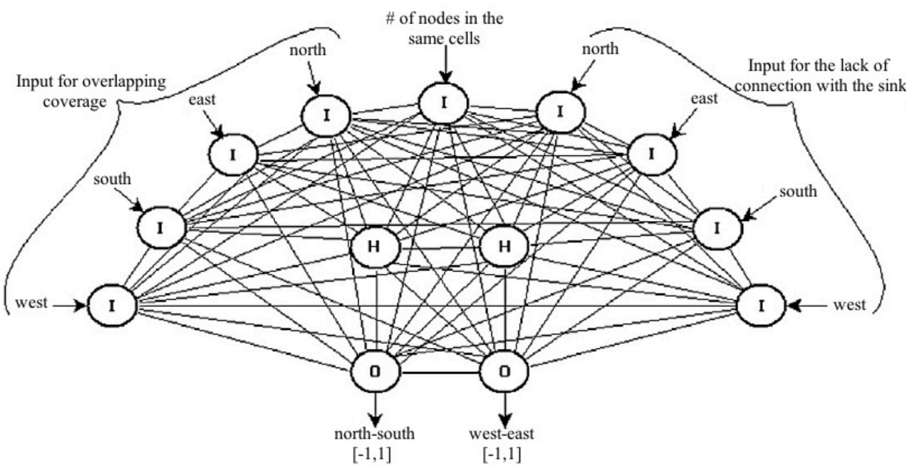



Fig. 4.5: Neural network architecture of one node

#### 4.2.1.2 The Genetic Algorithm

A conventional and real-value Genetic Algorithm (GA) is used in the training phase of the Neural Algorithm. The genes are associated with the connections weights between each couple of neurons and the bias of each neuron. Through the typical operators of genetic approaches (*i.e.* crossover, mutation and selection), different weights to the neurons in the next generations will be assigned. Of course, the chromosome selected for the next generations is the one which has the best value of the fitness function. In our work, we consider a bi-objective function in order to: 1) maximize the coverage; 2) maximize the number of nodes connected to the sink either in a direct fashion or through a multi-hop path. The fitness function can be written as follows:

$$fitness = \alpha * Coverage + \beta * QoS_{connectivity} \tag{4.6}$$

where

$$Coverage = \frac{covered\_area}{whole\_area} \tag{4.7}$$

and

$$QoS_{connectivity} = \frac{\#nodes\_connected\_to\_the\_sink}{\#total\_nodes} \tag{4.8}$$

where $\alpha$ and $\beta$ are weights that take the priority of the objective to be reached into account.

The term $\#nodes\_connected\_to\_the\_sink$ represents the number of nodes "connected" to the sink, namely nodes that are able to reach the sink directly or for which exists a multi-hop path [122] throughout links that are able to deliver data by guaranteeing a certain value of BER given as an input constraint. In Algorithm 3 we show the pseudo-code of the Neural/Genetic Algorithm.

**Algorithm 3** Neural/Genetic Algorithm

```
Random Deployment of Wireless Devices;
for all generation i do
    for all chromosome j do
        for all node n do
            while time < time_MAX do
Compute the new position of n through the neural algorithm;
Compute the modulations that n must use to reach either the other nodes and the sink by guaranteeing a specific QoS; (see Section 4.2.3);
Among all the modulations satisfying the QoS choose those that require less energy (this only a possible choice, we could also consider the modulations that maximize the throughput, etc.) (see Section 4.2.4);
            end while
        end for
Compute chromosome fitness j;
    end for
Consider the chromosome with the highest fitness value, apply genetic operators and then consider it as input for the next generation i+1;
end for
```

### 4.2.2 Supported Connectivities and Communication Complexity

As already explained, each node has a set of possible modulations that can be "used" for data transmission by guaranteeing different connectivity levels. In this work, we figure out two different types of connectivities:

- $Basic_{Connectivity}$: according to a specific propagation model, it is possible to compute the maximum distance at which a node $n_1$ is able to transmit, that is the transmitting radius. If a node $n_2$ is inside the area delimited by the circle with radius equal to the transmitting radius of the node $n_1$, then $n_1$ and $n_2$ are connected. In this work we consider the propagation model as defined in [123]:

$$PL_{generic} = \left(\frac{4\pi d_0}{\lambda}\right)^2 \cdot \left(\frac{d}{d_0}\right)^\gamma + \chi \tag{4.9}$$

  where $d$ is the distance between the $Tx$ and the $Rx$, $\gamma$ is the path loss exponent, $\lambda$ is the wavelength, $\chi$ is the shadowing effect value (neglectable) and $d_0$ is the critical distance.
- $QoS_{Connectivity}$: each node $n$ has a neighborhood. For every neighbor, the node $n$ computes the BER value on the specific link by considering the different available modulations. The node $n$ excludes all the modulations that do not respect the BER required as constraint in input. In practice, in this way the node $n$ has a set of neighbors and every link from $n$ to the neighbor meets the QoS constraint in terms of BER computed according to the formulas shown in the next subsection.

For each iteration of the algorithm and for every node, both the $Basic_{Connectivity}$ and the $QoS_{Connectivity}$ are computed.

Since the proposed algorithm is based on local communication, a node only needs to know the position of its neighboring nodes to make a movement. According to [121], after each node movement, an update on the nodes position is broadcast through a constant size message containing the node identifier (*Id*) and the node position (*x*,*y*), therefore the message size is in $O(1)$. As a consequence, considering a constant value for the number of time steps given as an input parameter, nodes will update their positions and broadcast their new information at each time step; this leads to a linear message sending complexity of $O(n)$ where $n$ is the number of nodes within the network.

### 4.2.3 BER Computation

In order to compute the BER value related to each specific modulation scheme, we used the following relations coming from an asymptotic approximation [144]:

$$BER_{M-FSK} \approx 2^{k-2} \cdot \mathit{erfc}\left(\sqrt{\frac{k}{2}\frac{E_b}{N_0}}\right) \tag{4.10}$$

$$BER_{M-PSK} \approx \frac{1}{k} \cdot \mathit{erfc}\left(\sqrt{k\frac{E_b}{N_0}\sin^2\left(\frac{\pi}{M}\right)}\right) \tag{4.11}$$

$$BER_{M-QAM} \approx 2\frac{\sqrt{M}-1}{\sqrt{M}k} \cdot \mathit{erfc}\left(\sqrt{\frac{3k}{2(M-1)}\frac{E_b}{N_0}}\right) \tag{4.12}$$

$$BER_{8-QAM} \approx \frac{5}{12} \cdot \mathit{erfc}\left(\sqrt{\frac{1}{2}\frac{E_b}{N_0}}\right) \tag{4.13}$$

In particular, the BER computation for the QAM modulation needs the use of two different equation according to the particular shape: equation (4.12) for squared modulations and formula (4.13) for non squared such as 8-QAM.

### 4.2.4 Transmitted Energy Computation

In order to save energy for the transmission always by still guaranteeing the required QoS level, it is necessary to choose the least power hungry modulation scheme within the set of the most common modulation schemes available in real devices. To this aim, the energy spent per information bit $[J]$ can be computed as follows [126]:

- For both MQAM and MPSK, by considering a signal bandwidth equal to $B[Hz]$ and, by assuming a sample time $T_s \approx 1/B$ [127], we can write:

$$E_{infBit} \approx \frac{(1+\delta)\cdot SNR \cdot N_0 \cdot N_f \cdot G_d}{R} + \frac{P_c}{R\cdot B} + \frac{P_{tr}\cdot T_{tr}}{L} \tag{4.14}$$

  where $\delta = \xi/\eta - 1$, $\xi$ is the peak-to-average power ratio (PAPR) of the signal depending on the specific modulation, constellation size and shape[1] whereas $\eta$ is the efficiency of PA drain chosen equal to $0.35$ as typical value of class A power amplifiers [127]. $P_{tr}$ and $T_{tr}$ are the consumed power and the time spent in *transient* mode respectively whilst $L$ is the total number of information bits. The $SNR = \frac{P_{rx}\cdot T_s}{N_0 \cdot N_f}$, where $P_{rx}$ is the received signal power, $N_0/2$ is the power spectral density of the noise and $N_f$ is the receiver noise figure. Moreover, by assuming a general path-loss model, the value of $G_d$ can be computed according to the Equation (4.9) and it is equal to $G_d = (\frac{4\pi d_0}{\lambda})^2 \cdot (\frac{d}{d_0})^\gamma$. Finally, the term $P_c$ represents the circuit power (*i.e.* $211\ [mW]$ for both MQAM and MPSK) and the term $R$ is the transmitting rate computed for each constellation by using the cutoff curves.

[1] $\xi = 3 \cdot \frac{(\sqrt{M}-1)}{\sqrt{M}+1}$ for square constellations whereas $M$ is the constellation size, while it assumes a value among those shown in Tab. 1 of the work [126] for cross-shaped constellations.

- For the MFSK modulation, by considering a noncoherent detection, the well known relation $M = 2T_S B$ [124] allows to derive $T_S = M/2B$, therefore the energy for the transmission will be equal to:

$$E_{infBit} = \frac{(1+\delta)\cdot SNR \cdot N_0 \cdot N_f \cdot G_d}{R} + \frac{P_c \cdot M}{2 \cdot R \cdot B} + \frac{P_{tr} \cdot T_{tr}}{L} \tag{4.15}$$

  where $\eta = 0.75$ is the typical value for class B or even greater (C, D, or E) power amplifiers [127], $\xi = 1$ according to [126] and $P_c = 165.3\ [mW]$ for general MFSK modulation schemes.

### 4.2.5 Cut-off rate curves

In this work, we decided to use the relation between cut-off rate and pre-detection SNR to model the required power of the received signal; this choice is mainly motivated by the fact that the cut-off rate is considered as a meaningful measure of the effective maximum rate for convolutional coding with sequential decoding [124]. These relations can be calculated for MQAM and MPSK by the following formulas [125]:

$$R_0 = 2\log_2(M) - \log_2\left(\sum_{m=1}^{M}\sum_{i=1}^{M} C(x_m, x_i)\right)$$

where $C(x_m, x_i)$ is the Chernoff bound on the pairwise error probability that for an AWGN channel having a Rician factor of $K = \infty$ we have:

$$C(x_m, x_i) = \exp\left(-\frac{1}{4}|d_{mi}|^2\right)$$

with $|d_{mi}|^2 = |x_m - x_i|^2/N_0$ and $x_j$ is the $j^{th}$ signal.

For noncoherent MFSK we have [124]:

$$R_0 = -\frac{1}{T_s}\cdot\log_2\left\{\frac{1}{M} + \left(1 - \frac{1}{M}\right)\cdot\exp\left(-\frac{\alpha^2}{2}\right)\left[\int_0^{\infty} x\cdot\exp\left(-\frac{x^2}{2}\right)\cdot\sqrt{I_0(\alpha x)}\,dx\right]^2\right\} \tag{4.16}$$

where $\alpha^2/2 = SNR$ and $I_0(\alpha r)$ is the modified bessel function of the first kind. They are shown in Fig. 4.6.

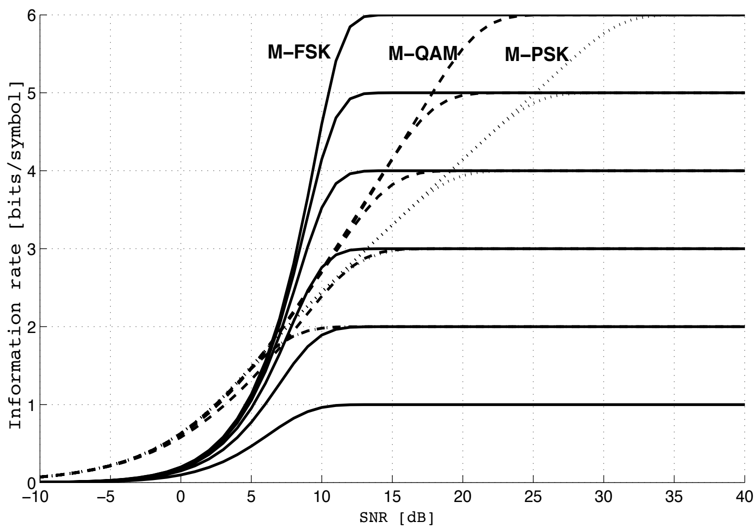



Fig. 4.6: Capacities and cutoff rates of MQAM, MPSK, and MFSK in AWGN channel as a function of predetection SNR. Each curve represents a different constellation size. The curves $1 \le \log_2 M \le 6$ for M-FSK, and $2 \le \log_2 M \le 6$ for M-QAM and M-PSK are shown, where M is the constellation size.

### 4.2.6 Smart mobile devices supporting SDR

New powerful devices supporting SDR capabilities will be used in the next future to form a self-evolving wireless network in which several goals such as coverage increase, high data rate and connectivity will be achieved in diverse communication scenarios. For this reason, with the aim of considering a quite modern communication context, we studied the case in which both simple mobile or fixed sensor nodes equipped with a wireless IEEE 802.15.4/ZigBee compliant RF transceiver, are considered. Furthermore, we also took into account the presence of more complex mobile devices, with a high processing capability, able to dynamically change the modulation scheme between different transmitter/receiver pairs by using the SDR support as shown in Figure 4.7. In addition, we assume that these wireless devices are equipped with a GPS module coupled with a software application for position coordinates exchange to perform a specific positioning strategy as detailed in the next section.

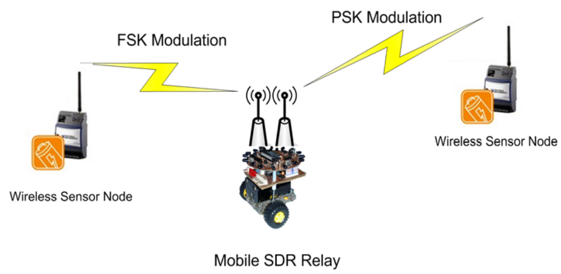



Fig. 4.7: Mobile relay devices supporting SDR capabilities

By exploiting the new features of programmable SDR architectures, a flexible implementation of several modulation schemes (*i.e.* MFSK, MPSK, MQAM) can be realized in a simple and effective way. This flexibility turns into a great adaptivity to optimize different network performance indexes such as throughput, coverage and degree of connectivity of a wireless network operating under varying channel conditions. In this context, the devices equipped with SDR functionalities can easily work as relay nodes in a multi-hop communication scenario by dynamically adapting different modulation schemes between the receiving and transmitting phases with the aim of optimizing network performances such as BER (Bit Error Rate), energy consumption and overall coverage.

It is well known that channel modulation has a relevant impact on the quality of the wireless link measured in terms of BER and on software/hardware complexity; furthermore, digital modulation/demodulation techniques need specific channel waveform coherence, coding/decoding and spreading/despreading of the radio spectrum [116]. Since the bit error probability is a function of the channel modulation, a radio channel with better quality has to be assigned to a larger number of bits and a higher order modulation, whereas a channel with poorer quality has to be assigned fewer bits or even no bit when the channel quality is too bad. For example, by working with three main digital modulation schemes (*i.e.* MFSK, MPSK, MQAM) having different modulation orders ($M$=*2*,*4*,*8*,*16*), it is possible to select and to use the most suitable combination by implementing it on-the-fly throughout SDR techniques. Moreover, to guarantee a certain BER value, the modulation schemes could be dynamically changed according to the channel quality experienced by the nodes and the distance variation between nodes due to the mobility.

