# *Center of Excellence for Research DEWS*

## *Research Activity Report*

## *Years 2009-2012*

*University of L'Aquila, May 2012*

*"Design methodologies for Embedded controllers, Wireless interconnect and Systems-on-chip"*

DEWS
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# Summary

# Activity Overview

DEWS started its operations in 2001 after the Ministry of Scientific Research and University awarded grants for the formation of centers of excellence on a competitive basis. DEWS was among the very first organizations that proposed research on the use of networks of sensors, controllers and actuators to solve societal scale problems such as health, disaster recovery, transportation systems, and education. Its mission is still quite relevant as the EU intends to focus the FP VIII on societal problems. DEWS promotes interdisciplinary cooperation among researchers to achieve its research objectives. In particular, DEWS researchers are active in networked embedded systems automatic control, analog and digital electronics, computer science and telecommunications. The activities at DEWS currently pursue the objective ICT-2011.3.3 "New paradigms for embedded systems, monitoring and control towards complex systems engineering" of the EC ICT Work Programme 2011-2012:

*"Objective ICT-2011.3.3 pushes forward the limits of embedded systems, monitoring, control and optimisation technologies and introduces a new domain, "System-of-Systems" engineering. The aim is to develop novel methodologies and advanced engineering approaches for designing, developing and executing/running complex/large scale, distributed, and cooperating systems."*

## Research Strategy

The research activities at DEWS are structured into six research areas, as depicted in Fig.1:

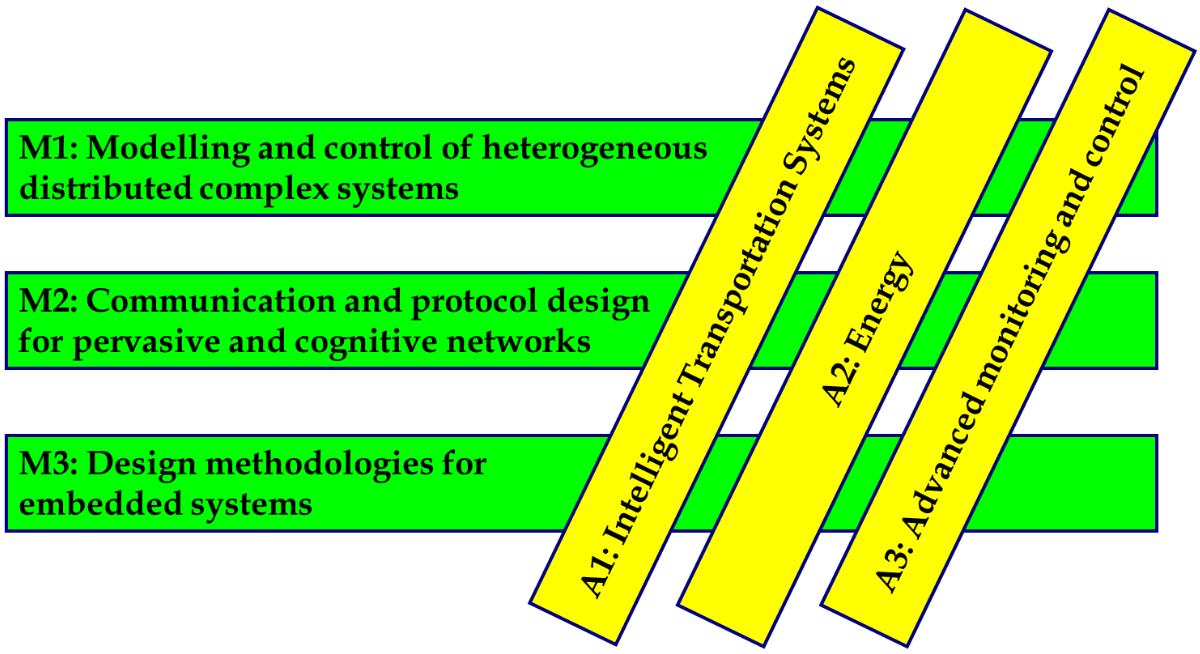


Figure 1: DEWS methodological and applicative research areas.

*Methodologies and Technologies:*

- M1: Modelling and control of heterogeneous distributed complex systems
- M2: Communication and protocol design for pervasive and cognitive networks
- M3: Design methodologies for embedded systems

Research Areas M1, M2 and M3 are foundational, they are aimed at developing new methodologies for the design of complex embedded systems and communication paradigms for their mutual interaction. In particular: M1 provides the basic mathematical background and tools for analysis, verification and design of networked embedded control systems; M2 provides the fundamental background for networked systems, their architectures and design methodologies; M3 provides the fundamental background on models, metrics and tools for embedded systems development.

*Applications:*

- A1: Intelligent Transportation Systems
- A2: Energy
- A3: Advanced monitoring and control

Research Areas A1, A2 and A3 are orthogonal to the foundational areas, each covering an application specific research domain.

In 2001 DEWS created the DEWSLab, a laboratory for the design and implementation of wireless sensor networks using products developed by Memsic (ex Crossbow) and Texas Instruments. The lab has been configured as a "testbed" for innovative solutions related to routing and coding algorithms and it is used as a web service to allow remote access to interested parties. Within the FP7 Network of Excellence HYCON, DEWS has been chosen as the node of the European Embedded Control Institute (eeci-institute.eu) for the realization of the European Networked Control Systems Laboratory (NCSlab).

# Education

DEWS has been awarded a grant to set up an Advanced ICT School on pervasive computation, communication and control systems. This initiative gained enthusiastic support from industry because of its goal of connecting the ICT research and industry communities. This award had a number of important outcomes: i) the ICT School was considered as a founding pillar of the recently approved Innovation District (Polo di Innovazione) "ICT Abruzzo", ii) it was supported by OCSE as an enabling initiative to reinforce\innovate the local economic context after the 2009 earthquake, iii) it created the framework for joint research initiatives and laboratories funded by industry in recognition of the School's potential economic impact. DEWS is now in the process of establishing the School with a target of 20-30 students enrolled from the international community.

Further, DEWS signed a Joint Doctoral Degree agreement with the *Royal Institute of Technology* (KTH, Stockholm, Sweden) and with the *Centro de Investigación y Estudios Avanzados* (CINVESTAV, Instituto Politécnico National, Campus Guadalajara, Mexico). The doctoral candidates carry out their activities under the responsibility and the guidance of thesis advisors from each of the two universities. The two advisors act in all respects as academic mentors for the doctoral candidate. The joint doctoral degree allows a doctoral candidate to obtain a PhD degree from each of the co-advising universities.

DEWS is partner of the International Curriculum Option (ICO, centropiaggio.unipi.it/ICO) of Doctoral Studies in Hybrid Control for Complex, Distributed and Heterogeneous Embedded Systems. ICO started in January 2006 to provide a common cultural and academic platform by establishing a network of institutions that have a set of common supplementary criteria for the participating PhD students in addition to those of their already-existing doctoral programs.

## Academic Collaborations

As a consequence of the participation to high-level EU funded research projects and of exchanges of researchers/PhD students, DEWS has established strong research collaborations with some of the most prestigious universities and research centers in the world such as the University of California at Berkeley, the University of California at Los Angeles, the University of California at Santa Barbara, the Ohio State University, the University of Pennsylvania, the Royal Institute of Technology (KTH, Stockholm), the Technical Universities of Delft and Eindhoven, Supélec (Paris), the Berkeley Wireless Research Center (BWRC), the Berkeley Center for Hybrid and Embedded Software Systems (CHESS), the Center for Automotive Research (CAR, US), the Italian Center for aerospace research (CIRA, Italy), the National Aerospace Laboratory (NLR, Netherlands). The worldwide academic and industrial collaboration network of DEWS is depicted in Figure 2.

In particular, DEWS signed formal cooperation agreements with the University of California at Berkeley (UCB, US) at the beginning of its operation and with the "Antonio Ruberti Institute on Systems Analysis and Computer Science" (IASI-CNR, Italy) recently, which involve the mutual exchange of researchers and students working on joint projects.

DEWS is coordinator of the Committee of the Centres of Excellence established during the period 2001-2003 by the Ministry of Education, University and Scientific Research (centrieccellenza.it).

## Industrial collaborations and SPIN-OFF activities

DEWS has ongoing collaborations with multinational companies such as Selex Communications and Selex Elsag (Chieti, Florence, Genoa, Pomezia - Italy), TechnoLabs (L'Aquila - Italy), Thales Communications (Chieti - Italy), Thales Alenia Space (L'Aquila - Italy), Micron Technology (Avezzano - Italy), Akhela S.r.l. (Cagliari - Italy), ITACO (Roma - Italy) and Ford (Aachen – Germany), ICT Abruzzo Innovation District and the partners of EU and national research and industrial projects. In this context DEWS has been able to plan and manage projects of significant complexity as well as to spin-off an engineering company (WEST AQUILA, westaquila.com).

After a competitive call issued by the local government (Regione Abruzzo) in agreement with the EU policy for stimulating the creation of Innovation Districts (Poli di innovazione) in the globalized economy, the Center of Excellence DEWS has been very active in preparing a successful proposal for the foundation of "ICT Abruzzo". ICT Abruzzo includes about 50 companies (among those Micron Technology, Selex-Elsag, Telespazio, Fastweb, several SMEs, while other companies have applied to join), University of L'Aquila-DEWS and other research centers (e.g. Radiolabs and CNIT). In this context, the ICT School has been included as a founding pillar for promoting and implementing innovation through advanced training at the doctoral level: the School is intended also as a fundamental environment for improving cooperation among companies and between companies and universities\research centers as well. The School will be supported by ICT Abruzzo as an integral part of its program.

As an enabling and complementary initiative for promoting innovation and technology transfer, the Center of Excellence DEWS has joined a new initiative targeted to support the creation of high-tech start-ups in the Abruzzo region through an international competition for accessing seed capital (see 10to6competition.org for details). The financial support and coordination is provided by M31, Vertis SGR and Fondamenta SGR, with the first call having been launched and still open. Furthermore, M31 is planning to open a site in L'Aquila with the aim of interacting more closely with University of L'Aquila and contributing to setup a high-tech park in the ICT area.


Figure 2: DEWS worldwide collaboration network.

## Projects

The activities of DEWS are supported by the participation in several research and industrial international projects, in particular:

**CRAFTERS:** ConstRaint and Application driven Framework for Tailoring Embedded Real-time Systems. Call ARTEMIS JU 2011, 2012-2015 (36 months). This project brings to bear an holistically designed ecosystem, from application to silicon, for real-time, heterogeneous, networked, embedded many-core systems. The ecosystem is realized as a tightly integrated multi-vendor solution and tool chain complementing existing standards.

Total cost of the project: 17.861.802 €

DEWS cost: 518.400 € - Contribution from ARTEMIS JU: 86.573 € - National contribution (MIUR): 172.627 €

**RICOSTRUIRE:** Trasferimento tecnologico e creazione di nuove imprese nell'ambito delle tecnologie ICT avanzate applicate allo sviluppo economico e territoriale post-sisma. Bando RIDITT 2009, 2012-2014 (21 months). The project aims at developing laboratories for knowledge and technology transfer on the following topics: Open Source SW, Smart heterogeneous networks, ICT services for smart and secure buildings.

Total cost of the project: 2.000.000,0 €

DEWS cost: 1.675.000 € - National contribution (MSE): 837.500 €

**SMILING:** SMart In home LIviNG: Tecnologie innovative per la sensoristica e l'automazione dedicate alla Domotica. Bando RIDITT 2009, 2012-2014 (21 months). The project aims at realizing a laboratory for knowledge and technology transfer from the research to the world of industries focusing on advanced automation and sensing technologies for the home automation domain.

Total cost of the project: 1.999.687,5 €

DEWS cost: 501.250 € - National contribution (MIUR): 250.625 €

**PRESTO**: ImProvements of industrial Real Time Embedded SysTems development process. Call ARTEMIS JU 2010, 2011-2014 (36 months). PRESTO aims at improving test-based embedded systems development and validation, while considering the constraints of industrial development processes.