In the last few years, the SDR paradigm is becoming more attractive and feasible thanks to the development of open-source software tool-kit such as GNU radio [118] and hardware devices such as Universal Software Radio Peripheral (USRP) [119]; therefore, several modulation/demodulation software blocks can be developed within the generic SDR architecture [117] for both transmitter and receiver (see Figure 4.8) allowing the design of new and more powerful devices well suited to support the dynamic modulation changing and adaptation strategies proposed in this work [112], [120].

In particular, it is worth noting that, with reference to the complexity of such software/hardware architecture, the Hybrid Radio Architecture (HYRA) proposed in [120] addresses the implementation of SDRs in the context of embedded systems by using reconfigurable hardware platforms with minimal additional resources.

Regarding the mobility features implementation, we would like to highlight that this feature can be implemented by equipping a network device with two or four wheels and a servo motor controlled by Arduino-based modules. The estimated cost of implementing controlled mobility and reconfiguration capability in such platforms is reported in the Table 4.1. Even if this kind of software/hardware architectures seem quite expensive, the fast technological advancements will favour the reduction of estimated costs; thus, it is plausible that the mentioned embedded architectures will shortly be available at a much lower cost.

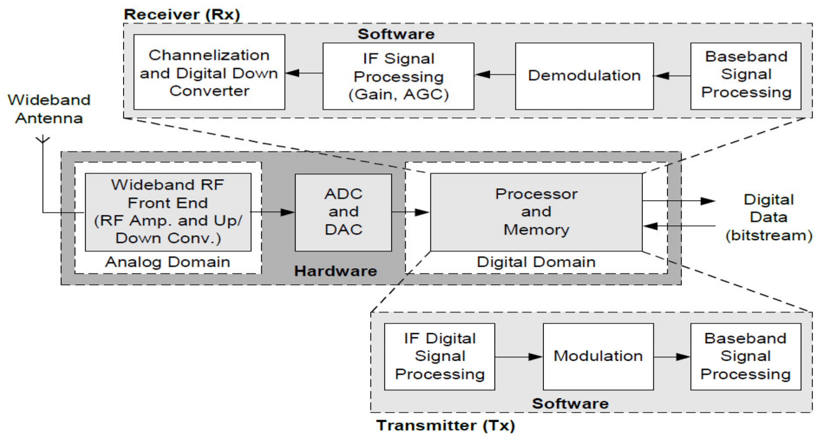



Fig. 4.8: SDR architecture for Relay Node [117].

Table 4.1: Costs to implement SDR devices.

| Mobility Support | SDR Support |
|---|---|
| Wheels + Servo Motors + Arduino | USRP B200 |
| 250$ | 800$ |

### 4.2.7 The optimization model

In this section, we give the mathematical formulation of the problem under study, as an integer nonlinear programming model. It is assumed that the field is represented by a two-dimensional grid. The parameters used for the formulation are the following: $h$: the grid height; $w$: the grid width; $d_s$: the discretization step; $sink$: a particular node that is located in a defined a-priori position; $n$: the total number of available nodes, including the $sink$; $r$: the sensing radius; $tx_{radius}$: the transmission radius; $M$: a large positive number.

The variables of the proposed model are:

- $(x_k, y_k)$, $k = 1, \dots, n$ the Cartesian coordinates that indicate the location of the node $k$ in the field;
- $\phi_{ijk}$, $i = 1, \dots, \lceil h/d_s \rceil$, $j = 1, \dots, \lceil w/d_s \rceil$, $k = 1, \dots, n$ a binary variable that takes the value one if the location $(i, j)$ is covered by node $k$, and zero otherwise;
- $\phi^+_{ijk}$, $\phi^-_{ijk}$, $i = 1, \dots, \lceil h/d_s \rceil$, $j = 1, \dots, \lceil w/d_s \rceil$, $k = 1, \dots, n$ are support variables;
- $\delta_{ij}$, $i = 1, \dots, \lceil h/d_s \rceil$, $j = 1, \dots, \lceil w/d_s \rceil$, a binary variable that takes the value one if the location $(i, j)$ is covered by at least one node, and zero otherwise;
- $\gamma_{ij}$, $i = 1, \dots, n$, $j = 1, \dots, n$, a binary variable that takes the value one if the node $i$ is linked to node $j$, and zero otherwise;

- $x_{ij}$, $i = 1, \dots, \lceil h/d_s \rceil$, $j = 1, \dots, \lceil w/d_s \rceil$, an integer flow variable that is used to represent the paths from each node to the $sink$;
- $\psi_k^+$, and $\psi_k^-$ $k = 1, \dots, n$ variables used to represent a relaxed version of the flow conservation constraints.

The considered problem can be mathematically stated as follows:

$$max \quad \alpha \times (\frac{\sum_{i=1}^{\lceil h/d_s \rceil} \sum_{j=1}^{\lceil w/d_s \rceil} \delta_{ij})}{h/d_s \times w/d_s}) - \beta \times \frac{\sum_{k=1}^{n} \psi_k^+ + \psi_k^-}{2 * (n-1)} \tag{4.17}$$

$$r - |i - x_k| \geq M\ (\phi_{ijk}^+ - 1), \quad \forall i, j \ and \ k = 1, \dots, n-1 \tag{4.18}$$

$$r - |j - y_k| \geq M\ (\phi_{ijk}^- - 1), \quad \forall i, j \ and \ k = 1, \dots, n-1 \tag{4.19}$$

$$2 * \phi_{ijk} \leq \phi_{ijk}^+ + \phi_{ijk}^- \ , \quad \forall i, j \ and \ k = 1, \dots, n-1 \tag{4.20}$$

$$\delta_{ij} \leq \sum_{k=1}^{n-1} \phi_{ijk}, \quad \forall i, j \tag{4.21}$$

$$M\ \delta_{ij} \geq \sum_{k=1}^{n-1} \phi_{ijk}, \quad \forall i, j \tag{4.22}$$

$$|x_i - x_j| - tx_{radius} \leq M\ (1 - \gamma_{ij}^+), \quad \forall i, j = 1, \dots, n \tag{4.23}$$

$$|y_i - y_j| - tx_{radius} \leq M\ (1 - \gamma_{ij}^-), \quad \forall i, j = 1, \dots, n \tag{4.24}$$

$$2 * \gamma_{ij} \leq \gamma_{ij}^+ + \gamma_{ij}^- \ , \quad \forall i, j = 1, \dots, n \tag{4.25}$$

$$x_{ij} + x_{ji} \leq (n-1) * \gamma_{ij}, \quad \forall i, j = 1, \dots, n \tag{4.26}$$

$$\sum_{j=1, j \neq i}^{n} x_{ij} - \sum_{j=1, j \neq i}^{n} x_{ji} + \psi_i^+ - \psi_i^- = 1, \quad \forall i = 1, \dots, n-1 \tag{4.27}$$

$$\sum_{j=1, j \neq i}^{n} x_{sink\ j} - \sum_{j=1, j \neq i}^{n} x_{j\ sink} + \psi_{sink}^+ - \psi_{sink}^- = n-1 \tag{4.28}$$

$$0 \leq x_k \leq \lceil h/d_s \rceil, \quad 0 \leq y_k \leq \lceil w/d_s \rceil, \quad \forall k \tag{4.29}$$

$$x_k, \ y_k \ \ integer, \quad \forall k \tag{4.30}$$

$$\phi_{ijk}, \phi_{ijk}^+, \phi_{ijk}^- \quad binary, \quad \forall i, j, k \tag{4.31}$$

$$\delta_{ij} \quad binary, \quad \forall i, j \tag{4.32}$$

$$\gamma_{ij}, \gamma_{ij}^+, \gamma_{ij}^- \quad binary, \quad \forall i, j = 1, \dots, n \tag{4.33}$$

$$x_{ij} \geq 0, \ integer \ \ \forall i, j = 1, \dots, n \tag{4.34}$$

$$\psi_i^+, \psi_i^- \geq 0, \ integer \ \ \forall i = 1, \dots, n \tag{4.35}$$

The objective function in (4.17) maximizes the number of locations covered by at least one node and the number of nodes that reach the $sink$. Conditions (4.18) - (4.20) state that if the distance between the node $k$ and the location $(i, j)$ is lower than or equal to the sensing radius $r$ than the variable $\phi_{ijk}$ takes the value one, otherwise it is set to zero. Constraints (4.21) and (4.22) are logical constraints and ensure that the indicator variable $\delta_{ij}$ takes on a value of one whether the location $(i, j)$ is covered by at least one node and zero otherwise. Conditions (4.23) - (4.25) state that if the distance between the node $j$ and the node $j$ is lower than or equal to the $tx_{radius}$ than the variable $\gamma_{ij}$ takes the value one, otherwise it is set to zero. Constraints (4.26) ensure that a flow can be sent from node $i$ to node $j$ only if a link between the two nodes exists.

Constraints (4.27) and (4.28) represent a relaxed version of the flow conservation constraints, where the variables $\psi_i^+$ and $\psi_i^-$ give a measure of the violation of these constraints.

Finally, conditions (4.29)-(4.35) represent the variable domain constraints.

The mathematical formulation reported above is an integer nonlinear programming model, where the nonlinearity is confined to the constraints (4.18) - (4.19) and (4.23) - (4.24).

To eliminate the terms with the absolute value, we introduce the additional constraints reported below:

$$d_{x_{ik}} \geq i - x_k \quad \forall i, k \tag{4.36}$$

$$d_{x_{ik}} \geq -i + x_k \quad \forall i, k \tag{4.37}$$

$$d_{y_{jk}} \geq j - y_k \quad \forall j, k \tag{4.38}$$

$$d_{y_{jk}} \geq -j + y_k \quad \forall j, k \tag{4.39}$$

$$d_{x_i x_j} \geq x_i - x_j \quad \forall i, j = 1, \ldots, n \tag{4.40}$$

$$d_{x_i x_j} \geq -x_i + x_k \quad \forall i, j = 1, \ldots, n \tag{4.41}$$

$$d_{y_i y_j} \geq y_i - y_j \quad \forall i, j = 1, \ldots, n \tag{4.42}$$

$$d_{y_i y_j} \geq -y_i + y_j \quad \forall i, j = 1, \ldots, n \tag{4.43}$$

Thus, constraints (4.18) - (4.19) and (4.23) - (4.24) are replaced by the following conditions:

$$r - d_{x_{ik}} \geq M\ (\phi_{ijk}^+ - 1), \quad \forall i, j, k \tag{4.44}$$

$$r - d_{y_{jk}} \geq M\ (\phi_{ijk}^- - 1), \quad \forall i, j, k \tag{4.45}$$

$$d_{x_i x_j} - tx_{radius} \leq M\ (1 - \gamma_{ij}^+), \quad \forall i, j = 1, \ldots, n \tag{4.46}$$

$$d_{y_i y_j} - tx_{radius} \leq M\ (1 - \gamma_{ij}^-), \quad \forall i, j = 1, \ldots, n \tag{4.47}$$

### 4.2.8 Validations, Simulations and Results

The proposed *Neural/Genetic* algorithm is evaluated by simulations using FREVO [151], an open source framework for evolutionary design. We took into account a $40 \times 40$ cells field, where $64$ nodes are placed in a random way according to an uniform distribution. We considered one cell and one time step as discrete units of space and time, respectively. Also the sensing radius of the nodes is $r = 2\ [cells]$ and it expresses the number of cells that nodes are able to cover in each of the four main direction (north, south, east and west). For the neural network, we use $9$ input neurons, $2$ hidden neurons and $2$ output neurons. For the genetic algorithm, we use $300$ chromosomes and $100$ generations. All the results have been averaged over $10$ different runs to respect a confidence interval of $95\%$.

In order to conduct a quite realistic analysis on the energy consumption, we chose to set transmitting power ($12dBm$) and receiver sensitivity ($-80dBm$) of our devices by referring to an off-the-shelf Bluetooth module made by *Roving Networks* [128]. Table 4.2 summarizes all the other simulation parameters used.

Table 4.2: Values of the relevant parameters used for the simulations

| **Device Parameters** | |
|---|---|
| Power spent in *transient* mode ($P_{tr}$) | 100 $[mW]$ |
| Time spent in *transient* mode ($T_{tr}$) | 5 $[\mu s]$ |
| Wavelength ($\lambda$) | 0.125 $[m]$ |
| Information bits ($L$) | 1000 $[bits]$ |
| Receiver noise figure ($N_f$) | 10 |
| Bandwidth ($B$) | 10 $[kHz]$ |
| **Scenario Parameters** | |
| Path Loss Exponent ($\gamma$) | 3.8 |
| Critical distance ($d_0$) | 1 $[m]$ |
| PSD of the noise ($N_0/2$) | $10^{-15}/2$ $[W/Hz]$ |
| Bit Error Rate ($BER_{threshold}$) | $10^{-3}$ |
| Maximum number of time steps | 100 |
| **Genetic Algorithm Parameters** | |
| % of elite selection ($e$) | 15% |
| % of mutation ($mu$) | 45% |
| % of crossover ($c$) | 30% |
| % of created offsprings ($\mathit{off}_c$) | 5% |
| % of selecting an offspring ($\mathit{off}_s$) | 5% |

#### 4.2.8.1 Validation of the Optimizazion Model

This first simulation campaign aims at validating the optimization model formulated in section 4.2.7. The presented results have been achieved by using LINGO 9.0 [103] for the mathematical model and they have been averaged over 100 runs with a confidence interval of $95\%$. For this simulation campaign we use a simple scenario with a $6 \times 6$ cells field, where $\{3; 4; 5\}$ nodes are placed in a random way according to an uniform distribution. Also the sensing radius of the nodes is $r = 1$ $[cell]$ and the transmission radius is $tx_{radius} = 1$ $[cell]$. The discretization step is $d_s = 1$ and the large positive number M is equal to 1000. Fig. 4.9 shows that the behavior of the algorithm proposed is very close to the centralized optimum obtained through the mathematical model for each value of *alpha/beta* within the Fitness function. In order to assess the behavior of the proposed optimization model, test problems, characterized by a small field size and a limited number of nodes, have been considered. This choice is motivated by the fact that the intrinsic complexity of the model allows to solve, in a reasonable amount of time, only small size instances. For this reason, once we validated the satisfying accuracy of the optimization model respect to the proposed heuristic scheme, we conducted a more intensive simulation campaign to explore several configuration parameters with a higher number of nodes within a wider area.

#### 4.2.8.2 Fixed nodes analysis supporting SDR

In this section we show the results obtained throughout the support of SDR capabilities; in this context the communication devices are all fixed but they can autonomously decide to use one of three different modulation schemes (MFSK, MPSK, MQAM) with three different symbol levels $M$ (4, 8, 16) thus the set of possible choices is extended to nine. However, since the mobility support is out of the scope of this first reference simulation scenario, the Neural/Genetic algorithm described in Section 4.2 cannot be executed every new generation and the result, in terms of more suitable modulation schemes, in agreement with the desired QoS, is always the same representing the reference benchmark point for the next analysis in which the mobility of the nodes allows to achieve better performances.

Figure 4.10, obtained throughout the implemented simulation framework, shows a clear example of a communication scenario in which the nodes are fixed but the use of SDR capabilities allows them to achieve different results in terms of QoS$_{connectivity}$. In particular, in Figure 4.10.(a) the circles representing the nodes, are colored in different ways according to the different supported modulation schemes (i.e., yellow for FSK, cyan for QAM and magenta for PSK). The square around the circle represents the communication ability of each node (i.e., blue if they can reach the sink node, red if they can communicate between each others

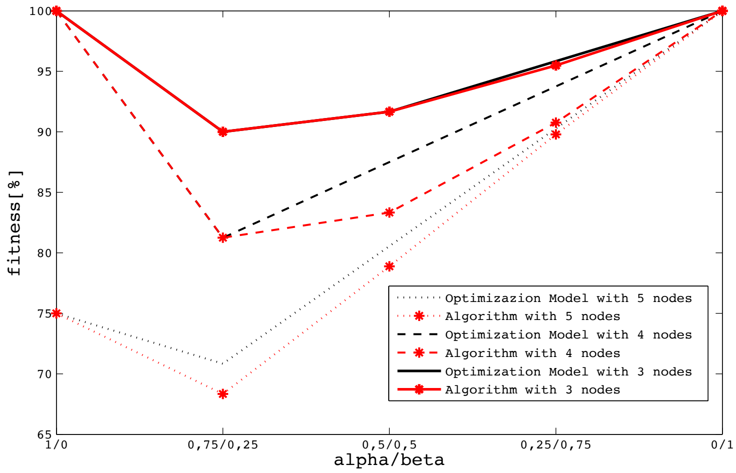
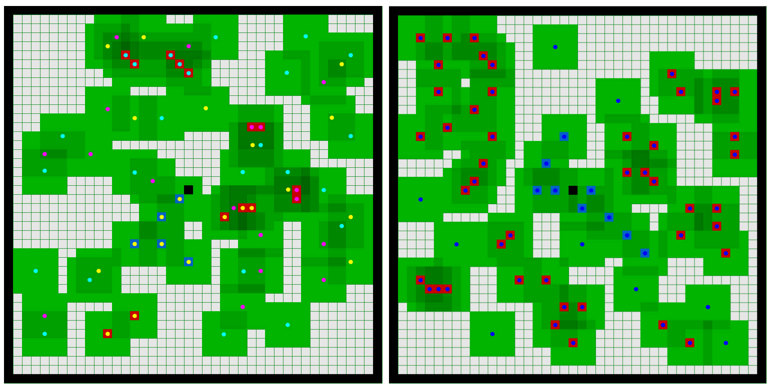



Fig. 4.9: Validation of the Neural/Genetic Algorithm: Heuristic vs. Optimization model.

without reaching the sink node). On the other side, the nodes displayed in figure 4.10.(b) are all colored in blue because they can choose to use all the different modulation schemes according to the new features provided by the SDR technology. Thus, they can communicate with more neighbors respect to the previous scenario in order to reach the sink node by increasing the performance in terms of $\text{QoS}_{connectivity}$. On the contrary, the $Coverage$ cannot take advantage from the SDR technology due to the lack of mobility support.

Table 4.3 summarizes the obtained results over 1000 simulation runs, also specifying the percentage of nodes that have chosen any specific modulation scheme and the average energy consumption for the transmission. It is worth noting that in the simulated scenario few modulation schemes such as 4-8-PSK have never been chosen due to the worst performance in terms of BER and to the highest energy consumption.



(a) No mobility without SDR (b) No mobility with SDR

Fig. 4.10: Fixed nodes communication scenario: (a) No mobility without SDR, (b) No mobility with SDR.

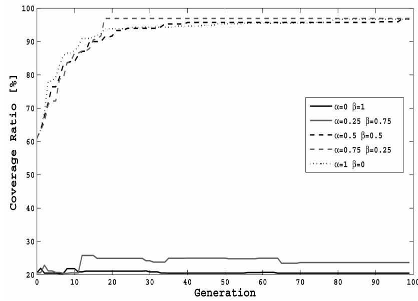
#### 4.2.8.3 Mobile nodes analysis supporting SDR

In this section, we show how controlled mobility can be efficiently exploited to reach better configurations both in terms of $Coverage$ and $QoS_{connectivity}$. In Figure 4.11, we show results obtained when all nodes are equipped with motion capabilities but they are not able to select, in a dynamic fashion, the most suitable modulation. Specifically, all nodes will support only a specific modulation scheme

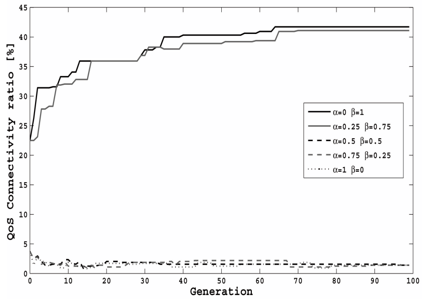
Table 4.3: Fixed nodes analysis supporting or not supporting SDR capabilities

| **Output Parameters** | **Without SDR** | **With SDR** |
|---|---|---|
| $Coverage$ | 61.57% | 61.47% |
| $\text{QoS}_{connectivity}$ | 2.03% | 12.20% |
| Energy per Information Bit | $2.4 \cdot 10^{-5}$ $[J]$ | $2.75 \cdot 10^{-5}$ $[J]$ |
| Nodes choosing 4-FSK | 12.59% | 0% |
| Nodes choosing 8-FSK | 28.34% | 38.57% |
| Nodes choosing 16-FSK | 34.82% | 43.92% |
| Nodes choosing 4-PSK | 0% | 0% |
| Nodes choosing 8-PSK | 0% | 0% |
| Nodes choosing 16-PSK | 10.80% | 10.94% |
| Nodes choosing 4-QAM | 0% | 6.57% |
| Nodes choosing 8-QAM | 0% | 0% |
| Nodes choosing 16-QAM | 13.45% | 0% |

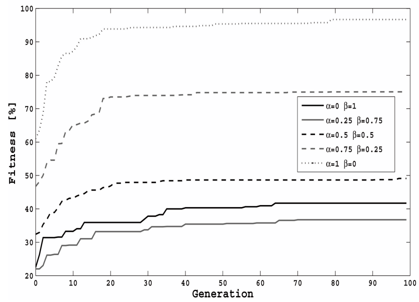
in a random way, by keeping the percentage of nodes that choose a certain modulation equal for all the modulation schemes. In this specific case, the 33.33% of nodes will support FSK or QAM or PSK modulation. Of course, in order to obtain reliable results we averaged them complying a confidential interval of 95%. In this scenario, all nodes will move in a distributed fashion towards novel positions computed through the neural network by considering a genetic approach during the training phase as explained in Section 4.2. It is worth noticing that in the configuration where nodes are not able to move, $Coverage$ cannot be improved and nodes are only allowed to choose a better modulation in order to improve $QoS_{connectivity}$. When nodes are able to move, better configurations in terms of both $Coverage$ and $QoS_{connectivity}$ are obtained. For $\alpha$ values ranging from $0.5$ to $1$, after $20$ Generations the nodes are able to reach a percentage of coverage higher than $90\%$. Concerning the $QoS_{connectivity}$ index, it is increased from $12.2\%$ to $35\%$ after $\approx 35$ Generations by tuning the connectivity parameter ($\beta$) with higher values, $0.75$ and $1$. Unfortunately, if we observe the curves related to $Coverage$ and $QoS_{connectivity}$ in a cross-way, we notice as controlled mobility is a valid tool to improve performance of the system, but coverage and connectivity are opposite goals, and then controlled mobility is able to generate configurations that "answer" in an effective way to the setting of $\alpha$ and $\beta$, but it is not able to handle the opposition of those two QoS requirements. In fact, in Figure 4.11 (a), when the value of $\alpha$ is chosen equal to $0.25$, the network is not able to reach a degree of coverage higher than $\approx 24\%$, and this is the case (see Figure 4.11 (b)) where the connectivity value reaches $\approx 42\%$. By considering an additional freedom degree consisting into the possibility to set the most suitable modulation, the overall performances of the system are improved as shown in Figure 4.12 (a) and (b). A strange effect of the dynamic modulation setting occurs when $\alpha$ and $\beta$ are both set equal to $0.5$. In this case (see Figure 4.12 (a)), coverage reached is smaller than in the previous case, but it is worth analyzing this behavior in combination with the connectivity value. In fact, in Figure 4.12 (b), in correspondence of the same $\alpha$ and $\beta$ values, we are able to obtain a connectivity degree higher than $93\%$ after very few Generations. On the other hand, the system gives an answer matching the interest we express with the $\alpha$ value, since we set $\alpha$ equal to $0.5$. When the $\alpha$ value is higher than $0.5$, the system takes properly into account this setting and the coverage increases. From this analysis, we can argue that, by considering in a similar way the importance of both $\alpha$ and $\beta$ parameters, the system will behave in a very effective fashion guaranteeing a very high level of $QoS_{connectivity}$ and a good degree of $Coverage$. These results are also confirmed by the *Fitness* curves shown in Figures 4.11 (c) and 4.12 (c) respectively. In fact, we can observe that *Fitness* improves by reaching very high values after a few number of generations when the weight associated with connectivity is the highest possible ($\alpha = 0$ and $\beta = 1$). In respect of the case in which nodes are only equipped with motion capabilities, SDR mobile nodes are able to react to the connectivity requests of the networks. Moreover, in all the studied cases we can notice an improvement of the *Fitness* except when coverage is considered as a kind of high priority (*i.e.* $\alpha = 0.75$ or $\alpha = 1$) making the *Fitness* trend similar to the case with no-SDR mobile nodes. As main conclusion of this simulation campaign, we can argue that, by correctly tuning the $\alpha$ and $\beta$ weights of the *Fitness* function, the wireless network consisting of self-configuring SDR devices can dynamically react in order to face different communication scenarios by favoring, from time to time, the $Coverage$, the $QoS_{connectivity}$ or both.




(a) $\text{Coverage}_{ratio}$

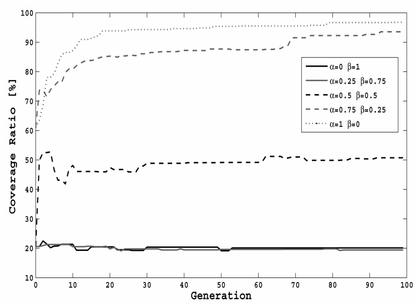



(b) $\text{QOS}_{connectivity\_ratio}$

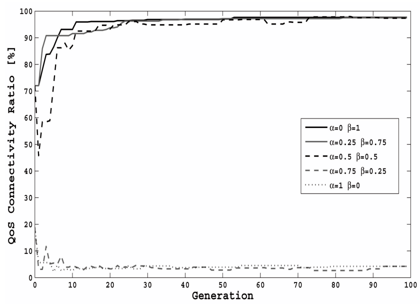



(c) Fitness

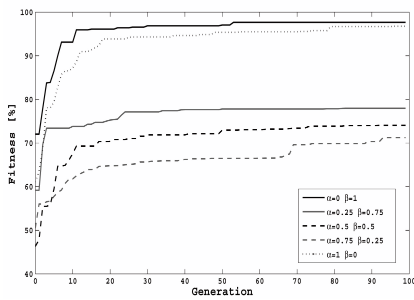
Fig. 4.11: Neural/Genetic algorithm supporting mobility without SDR capabilities




(a) $\text{Coverage}_{ratio}$




(b) $\text{QOS}_{connectivity\_ratio}$

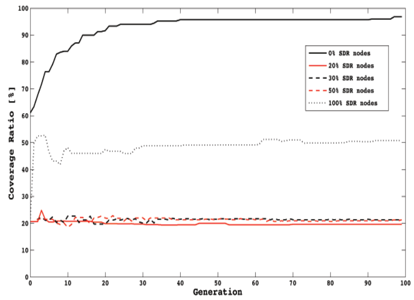



(c) Fitness

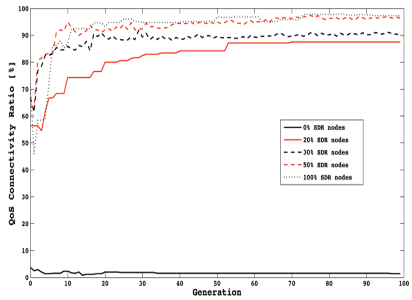
Fig. 4.12: Neural/Genetic algorithm supporting mobility and SDR capabilities

#### 4.2.8.4 Mobile nodes analysis with variable amount of SDR nodes

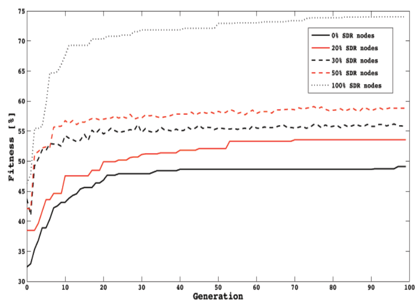
In this section, we investigate the impact of the amount of SDR nodes on the overall network performances because, as detailed in Section 4.2.6 and in Table 4.1, the SDR nodes are still quite expensive devices; thus it is convenient to reduce their number as much as possible. We tested the system with mobile nodes by choosing the same value for the parameters of the Fitness function (i.e. $\alpha = \beta = 0.5$) and varying the percentage of SDR nodes (i.e. $0\%; 20\%; 30\%; 50\%; 100\%$). The obtained results, shown in Figure 4.13, demonstrate that even using a small amount of SDR nodes, it is possible to achieve good performances in terms of $QoS_{connectivity}$ (figure 4.13.b) but the $Coverage$ turns out to be considerably reduced due to the fact that the nodes equipped with SDR capabilities work as attractors for the nodes without those features by greatly reducing the possibility to expand to cover larger areas.




(a) Coverage$_{ratio}$




(b) QOS$_{connectivity_ratio}$




(c) Fitness

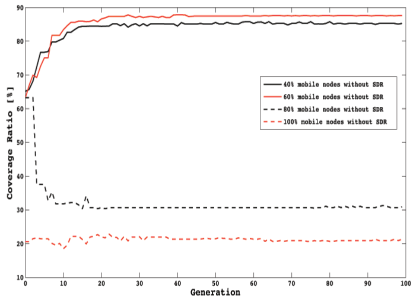
Fig. 4.13: Neural/Genetic algorithm supporting mobility and percentage of nodes with SDR capabilities

#### 4.2.8.5 Varying the percentange of mobile nodes

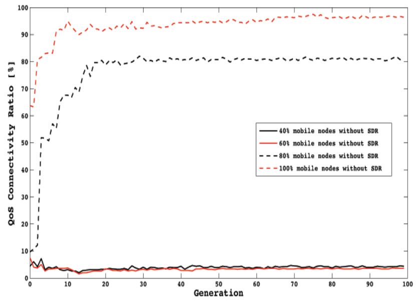
In this scenario we investigate the impact of high number of mobile SDR nodes on the overall network performances. This analysis is mainly motivated by the fact that the mobility capability has a quite expensive cost and the SDR equipment is still a bit expensive at the present day. According to these remarks, it makes sense to test how these capabilities impact on the performance of the network, both in terms of coverage and connectivity toward the sink; thus we consider only a portion of nodes equipped with SDR capabilities by varying the number of nodes able to move toward "better" positions. In this way, we aim at dimensioning the right number of mobile nodes in order to save money without excessively reducing the network performances. With this goal in mind, we decided to test a network scenario in which only half of the nodes are provided with SDR functionalities and, among the standard nodes, a variable percentage are equipped with mobile capabilities (i.e. $40\%; 60\%; 80\%; 100\%$). Just to give a numerical example, let us consider $64$ nodes in the network field, $32$ among them are equipped with SDR capabilities and are static whilst the number of mobile nodes, without SDR capabilities, varies as follows: $12$, $19$, $25$ and $32$.