Total cost of the project: 8.662.934 €

DEWS cost: 518.400 € - Contribution from ARTEMIS JU: 86.573 € - National contribution (MIUR): 172.627 €

**MAREA:** Mathematical approach towards resilience engineering in ATM. SESAR WP-E, 2011-2013: in the MAREA project, the results achieved in the iFly Project provide the formal methodology to address the new SESAR 2020 concepts of operation, at present under study by the air traffic management systems' experts at EUROCONTROL.

Total cost of the project: 649.658 €

DEWS cost: 182.000 € - EU contribution: 163.800 €

**HYCON2:** Highly-complex and networked control systems. EU FP7 NoE, 2010-2014. HYCON2 started in September 2010, is a four-year project coordinated by the CNRS. It aims at stimulating and establishing a long-term integration in the strategic field of control of complex, large-scale, and networked dynamical systems. It focuses in particular on the domains of ground and aerospace transportation, electrical power networks, process industries, and biological and medical systems. The FP7 NoE HYCON2 provided its vision on the challenges of future for systems and control science technology in the Position Paper on Systems and Control in FP8.

Total cost of the project: 4.905.855 €

DEWS cost: 332.926 € - EU contribution: 273.000 €

**VISION:** Video-oriented UWB-based Intelligent Ubiquitous Sensing. FP7 "Ideas" Specific programme ERC Staring Grant 2009, 2010-2014 (48 months): VISION will develop an innovative infrastructure aiming at strengthening future wireless sensor networks (WSN) with the capability of supporting intelligent services for ubiquitous sensing, with particular emphasis on real-time 3D video sensing.

Total cost of the project: 1.173.680 €

DEWS cost: 120.342 € - EU contribution: 120.342 €

**CASA+:** Integrated domotic platform for enabling autonomy of disabled people. The project started in 2010 and it is funded by AIPD (No profit association for disabilities) and Vodafone Foundation (2010-2012). The research is focused on developing smart and non-intrusive solutions for networking, tracking and user interfaces to help people with disabilities to carry out basic daily life operations. A test bed has been developed in cooperation with WEST Aquila srl.

DEWS cost: 82.000 € - National contribution (AIPD): 82.000 €

**PAR2010:**Analisi dei Sistemi di Supervisione, Controllo e Protezione per Reattori Nucleari di Nuova Generazione. MSE, 2010-2011. The Italian Ministry of Economic Development (Ministero dello Sviluppo Economico, MSE) and the Italian Agency for new technologies, energy and sustainable economy (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, ENEA) established an agreement to grant financial assistance for the execution of the three-year plan of research and development of general interest to the "National Electric System". In particular, ENEA has signed a research contract on the theme "Analysis of core instrumentation and simulation" under the area "Nuclear Fission: Methodologies for analysis and verification of nuclear projects fueled by pressurized water". The themes developed under this collaboration agreement between ENEA and the Center of Excellence DEWS, University of L'Aquila focus on the supervision, control and protection for pressurized water nuclear reactors of new generation.

DEWS cost: 130.000 € - National contribution (MSE): 130.000 €

**ESSOR:** European Secure SOftware Radio programme. (MP-IST-083-04, 2008-2012). ESSOR is a major European research program in SDR, supported by several european countries and led by major industrial manufacturers, whose main objectives are to strengthen European autonomy on a crucial technological area, federate European industries activities to support production equipment and support development of open standards. The focus is on developing MANETs with a large number of nodes (hundreds) that are able to operate in harsh environments. Activities of this project have been carried out in the frame of the Radiolabs Consortium. The second phase of this will start at the end of 2012.

DEWS cost: 120.000 € - EU contribution: 120.000 € (managed through Radiolabs Consortium)

Former research activities of DEWS are related to the participation in the following projects:

**iFly:** Safety, Complexity and Responsibility based design and validation of highly automated Air Traffic Management. EU FP6 STREP, 2007-2011: During recent years the ATM community research trend is to direct large airborne self-separation research projects to situations of less dense airspace. iFly aims at fostering this transition through a systematic exploitation and further development of the advanced mathematical techniques that have emerged within the HYBRIDGE project of EC's 5th Framework Programme. iFly research intent is to establish an upper bound on traffic levels for which airborne self-separation is safe. For en-route traffic, iFly has the objective to develop an advanced control design for airborne self-separation within the SESAR framework. The goal is to accommodate a three- to six-fold increase in current en-route traffic levels. The approach is to develop an overall validation plan which incorporates safety analysis, complexity assessment and pilot/controller responsibilities together with an assessment of ground and airborne system requirements.

Total cost of the project: 3.309.000 €

DEWS cost: 330.000 € - EU contribution: 166.500 €

**DISTRETTO ABRUZZO:** Wireless Networks and Advanced Platform for Smart Agriculture. Funded by Ministry of Research (MIUR, 2007-2011) and Selex Communications. The aim of this project is to define and develop a platform relying on wireless sensor networks for constant and energy efficient environment monitoring oriented to support advanced practices in the food chain. The project has already led to a test-bed development.

Total cost of the project: 1.500.000,0 €

DEWS cost: 54.500+80.000 € - National contribution (MIUR): 35.560 € + 80.000 €

**IRMA:** Impulse Radio for Multimedia Applications. Research Contract with Thales Communications in the frame of a project funded by the Italian Ministry of Defense (MD). The project was concerned during the first two phases (2006-2010) with definition and validation of an UWB physical layer for integrated communications, positioning and multi-static radar scanning. The third phase is now concerned with the development of a demonstrator (HUMANET) that involves our startup WEST Aquila srl.

DEWS cost: 105.000 € - National contribution (MD): 105.000 €

**PRIN 05:** Forecast and control systems for landslides: local sensor distributed networks integration, monitoring techniques and hydro-geological models. MIUR, 2006-2007. The research project aims at combining locally deployed sensors and remote sensing for acquisition of a multitude of physical parameters that are directly or indirectly related to those phenomena that may determine landslides events in unstable slopes. If compared to currently employed techniques, the proposed method is characterized by the use of advanced technologies such as remote sensing e dense wireless sensor networks: thus, a large set of measurements can be performed and collected, and then used to feed advanced models and algorithms, with the ultimate goal of performing more reliable and economic forecast tools.

Total cost of the project: 84.000 €

DEWS cost: 52.000 € - National contribution (MIUR): 36.000 €

**HYCON:** Hybrid Control: Taming Heterogeneity and Complexity of Networked Embedded Systems. EU FP6 NoE, 2004-2008: The objective of the NoE HYCON is establishing a durable community of leading researchers and practitioners who develop and apply the hybrid systems approach to the design of networked embedded control systems that are found, for example, in industrial production, transportation systems, generation and distribution of energy, communication systems. Hybrid systems provide a scientific paradigm to systematically address the analysis, modelling, simulation, synthesis, and optimisation of digital controllers for physical plants that communicate directly or via networks with other computerized systems and with human users and supervisors. HYCON aimed at a major advancement of the methodology for the design of such systems and their application in power management, industrial controls, automotive control and communication networks. The long-lasting result was the establishment of a European Embedded Control Institute (EECI) that is a worldwide focal point for hybrid and embedded systems research. The network contributed significantly to bridge the gap between traditional control engineering and embedded system design.

Total cost of the project: 5.608.166 €

DEWS cost: 236.000 € - EU contribution: 236.000 €

**HYBRIDGE:** Distributed Control and Stochastic Analysis of Hybrid Systems Supporting Safety Critical Real-Time Systems Design. EU FP5 STREP, 2002-2005: HYBRIDGE was a project within the 5th Framework Programme IST-2001-IV.2.1 (iii) (Distributed Control), funded by the European Commission under contract number IST-2001-32460. The 21st century finds Europe facing a number of remarkable changes, many of which involve large complex real-time systems the management and control of which undergoes a natural trend of becoming more and more distributed while at the same time the safety criticality of these systems for human society tends to increase. However good the control design for these systems will be, humans are the only ones carrying responsibility for the operational safety. This implies that control system designs for safety critical operations have to be embedded within sound safety management systems such that the level of safety stays under control of humans. The objective of HYBRIDGE was to develop the methodologies to accomplish this, and to demonstrate their use in support of advanced air traffic management design. In addition to direct application to air traffic management, these contributions formed the nucleus for further research and development into a complex, uncertain system theory, and into application of this theory to distributed control of other real time complex systems such as communication, computer and power networks.

Total cost of the project: 3.991.156 €

DEWS cost: 453.697 € - EU contribution: 226.848 €

**PRIN02:** Methods for the design of embedded controllers for hybrid systems. MIUR, 2003-2004. The aim of this project is about bridging the dichotomy between functional design and implementation. To achieve this goal, we drew on the theory of hybrid system control with safety specifications and the principles of platform-based design. In this method, the design process is decomposed into a sequence of steps that involve different levels of abstraction (platforms) related by a refinement relation. The choice of the layers of abstraction and of the corresponding parameters is essential for the quality of the final solution of the design problem. Platforms for the embedded control design problem were defined in terms of their parameters and appropriate cost functionals introduced. The design of the engine control unit for automotive applications was considered for illustrating the advantages of the proposed method.

Total cost of the project: 171.000 €

DEWS cost: 96.900 € - EU contribution: 67.800 €

**COLUMBUS:** Design of Embedded Controllers for Safety Critical Systems. EU FP5 STREP, 2002-2004: The design of embedded systems deals with the implementation of a set of functionalities satisfying a number of constraints ranging from performance to cost, emissions, power consumption and weight. The choice of implementation architecture implies which functionality will be implemented as a hardware component and which as software running on a programmable component. The design of embedded hardware and software poses a number of problems that cannot be addressed by traditional methods. These include hard constraints on reaction speed, memory footprint, power consumption, and, most importantly, the need to verify design correctness. The latter is a critical aspect of embedded systems since several application domains, such as transportation and environment monitoring, are characterized by safety considerations that do not arise in traditional, PC-like software applications. In this project we developed design methods and tools for embedded systems in safety critical applications.

Total cost of the project: 1.919.154 €

DEWS cost: 600.141 € - EU contribution: 300.070 €

# M1: Modeling and control of heterogeneous distributed complex systems

The research activities of M1 aim at providing the basic mathematical background and tools for analysis and control of complex heterogeneous Networked Embedded Control Systems. The growing relevance of Networked Embedded Control Systems is due to the development of key enabling technologies such embedded systems and networks. Embedded systems are computing systems designed to perform one or a few dedicated functions often with real-time constraints.

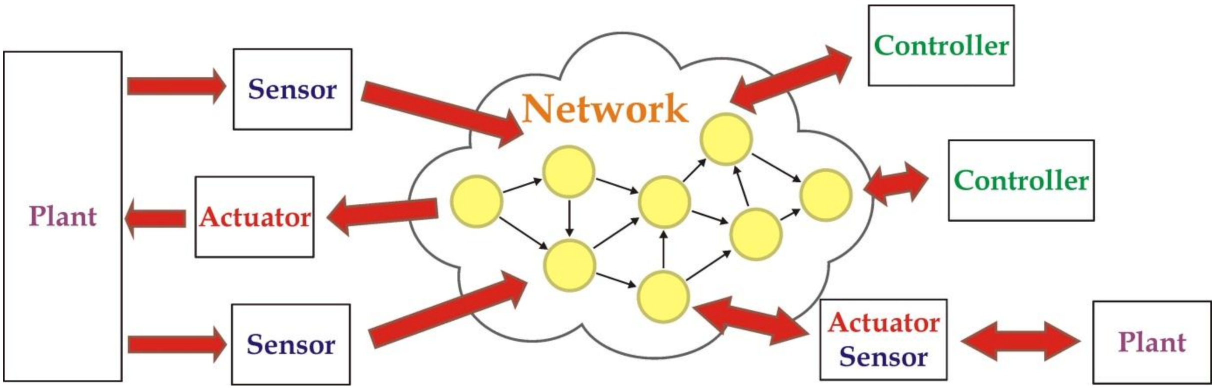


Figure M1.1: Abstract scheme of a Networked Embedded Control System.