The obtained results are shown in Figure 4.14. As already explained, by using a certain percentage of SDR nodes, it is possible to improve the network performances in terms of connectivity but at the expense of coverage; on the other side, by considering a more realistic network scenario in which not all the nodes can move, the effect of attraction mechanism, due to the SDR nodes, decreases thereby improving the performance in terms of coverage. However, if the percentage of standard mobile nodes is lower than $80\%$, we experienced a bad connection management toward the sink node; i.e. to reach the more isolated fixed nodes, the SDR nodes prefer to ensure optimal coverage rather than communicate with the sink.

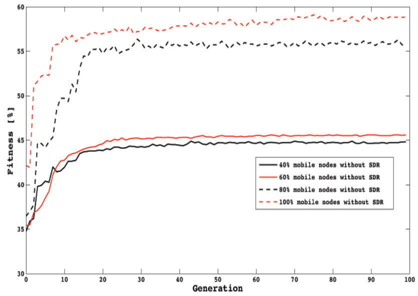
As a main conclusion of this simulation campaign, we can argue that it is possible to decouple the effects due to both SDR and mobility features; in fact, in a mixed scenario in which only a portion of fixed nodes are equipped with SDR capabilities, a good $QoS_{connectivity}$ level can be guaranteed by increasing the number of mobile standard nodes.




(a) $\text{Coverage}_{ratio}$




(b) $\text{QOS}_{connectivity\_ratio}$




(c) Fitness

Fig. 4.14: Neural/Genetic algorithm supporting SDR capabilities and percentage of mobile nodes

## 4.3 Conclusions

In this chapter I investigated heterogeneous networks composed of several spatio-temporal evolving devices.

In order to make the system able to rapidly converge towards new equilibrium states, we leverage on the heterogeneous aspects of the devices.

The term equilibrium is referred on the basis of new tasks to be accomplished in order to achieve a global goal (e.g. area coverage, Point of Interest (PoI) coverage, connectivity, etc.).

In the first part I described some of the theoretical tools that have been exploited to design completely distributed solutions.

In the second part I have given a practical example of how we have combined different tools to organize a complex system. In particular, we have considered heterogeneous networks where nodes more powerful (e.g. robots equipped with more powerful computational resources and memory and equipped with Software Defined Radio SDR capability) are able to self-reconfigure their role (e.g. transmission modulation) based on the changes of the environment. All nodes run an algorithm based on a totally distributed Neural/Genetic approach by using only local information. Reconfiguration and dynamic self-adaptation have been integrated as control primitive in the network in order to better face both the external (environment) and internal (system and devices) evolution.

The type of approach adopted in the work described in this chapter, reflects the bottom up methodology, different than the traditional systems, as we claimed in the chapter describing Complex Self-Organized Networ Systems (Chapter 2). Indeed, we started by considering the local interactions among the single components of the system. The nodes take decisions on the basis of their own current condition and the neighborhood situation. Nodes that are able to adapt their behavior based on their capabilities receive external inputs (information about the environment such as an event that is occurring and that needs to be managed and also information of the other neighbors nodes), elaborate them since we have equipped them with intelligence and adapt their behavior with an evolutionary perspective.

The acquisition of this type of methodology has played an important role in my research activity, since I have acquired the capability to apply it to CSONSs by also using other artificial intelligence approaches such as Particle Swarm Optimization (PSO) [201] and giving the possibility to combine multidiciplinary approaches such as artificial intelligence mechanisms and schemes well-known in multi-agents domain such as consensus approaches.

The perspective is to face compexity of the ssystems, by trying to represent it with the simpler abstractions as possible and then try to identify which tools of other domains can be the most appropriate to "solve" simpler tasks by always keeping in mind the global complex objectives.

This was exactly the perspective adopted in [70] and [69]. We have considered radio cognitve aware nodes that need to opportunistically select the better channel based on the occupancy state of the channels changing over the time and based on the different types and number of users present in a certain time. We have had SDR nodes but in respect of the previous considered scenarios, the goal was different and we needed an high reactiveness of the system in order to avoid to drastically depleting the performance of the system in terms of throughput. Thanks to several exchanges with Machine Learning experts, we finally achieved to formulate the channel selection as a Multi-Arm Bandit problem. We implemented a Thompson heuristic both via simulation and on real very simple sensors and this approach has shown to be very performing both in terms of reactiveness (the velocity to select a better channel when system conditions change) and in terms of throughput.

As anticipated before, the capacity to reduce the complexity of the system at units level, has been important also in this context. In fact, this approch allowed the selection of the appropriate tools, since neural approaches or genetic algorithms were not applicable in this specific context for different reasons. Firstly, neural networks need a long and accurate training phase. Secondly, high resources in terms of memory and computational are required to run a neural network and we were costrained in terms of devices capabilities.

This type of approach is of paramount of interest in my next research, since I will always consider complex systems that need to self-organize and are composed by heterogenous components. In particular, I will explore different types of communication paradigms and down-sized newtorks (nanonetwork), where the dynamics and phenomena are different and need to be studied and understooid, but the methodology acquired can absolutely been applied.

**Publications**

[J2][J14][J15][J22][J23][J24][J25][J26][J28][J30][C25][C29][C30][C31][C32][C33][C34][C35][C37][C41][C44][C45]

# 5

# From Indoor to Outdoor applications based on real architectures

Right now we have seen what a Complex Self-Configured Network System is and the approach adopted to treat with this type of systems. We have realized that new complex systems based on Internet of (X) things, where X can be Cloud, Robotic, Every, etc. need new discovery functionalities allowing the "discovery" of the resources that the user really needs. This has become a fundamental aspect in the Big Data era where there are billions and billions of connected objects providers and/or consumers of data. After an effective discovery is implemented, we need to deal with the complexity of the system and we have learned that we have to acquire the analytical capability to "reduce" the complexity in simpler entities and to treat with them at a "local" level.

We have learned as multi-disciplinary approaches can be very effective in this context.

The last but not the least point I aim to focus on, is how the implemented mechanisms can be "translated" the implemented mechanism and the solutions conceived can be "translated" in real experiments.

This is a laborious activity, atarting from the selection of hardware and software tools to be used.

The main goal of this chapter is to describe three different real application scenarios, where the techniques and background acquired and described in the previous chapters have been exploited in order to implement effective and efficient solutions and where I will show the methodology applied.

In particular, I will consider a first scenario based on surveillance applications performed through Video Surveillance Camera (VSC) non permanently active. The VSC can be opportunistically "woken-up" by the means of ultra Low Power wireless Sensor Nodes (LPSN), able to monitor continuously the area. The LPSNs are equipped with PIR (Passive Infrared) sensors to detect the movement, thus they have a specific transmission range to wirelessly send a "wake-up" message to the camera and a sensing range to detect events of interest. Since different deployments have a high impact both in terms of detectable events and in terms of number of cameras that can "woken-up", we will show how the combination of neural/genetic algorithm with SDR paradigm, proposed in the previous chapter can be exploited to compute the most low-energy deployment.

The other scenario I will present is regarding modern vehicles and the consideration that the implementation of new functions requires more and more computing and communication resources to be installed on board. The choice we have done is to implement a gateway-based architecture and to realize an "intelligent" gateway, where we have moved some important functionalities. The idea to realize a similar application came up by the increasing demand of safety applications that boosted the trend to equip vehicles with single and multiple cameras that transfer recorded videos on the vehicle bus, to be processed by the On Board Unit (OBU) [129]. Also the recent development of Social Vehicular Networks [130] has been considered as another driver for the increase in the amount of generated data. Based on these considerations, we have realized that a more powerful mean was necessary to manage the data and the processes in a similar context. We considered a Docker-based lightweight virtualization as enabling technology for the fulfillment of the new vehicular-based applications requirements.

The third scenario considered is regarding the application of an IoT based solution for smart agriculture. A concrete example of smart agriculture is the PEACH project proposed in [218]. The goal of this project is to dramatically increase the predictability of frost events[1] in peach orchards by means of dense monitoring using low-power wireless mesh networking technology. In three months of operation, the network produced more than four million data just for the temperature data collection [209]. If the acquisition of this huge amount of data is essential for avoiding frost damage on time, their sending on the network may affect the energy consumption of sensing devices and can also cause network congestion. Reduction of massive amount of data generated by these sensing devices is therefore necessary. In order to reduce the huge amount of data to be sent and hence increase the network lifetime, we propose an efficient Bayesian Inference Approach (BIA) for IoT scenario.

## 5.1 Video Surveillance Applications based on Ultra-Low Power Sensor

In the last few years, a significant effort has been made in the context of wireless networks, by effectively exploiting their ability to monitor real-world phenomena [153], [155]. The applications involving wireless sensor networks are several and with different features, but one common factor of many applications, is the energy-constrained aspect of battery-powered devices. Normally, the wireless networks based on battery-powered devices, are mostly influenced by an effective and valid deployment of the nodes in the space. Deployment is concerned with setting up an operational heterogeneous wireless network in a real-world environment. Usually, the realization of an effective deployment is a labor-intensive and cumbersome task. Since energy is a limited and very precious resource, the extension of the lifetime of a battery-powered nodes network has to be addressed from different levels: 1) at the device level, by considering circuits with specific features; 2) at the network level, by implementing effective medium access solutions [160], routing protocols, deployments etc. In this work we try to devise a solution that combines an effective deployment of specific ultra low power wireless sensors nodes with LPSN sensors for monitoring objects' movements of specific areas. Specifically, LPSN nodes [156] are able to sense motion. Since VSC are energy-expensive nodes, it would be useful, for surveillance purpose [158], to wake-up video-camera [159] if and only if there is an interesting event that occurs (i.e. human being presence detected). In order to increase the "detectable" area, namely the zone where the events of interest can occur, and realize the maximum connected VSC nodes with the sensors (each VSC has to be connected to at least a LPSN sensor in order to be woken-up), we propose a neural/genetic approach. Neural/genetic approaches can be very effective for the solution of multi-objective problem as shown in [115]. This algorithm has the capability to consider in a synergistic way two "opposite" objectives. Usually, the greater is the area to be covered, the smaller is the number of VSC that are connected with at least a LPSN node. In order to take into account the two goals in a simultaneous way, two weight factors are introduced that give a kind of priority to the objectives.

### 5.1.1 Reference Model and Problem Formulation

In this section, we will describe the specific characteristics of the LPSN sensors and the deployment problem. As described in [152] and [157], the Pyroelectric passive InfraRed (PIR) nodes, can be used as a trigger to wake-up a node from "sleep" mode to a power-hungry video capture mode. LPSN sensors are exploited in this specific context for event detection purpose [161], [162]. Specifically, they allow to sense motion and are able to detect if a human being is moving in or out of the sensor range. In Figure 5.1, we show the architecture of LPSN nodes considered in this work. The hardware architecture is divided into three modules, powered by a single source:

- The sensor module which hosts a LPSN sensor, and the conditioning circuitry to give an analog and a digital output;
- Microcontroller board, the controller module built around a TI MSP430, which includes the power harvester module and batteries;

[1] A frost event occurs when ice forms inside the plant tissue and injures the plant cells plant.

- The communication module consisting of a nanoWatt WUR circuit and an ADF7020 transceiver to send information and/or to wake-up the neighbor.

  More details about each module can be found in [152].

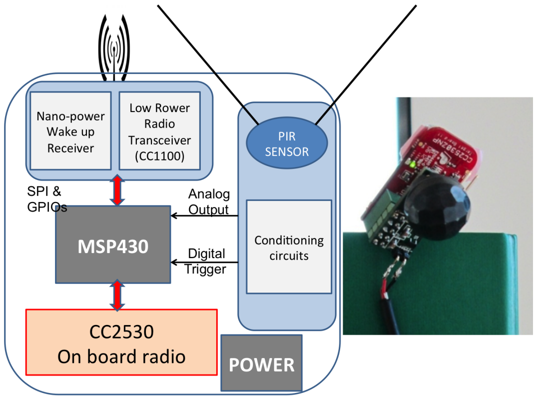



Fig. 5.1: Architecture and image of the implemented LPSN sensor node.

In this work, the low-power LPSN sensor, that can sense the motion, is used to detect the presence through continuous low-power sampling. Once motion is detected, a signal is sent to turn on the video camera for higher resolution sensing of the event. The main motivation beyond the combined use of LPSN nodes and video camera, is that LPSN sensors exhibit significantly lower energy consumption than VSC only. An example of how LPSN network can be inserted in an existing energy expensive sensor network is shown in Figure 5.2.

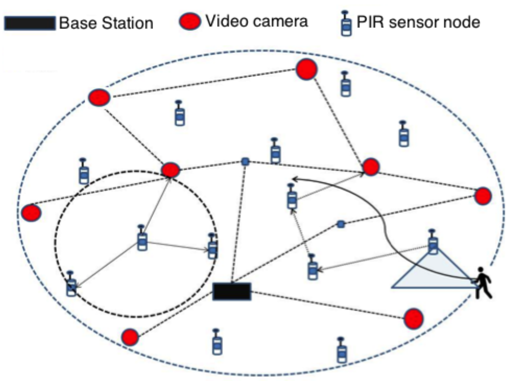



Fig. 5.2: Ultra-low power sensor network overlayed on an existing WSN.

From Figure 5.2, we can notice that the existing network is not modified with the additional LPSN nodes and the LPSN sensor network is overlayed to the primary network. When a LPSN sensor detects an intruder, it broadcasts a message to its neighborhood (the set of nodes that are in the transmission range). The message is to wake-up the reachable nodes.

Associated with the LPSN, nodes have two different ranges: 1) transmission range to send broadcast messages (to the video camera) to wake-up them. We will refer to it as *wake-up radius*; 2) directional sensing range to detect events of interest. Whether a VSC is in the *wake-up radius* of a LPSN, this means that this node can be woken-up, since there is at least one LPSN able to wake-up it if some event occurs. We will refer to the number of video camera that can be woken-up with the term "connectivity" and our goal is to maximize it by the mean of a good deployment of the overlayed LPSN network. If the percentage of VSC that can be woken up is not equal to the maximum (100%), this means that some VSC can not react to some events and are isolated. On the other hand, we are also interested to each other maximum coverage, namely to maximize the areas covered through the sensing range of the LPSN nodes. This means, that we ensure that all the events will be detected by at least a LPSN.

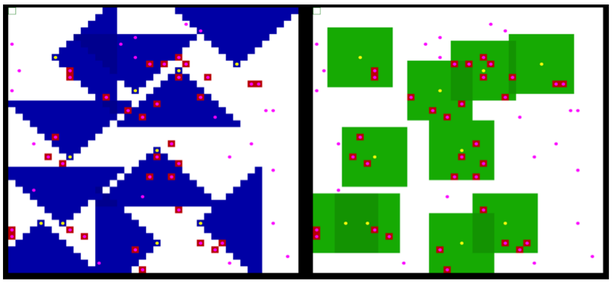


Fig. 5.3: (left) Example of coverage realized with 10 LPSN nodes (sensing radius = 8 meters); (right) connectivity exampke with 10 LPSN nodes (transmission range = 4 meters).

In the Figure 5.3, we show a deployment example realized with $10$ LPSN nodes (yellow nodes in the picture) and $54$ VSC (pink nodes). By setting a directional sensing radius (blue area) equal to $8$ meters and an omnidirectional *wake-up radius* equal to $4$ meters (green area), the LPSN sensors will be capable to wake-up a certain number of VSC (pink nodes with red squares) by covering an area (the covered area is the total blue area). The VSC that are out from the coverage of at least a LPSN (pink nodes) will be isolated and then cannot be woken-up. Following this reasoning, we can argue that the objectives to maximize the number of video camera that can be woken up and the maximization of the detection areas are opposite. Based on these considerations, we formulate a neural/genetic approach, where we formulate the problem by considering two weight factors, that can be adapted to the specific requirements of the user (that would give priority to the connectivity, that is the number of VSC that can be woken up, or to the coverage).

In the next Section we will give the details for this approach.

### 5.1.2 Evolutionary algorithm for the neural network training phase

For the neural network, we use the same algorithm and parameters used in the previous chapter. In order to train the network, in a self-organizing perspective, unsupervised reinforcement learning is used. Instead of a supervisor a fitness function is provided to evaluate the neural network's performance.

The global optimization method used for training the neural network is a genetic algorithms. The genetic algorithm is encoded with the neural network weights in a predefined manner where one gene in the chromosome represents one weight link. There are many chromosomes that make up the population, therefore, many different neural networks evolve until a stopping criterion is satisfied as in our case the maximum number of training generations has been reached. The goal of the genetic algorithm is to maximize the fitness function that is evaluated during the training phase and influences the genetic selection process.

Since the goal of genetic algorithm is to find a population that permits to achieve the maximum value of a given fitness function, we need to relate the fitness function to a measure of coverage and time needed for coverage. To this scope, the fitness function proposed for our scheme to make possible the evolution of the neural network is the following:

$$fitness\_function = achieved\_coverage - time \tag{5.1}$$

At each generation, the fitness function (5.1) is evaluated and the new population encoding the weights's value of the neural network is generated by selection, mutation and crossover of the previous member of population that guarantee a high fitness function's value. In this sense, the fitness function is used as feedback for next generation. Notice that since time and space are discretized in this equation we're not summing seconds and meters but just counting how many cells are covered with current generation taking into account how many time steps are needed. Increasing the fitness function value by one unit in respect to previous generations means that evolution has led to cover one more cell or to cover the same number of cells but with one time step less. Table 5.1 shows the parameters used for the genetic algorithm.

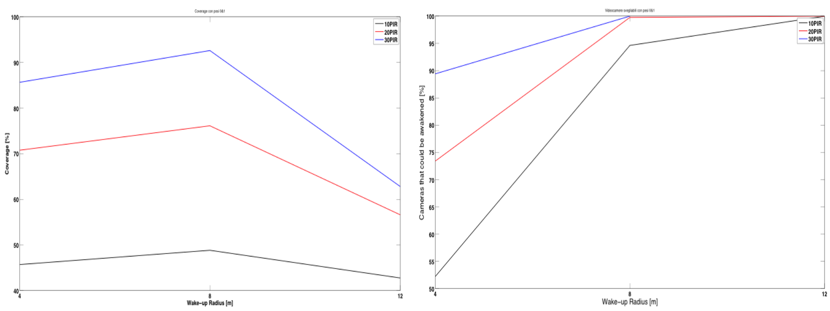
Table 5.1: Parameters of genetic algorithms

| | |
|---|---|
| Population size | 100 |
| Number of generation | 100 |
| Percentage of elite selection | 15 |
| Percentage of mutation | 45 |
| Percentage of crossover | 30 |
| Percentage of randomly created offsprings | 5 |
| Percentage of randomly selecting an offsprings from previous generation | 5 |

### 5.1.3 Performance Evaluation

In order to compute effectively and adaptively a deployment of LPSN nodes that overlay the VSC network, we considered the neural/genetic technique described above. This algorithm is effective to compute the best deployment of the LPSN nodes, by responding to the specific requirements of the user, by taking into account the environment and the number of devices available. The simulation tool considered is FREVO [151]. The synergistic combination of the neural network and the genetic algorithm is able to take into consideration different objectives in a simultaneous way, by introducing two weights with value ranging from 0 to 1 (the sum of these two weight factors has to be equal to 1). As for instance, if we assign to the coverage weight 1, the weight connectivity will be 0, and this means that the coverage will be "prioritized", and the connectivity will not be considered at all and viceversa. We tested the algorithm, by varying the weights between 0 and 1., the number of the LPSN nodes (10, 20, 30) and the wake-up radius (4, 8, 12 meters).

In Figure 5.4(a), we show the results we obtain when the weight assigned to the *coverage* is 0 and the *connectivity* weight is 1.




(a) Coverage (b) Connectivity

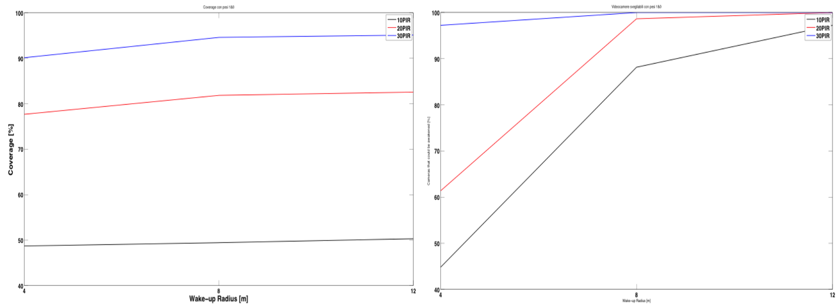
Fig. 5.4: Performance when the *coverage* is 0 and the *connectivity* is 1.

In Figure 5.4(b), we show the results concerning the connectivity, when the weight factor associated with the coverage is equal to 0 and the connectivity factor is 1.

In Figure 5.5(a), we show the results we obtain when the weight assigned to the coverage is 1 and the connectivity weight is 0.

In Figure 5.5(b), we show the results concerning the connectivity, when the weight factor associated with the coverage is equal to 1 and the connectivity factor is 0.

As we can remark from Figure 5.4, when the user requires to the algorithm to prioritize the connectivity, the algorithm will deploy the nodes in a way to achieve the 100% of the VSC that can be woken up. In practice, the technique will try to




(a) Coverage (b) Connectivity

Fig. 5.5: Performance when the *coverage* is 1 and the *connectivity* is 0.

cover a VSC with at least a LPSN node. This means that the coverage is not required to achieve the $100\%$. On the other hand, in Figures 5.5, we can observe that the area can not be totally covered, by considering the specific number of LPSN nodes and the correspondent sensing radius to detect the events, but in any case, the coverage achieved is greater than in the previous case. On the other hand, the connectivity will achieve the maximum value by increasing the wake-up radius.

## 5.2 Virtualized Smart Car

Nowadays, modern vehicles are equipped with very sophisticated electronic systems and associated in-vehicle communication infrastructures, aimed to provide different functionalities which vary from engine control, predictive diagnostics, driving assistance, and infotainment. Implementing new functions requires more and more computing and communication resources to be installed on board. By envisaging innovative real-time applications in next generation vehicles, we realize the great impact that an efficient and effective use of the bandwidth can play for the always-increasing bandwidth demanding applications.

The expectation for the near future is the above described trend to grow, fueled by the recent sales boom in the automotive market that has also revamped research funding on this topic [131]. In spite of such favorable perspectives, there are still many open issues and challenges to be addressed. Nowadays, OBUs are embedded systems with limited resources and hardly modifiable. Software updating of an OBU requires a long and cumbersome procedure to be carried out in a properly equipped workshop. This hardness combined with the typical software lifetime, which is much shorter than the lifetime of mechanical components, may result in a rapid obsolescence of modern vehicles. It is therefore crucial to devise a suitable mechanism to make OBU programming (and re-programming) easier. Also, the limited resources of current OBUs may cause long latency in carrying out time-critical tasks. A clever way to manage resources and allocate them to more critical tasks is necessary. In this context—which is continually evolving—an efficient OBU design has to meet a number of requirements that makes the OBU updating process easier, enable the deployment of new software, and efficiently manage parallel processes with real-time constraints.

In this work, we investigate the potentialities of lightweight virtualization as enabling technology for the fulfillment of the aforementioned requirements. Docker is an open-source container-based virtualization technique, easy to use and deploy, which represents a mandatory feature for applications development in modern smart vehicles. This feature also brings high flexibility, allowing flexible "activation" and "de-activation" of processes with a minimal impact in terms of overhead.

To achieve our objectives, we follow a pragmatic approach and address two main points. First, we design a feasible architecture for a virtualized OBU and we illustrate how common vehicular applications can be implemented on it, while outlining the guidelines to extend our approach to a generic implementation. Second, we evaluate the achievable performance to assess if virtualization has caused some detrimental effect and to which extent this natural decay in performance remains within tolerable margins.

Our main contributions can be summarized as follows:

- we propose the use of Docker containers in order to customize a smart car platform [132] and make it compliant with different end user requirements;
- we show how efficiently using containers to instantiate and schedule dedicated applications according to the vehicle status and/or on-demand services;
- by means of an empirical evaluation, we demonstrate that the proposed lightweight virtualization technique developed on top of devices with limited computational capability—such as a Raspberry Pi3—has an almost negligible adverse impact in terms of performance, also under heavy and heterogeneous workload conditions, and it allows the end user to dynamically add/eliminate running processes according to his/her needs.

In the next section, we first introduce the technologies used in the implementation of our prototype. Then, the entire platform architecture will be described in detail. Finally, through the analysis of different examples, we show how the main benefits introduced by container technologies can boost the development of a versatile and flexible platform.

### 5.2.1 Enabling Technologies

Raspberry Pi (RPi) is a single-board computer that leverages the low-power low-cost ARM processor architecture [140] and became popular thanks to its flexible use in several contexts. Raspberry Pi has been already used in the vehicular context in projects like CarBerry and in OBD-Pi[2]. For the development of our platform, we selected the last generation of the Raspberry Pi, which is the Raspberry Pi 3 (RPi3) model B3. The main hardware characteristics of the board are summarized in Table 5.2.

Table 5.2: Raspberry Pi 3 hardware features.

| **Parameter** | **Description** |
|---|---|
| Chipset | Broadcom BCM2837 |
| CPU | Quad Core @900MHz ARMv7 Cortex-A7 |
| Memory | 1GB LP-DDR2 900 MHz |
| GPU | Broadcom VideoCore IV |
| Ethernet | 10/100 Mb/s |
| Flash Storage | MicroSD |
| Connectivity USB | 4× USB 2.0 Host |
| OS | Linux, Windows 10 |
| Price | $35 (Oct-2016) |

Data coming directly from the vehicle can be read through the OBD-II standard [141] interface that provides two types of data: real-time vehicle data and several Diagnostic Trouble Codes (DTCs). The entire subset of such data can be efficiently used in order to monitor the current operating status of a vehicle, and to identify malfunctioning in the vehicle itself.

### 5.2.2 Functional Modules

The architecture of our prototype is depicted in Fig. 5.6. The platform has been designed to meet specific requirements: *(i)* fast allocation and flexibility in managing different services; *(ii)* isolation; *(iii)* backup capabilities. In the following, each key component is described in detail.

The Hardware is a Raspberry Pi 3 board used to develop our platform. A key aspect that led us to the choice of the Raspberry Pi platform is its capability to efficiently run virtualized applications through the use of container technologies, in particular Docker. Furthermore, the ease with which different applications can be managed through containers well match our platform requirements. Finally, as

[2] `http://www.instructables.com/id/OBD-Pi`

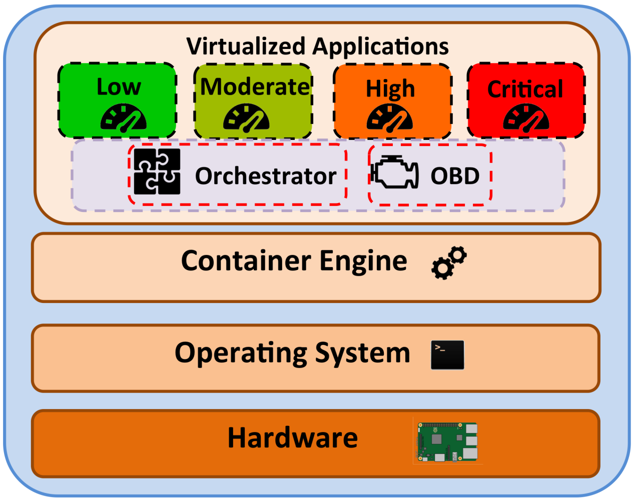



Fig. 5.6: Platform architecture.

demonstrated in [142], the introduction of the virtualization layer in devices with low computational resources does not adversely impact the performance.

As basis Operating System we use the image provided by Hypriot running Raspbian Jessie with Linux kernel 4.4.10, with Docker version 1.12.0. As storage device, a 16 GB (Transcend Premium 400x Class 10 UHS-I microSDHC) memory card has been used.

At the application level, our architecture entails three main components: *(i)* a set of singularly virtualized applications tagged with different priority levels; *(ii)* an *OBD* Container that is in charge of receiving and handling the data from the vehicle; and *(iii)* the Orchestrator that has the task of monitoring the resources used by the entire system and by each virtualized application. Orchestrator and OBD are in the same functional block since they frequently interact. The central role played by the Orchestrator component will become clearer in the following sections.

We defined four application/service types (Fig. 5.7):

- **Critical** priority applications are characterized by the highest level of priority (e.g., applications dedicated to firmware update/restore, or demanding control data).
- **High** priority applications, which include e.g., driver assistance, camera data.
- **Moderate** priority applications consist of applications provided by auto insurance companies, which offer reduced premiums if OBD-II vehicle data loggers[3] are installed.
- **Low** priority applications include Entertainment/Multimedia contents streamed by an internal and/or external device.