They are embedded as part of a complete device often including mechanical parts. Today embedded systems span all aspects of everyday life, from automotive to avionics systems, from white goods to consumer electronics. The architecture of embedded systems has changed over the years as technological advances made it possible to integrate increasingly complex subsystems. In particular, it has become possible to coordinate different systems performing a particular function into delivering a global emerging behavior; for example, Unmanned Autonomous Vehicles (UAVs) are increasingly used in defense applications where they are called to fulfill missions that require close collaboration. Monitoring the environment, energy efficient buildings and industrial plants is today possible with a possibly large number of sensors distributed over a wide region. In these applications, communication is an important feature. Given the operation they are called upon to perform and the physical locations where they are deployed, wireless communication has become an essential feature. Possibly the most advanced application of networked embedded systems is control. Industrial plant control and autonomous driving in freeways are typical examples of distributed embedded control. In these systems, sensors, actuators and computing elements are connected by means of a shared (wired or wireless) network as shown in Figure M1.1. Together with the opportunities offered by the wealth of sensing devices, the communication devices and the increasing computing power of control nodes, come tough challenges: control theory was based on mathematical paradigms that do not consider the non-idealities introduced by hardware and software devices, and communication protocols. These effects pose a number of theoretical and practical problems that must be solved to advance the state-of-the-art in distributed control: stabilization, safety control, pole placement, Linear Quadratic Regulator (LQR), control with logic-type specifications and other classical control problems must be cast in a different framework. When a control system is subject to non-idealities of the implementation and communication infrastructures, operative systems and communication protocols need to be considered in the design of the control policy. Consequently, the design of distributed systems must jointly address control, real-time computing and communication protocol design. The expertise of the Center of Excellence DEWS on Networked Embedded Control Systems is recognized by all international academic and industrial partners of the Networks of Excellence HYCON and HYCON2. In particular, DEWS has been leader of the HYCON Work Package on Networked Control and is currently leader of the HYCON2 Work Package on Networked Control Systems. In Work Package M1 we address analysis and control of Networked Embedded Systems by considering non-idealities introduced i) by computing and hardware devices, and ii) by network and communication protocols.

## Symbolic Control of Embedded Systems

Discrete abstractions of continuous and hybrid systems have been the topic of intensive study in the last twenty years from both the control systems and the computer science communities. While physical world processes are often described by differential equations, digital controllers and software and hardware are usually modeled through discrete/symbolic processes. During the years, the heterogeneity of these mathematical models has posed interesting and challenging theoretical problems that must be addressed to ensure the formal correctness of control algorithms in the presence of non-idealities at the implementation layers. From the synergistic collaboration of researchers in the control systems and computer science communities, a novel and sound approach has recently emerged, which is termed "Correct-by-Design Embedded Control Software". This research line can be roughly described as a three-step process, as shown in Figure M1.2, and detailed hereafter:

1. A finite state machine (or symbolic model) is firstly constructed, which is equivalent or approximates the continuous control system.
2. The original control design problem is solved at the discrete abstraction layer on the symbolic model obtained.
3. The symbolic controller synthesized at the discrete layer is appropriately refined so that it can be successfully applied to the original continuous control system.

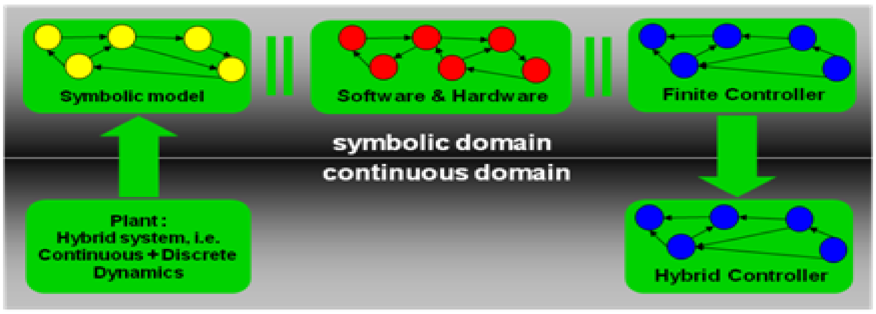


Figure M1.2: Correct-by-Design Embedded Control Software.

The correct-by-design approach guarantees that controllers synthesized at the symbolic layer enforce the desired specification on the continuous layer with guaranteed approximation bounds. Moreover, this approach provides the designer with a systematic method to address a wide spectrum of novel specifications that are difficult to enforce by means of conventional control design paradigms. Examples of such specifications include logic specifications expressed in linear temporal logic or automata on infinite strings. The kernel of this approach resides in the definition and construction of symbolic models that are equivalent or approximate continuous and hybrid systems (Step 1 in the aforementioned methodology).

Several classes of dynamical and control systems that admit symbolic models have been identified during the years. We recall timed, multi-rate, rectangular automata and o-minimal hybrid systems in the class of hybrid automata; controllable discrete-time linear systems, piecewise-affine systems and multi-affine systems, in the class of control systems.

DEWS researchers have been active in this research topic and their collaboration with researchers from the University of California at Los Angeles (USA) and the Université Joseph Fourier (France) was fruitful. The initial goal was developing a theory towards the definition and construction of symbolic models for the class of nonlinear control systems. We identified two key ingredients to accomplish this ambitious goal: the notion of approximate bisimulation, introduced by Antoine Girard and George Pappas in 2007 and the notion of incremental stability introduced by David Angeli in 2002. Pola et. al.[1] in 2008 showed that these two key ingredients can be combined so that for any incrementally input-to-state stable nonlinear control system with compact state space it is possible to construct a symbolic model that approximates the original system in the sense of approximate bisimulation with arbitrarily good accuracy. This key result was then generalized to more general classes of continuous and hybrid systems, as follows.

First, nonlinear control systems affected by disturbances were considered. In [PT09] we introduced an appropriate notion of approximate equivalence, which is termed alternating approximate bisimulation. This notion has been obtained by combining the notion of approximate bisimulation introduced by Antoine Girard and George Pappas in 2007 with the one of alternating bisimulation introduced by Rajeev Alur and co-workers in 1998. This notion guarantees that control strategies synthesized on symbolic models, based on alternating approximate bisimulations, can be readily transferred to the original model, independently of the particular evolution of the disturbance inputs. In [PT09] we showed that for any incrementally globally stable nonlinear control system affected by disturbances there exists a symbolic model that approximates the original system with arbitrarily good accuracy in the sense of alternating approximate bisimulation. H0wever, the results reported in [PT09] rely on the computation of reachable sets which is a hard task in general. In [BPDB12b] we overcome this difficulty by proposing alternative symbolic models that can be effectively constructed. More specifically, we show that if the control system is incrementally input-to-state stable and the disturbance inputs are bounded and Lipschitz continuous then it is possible to effectively construct symbolic models that approximate the original systems in the sense of alternating approximate bisimulation. The key ingredient in the results reported in [BPDB12b] is the use of first-order spline approximations of the disturbance input functional space.

The results obtained for nonlinear control systems were then generalized in [GPT10] to a class of hybrid control systems that is called switched systems. After generalizing the theory of incremental stability from nonlinear control systems to nonlinear switched systems, we proposed symbolic models that approximate incrementally globally asymptotically stable nonlinear switched systems with arbitrarily good accuracy. The proposed theory was then

[1] G. Pola, A. Girard and P. Tabuada. Approximately bisimilar symbolic models for nonlinear control systems. Automatica, 44(10):2508-2516, October 2008.

tested on the Boost DC-DC converter, a benchmark selected within the Network of Excellence HYCON consortium.

Our next research goal was to investigate further results which can ensure formal correctness of control algorithms in the presence of delays that are rather frequent in the exchange of information in distributed embedded systems. We therefore faced the problem of generalizing the results concerning the construction of symbolic models from nonlinear control systems to nonlinear time-delay systems. This generalization was not straightforward because time-delay systems are infinite dimensional systems. We first generalized the notion of incremental input-to-state stability from nonlinear control systems to nonlinear time-delay systems and provide sufficient conditions for checking this property in terms of Lyapunov-Krasovskii types dissipation inequalities. We then proposed first order spline-based approximation schemes to approximate the state of the time-delay system. The results reported in [PPDB+10b] mimic the one of nonlinear control systems in the sense that they show that any incrementally input-to-state stable time-delay system with constant time-delays, admits a symbolic model which is approximately bisimilar to the original system. The results of [PPDB+10b] were then generalized to time-delay systems with time-varying delays in [PPDB10]: we showed that for any incrementally input-to-state stable time-delay system with time-varying delays it is possible to effectively construct a symbolic model which is an alternating approximate bisimulation of the original system.

All these results were based on a notion of incremental stability. In collaboration with researchers from the University of California at Los Angeles, in [ZPMT12] we relaxed this assumption and showed that any incremental forward complete nonlinear control system admits symbolic models that approximate the original system in the sense of alternating approximate simulation. Incremental forward complete assumption is a rather mild assumption which is fulfilled for example by unstable nonlinear control systems.

The use of symbolic models for the control design of continuous and hybrid systems provides the designer with a systematic method to address a wide spectrum of novel specifications that are difficult to enforce by means of conventional control design paradigms. In this context we faced the problem of designing symbolic controllers that enforce a nonlinear control system to satisfy a specification expressed in terms of automata on infinite strings and so that the interactions between the nonlinear control system and the symbolic controller is non-blocking. An explicit solution to this problem has been explicitly derived, resulting in the non-blocking part of the approximate parallel composition between the specification automaton and the symbolic model of the continuous system. While being powerful, this approach often encounters some limitations in concrete applications, because of the large size of the symbolic models needed to be constructed in the implementation. Inspired by on–the–fly techniques for verification and control of finite state machines, we proposed in [BPDB12a] efficient algorithms that integrate the construction of the symbolic model of the continuous system with the design of the symbolic controller. This method provides substantial complexity reductions in most of practical cases, and we believe that it is one of the key ingredients to apply the "Correct-by-Design Embedded Control Software" research line to concrete and realistic applications.

We extended the paradigm of symbolic abstractions of nonlinear systems to stochastic dynamical systems. In particular, in [ADID+11] we proposed a constructive procedure for obtaining a symbolic model of discrete-time stochastic hybrid systems. The procedure consists of a partition of the state space of the system and depends on a parameter. Given proper continuity assumptions on the model, the approximation errors introduced by the abstraction procedure are explicitly derived and it is shown that they can be tuned through the parameter of the partition. It has been shown that certain ergodic properties on the stochastic hybrid model guarantee existence of a finite abstraction with finite error over the concrete model, and allow introducing a finite-time algorithm to compute an approximate abstraction of a discrete-time stochastic hybrid system. In order to relate the results derived in [[ADID+11] to the notions of approximate probabilistic bisimulation (APB) and to probabilistic temporal logics (e.g. Probabilistic Computation Tree Logic, PCTL), we considered in [DIAK12] the notion of APB relation for discrete-time labeled Markov Chains (LMC). We provided a quantified upper bound on a metric over probabilistic realizations for LMC and, based on this bound, we proved that the existence of an APB implies the preservation of robust PCTL formulae, which are formulae that are properly relaxed or strengthened according to the precision of the APB. This led to a notion of robustness for probabilistic model checking, which can be used to validate PCTL model checking algorithms executed over a symbolic model of a concrete model, where transition probabilities are approximated with finite precision. Our next goal is exploiting the abstraction procedure in [ADID+11] and the results developed in [DIAK12] to verify properties of continuous models as general as stochastic hybrid systems, by using classical PCTL model checking algorithms over a finite LMC abstraction that satisfies some accuracy constraints.

# Modeling, analysis and design of Networked Control Systems

Wireless networked control systems are spatially distributed control systems where the communication between sensors, actuators and computational units is supported by a shared wireless communication network. Control with wireless technologies typically involves multiple communication hops for conveying information from sensors to controllers and from controllers to actuators. The main motivation for studying such systems is the emerging use of wireless technologies in control. The use of multi-hop (wireless) control networks in industrial automation results in flexible architectures and generally reduces installation, debugging, diagnostic and maintenance costs with respect to wired networks. Although wireless networks offer many advantages, their use for control is a challenge when one has to take into account the joint dynamics of the plant and of the communication protocol. Wide deployment of wireless industrial automation requires substantial progress in wireless transmission, networking and control, in order to provide formal models and verification/design methodologies. In particular, co-design of the network configuration and of the control algorithm requires addressing issues such as scheduling and routing using real communication protocols.

The challenges in designing and analyzing multi-hop control networks are best explained by considering the recently developed wireless industrial control protocols, such as WirelessHART (www.hartcomm2.org) and ISA-100 (www.isa.org) as shown in Figure M1.3. These standards allow designers to distribute a synchronous communication schedule to all communication nodes of a wireless network. More specifically, time is divided into slots of fixed length and a schedule is an assignment of nodes to send data in each slot. The standard specifies a syntax for defining schedules and a mechanism to apply them. However, the issue of designing schedules and routing remains a challenge for engineers, and is currently done using heuristics rules. To allow systematic methods for computing and validating schedules, a proper formulation of the effect of schedules on control performance is needed.

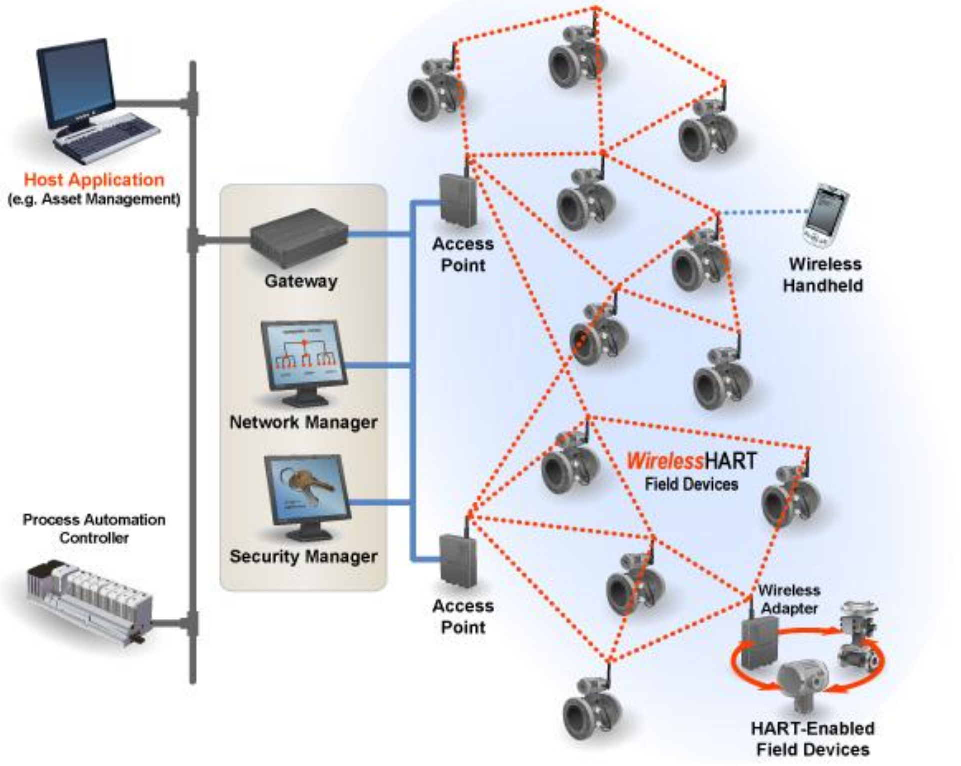


Figure M1.3: Device level architecture of the WirelessHART specification.

Motivated by these challenges, we proposed in [ADIJ+11] a formal modeling and analysis approach for multi-hop control networks designed for systems consisting of multiple control loops closed over a multi-hop (wireless) communication network, where we take into account the effect of topology, routing and scheduling in the control performance. An important feature of this approach is compositionality, namely it addresses the problem of designing scalable scheduling and routing policies for multiple control loops closed on the same multi-hop control network.

In [WDIA+09] we proposed formal models for analyzing robustness of multi-hop control networks, where data are exchanged through a multi-hop communication network subject to disruptions.

In [DBDI+11a] we exploited redundancy in data communication (i.e. sending sensing and actuation data through multiple paths) with the aim of rendering the system robust with respect to link failures (e.g. when the battery of a node discharges or a communication channel goes down), and to mitigate the effect of packet losses (e.g. transmission errors). We modeled redundancy by defining a weight function that specifies how the duplicate information transmitted through the multi-hop network is merged and by defining the semantics of the redundant data flow through the network. We stated necessary and sufficient conditions on the scheduling and routing of the communication network that guarantee to design a controller that stabilizes the plant dynamics. Moreover, in order to design fault tolerant networked control systems, we provided a methodology to design scheduling and routing of a communication network, which guarantee the existence of a stabilizing controller for any fault occurrence in a given set of failures configurations.

In [DIDB+11] we addressed the problem of designing a set of controllers and the communication protocol parameters, which make it possible to detect, on-the-fly, the current configuration of failures of the controllability and observability networks and to apply an appropriate controller to stabilize the system. Link failures may be due to malfunctions or battery discharge of a communication nodes, communication link drops and malicious intrusions to the system, e.g. when a malicious signal is injected in a communication node of the network. We leveraged the model-based approach introduced by the pioneering work of Massoumnia in 1971 for linear systems and Isidori in 1973 for nonlinear systems, which provide observer-based Fault Detection and Isolation (FDI) algorithms. We derived necessary and sufficient conditions on the plant dynamics, on the communication protocol and on the network topology so that it is possible to detect failures in a wireless network using the input applied to and the measure received from the network.

Our results show that independently from the complexity of the topology of the network, it is always possible to design a controller and a network configuration (scheduling and routing) that guarantee asymptotic stability of the networked closed loop system. We are currently addressing the problem of co-designing a digital controller and the network parameters (scheduling and routing) in order to guarantee stability and maximize a performance metric. More precisely, we aim at minimizing the L2 norm of the error signal while requiring the closed loop system to follow a step reference with zero steady state error in finite time (deadbeat control), with constraints on the maximum overshoot in the input and output signal of the plant and on the maximum data rate on the communication links.

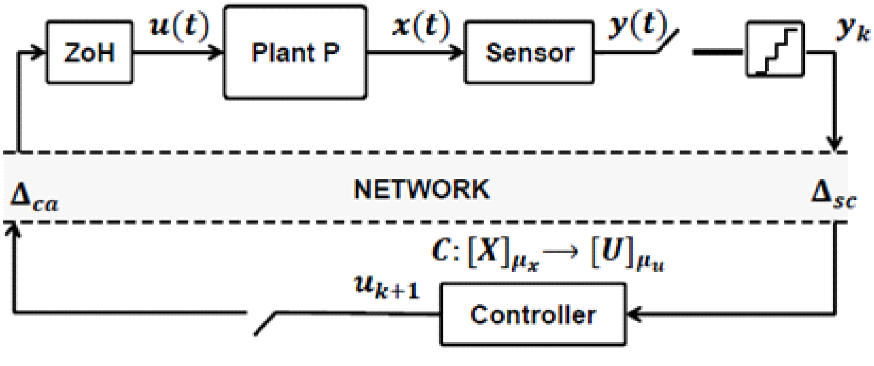


Figure M1.4: Networked control system architecture.

The research developed at DEWS in the HYCON2 NoE has pioneered the study of the controller design problems for multi-hop control networks that implement standardized scheduling and routing communication protocols, in order to enable co-design of controller, scheduling and routing. Although this approach enables formal analysis of the effect of industrial wireless communication protocols on control loops, it is currently restricted to linear control systems. To overcome this limitation, we focused on the symbolic control design of nonlinear Networked Control Systems (NCSs). We considered a fairly general framework of NCSs which comprises most relevant non-idealities in the communication channel as quantization errors, saturations in the control action, bounded time-varying network access times, bounded time-varying communication delays induced by the network, bounded time-varying computation time of computing units, limited bandwidth in the communication channel and bounded packet losses. The NCS scheme we considered is depicted in Figure M1.4. In [BPDB12a] we showed that NCSs with incrementally input-to-state stable plant nonlinear control systems admit symbolic models that are an alternating approximate bisimulation of the original NCS. The proposed symbolic models are then used to solve symbolic control design problems for NCS where specifications are expressed in terms of automata on infinite strings. The results of [BPDB12a] have been recently generalized to the case where plant control systems are incrementally forward complete, hence, possibly unstable. On-the-fly type algorithms studied in [PBDB12] for nonlinear control systems have been also generalized to the symbolic control design of nonlinear NCS.

# M2: Communication and protocol design for pervasive and cognitive networks

The object of research in M2 is the overall development of communication and networking technologies for supporting advanced applications. Since the early stage of DEWS activities in 2001, M2 has pursued theoretical research in close cooperation with M1; further, it has leveraged embedded SW methodologies and tools researched in M3. In the present research organization M2 has increased its focus on algorithms, techniques and models for signal processing, transmission systems and protocols for secure and efficient networking, while maintaining close collaboration with M1 and M3. Our research activities have been almost uniquely focused on the wireless domain, albeit our concept of networking is more general as it spans across a set of heterogeneous components that have to be integrated not only on the traffic side but also in terms of management and control.

In the following we provide a short description of recent achievements and work in progress, according to four major topics:

- signal design and physical layer techniques for novel communication paradigms, that include cooperative, cognitive and energy-efficient systems;
- characterization of network interference as a prominent feature of future wireless environments, along with evaluation of their impact on achievable performance and development of novel techniques for interference-aware processing and network management;
- definition of complete protocol stacks that are able to meet specific application requirements, along with sound methodologies for (cross-layer) modelling, specification and implementation;
- algorithms and tools for upper layer (middleware) services, i.e. distributed coding and estimation for compression, positioning and security.

## Cooperative wireless techniques towards green communications

During the last decade, there has been a tremendous growth in the cellular networks market, and mobile data is well on its way to become a necessity. One of the most astonishing developments of the last few years has been the extension of mobile services even beyond the boundaries of the power grid.

Such unprecedented surge of mobile data traffic in the cellular industry has already motivated telecom operators and researchers to develop new transmission technologies, protocols, and network infrastructures to maximize achievable throughput and spectral efficiency. However, little or no attention has been paid to energy consumption and signal processing complexity. Furthermore, with the current design methodology at hand, wireless systems can achieve energy savings only at the cost of performance and Quality of Service (QoS) degradation. Therefore, the key stakeholders in the mobile industry require a network delivery platform for the future that is: i) heterogeneous and characterized by a small cell infrastructure through the use of small, inexpensive, and low-power base stations to achieve high data rates in a capillary fashion; ii) green, by evolving from throughput optimized networks towards energy optimized networks; and iii) characterized by a high level of cooperation among base stations and mobile terminals, by achieving better coverage and reduced energy consumption through network-coded relay-aided transmission, as well as better reliability and reduced energy consumption through distributed diversity.

The path followed by DEWS researchers towards the development of green communications arises was originated by analysis on cooperative diversity. The basic premise of cooperative diversity is to achieve the benefits of spatial diversity without requiring each mobile radio to be equipped with co–located multiple antennas. As a matter of fact, cooperative systems take advantage of relayed and spatial diversity technologies to boost channel capacity, and to reduce the error probability due to multipath fading.

In order to analyze the ultimate performance of cooperative systems over fading channels, firstly we proposed a comprehensive framework for performance analysis of a generic cooperative system, often denoted as multi–hop multi–branch network. More specifically, we consider Channel State Information(CSI–) assisted Amplify and Forward (AF) relay methods. The framework relies on the Moment Generating Function (MGF) based approach for performance analysis of communication systems over fading channels, and on some properties of the Laplace Transform, which allow to develop a simple single–integral relation between the MGF of a random variable and the MGF of its inverse. By exploiting this integral relation, we develop explicit formulas to estimate Average Bit Error Probability (ABEP), Outage Probability (Pout), average SNR, and Outage Capacity (OC), which are applicable to any environment with arbitrary fading distribution [DRGS09g].