In defining the priorities, we refer to the application requirements in [129]. Since the Raspberry Pi is a low-resource device with limited computation capabilities, specific allocation policies have to be defined – and executed by the Orchestrator – in order to give priority to the execution of a virtualized application over another. For each level of priority, an application that provides backup functionality is planned. This implementative choice is done by considering that possible malfunctions recorded by the OBD-II can have different priorities.

### 5.2.3 Application Scenarios

The Orchestrator dynamically allocates applications/services in the platform. This feature brings several benefits in terms of resource usage. Indeed, the container instances can be instantiated only when required or when specific events like a car operating anomaly occur.

For example, we analyze the case of an anomalous gas emission detected by the OBD (corresponding to the OBD code P0442). According to our requirements, the system must store in memory what happens at the time when the anomaly has

[3] https://www.progressive.com/auto/snapshot/

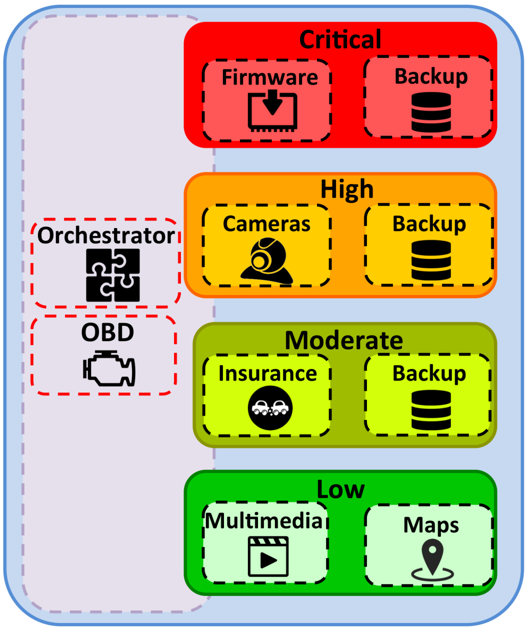



Fig. 5.7: Functional modules.

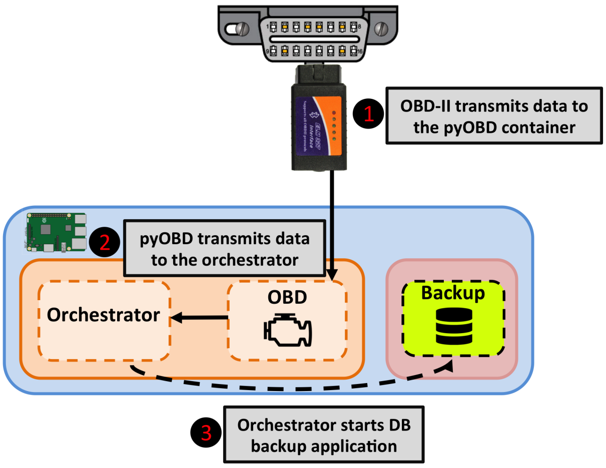



Fig. 5.8: Data Base Container activation.

been detected. The dynamic allocation of a container dedicated to this purpose will provide a detailed snapshot of the evolution of this anomaly. In practice, as soon as the orchestrator—which constantly receives data from the OBD—detects the anomaly, it activates of another virtualized application dedicated to the execution of a particular task. Referring to this example, a database is initialized in order to record all the parameters associated to the evaporative (EVAP) emission system (Fig. 5.8).

In the second example (Fig. 5.9), we consider the case in which the OBD detects a sudden vehicle speed decrease. This particular situation may correspond to an imminent danger. Also in this scenario, the Orchestrator can activate a container, which in turn starts the video recording of the surroundings through the camera connected to the Raspberry.

The aforementioned examples show how the flexibility related to the use of containers in this context enlarges the potentialities of our platform in terms of backup functionality and capacity of running-dedicated applications at given times. Flexibility can also be used to optimize the performance of the platform itself. Considering that the number of applications that can simultaneously run on top of the RPi3 is limited, the definition of different priorities, together with the dynamic management of containers, is also useful to schedule which application takes priority when the hardware resources are kept busy.

To better explain how containers can help on pursuing this goal, we suppose that two applications characterized by different priority levels, e.g., *Moderate* and *Low*, are simultaneously running 5.10. Similarly to the previous examples, the Or-

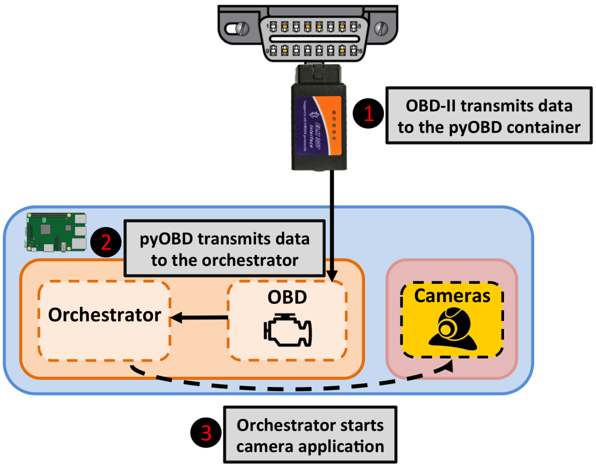



Fig. 5.9: Dash Cam container activation.

chestrator recognizes a possible critical status for the vehicle by means of data received by the OBD. The platform has to guarantee the execution of a specific application that can somehow help solve and/or trace the vehicle behavior during the critical status. At the same time, it has to be fast on reacting to this potential danger. Considering that the execution of this task has the highest priority, all the concurrent instances that are running on that given time have to be paused to make available all the resources to the application marked by critical priority. This can be easily achieved thanks to the Docker API, which allows every running container to pause (and un-pause). When the containers are in pause mode, no hardware resources are employed.

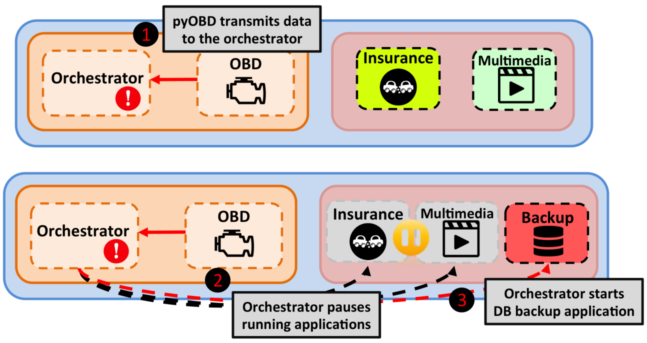



Fig. 5.10: Anomaly detected case.

### 5.2.4 Performance Evaluation

The validation of our proposal covers two different aspects. First, we evaluate how a Raspberry Pi reacts, in terms of performances, to specific workloads generated by applications running within Docker containers. This operation lets us to quantify potential overhead introduced by the virtualization layer. Then, we present a first performance evaluation of our platform while performing specific tasks.

#### 5.2.4.1 General Performance

The impact of virtualization of Docker on ARM devices has been already discussed in [142]. However, in this work the performance evaluation is carried out by means of benchmark tools that stress specific hardware segments of the device. Although this is a reasonable approach—which enables to assess an upper-bound to the performance of each system hardware portion—it can not be neglected that real-world applications challenge the hardware in a more distributed way. For this reason, we decide to evaluate the impact of virtualization on Raspberry 3 by means of the stress[4] benchmark tool, which is a workload generator that allows to allocate a configurable amount of CPU, memory, I/O, and disk stress on the system. This analysis also aims to evaluate the behavior of the Raspberry when it is subjected to an increasing workload. For this purpose, we have defined four different workload levels: *(i)* Base load; *(ii)* Low Load; *(iii)* Average Load; *(iv)* High Load. Table 5.3 shows more details about the four generated workloads.

Table 5.3: Workload Characterization For General Performance Analysis.

| Workload | Description |
|---|---|
| **Base** | A load average of one is imposed on the system by specifying one CPU-bound processes. |
| **Low** | A load average of two is imposed on the system by specifying one CPU-bound processes, and one memory allocator process. |
| **Average** | A load average of three is imposed on the system by specifying one CPU-bound processes, one memory allocator process, and one disk-bound process (50MB). |
| **High** | A load average of four is imposed on the system by specifying one CPU-bound processes, one memory allocator process, and one disk-bound process (100MB). |

The performance metric that we are interested in monitoring is the *system load*, which indicates the overall amount of computational work that a system performs. The average load represents the average system load over a period of time. In our evaluation, such time interval is set to 400 seconds. We decided to use the *system load average* metric, as it includes all the processes or threads waiting on I/O, networking, database, etc. [143]. This process can help us to well characterize the platform performance, by taking into account the heterogeneous features of the applications that run on top of it. The aforementioned metric can be monitored by means of Unix tools like *dstat*[5]. This tool calculates the average load and provides three values for it referring to the past one, five, and fifteen minutes of system operation. In our experiments, we only consider the 1-minute average system load. Each test is started when the RPi3 shows a load number of 0.

To better understand what this metric expresses, we can consider the example of a single-CPU system that shows a 1-minute load average of 1.46. This means that during the last minute, the system was overloaded by 46% on average—1.46 runnable processes, so that 0.46 processes had to wait for a turn for a single CPU system on average. In other words, this also means that a system load average equal to one represents an upper-bound for this metric in a system with one CPU, after which the Operating System could behave unstably. Similarly, a system average load equal to four represents the upper-bound in a system with four CPUs.

In our evaluation, the *native performance*—i.e., running the *stress* tool without including any virtualization layer running on top of the underlying hardware—is used as a reference for comparison. This will be useful to quantify a possible overhead introduced by container technologies on the Raspberry Pi.

Fig. 5.11 shows the result of the *General Performance* test. Several insights about the performance impact introduced by Docker can be drawn. First, it can be noticed how for three of the four workloads (base, low, and average), native and Docker performance curves basically overlap. This represents an important outcome since it confirms the lightweight characteristics of container technologies, even when the RPi3 has to handle mixed workload.

The only case in which a tangible overhead between native and Docker performance can be observed is when a *High* workload is assigned to the Raspberry. By analyzing the *High workload* curve, we notice that Docker reaches earlier the average system load upper-bound. The performance difference can be quantified in the order of 15%. We can also observe the unstable behavior of the system -both for the native and virtualized cases- when the upper-bound is exceeded. As previously explained, this behavior is attributable to the system overloading. How-

[4] `http://manpages.ubuntu.com/manpages/wily/man1/stress.1.html`
[5] `http://dag.wiee.rs/home-made/dstat/`

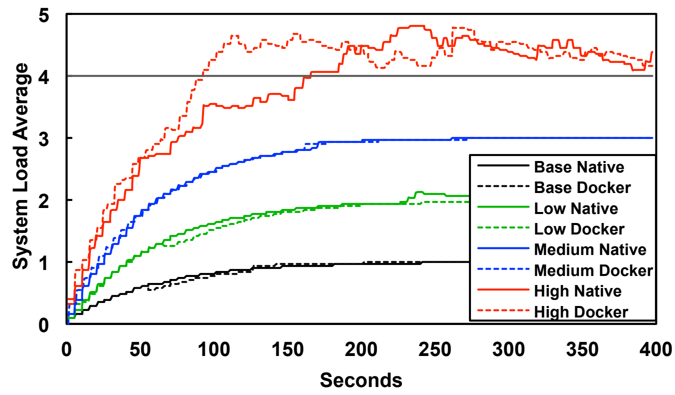



Fig. 5.11: General performance.

ever, it is worthy clarify that the High workload has been defined in such a way to heavily challenge the system. Indeed, when memory and disk-bound processes are imposed to the system, the CPU has extra tasks to be executed.

#### 5.2.4.2 Platform Performance

After showing that the RPi3 can efficiently handle mixed workload running within Docker containers, we want to test the performance of our platform when it has to manage dedicated virtualized applications. To accomplish this, we have defined a set of workloads that are closely related to the *application scenarios* described in Section 5.2.3. A detailed explanation of five workloads is provided in Table 5.4. It can be observed how those scenarios are characterized to deliver increasing load to the system. To accomplish this evaluation, we assume that the functional block *OBD+Orchestrator* is receiving data from the OBD-II interface—which is directly connected through serial port at the Raspberry Pi—every 10 ms.

Table 5.4: Workload characterization for platform performance analysis.

| **Workload** | **Description** |
|---|---|
| **Workload 1** | This workload refers to the simple scenario in which the OBD/Orchestrator container receives data from the OBD-II interface through the CAN bus, and send the received data to a database in which the OBD logs are stored. |
| **Workload 2** | The second workload refers to the case in which the orchestrator has to activate and manage a single virtualized application. The application handles video content from a camera directly connected to the Raspberry Pi. The video content is encoded in mp4v format, and made available through to HTTP connection. |
| **Workload 3** | The third workload is a combination of Workload 1 and Workload 2. |
| **Workload 4** | In the fourth case, we add the streaming of a multimedia content to the Workload 3. |
| **Workload 5** | The Workload 5 combines the previous case with the activation of another container that interacts with the connected web-cam for recording and storing (on the MicroSD card) the steamed video content. |

Fig. 5.12 shows the results for the platform performance evaluation. The main outcome in the platform evaluation lies in the fact that, even when several virtualized instances are simultaneously running, the average system load is lower than the upper bound. The result is the same also for the case of a workload in which

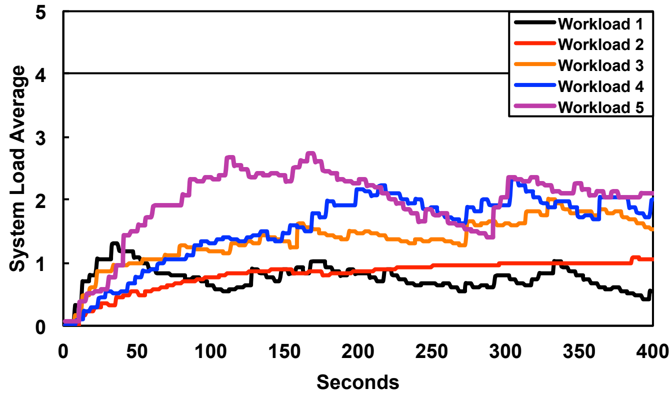



Fig. 5.12: Platform performance characterization for different workloads.

there are five containers running different services/applications, by enforcing the deployment feasibility of an efficient platform also in terms of scalability.

The only tangible difference between the behavior introduced with the different workloads is that, when disk operation -such as database writing- are included, the system load average grows introducing a sort of oscillating characteristic. On the contrary, if disk operations are excluded -like in the Workload 2 case- the aforementioned behavior is not observable.

## 5.3 Smart Agriculture Application

To meet the food demand of the future, farmers are turning to the Internet of Things (IoT) for advanced analytics. In this case, data generated by sensor nodes and collected by farmers on the field provide a wealth of information about soil, seeds, crops, plant diseases, etc. Therefore, the use of high tech farming techniques and IoT technology offer insights on how to optimize and increase yield. However, one major challenge that should be addressed is the huge amount of data generated by the sensing devices, which make the control of sending useless data very important. To face this challenge, we present a Bayesian Inference Approach (BIA), which allows avoiding the transmission of high spatio-temporal correlated data. In this work, BIA is applied to the PEACH project [218], which aims to predict frost events in peach orchards by means of dense monitoring using low-power wireless mesh networking technology. Belief Propagation algorithm has been chosen for performing an approximate inference on our model in order to reconstruct the missing sensing data. According to different scenarios, BIA is evaluated based on the data collected from real sensors deployed on the peach orchard. The results show that our proposed approach reduces drastically the amount of transmitted data packets and the energy consumption, while maintaining an acceptable level of data prediction accuracy.

### 5.3.1 Network Model

The PEACH network consists of 21 low-power wireless motes deployed in a peach orchard in Junin, a city close to Mendoza, in the West of Argentina (see Fig. 5.13). The temperature and humidity sensor built into the motes publish their value every 30s. Then, all the measurements were sent to the network gateway. The gateway is composed of a Raspberry Pi single-board computer and a DC2274 SmartMesh IP manager. These two components are connected to each other via a USB port. The gateway is connected to the Internet thanks to the solmanager application which runs on the Raspberry Pi. All the information received by the SmartMesh IP Manager will be transmitted by the solmanager to a remote server located in the Inria-Paris research center. The server in Paris, in turn stores the data into a database by means of the solserver application.

What we described above is the basic model proposed in the PEACH project. However, to reduce the huge amount of data generated by the sensor devices we

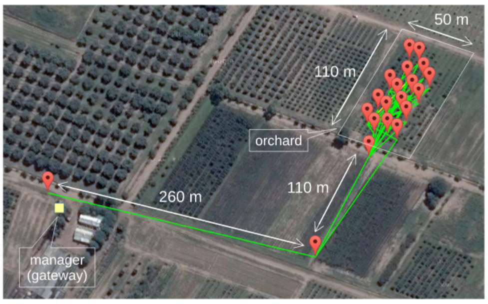



Fig. 5.13: The PEACH network [209].

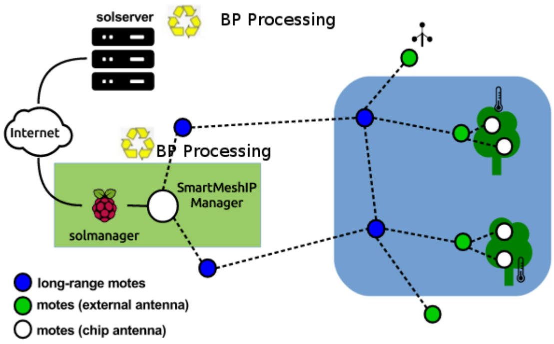



Fig. 5.14: Modified version of the BIA model applied to the PEACH network architecture.

have to modify this network model. Precisely, we have to implement our BIA approach on the remote server and on the gateway. Fig. 5.14 illustrates the modified version of the network model. In this case, the gateway has become intelligent and is able to send only the useful data. Using the inference algorithm which we will detail later, the server application will be able to reconstitute the missing data.

### 5.3.2 Bayesian Inference Approach (BIA)

In this section, we describe our BIA technique. As mentioned before, our main goal is to avoid sending useless data, while keeping an acceptable level of data content accuracy. BIA is based on Pearl's BP algorithm that will be described below.

As a starting point before any inference procedure, the design of a graphical model should be provided. Graphical models are schematic representations of probability distributions. They consist of nodes connected by either directed or undirected edges. Each node represents a random variable, and the edges represent probabilistic relationships between variables. Models which are comprised of directed edges are known as *Bayesian networks*, whilst models that are composed of undirected edges are known as *Markov random fields* (MRF) [217]. We consider an inference approach under the hypothesis of MRF, modeled by means of Factor Graphs. It follows that our goal is to estimate the state $Y$ of the sensed environment starting from the sets of data collected by each sensor node. Based on the remarkable Hammersley–Clifford theorem, the joint distribution P(y) of an MRF model is given by the product of all the potential functions

$$P_Y(y) = \frac{1}{Z}\prod_i \psi_i(y_i) \prod_{i,j\in E} \psi_{ij}(y_i, y_j), \tag{5.2}$$

where $Z$ is the normalization factor, $\psi_i(y_i)$ is the evidence function, $E$ is the set of edges encoding the statistical dependencies between two nodes $i$ and $j$, and $\psi_{ij}()$ represents the potential function. Note that the graphical model parameters (i.e. $\psi_i$ and $\psi_{ij}$) can be estimated from the observed data by using a learning algorithm like in [210]. Fig. 5.15 illustrates an example of the MRF model. The filled-in circles represent the observation nodes (*i.e.*, $N_{\varepsilon_i}$) and the empty circles represent the hidden nodes (*i.e.*, $y_i$). The potential functions are associated with the links between $y_i$

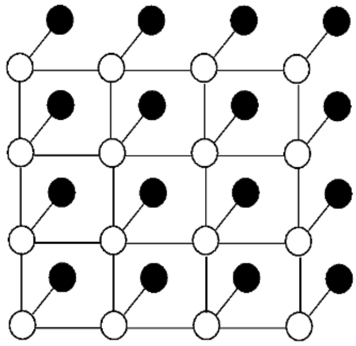


Fig. 5.15: An example of MRF model.

whilst the evidence functions are associated with the links between $N_{\varepsilon_i}$ and $y_i$. For simplicity, we consider widely used pairwise MRF, i.e., MRF with the maximum clique[6] of two nodes.

One of the main goals when dealing with graphical models is the margnial distribution computation (Eq. (5.3)). They are used to predict the most probable assignment for a variable node. For notation convenience, let us assume that $X$ and $Y$ are two distinct multivariate random variables with assignments $x \in \mathcal{X}^m$ and $y \in \mathcal{Y}^n$. The nodes in $Y$ are called hidden nodes and those in $X$ are the observed ones. So, given the $i$-th device in our network, $x_i$ will be the observation of the phenomenon we intend to share (e.g. temperature) and $y_i$ will be associate to the phenomenon we want to infer, (e.g. humidity)

$$p(y_v|x) = \sum_{y_1}\sum_{y_2}...\sum_{y_n} p(y_1, y_2, y_3, ...., y_n|x) \tag{5.3}$$

Obviously, using Eq. (5.3), the complexity of a complete enumeration of all possible assignments to the whole graph is $O(|\mathcal{Y}|^{n-1})$, which is intractable for most choices of $n$. Therefore, we need a faster algorithm like Belief Propagation[7] (BP) for computing the marginal probability. BP is a well known algorithm for performing inference on graphical models [222].

Let $p(y_i)$ represents the marginal distribution of $i$-th node, and BP allows the computation of $p(y_i)$ at each node $i$ by means of a message passing algorithm. The message from node $i$ to $j$ related to the local information $y_i$ is defined as:

$$m_{ji}(y_i) \propto \int \psi_{ji}(y_j, y_i)\psi_j(y_j) \prod_{u\in\Gamma(j),u\neq i} m_{uj}(y_j)dy_j, \tag{5.4}$$

where $\Gamma(j)$ denotes the neighbors of node $j$ and the incoming messages from previous iteration are represented by $m_{uj}$.

Eq. (5.4) will be performed between all nodes in the model until the convergence or if a maximum number of iterations $I_{max}$ will be reached. Thus, the prediction *i.e.*, the belief at the $i$-th node, is computed through all the incoming messages from the neighboring nodes and the local belief, *i.e.*:

$$\hat{y_i} = belief(y_i) = k\psi_i(y_i) \prod_{u\in\Gamma(i)} m_{ui}(y_i) \tag{5.5}$$

where $k$ is a normalization constant.

It is worth mentioning that the BP is able to compute the exact marginalization in the case of tree-structured graphical models. Fig. 5.16 illustrates the message passing process in BP.

### 5.3.3 Evaluation & discussion of the results

In this section we provide the experimental results of our approach. Real data collected from sensors deployed in the peach orchard have been used. As mentioned

[6] Clique is defined as a fully connected subset of nodes in the graph.
[7] Only take linear time

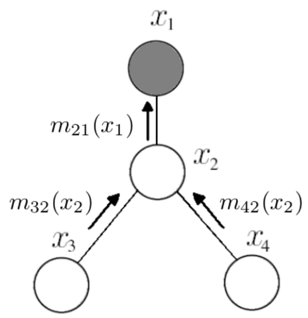



Fig. 5.16: Message passing process in BP algorithm.

before, these sensors collect temperature and humidity. Each data collection has been performed every 30 seconds. We focused on the data collected between 16 and 17 October 2016. Fig. 5.17 illustrates the relationship between data during the sensors reading. We can notice that there is a good correlation between temperature and humidity data. Hence, we can easily infer the humidity data from temperature data and vice versa. We decided to infer humidity from temperature. The temperature is in Celsius degrees, whilst the humidity is a value ranging from 0 to 100.

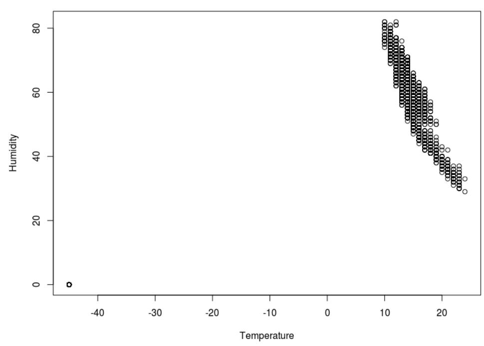



Fig. 5.17: Relationship between humidity and temperature data.

We assess our approach w.r.t. (*i*) the amount of transmitted data, (*ii*) the average value of the estimation error, (*iii*) the average value of the distortion level, and (*iv*) the energy consumption.

The number of transmitted data packets represents the total number of data transmission performed by all the sensors during the readings. The inference error is an important metric for any inference procedure. The goal is to have an errorless inference approach, *i.e.* an approach that is able to estimate the true value of data during all the inference procedures. However, this is almost never the case but we want that this error is as low as possible. In addition to the inference error, computing the distortion level is also important. This allows us to determine the difference between the real and the estimated value. The distortion level can be expressed using the Mean Squared Error (MSE) metric, which is defined as:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2, \tag{5.6}$$

where $\hat{y_i}$ and $y_i$ are respectively the predicted and true value during the $n$-th reading.

In our energy consumption evaluations, we assume that the energy cost for sending each temperature and humidity value is 3 mW. This energy cost has been obtained on the SHT-31 used mote. Furthermore, all of our assessments are based on three different scenarios.

| *Scenario* | *#Transmitted data* | $EC$ (W) | $MSE$ | $ER$ |
|---|---|---|---|---|
| s1 | 8408 | 25.224 | - | - |
| s2 | 4204 | 12.612 | 0.62 | 0.295 |
| s3 | 4260 | 12.78 | 0.022 | 0.0066 |

Table 5.5: Results obtained during the one day of readings.

In scenario $s1$, the gateway sends to the remote server all the temperature and humidity data it receives. This means that the server application does not perform any inference.

In the second scenario $s2$, the gateway sends only the temperature data to the remote server, and the cloud in turn infers the corresponding humidity data by using the BP algorithm.

Finally, in scenario $s3$, we consider that the gateways are "smart" devices, meaning that before sending their data to the remote server, they first compute the probability $p(e|T, h)$ of making an inference error $e$ on the cloud given the temperature $T$, and the humidity $h$. If there is a high probability that the error magnitude exceeds a predefined threshold, the gateway sends both humidity and temperature data to the remote server, else the gateway sends only the temperature data, and the humidity value will be inferred in the remote server using the BP algorithm. The computation of $p(e|T, h)$ is done by means of the BP algorithm also. It should be noted that this computation requires the knowledge of the a priori probability of inference error, *i.e.*, $p(e)$.

#### 5.3.3.1 Obtained results

As mentioned before, we evaluate the performance of our approach in terms of number of transmitted data packets, average value of the estimation error (*i.e.*, $ER$), average value of the distortion level (*i.e.*, $MSE$), and energy consumption (*i.e.*, $EC$). Our approach has been implemented in C++, and the assessments have been performed with respect to the ground truth collected on the peach orchard.

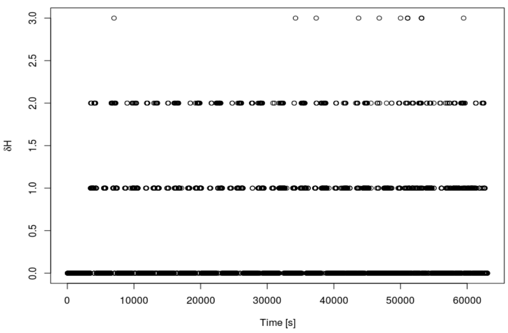
Table 5.5 illustrates the obtained results during one day of readings (16-17 October 2016), for different simulated scenarios. We can notice that our Bayesian inference approach drastically reduces the number of transmitted data packets and the energy consumption, while maintaining an acceptable level of prediction accuracy and information quality. We can notice also that we decrease considerably the estimation error by using the scenario s3. Indeed, the gateway is smarter in this case since it will be able to estimate the right moment and the proper data type to send to the remote server. However, this increases the number of transmitted data (and hence the energy consumption), as compared to scenario s2. This is due to the fact that in s2 gateways send only the temperature data without worrying of the risk of inference error in the cloud.

Fig. 5.18 shows the variation of $\delta H$ during one day of reading using S2 and S3, where $\delta H$ is the the difference between the true value and the inferred value of humidity data i.e. $\delta H = \hat{y}_i - y_i$. This metric illustrates therefore the inference error of our BIA approach during all the readings. There is no inference error when $\delta H = 0$ i.e when $\hat{y}_i = y_i$. It should be noted that we did not consider S1 in this figure since it does not use an inference approach.

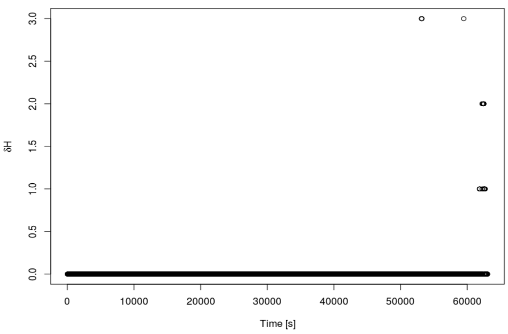
## 5.4 Conclusions

In this chapter I have presented three different real applications where I have shown how the tools and the algorithms designed and implemented in the previous chapters can be effectively exploited. In particular, I have shown a surveillance monitoring application, a smart car application and a smart agriculture application.

In the first scenario, we have exploited the neural/genetic solution presented in the previous chapter and we have evaluated the impact of the deployment on a survellance monitoring application.




(a) Using S2




(b) Using S3

Fig. 5.18: Variation of $\delta H$

In the second case, we have considered a gateway-based architecture. In particular, the prototype that we have developed is based on Raspberry Pi3 and implements a container-based virtualization solution to manage different parallel processes, including the treatment of information generated by the CANbus. The different processes can be opportunistically scheduled based on specific requirements (e.g., the management of alert processes). It is worth to note that for implementing this logic, we have exploited the *process-as-a-service* concept investigate before. Through a proof-of-concept testbed we have demonstrated both the feasibility of a smart car design based on Docker virtualization containers and its effectiveness in terms of responsiveness and reactivity of the system. The derived system is customized and compliant with the final user requirements.