Then, by focusing on the dual–hop scenario with an Amplify and Forward (AF) relaying mechanism with blind and semi–blind relays, DEWS researchers developed a unified framework that allows to obtain either exact or very accurate formulas for the Moment Generating Function (MGF) of the end–to–end Signal– to–Noise Ratio (SNR) for various fading distributions [DRGS09h].

However, the efficient exploitation of cooperative/multi–hop networking is faced by the following challenges: i) due to practical considerations, such as the half–duplex constraint or to avoid interference caused by simultaneous transmissions, distributed cooperation needs extra bandwidth resources (e.g., time slots or frequencies), which might result in a loss of system throughput; ii) relay nodes are forced to use their own resources to forward the packets of other nodes, usually without receiving any rewards; and iii) in classical cooperative protocols, the relay nodes that perform a retransmission on behalf of other nodes must delay their own frames, which has an impact on the latency of the network.

At the technical level, the drawbacks of cooperative communications can be effectively balanced by synergic exploitation of two breakthrough access paradigms such as Network Coding (NC) and Multiple–Input–Multiple–Output (MIMO) Spatial Modulation (SM). These three main research domains interact and work together to provide ubiquitous high quality services (high data rates with low energy requirements).

To overcome these limitations, NC has recently been introduced to improve the network performance [DRIG10]. NC can be broadly defined as an advanced routing or encoding mechanism at the network layer, which allows network nodes not only to forward but also to process incoming data packets. It can be considered a potential and effective enabler to recover the throughput loss experienced by cooperative/multi–hop networking.

The challenge faced by DEWS researchers consists in the analysis of the multiplexing gain introduced by NC and the achievable diversity/coding gain introduced by cooperation when practical communication constraints (erroneous decoding and fading) are taken into account.

As a matter of fact, the typical approach considered so far in literature has mainly relied on information-theoretic assumptions, according to which data packets are processed by the network layer only if they are without errors. While this prevents possible performance loss, this might be highly spectral inefficient as, even though a single bit in the packet is in error, the packet is dropped. In order to avoid this sub-optimal operation mode and to consider more realistic communication-theoretic assumptions, we have considered the MIMO-NC approach, which can be considered as a sort of network-coded aware Chase combiner.

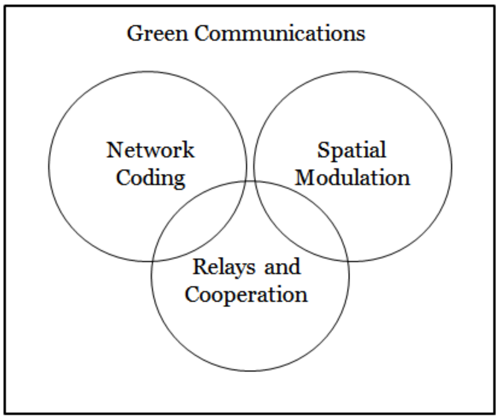


Figure M2.1: Main research domain.

The main idea is that all received packets are kept at the destination and processed at the network layer even though some bits of the packet are not received correctly [IDRG11a], [IDRG12b] . Our research activity has two research lines: i) how to develop the optimal Chase combiner in the presence of NC; and ii) to study the achievable diversity gain as a function of the adopted network code [IDRG11b].

Some recent results, obtained by collaboration with Laboratoire des signaux et systèmes (L2S), Supélec (France), have highlighted, for some network topologies and encoding schemes, the potential benefits of NC to recover the throughput loss of cooperative/multi–hop networking. The additional research goal was to investigate the scenario when the relays do not act as dedicated network elements with no data to transmit but have their own data packets to be transmitted to a common destination, and exploit NC to transmit them along with the packets that have to be relayed on behalf of the sources. This way, the relays can help the sources without the need to: i) delay the transmission of their own data packets; and ii) use specific resources (energy and processing) to forward the packets of the sources [IDRG12a]. Furthermore, we proposed a network code design based on Unequal Error Protection (UEP) codes. To the best of our knowledge, this is the first time that UEP coding theory is exploited for the design of distributed network codes for diversity purposes [DRIG12].

A different and alternative technology for green communications is SM, which is able to outperform, with low implementation and computational complexity, many traditional transmission schemes, such as multiple-antenna in Multiple-Input-Multiple-Output (MIMO) systems, which can be exploited in different ways to achieve multiplexing, diversity, or antenna gains. However, regardless of the use as spatial multiplexing, diversity, or smart antenna system, the main drawback of any MIMO scheme is an increase in complexity and cost.

Spatial Modulation (SM) has been recently proposed as a new modulation concept for MIMO systems, which aims at reducing the complexity and cost of multiple-antenna schemes without deteriorating the end-to-end system performance and still guaranteeing good data rates.

The spatial modulation principle is known in the literature in various forms, such as Information–Guided Channel Hopping (IGCH), Spatial Modulation (SM) and Space Shift Keying (SSK) modulation; although different from one another, all these transmission technologies share the same fundamental working principle, which makes them unique with respect to conventional modulation schemes: they encode part of the information bits into the spatial positions of the transmit–antennas in the antenna–array, which plays the role of a constellation diagram (the so–called "spatial–constellation diagram") for data modulation. In particular, SSK modulation exploits only the spatial–constellation diagram for data modulation, which results in a very low–complexity modulation concept for MIMO systems. SSK modulation exploits the location–specific property of the wireless channel for data modulation: the messages sent by the transmitter can be decoded at the destination since the receiver sees a different Channel Impulse Response (CIR) on any transmit–to–receive wireless link. If the receiver has Perfect Channel State Information (PCSI), space modulation can provide better performance than conventional modulation schemes with similar complexity. However, due to its inherent working principle, the major criticism about the adoption of SSK modulation in realistic propagation environments is its robustness to the imperfect knowledge of the wireless channel at the receiver. The main contribution given by DEWS researchers is to shed light on this matter and to develop a very general analytical framework to assess the performance of space modulation with coherent detection and practical channel estimates [DRDL+12]. In particular, DEWS researchers focused their attention on two transmission technologies, which are the building blocks of space modulation: Space Shift Keying modulation and Time–Orthogonal–Signal–Design (TOSD) SSK modulation, which is an improved version of SSK modulation providing transmit–diversity. Our theoretical and numerical results highlight three important outcomes: i) SSK modulation is as robust as single–antenna systems to imperfect channel knowledge; ii) TOSD–SSK modulation is more robust to channel estimation errors than the Alamouti scheme; and iii) only few training pilots are needed to get reliable enough channel estimates for data detection.

The bridge between cooperative communications and spatial modulation principle, which is the third investigated research domain, allows to propose innovative and advanced solutions to reduce energy consumption and complexity for relay-aided cooperative cellular networks. More specifically, DEWS researchers focused on the design, the analysis, and the optimization of both the uplink and the downlink of cellular networks. Specifically, we considered the scenario where fixed relay nodes or other mobile terminals, which are in close-proximity of a single or multi-antenna terminal, are willing to help forwarding data to the intended BS and to transmit their own data, without any drawback in terms of throughput. In addition to exploiting relay-aided and cooperative wireless communications to take advantage of the SM-MIMO approach for the uplink, the effort aimed at exploiting the multiplexing gain introduced by the (virtual) spatial-constellation diagram to develop innovative relaying protocols that allow us to recover the throughput loss experienced by multi-hop networking and caused by the half-duplex constraint, while keeping the energy gain introduced by multi-hop transmission.

The developed protocol provides that data symbols transmitted from the source are univocally encoded into the channel impulse responses of different relay–to–destination links. Thus, source's data is implicitly relayed to the destination through a relay activation process, rather than using conventional amplitude/phase modulation, as already seen in literature. As a consequence, this latter degree of freedom can be used by the relays to transmit their own data without any reductions of the aggregate throughput, and by still guaranteeing the protection (i.e., distributed diversity) of the source's data. The specific research contributions have been obtained in GREENET [DRG11], thanks to the fruitful collaboration with Laboratoire des signaux et systèmes (L2S), Supélec (France).

# Network interference modelling for wireless coexistence

In a wireless network composed of many spatially scattered nodes, communication is constrained by various impairments, such as wireless propagation effects, thermal noise and network interference. In particular, with the increasing proliferation of different communication devices sharing the same spectrum, along with its increasing and aggressive spatial reuse (e.g., in cognitive radio networks, in femtocells-overlaid (multi-tier) cellular networks, etc.), network interference is becoming the dominant noise source, which may severely degrade the communication performance of wireless transceivers.

More specifically, in cognitive radio networks (CRNs), which envisage the deployment of different communication devices sharing the same spectrum, network interference represents a crucial aspect in their deployment and its characterization is of critical importance.

As a matter of fact, network interference might be mitigated in systems with a centralized control, where the coordinator is able to assign different channelizations and power levels to the network nodes. However, this is not possible in many emerging systems, like CRNs, where a centralized control is often not feasible, and there is the need for a distributed resource allocation. Moreover, the main requirement for a CRN is that it must not generate harmful interference on the primary users operating on the same frequencies.

In this context, spectrum sensing is acknowledged as an important challenge to enable the benefits of CRNs, and cooperative techniques an efficient method to guarantee the detection of unused frequency bands with high reliability. Furthermore, several studies have shown that the achievable performance of cooperative spectrum sensing methods depends on the assumed fading channel model and have pointed out that correlated Log–Normal shadow–fading is the key element of wireless propagation to be taken into account for a sound design and optimization of these systems [DRGS10a], [DRGS09a], [DRGS09e].

The main driver for the emergence of a framework for CRNs over realistic propagation environments has been the application of decentralized data fusion to Wireless Sensor Networks (WSNs), where the stringent power and bandwidth constraints of sensor nodes make unrealistic the assumption of highly reliable links among all nodes in the network.

Motivated from all the above, the aim of DEWS researchers has been the development of a simple but accurate framework for the analysis and design of cooperative spectrum sensing methods by taking into account realistic channel conditions and system operations. Furthermore, a novel method for approximating the power–sum of correlated Log–Normal

Random Variables (RVs) is introduced and shown to be accurate and flexible enough for the system setup under consideration [DRIG+09a].

An important effort in this field is to accurately model network interference and to understand its impact on the performance of heterogeneous wireless networks. In fact, network interference modeling has numerous applications, which encompass the analysis and design of communication systems (e.g., the design of transceivers with improved communication performance), the development of interference mitigation techniques, and the control of electromagnetic emissions, among many others.

In general, interference statistics in wireless networks are affected by three key factors: i) the spatial distribution of interferers, ii) the spatial region over which the interferers are distributed, and iii) the propagation characteristics including the power path loss exponent, shadowing, and fading. More specifically, the next generation (heterogeneous) wireless networks, which aim at providing high capacity network access, are characterized by randomly located nodes, irregularly deployed infrastructures, and uncertain spatial configurations due to factors like mobility and unplanned user installed access points. This major shift with respect to traditional cellular deployments is just beginning, and it requires new design approaches that are robust to spatial randomness, just as wireless links have long been designed to be robust to fading.

Hence, accurately modeling network interference, understanding its impact on the end-to-end performance, and developing efficient techniques to mitigate or exploit it are three important and fundamental research assets. Accurate performance prediction of these emerging heterogeneous wireless communication systems is instrumental to circumvent time-consuming computer simulations, to avoid expensive field test campaigns, as well as to facilitate system optimization via a suitable design choice for some given practical implementation constraints, and, ultimately, to inspire optimal and innovative algorithms and designs. More specifically, small-cell (micro, pico, femto) cellular networks are characterized by a large number of nodes, i.e., femto/pico and macro base stations, which coexist and contend to have access to the wireless medium. Unlike traditional wireless networks, these systems are characterized by inherently unplanned, irregular, and random location of nodes, whose positions may vary widely over a very large area. System performance depends critically on the spatial configurations of the nodes, and the computation of new "average" performance metrics, are instrumental for the system designer and the network planner. The analysis of such systems requires extensive, complex, and time-consuming system-level simulations to average over the spatial distributions of the network nodes. Thus, new and advanced mathematical and statistical tools are required to explicitly and accurately model the random distribution of these nodes, as well as to avoid lengthy and seldom insightful numerical simulations.