The third scenario is also representing a gateway-based architecture. BIA is based on a hierarchical architecture with simple nodes, smart gateways and data centers. Belief Propagation algorithm has been chosen for performing an approximate inference on our model in order to reconstruct the missing sensing data. BIA is evaluated based on the data collected from real sensors and according to different scenarios.

The three scenarios have some common features, since they are constituted by heterogenous nodes with different roles. An hierarchical architecture is envisageable in all the considered contexts. Most important, in all the applications, we "implicitly" need to perform either an *in-network* or an *out-network* discovery functionality.

The experience acquired to really implement theoretical solutions and simulated algorithms has been an important aspect, above all in the last 4 years of my research activity. An important lesson learned is about the identification of which part of the system is the most important to be demonstrated at the beginning. This not obvious at first, above all when we deal with complex systems, and it is most important when we consider a loop-wise based approach to "re-use" the results as input for the implemented (simulated/theoretic) algorithms.

**Publications**

[J4][J8][J16][C1][C3][C5][C6][C7][C8][C23]

# 6

# Conclusions and Future Perspectives

In this chapter, I first present the general conclusions and then enumerate my perspectives for future work.

## 6.1 Conclusions

In this manuscript, I developed my research activity during the last seven years. I mainly dealt with Complex Self-Organized Network Systems (CSONS) where heterogeneous objects need to cooperate and interoperability needs to be ensured. I have had the opportunity to address many types of networks in the end-to-end global architecture from IoT to IoRT passing from Wireless Sensor Networks.

The **first important lesson learned** by approaching with this type of system is the identification of the most important challenges, namely the achievement of self*-properties as self-management, self-configuration, self-handling, self-optimization, etc. This exercise forced us to reasoning through a "bottom up" approach, in the sense that, unlike the traditional systems, in CSONS we need to think at the local information among components in order to be able to apply "actions" that will impact at a global level.

Following this type of approach, we envisaged basic but fundamental functionalities such as *in-network* and *out-network* device/service discovery.

In all systems we have treated right now, even if discovery is not explicitly mentioned, it is implicitly performed. For that reason, I have dedicated the second chapter to this important topic.

The **second lesson learned** is regarding the "heterogeneity" that we explicilty integrated in the system design. One of the first source of heterogeneity among devices is if they are equipped or not with motion capabilities [57]. Regarding mobility we have experienced that if we are able to "control" or "predict" it, we can use it as a primitive control of the network design and then we are able to take advantage of it. We have extended this approach to other types of "heterogeneity", by working on the potential "smartness" of the nodes.

In practice, we have put some kind of intelligence on the most powerful nodes in the network by developing Artificial Intelligence (AI) approaches based on bio-inspired mechanisms such as neural networks and genetic approaches. In chapter 3 I have demonstrated that the AI approaches can be combined with technological advances (i.e. Software Defined Radio). This approach allows a sinergic combination between theoretical results (e.g. capacity channel computation) with specific "features" of nodes by leveraging the most advanced technologies. This type of approach is not only very performing as demonstrated by the evaluation results, but it is also very impactful in higly variable environments. A very important feature of this type of approach is that it can be integrated at each layer of the communication protocol stack, by resulting of general applicability.

The last part of the thesis was devoted to the implementation of proof-of-concept based on real test-bed of the solutions described. Despite this activity is really energy consuming and time consuming, its impact is really important. Most important we have implemented a loop-wise approach, by considering the output of the real implementation as corrective factors for the theoretic/simulated solutions. With this perspective in mind, we have proposed three different real scenarios with different goals and constraints in the last chapter.

## 6.2 Perspectives: Alternative Communication Paradigms

Hereafter, I expose the main research directions I propose to follow.

The solutions developed right now and presented in this work, were mostly implemented for "traditional" frequency spectrum ranging from 800-900 MHz to 5 GHz. The sinergic approach based on neural/genetic algorithm and SDR capabilities to compute the most suitable modulation scheme has been considered and proved for wireless sensor nodes working in a spectrum range up to 2.4 GHz. By considering the spectrum inefficiency and the interferences problems, I have started to dedicate my research efforts towards alternative communication paradigms such as paradigm based on Terahertz spectrum bandwidth and Visible Light Communications (VLC).

**Terahertz spectrum bandwidth**

TeraHertz (THz) technologies have recently gained greater interest and expectations to meet an ever-increasing demand of objects to be wirelessly connected and at higher speed. Among the most important requirements for the Future Beyond the Fifth Generation (B5G) mobile networks offer very high throughput per devices, the capability to handle a huge amount of data with a low delay, in an heterogeneous context (i.e. connected heterogeneous devices) with different resource capabilities, equipped or not with mobility capacity, etc.

THz band is envisaged as a next-frontier for wireless communications, but it has been realized that novel protocols at each layer need to be developed, since classical solutions are inadequate to capture the peculiarities of THz band. In particular, novel link layer solutions taking into account the specific challenges at the link layer in terms of Medium Access Control approaches, packet size design, error control policy, etc. need to be considered. By correctly identifying the new challenges, we can exploit the bio-inspired AI approaches to take into consideration the specific physical THz features and then implementing this approach at the transmitter side in order to make it able to choose the best physical layer parameters in a very adaptive way and by accounting for the communication distance and estimated channel conditions.

The specific challenges of THz band require the investigation of novel communications paradigms at 1) Signal Level: 2) Material Level; 3) Novel communication mechanisms and 4) Performance evaluation tools (see Figure 6.1).

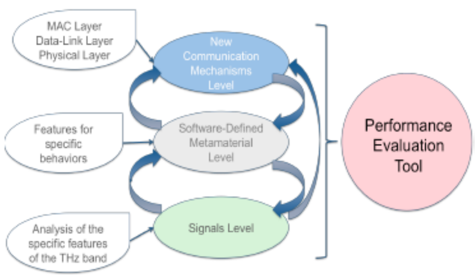



Fig. 6.1: Terahertz model.

- *At the Signal Level* Phenomena at signal level such as negative refractive index, super-focusing, extraordinary transmission, chirality, giant optical activity, deserve to be deeply studied under the communication perspective, by considering an information theory approach for these specific features as we have done for chirality in [202–204]. Chirality refers to the geometric property of a structure lacking any mirror symmetry plane. There exist several naturally chiral materials such as DNA, sugar and many other bio-molecules that exhibit a modest chiral activity.
- *At the Material Level* Recently, artificial chiral metamaterials have been shown to exhibit large optical (chiral) activity. In that context, a novel paradigm named Software Defined Metamaterials (SDMs) has been proposed [205]. SDMs are

a new class of programmable metamaterials, whose electromagnetic properties can be controlled via software. Their existence is crucial for TeraComm for twofold reasons. Firstly, we aim to advance the comprehension of key features of THz band signals in specific types of materials and then we aim to become provider of interesting results for researchers as contributors of working on SDM paradigm [205]. The other reason is that the Terahertz Communication Mechanisms can be based on this type of (meta)material and in the future we could think to exploit SDMs as validation tools of our theoretical founds and as driven material for new types of communication devices.
- *At the Communication Mechanisms Level* THz based communication mechanisms are still in their infancy, since this portion of spectrum has recently started to attract research and industrial interests, also boosted by recent technological and material advancement (e.g. graphene). Based on previous results we have obtained [202–204], where we have approached to THz band through an information theory perspective, we are persuaded that the specific features of THz band signals with specific types of material can provide the needed control of the global communication system, allowing the design and development of fast-adaptive communication mechanisms that are able to self-react to the surrounding changes. We have already demonstrated the availability of a similar paradigm for WiFi in [7].

From a methodological point of view I am planning to address the different identified challenges as follows:

- At the *Signal Level*: the scientific methodology includes the investigation of specific features and if/how they could be controlled and in which type of (meta)material. Even though scientific community is aware about specific features as chirality, giant optical activity, etc., most of the time their "consideration" under a communication perspective has not been done. We have already demonstrated how specific features can impact the communication capacity by considering an information analysis of the systems.
- *At the Software-Defined Metamaterial Level*: the scientific methodology includes the investigation of 1) novel types of metamaterial, 2) the analysis of the output of the system based on specific input signals and by considering different spectrum portions. The technological methodology includes building an ad-hoc general emulator tool, in order to facilitate the prototyping phase of SDMs.
- *At the New Communication Mechanisms Level*: based on the previous levels, in terms of scientific methodology we will be able to design new adaptive communication paradigms.
  The mechanisms envisaged will be adaptive since they will be based on smart devices able to analyze the surrounding and "adapt" their behavior for providing the best configuration (e.g. in terms of modulation, data rate, type of communication scheme, etc.). The adaptivity will be possible thanks to SDM level analysis and will be based on learning approaches that will make the devices autonomous and smart. These communications approaches could be very efficient in vehicular contexts and for opportunistic communication paradigms, where short-life Tera links can allow a rapid and huge data transfer.

Indeed, a very interesting domain for Tbps links is represented by **vehicular networks**, since when transmitting at high data-rates, even if users are mobile, the link appears to be static from the data perspective, due to the transmission that appears almost as "instantaneous". In my future research activities I plan to highly focus on this research domain. Indeed, even if it is not new from a chronological point of view, in terms of practical solutions it can be considered at earlier stages, since the specific features of context make real solutions difficult to actually work.

**Visible Light Communication**

Another very interesting research domain on alternative communication technologies is Visible Ligth Communication (VLC). (VLC) is gaining a lot of interest both in the scientific and industrial community. Despite to this increasing interest, VLC is still at its infancy and it has been realized that communication techniques at physical and Medium Access Control (MAC) that are well assessed in traditional (wireless) communication contexts cannot be applied in VLC domain. Indeed, the external interferences are different in nature and impact. Both artificial lights and sun light may disturb the communication and we have observed that the external conditions change unpredictably and abruptly. Based on these considerations, it has been realized that transmitters and receivers need to be equipped with a sort of intelligence making them capable to dynamically react to the external changes in order to make the communication system more robust. By working on a VLC communication prototype we have realized that the external conditions are extremely varying and higly impactful on the system performance in terms of Bit Error Ratio (BER) and throughput [71,72]. In order to face with this extremely interference environment, we are investigating on different aspects. Just as an example, we have started to consider the carrier recovery phase in a basic VLC system constituted by a transmitter and a receiver working in a bi-directional fully connected way. By analyzing the preamble length in frame sent by the transmitter, we have evaluated the impact of the preamble length in terms of Bit Error Ratio (BER) and throughput. Results of this analysis were surprising, since different preamble sizes can be very impactful in terms of carrier recovery efficiency and throughput. Based on these remarks, we have realized that it is necessary to put some intelligence directly on the devices, in order to make the system more reactive. We elaborated the preamble length set as a multi-arm bandit problem in order to dynamically set the most suitable preamble size based on the external interference conditions. In order to validate the performance of the system, we have implemented a low cost prototype and the algorithm has been implemented at the receiver side.

In this specific context we are considering:

- An accurate analysis of the impact of the preamble length in different real conditions;
- Design and implementation of the preamble length set as a multi-arm bandit problem with a Thompson sampling approach;
- Validation of the Artificial Intelligence logic implemented by the means of a real low cost based prototype in order to show that the solution is extensible to all kinds of VLC systems since it is not requiring powerful devices to run.

Right now we have implemented a Frequency Shift Key (FSK) modulation, because of its easier implementation on top of a low cost architecture, but we are planning to evaluate performance of the VLC system equipped with this AI logic with different communication schemes, OOK, PSK, QAM, OFDM, etc.

Another interesting perspective would be to adapt, by the mean of a software defined approach, the modulation scheme. Just as an example, we have already verified that if the pair transmitter-receiver are close to each otehr, OOK scheme performs very well allowing to reach higher data rate than FSK, but throughput performance degrade very fastly when distance increases.

**Predictive Approaches**

Concerning the BIA approach described in this work, it is based on a static MRF model. In fact, it is not updated after it is built. In order to address environmental dynamics, the MRF model should to be updated with an adaptive scheme. Another potential extension of this model consists in the inclusion of spatial correlations. In fact, this BIA approach could be applied to spatially-correlated devices by activating intelligent wake-up mechanisms including only a sub-set of devices and BIA inferring the data for the others. Another interesting perspective I am evaluating is the possibility to exploit the BIA approach implemented at signal level, by trying to "enrich" the information at signal level through an inference approach allowing the reconstruction of the signal when and where it is "distorted" due to the high noise level.

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# Publications

**Books Edited**

[B1] Anna Maria Vegni, **Valeria Loscrí**, A.V. Vasilakos Vehicular "Social Networks" CRC Press 2016.

[B2] Antonio Guerrieri, **Valeria Loscrí**, Anna Rosella, Giancarlo Fortino Management of Cyber Physical Objects in the Future Internet of Things Springer, 2016, 978-3-319-26869-9

**Book Chapters:** [BC1] **V. Loscri**, A. Maskooki, N. Mitton, A.M. Vegni, "Wireless Cognitive Networks Technologies and Protocols" in Modeling and Simulation of Computer Networks and Systems: Methodologies and Applications, Elsevier, 2015.

[BC2] N El Zoghby, **V Loscri**, E Natalizio, V Cherfaoui, "Robot Cooperation and Swarm Intelligence ," Wireless Sensor and Robot Networks: From Topology Control to Communication Aspects (2014).

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[J1] Antonio Costanzo, **Valeria Loscri**, Sandra Costanzo "Software Defined Platforms for Visible Light Communication: State of Art and New Possibilities" IEEE Communications Society Multimedia Communications Technical Committee Communications - Frontiers, IEEE, 2017, 12 (3), pp.14-18.

[J2] Francesca Guerriero, **Valeria Loscrí**, Pasquale Pace, Rosario Surace "Neural Networks and SDR Modulation schemes for wireless mobile nodes: a synergic approach" in Ad Hoc Networks, Elsevier, 2017.

[J3] Anna Maria Vegni, **Valeria Loscrí** "Analysis of the Chirality Effects on the Capacity of Wireless Communication Systems in the THz band" in IEEE Transactions on Wireless Communications, Institute of Electrical and Electronics Engineers, 2017.

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[J5] Valeria **Loscrí**, Anna Maria Vegni "Capacity evaluation of a quantum-based channel in a biological context" in IEEE Transactions on NanoBioscience, 2017

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[J12] Anna Maria Vegni, **Valeria Loscrí** "A Survey on Vehicular Social Networks" in Communications Surveys and Tutorials, IEEE Communications Society, Institute of Electrical and Electronics Engineers, 2015.

[J13] Valeria **Loscrí**, Anna Maria Vegni, "An Acoustic Communication Technique of Nanorobot Swarms for Nanomedicine Applications" in IEEE Transactions on NanoBioscience, Institute of Electrical and Electronics Engineers, 2015, pp.1-10.

[J14] Gianluca Aloi, Luca Bedogni, Luciano Bononi, Orazio Briante, Marco Di Felice, **Valeria Loscrí**, Pasquale Pace, Fabio Panzieri, Giuseppe Ruggeri, Angelo Trotta "STEM-NET: How to Deploy a Self-Organizing Network of Mobile End-User

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