By carefully looking at the above discussion, it can be concluded that current analysis of coexistence in heterogeneous wireless networks is quite limited, and can be applied to only very specific fading channel models (in general, Rayleigh fading only), to very simple transceiver designs (in general, single-input-single-output systems only), to limited modulation schemes (often binary modulations only), and to limited network topologies (in general, non-cooperative single-hop networks without in-network processing). Also, to date research has been mainly focused on the analysis of the interference, while neither interference-aware receiver nor interference-aware link adaptation schemes have been proposed based on the statistical characterization of the aggregate interference produced by randomly distributed sources of interference in heterogeneous wireless networks. In fact, interference awareness and management is an inherent and effective approach to achieve energy efficiency, as it translates into reduced transmit energy for both BSs and mobile terminals.

Luckily, recent research advances in this field have shown that stochastic geometry and Poisson point processes theory can be instrumental and essential tools to develop tractable and compact analytical frameworks, which can completely avoid Monte Carlo simulations. In our research work, all the previous issues have been investigated by exploiting flexibility and generality offered by stochastic geometry for interference modeling, analysis, as well as for system design and optimization.

We firstly move from the semi–analytical available framework introduced by Pinto and Win and provide a new, exact, and single–integral expression of the Average Symbol Error Probability (ASEP) of an intended link, which is subject to receiver noise and aggregate interference generated by network nodes distributed according to a homogeneous Poisson point process. Furthermore, we study and compare the performance of asynchronous and synchronous network scenarios, and show that the latter setup is a very tight upper–bound of the former. This is a relevant result, as for synchronous systems we show that all parameters of interest can be computed in closed–form [MGDR+12].

As a second purpose, we decided to propose an alternative analytical derivation to compute the rate of cellular networks. More specifically, by using stochastic geometry and Poisson point processes theory, we derived a single–integral expression of the rate, which can be used for arbitrary network and channel parameters, e.g., path–loss exponent, receiver noise, density of BSs, etc.

Compared to approaches available in literature, technical contribution obtained by DEWS researchers in this context is twofold: i) the rate can be computed via a single numerical integral, rather than via a three–fold numerical integral; and ii) the framework is applicable to arbitrary fading distributions on the intended link, rather than being useful for Rayleigh fading only [GDRC+12]. All research results have been obtained by collaboration with Laboratoire des signaux et systèmes (L2S), Supélec (France) and with DEIS-Fondazione Ugo Bordoni, University of Bologna.

# Cross-layer protocol design

Energy conservation is important for the sustainable development of new communication technologies. A potential infrastructure for developing energy-aware applications is represented by low power wireless networks. They include any network of devices with limited power, memory, and processing resources that are interconnected by a communication protocol such as IEEE 802.15.4, Bluetooth, or low power WiFi. Mobile ad-hoc networks (MANETs) and wireless sensor networks (WSNs) are examples of low power infrastructure interconnected by heterogeneous protocols. These networks introduce different design challenges, such as the need of energy efficient operation. In many applications, it is expected that each node of the network lasts for a long time because of the use in remote areas where recharging and replacing power supply units is difficult. In other cases, recharging is possible and not expensive but the aim of the application is to avoid users to cope with limited battery lifetime of devices. In other situations, it is important to limit the energy for communication in order not to create interference.

Currently, there is a major contrast between continuously increasing need of reliable information and energy saving. High throughput applications such as peer-to-peer file sharing are based on distributing information with high density. This means an increasing number of devices, complexity, cost, and also non negligible impact on the energy consumption of the whole system.

Understanding the basic interaction between communication paradigms and application requirements is then fundamental to obtain energy efficient operation. This is more critical and complicated when multi-hop communications are involved.

The underlying aspect that motivates this work is the relevance of analytical modeling in design, protocol selection, and optimization of energy efficient communication protocols and control applications. For an automation vendor, it is often the key to profitability to have an efficient engineering process for modeling. In the design of communication systems for transmitting information through physical channels, it is convenient to use an analytical model that reproduces the most important characteristics of the transmission medium. One of the advantages is that by distinguishing the different components of the networked system, the designer can study the interaction between design parameters and the effects of these parameters on the applications running on top of the network. Same approach is applied in the design of applications on top of the communication stack. By abstracting key network features in simple models, the design can be optimized according to the specified requirements. A drawback is that the abstraction needed for the sake of simplicity in the model may be inefficient to capture the behavior and the performance of a certain application over the communication stack.

In this framework, we propose an analytical model to help the design of physical, MAC, routing, and control application layers for energy efficient networks with application in industrial and building automation. The essence of our study can be represented by the block diagram in Figure M2.2, in which we synthesize the main components and the mutual interaction between the layers of interest in a wireless network protocol stack.

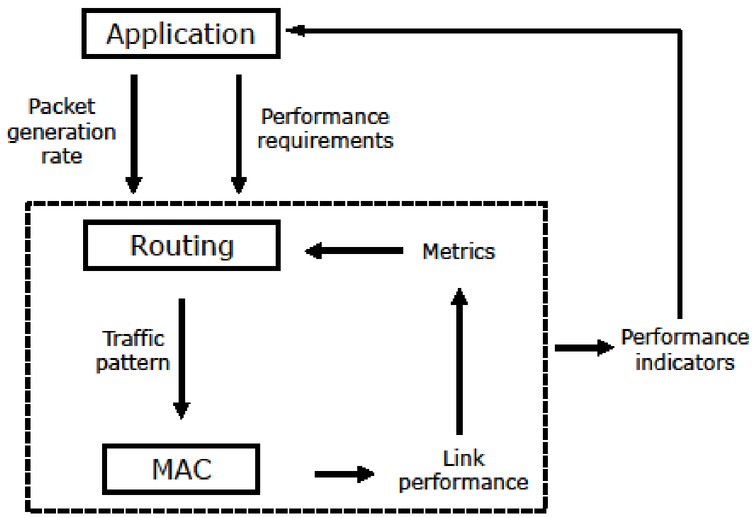


Figure M2.2: Network layers interaction for protocol modeling and design.

We proceed by analyzing the problem in three steps.

First, we study the mutual influence between routing decisions and MAC/physical layer performance in terms of reliability, delay, and load balancing, by considering the ROLL routing specifications over unslotted IEEE 802.15.4 MAC. To do so, we introduce an analytical model that includes the important features of multi-hop networks, such as heterogeneous distribution of the traffic, fading channel, and hidden terminal nodes [CEDM+09], [PDMS+09], [DMPF+10b], [TDMK11]. We showed that the distribution of traffic load in the network influences the performance in terms of reliability, delay, and energy consumption of the links. This effect depends strongly on the carrier sensing range of nodes in the network. Furthermore, we derive conditions in which routing decisions based on packet loss probability or delay may lead to an unbalanced distribution of the traffic load across paths with potential dangerous effects on the energy consumption [DMPF+12].

We can extend then our perspective by including the effect of the requirements from the application in the design of a communication protocol stack compliant with ROLL and IEEE 802.15.4, as we develop TREnD [DMPF+09], [DMPF+10a], a novel cross-layer solution for control applications over wireless networks, which satisfies application requirements on reliability and delay while minimizing energy consumption. We pose and solve an optimization problem to select the protocol parameters. Experimental results show that the protocol achieves the reliability and delay requirements also in practice, while minimizing the energy consumption. In addition, the protocol show good load balancing performance and scalability.

Furthermore, we consider the influence of communication performance indicators in the design and synthesis of a controller for an actuated under floor air distribution process based on wireless sensor network measurements [WDMP+10].

Finally, cross-layer protocol design has been carried out in the frame of ESSOR project for advanced MANETs contexts with large number of nodes and large mobilities. In this frame DEWS researchers have been developing component-based design methodologies [CFRS12], [CFRS12a] that are based on formal models for specifications, advanced tools for modelling, and automatic code generation for high fidelity simulators and subsequent implementation on target platform (DSP, programmable HW). This is particularly suited for the Software Defined Radio and emerging Cognitive Radio contexts.

# Architectures and algorithms for estimation/coding, positioning and security

Wireless Sensor Networks (WSNs) have been emerging as underlying infrastructures for new classes of large-scale and dense networked embedded systems. While there has been a plethora of scientific publications on WSNs, the vast majority focuses on protocol design (e.g. medium access control, routing, data aggregation) while only a scarce number of papers report real(istic) applications. This might be due to the following facts: (i) WSN technology is extremely expensive for large-scale systems, contradicting the initial "less than 1$ per node" vision; (ii) WSN technology is still very limited and unreliable, particularly in what concerns communications; (iii) difficulty on finding "killer" applications with a good cost/benefit trade–off; (iv) unavailability of standard, application-adequate, mature and commercially available technology; (v) lack of complete and ready-to-use system architectures, able to fulfill both functional and non-functional requirements. Despite relevant work on WSN architectures proposed so far, none of them fulfills all requirements for large-scale and dense real-time monitoring.

*Positioning.* In general, WSNs are required to possess self–organizing capabilities, so that little or no human intervention for network deployment and setup is required. A fundamental component of self–organization is the ability of sensor nodes to "sense" their location in space, i.e., determining where a given node is physically located in a network. In particular, node localization is a key enabling capability to support a rich set of geographically aware protocols for distributed and self–organizing WSNs, and for achieving context–awareness.

Several interesting applications are triggered by the possibility offered by the network to allow tracking of a mobile entity (ME). In this case it is important to differentiate among two distinct scenarios: (i) the ME is a node belonging to the WSN, and as a consequence it is equipped with the needed instruments, (i.e., collaborative localization) or (ii) the ME does not belong to the WSN, (i.e., not collaborative localization) as in "surveillance" applications.

In our work [TDR11] we try to overcome the above limitations, showing how our previously presented whole distributed positioning service for WSNs [TDRG+09b] can be integrated into a full network architecture, built upon the Zigbee Cluster-Tree model and IEEE 802.15.4 standard. Moreover, in [TVSD+11] we shown that although the idea of combining information from multiple types of positioning sensors to improve the final estimation is not new, the key to obtain an efficient position estimation, and, thus, a good tracking, through sensor fusion-based techniques is the implementation of valid (WSN-based) algorithms, together with the use of sensors able to provide very accurate measurements. +

*Security.* Due to the relevant innovations in the ICT domain, today, a lot of services is being provided with a self-service approach to an even more great number of people simplifying several tasks of everyday life (e.g. cash retrieval by ATM, remote-banking, etc...). However, some of such services could be very critical and so, their provisioning, should be managed very carefully in order to avoid the possibility of malicious operations. So, the best way to support the evolution of automatic services providing is to develop a system, also automatic, able to trust in a secure and flexible way the identity of people that need to access such services. Such a system should be of easy integration in several scenarios, especially with respect to existing infrastructures, and should be designed to respect all the relevant privacy issues while providing to the users all the feelings (about reliability, safety and usability) needed to make the system acceptable.

In such a context, in [TPTA+11], [TDRP+11], [TPGD+09a], [TPGD+09b], [TPGD+09c] we extensively presented an automatic personal identification system developed by WEST Aquila. The system, described in detail, can be used to manage physical access (e.g., to restricted areas or vehicles) as well as logical access (e.g., to personal services like e-banking). The main component of the system is a biometric badge, i.e., a smartcard equipped with a biometric reader (i.e., a fingerprint reader) and a short-medium range wireless transceiver which allow the identification of both the card and the card owner. In other words, when required, the card owner is identified through an on-system biometric matching and only the result of such a matching is sent (appropriately ciphered) through the wireless interface towards the rest of the system. Therefore, personal biometric data are always under the full control of its owner, leading to high levels of security and privacy protection.

Driven by perspectives related to the above system concept, we have undertaken an extensive research work that aimed at developing all relevant components of a secure platform operating over a distributed resource constrained network (e.g. a WSN). Platform architecture is sketched in Figure M2.3 and includes three major components: i) a topology-based authentication scheme with a hybrid key exchange, ii) a light intrusion detection system (IDS) based on weak process models, iii) a processing/computation architecture based on mobile agents [PPS11].

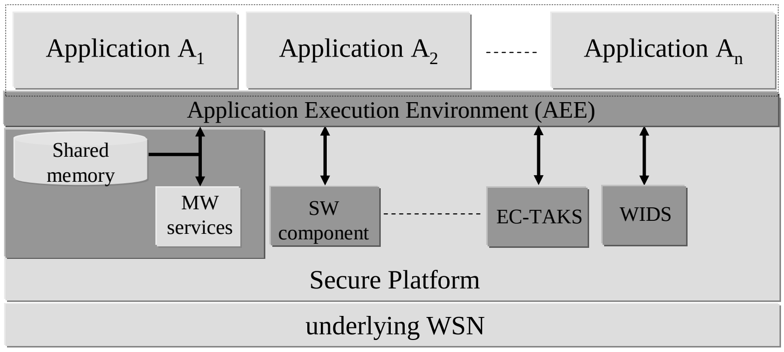


Figure M2.3: Architecture of the Secure Platform

*Distributed Source Coding.* Due to their limited power supply, energy consumption is a key issue in the design of protocols and algorithms for WSNs. Typically, energy consumption is dominated by radio communication. The energy consumption of radio communication is directly proportional to the number of bits of data, i.e., data traffic, transmitted within the network. Therefore, using compression to reduce the number of bits to be transmitted has the potential to drastically reduce communication energy costs and so increase network lifetime. Similarly, sampling level as well as communication level compressions can reduce energy costs in WSNs and increase network lifetime. In most cases, the savings due to compression are greater than linear since reducing the number of bits transmitted has the knock-on effect of reducing link-level congestion which, in turns, reduces the number of collisions and re-tries in the network. Consequently, researchers have been investigating optimal algorithms for compression of sensed data, sampling, and communications in WSNs.

Unfortunately, most conventional compression algorithms are not directly applicable to WSNs. Firstly, in conventional compression approaches the key objective is to save storage, not energy. In WSNs, energy is more important than memory. Thus energy saving is the primary evaluation metric. Secondly, it has been shown that, in terms of energy consumption, transmission of just one byte of data is equivalent to execution of roughly four thousand (Chipcon CC2420) to two million (MaxStream XTend) instructions. Moreover, these calculations only consider local energy consumption at the compressing node; network-wide energy savings due to compression can further compensate for the energy expense of compression. So compression algorithms with some degree of computational complexity are worth exploring. On the other hand, excessively computationally complex algorithm are not worth pursuing. Finally, conventional compression algorithms, originally designed for desktops or servers, must be restructured to reduce the code size and dynamic memory usage due to the limited memory capacity of WSN nodes - typically less than 50kB for code memory and even less for data memory. Recently, researchers have addressed these challenges by customizing conventional compression techniques and, some cases, by proposing new approaches.

Among them, Distributed Source Coding (DSC) techniques have gained momentum in the research community and in [FTSG09] we investigated the interplay of main communication system parameters that affect DSC performance. We developed a complete framework for a joint analysis of the reliability (loss factor) and overall energy consumption. We included four alternatives of coding topology and three packet aggregation techniques. However, we simultaneously consider DSC in a system scenario including an accurate model of the physical layer, a data link layer, packet aggregation, multi-hop routing, and the correlation pattern of the sensed phenomena.

# M3: Design methodologies for embedded systems

Embedded systems are pervasive in today's products and grow at an impressive pace considering instrumented, networked, intelligent systems that are at the core of the concept of smart cities and smarter planet. However, their growing complexity (multi/many cores, heterogeneous, distributed, reconfigurable, networked, etc…) could represent soon an unmanageable limit for design. In fact, apart from possible differences on composition and form factors, one consideration is always true: the *design methodology*, i.e. the set of adopted models, metrics and tools and the whole organization of the design activities, plays a major role in determining the success of a product. For this reason, in the last few years, design methodologies for embedded systems have been in continuous evolution towards the adoption of model-based approaches at increasingly higher abstraction levels. Essential parts of the proposed methodologies are tools for the automatic generation of HW/SW implementations.

The research lines on embedded system design methodologies are based on the experience gained during past (i.e. COLUMBUS) and current projects (i.e. VISION, PRESTO, CRAFTERS) and are described below.

## Embedded Systems Rapid Prototyping

This research is about experimenting innovative HW/SW technologies, industrial methodologies and commercial tools for the development of embedded system prototypes. Its goals are 1) to develop meaningful technology transfer capabilities, 2) to design novel courses and 3) to support other research activities with usable design frameworks (e.g. [PTGD+11] [TPTA+11]).

The VISION (Video-oriented UWB-based Intelligent Ubiquitous Sensing) project is funded by FP7 "Ideas" Specific Programme (European Research Council Staring Grant Agreement). VISION proposes to develop an innovative infrastructure for strengthening future wireless sensor networks (WSN) with the capability of supporting intelligent services for ubiquitous sensing, with particular emphasis on real-time 3D video sensing. One of the SW components of the project is the distribution of middleware on each node that allows the implementation of intelligent services. The main contribution of DEWS is the development of such an innovative middleware layer. In fact, the requirements for high-quality video transmission cannot be easily satisfied in a sensor field. The limitations in power supply and storage, and the necessity of keeping the size small, the complexity and the cost of sensor devices have up to now discouraged the use of real-time video sensing services. A middleware approach could significantly simplify this task. However, if we consider WSNs, the situation is quite different. In fact, although middleware is a well-established research area in distributed computing systems, WSNs pose new challenges because the traditional middleware techniques cannot be applied directly. In fact, most distributed system middleware is designed to hide the context. However, WSN-based applications should be context-aware. Moreover, although mobile computing middleware supports context-awareness, its major concern is to satisfy the needs of single nodes. In contrast, WSN-based systems are data centric, reflecting the application goals. Also, WSNs often use attribute-based addressing rather than relying on network-wide unique node addresses. Finally, WSNs require the middleware to be lightweight for implementation in sensor nodes with limited processing and energy resources. VISION intends to exploit full system adaptability to the context as a ground-breaking approach to overcome these limitations. Dynamic QoS management relays on a specific ultra-flexible middleware (MW) which links together all HW components of the system. The distributed middleware will allow these components to participate in the process of optimally managing the resources based on the status of the context.

## Model-Driven Engineering for Embedded Systems

This research line is about customizing classic Model-Driven Engineering approaches to embedded systems development. In particular, DEWS is focusing on automatic models transformation (e.g. from platform-independent to platform-specific models, from development models to analysis models, etc…) and code generation (C/VHDL) for (reconfigurable) HW/SW platforms (e.g. [PSLO+11]). Further, we are working on the development of innovative approaches and tools to support the designers in activities where they rely heavily on experience. In particular, we are focusing on *Design Space Exploration* (and related activities like system-level estimation, and simulation) that leads to HW/SW partitioning, architecture definition (following a Platform-Based approach) and mapping of the model on the defined architecture while trying to satisfy system constraints ([Pom11a], [Pom11b]). Finally, we are working on the development of innovative approaches for complex embedded systems *Verification & Validation*, for both functional (e.g., formal verification and model-checking) and non-functional (e.g., dependability and power consumption) properties. These approaches will be based on both formal analysis and simulation-based techniques.

The PRESTO project, funded by Artemis JU, started on April 2011, and addresses improvements on test-based embedded systems development and validation, while considering the constraints of the industrial development processes. This project is based on the integration of:

- test-traces obtained by test execution in the software integration phase that is carried out in common industrial practice to validate the requirements of the system;
- platform models;
- design space exploration techniques.

The expected result of the project is to establish a methodology based on functional and performance analysis and platform optimization at an early stage of the design development. The PRESTO approach is to model the software/hardware allocation, by using frameworks and standards such as the UML profile for Modeling and Analysis of Real Time and Embedded Systems (MARTE). The analysis tools, including Worst Case Execution Time (WCET) analysis, scheduling analysis and possibly more abstract system-level timing analysis techniques, will receive as inputs on the one hand information from the performance models of the HW/SW-platform, and on the other hand behavioral information on software design from results of the integration test execution. The use of traces for the exclusion of over-pessimistic assumptions during timing analysis is an innovative approach in PRESTO: instead of taking all possible inputs and states into account for the worst-case analysis, a set of relevant traces is separately analyzed to reduce the set of possible inputs and states for each trace.

Particular attention will be devoted to industrial development constraints, and in particular to:

- minimized cost in term of extra specification time and need of expertise;
- a simple use of the tools;
- a smooth integration in the current design process;
- a tool framework flexible enough to be adapted to different process methodologies, design languages and integration test frameworks;
- analysis results validated by comparison to real platform results, and platform modelling for fast prototyping.

The same research line related to PRESTO will be also involved in the context of a future project: CRAFTERS. The CRAFTERS project, which will start in June 2012, faces the problem that ICT-based service and product innovation is curtailed by the growing vertical chain of dependence on poorly interoperable proprietary technologies in Europe. This issue was identified to have high impact on European innovation productivity by the Report of the Independent Expert Group on R&D and Innovation, commonly known as the *Aho-report*. The report demanded efforts for the convergence of shared technologies and markets. Actions creating standardized, commercially exploitable yet widely accessible ecosystems in European priority areas should be publicly supported. Real-time applications for heterogeneous, networked, embedded many-core systems suffer from the lack of trusted pathways to system realization and application deployment. Service and product development efforts are high and live with many uncertainties discouraging such ventures. This project brings to bear a holistically designed ecosystem from application to silicon. The ecosystem is realized as a tightly integrated multi-vendor solution and tool chain complementing existing standards. Marketable applications and benchmarking on the fields of industrial & intelligent transport systems, video & image processing, and wireless communications will be produced. Key challenges include guaranteeing secure, reliable, and timely operation, back-annotation-based forward system governance, tool-tool, tool-middleware, and middleware-hardware exchange interfaces, and energy management with minimal run-time overhead.

# A1: Intelligent transportation systems

## Vehicle Control

Automotive electronics and control has evolved over the years to a level of complexity that only an integrated approach can be effective. The most visible advance in electronic capabilities in a car is the amount of computational power and sensing devices that have been made available to control engineers.

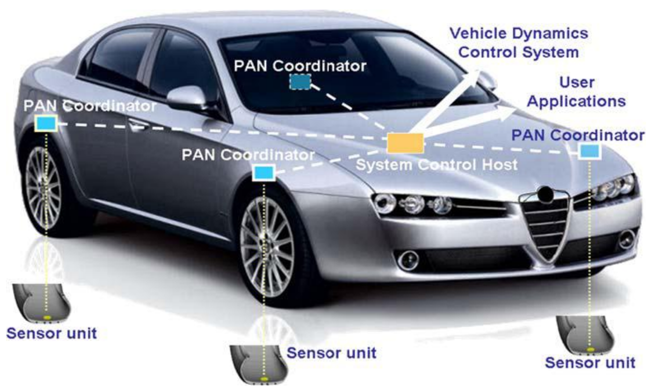


Figure A1.1: Intelligent tires for vehicle control.

The key element of integrated vehicle control is that the behavior of the various vehicle subsystems has to be coordinated, i.e. subsystems have to behave as cooperatively as possible in performing the desired tasks. In this context hierarchical control architectures can be used, where all control commands are computed in parallel in one core algorithm and where the control has to take into account the interactions among vehicle subsystems, driver and vehicle. Clearly, the fully integrated controller will be more complex than the sum of the stand-alone ones, but it will guarantee increased performance and robustness.

Active Safety Systems Integration is one of the main research topics in vehicle control area. In order to guarantee safety properties on the vehicle behavior, several active system technologies have been developed such as active braking, active steering, active differential and active suspension. These devices modify the vehicle dynamics imposing forces or moments to the vehicle body and can exploit smart sensors (for example the so–called intelligent tires[2]), allowing precise and distributed measurements from the environment, to increase the performance of control action, vehicle stability, safety and comfort of the driver.

DEWS researchers investigated Active Safety Systems Integration in the context of the HYCON2 NoE. In particular, an important design factor to be considered in the stand-alone or integrated controller design is the actuator saturation, which limits the maximum obtainable performance. In an integrated control structure more power is available for control, thus potentially limiting the saturation occurrences. In all cases, it is important to manage critical situations, whenever actuators are not physically able to apply the required input. In [BBCT+11b] a strategy for managing actuator saturation has been proposed, where different priorities are assigned to the fulfillment satisfaction of the tracking objectives of the

[2] S.C. Ergen, A. Sangiovanni-Vincentelli, X. Sun, R. Tebano, S. Alalusi, G. Audisio and M. Sabatini. The Tire as an Intelligent Sensor. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 28(7): 941-955. 2009.

state variable (yaw, lateral, and roll velocities) and, when the actuators saturate, only the tracking of the variables with higher priority is ensured. Along the same line, in [BBCT+11a] a hybrid controller for actuator saturation management is proposed, which relies on a mechanism to prevent the occurrence of input saturation based on input limiting functions and on a modification of the reference signal.

As a further complication to this setting, new technologies introduce problems regarding wireless communication , e.g., poses a number of challenges such as packet losses, fading effects, and synchronization. An analytic approach and formal models that take into account all non-idealities that are typical of Networked Control Systems (NCS) are needed. To date, we addressed the vehicle control problem in a non-linear setting with ideal communication, and proposed an integrated controller to guarantee vehicle stability/trajectory tracking. We are currently introducing the non-idealities of the communication system in the control scheme derived in the ideal case. In particular, we aim at applying the results obtained in M1 on nonlinear NCS and we are currently developing self-triggering control strategies [DBDG+11b], which allow triggering sampling and wireless transmission only when necessary to reduce energy consumption while guaranteeing the fulfillment of control specifications.

## Air Traffic Management Systems

In the last few years the trend in Air Traffic Management (ATM) systems research is to focus on airborne self-separation to yield less dense airspace. Typical examples of this trend are the research projects Mediterranean Free Flight and Advanced Safe Separation Technologies and Algorithms, funded by the European Commission. The research project "Safety, Complexity and Responsibility based design and validation of highly automated Air Traffic Management" (STREP iFly, 2007-2011) was funded by the European Commission in 2007 within the 6th Framework Programme. The Center of Excellence DEWS was one of the eighteen partners in the consortium, which included universities as well as industrial institutions. Project iFly aims at deploying the advanced formal methodologies developed in the project HYBRIDGE, funded by the European Commission in 2002 within the 5th Framework Programme, where the Center of Excellence DEWS participated as an academic partner. Currently, two approaches are pursued. One is to push for airborne self-separation which according to this view can safely accommodate traffic levels much greater than current en-route traffic. The other approach is based on the assumption that airborne self-separation cannot ensure safety in high density airspace. Both schools agree that airborne self-separation may be safe for airspace with sufficiently low traffic densities. From a research perspective point of view, this asks for evaluating at which air traffic levels airborne self-separation is safe. This is the main goal of the iFly project.

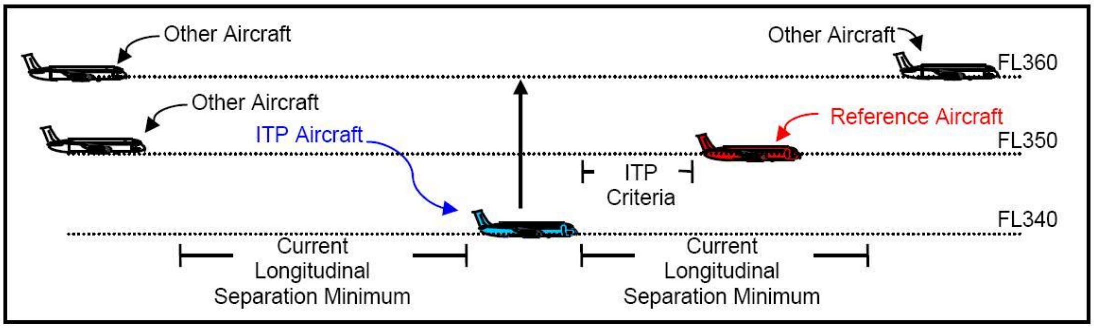


Figure A1.2. Airborne Separation In–Trail Procedure.

In this project, our group proposed formal methods for the analysis of the so-called *multi-agent situation awareness inconsistencies*. Safety of ATM procedures requires that any agent has a correct perception of his situation as well as of the situation of the surrounding agents. Situation awareness inconsistencies of own and surrounding agents can lead to the execution of maneuvers that are unsafe and in some cases, even catastrophic. A formal approach to model and analyze ATM systems is very important. In particular, the complexity of ATM systems requires appropriate mathematical models that adequately capture key features of ATM systems. While aircraft dynamics are generally described by differential equations, pilots' and air traffic controllers' behaviors are well modeled by finite state machines, whose states and transitions mimic the procedure the agents are requested to follow. It is evident that a unique mathematical model for describing ATM systems needs to deal with both continuous and discrete dynamics. Hybrid systems' formalism, featuring both discrete and continuous dynamics, is characterized by an expressive power that we proved to be general enough to adequately describe ATM systems. Formal analysis of situation awareness inconsistencies arising in ATM scenarios can be well approached through the notion of *critical observability*. Critical observability is a structural property of hybrid systems that corresponds to the possibility of detecting if the current state of a hybrid system is in a set of critical states, representing unsafe, disallowed or non–nominal situations.

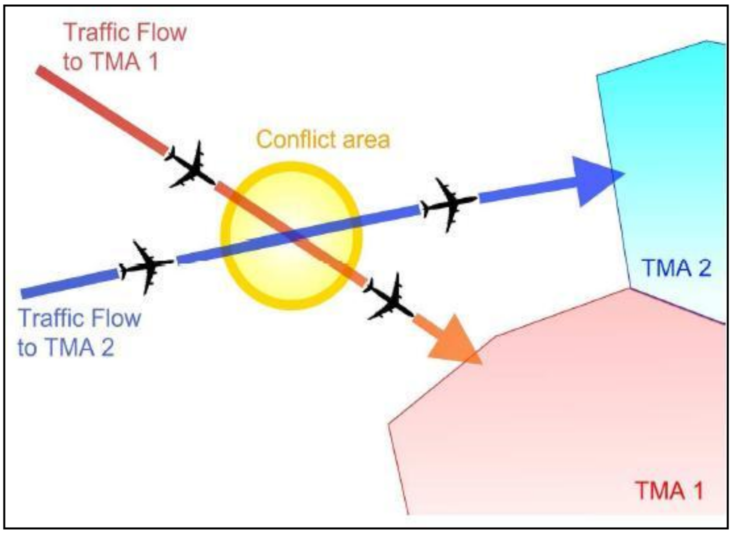


Figure A1.3. A3 ConOps Scenario.

Researchers at DEWS introduced this concept in the control and hybrid systems community and proposed efficient algorithms for its verification, see e.g. [DBDG+09] and the references therein. First investigations in this regard focused on critical observability of hybrid systems taken in isolation. However, when addressing the analysis of critical observability in ATM multi-agent scenarios, agents cannot be considered in isolation. Indeed, agents' interaction is responsible of the occurrence of unsafe situations that cannot be captured when considering different agents in isolation. For this reason, we proposed a compositional hybrid systems' framework that provides a formal model of the agents and a formal model of their interaction, as well. The interaction mechanism among the agents involved, has been modeled through an appropriate notion of composition that has been inspired by classical notions of parallel composition in automata theory and input–output composition for switching systems. This compositional hybrid systems' framework allowed us to formally approach the analysis of multi-agent situation awareness inconsistencies arising in relevant ATM procedures studied and under study in the ATM community. Although formally sound, this approach is applicable only with great difficulty to realistic ATM scenarios with a large number of agents. Indeed, the number of variables involved in realistic scenarios grows exponentially with number of agents, thus posing serious problems in the computational effort. For this reason we elaborated in e.g. [DSDB+09c], [PPDB+10a], formal results which guarantee in many cases, a drastic computational complexity reduction which allows us to deal with ATM scenarios where an arbitrarily large number of the agents operate.

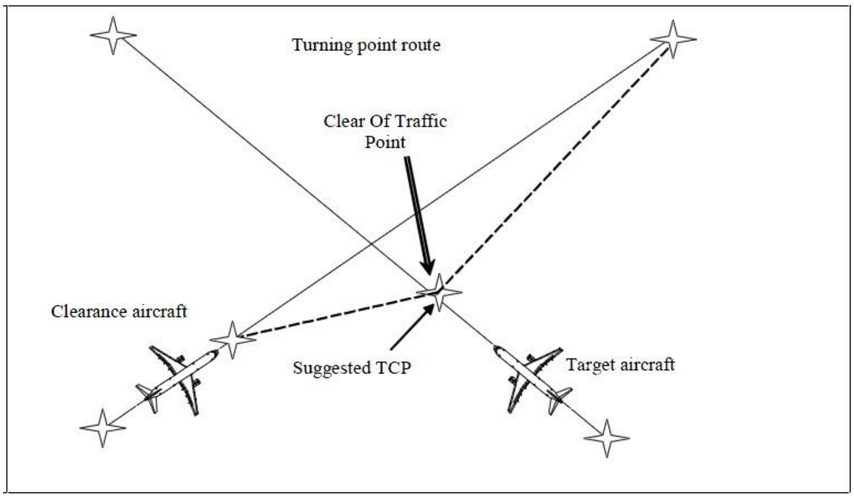


Figure A1.4. Lateral Crossing Procedure.

We used this mathematical framework to model and analyze a number of procedures studied and currently under study by the ATM community, which include Airborne Traffic Situational Awareness In–Trail Procedure, Airborne Separation In–Trail Procedure (as illustrated in Figure A1.2), ASAS Lateral Crossing (as illustrated in Figure A1.4) and some scenarios within the Autonomous Aircraft Advanced Operational Concepts (A3 ConOps) (see Figure A1.3). Our analysis revealed the need for supplementary means that can make the procedures under study critically observable. Our analysis also identified the weak steps of the procedures where additional alarm signals are needed in order to make the procedures critically observable. The expertise of DEWS researchers has been essential in the success of the iFly project and motivated the iFly project coordinator to select the Center of Excellence DEWS, as the unique academic institution to join the ATM Project "Mathematical Approach towards Resilience Engineering in ATM" (MAREA). The MAREA project proposal has been submitted to the SESAR WP-E Projects Call. Among 43 projects proposals only 18 projects were funded. The MAREA project was selected and started its research activities on March 2011. DEWS researchers are currently working in this project and providing formal tools for the verification of correctness of ATM procedures under study within the novel SESAR 2020 concept of operation. Preliminary results toward the formal analysis of this novel concept of operation are reported in [PPDB+12].

## Highway Traffic Management Systems

Traffic congestion has always been a serious problem in advanced countries, but today, it is becoming even more relevant because of ever increasing mobility, pollution and fuel consumption. Researchers have been investigating solutions to monitor and control traffic for decades. Yet, present technological developments, especially as far as sensors and communication devices are concerned, make the transfer of research results from the speculative level to the applicative one increasingly effective and reliable. This is the reason why, recently, the research in this field has been revitalized. A necessary step towards active congestion control is the creation of accurate and reliable traffic monitoring and control systems. Traffic control centers monitor the traffic situation on the basis of video images and measurements acquired, for instance, from loop detectors (magnetometers) placed in the roads. Information about traffic density, average velocities, accidents, weather conditions, used together with reliable traffic models, are some of the ingredients necessary to predict future traffic states and to determine the appropriate control actions to take. Work Package 5 (WP5) of the European Network of Excellence HYCON2 is about developing efficient traffic control strategies to face traffic congestion problems using advanced sensing technology. Another research objective is to apply to a real traffic system the proposed control strategies before the end of the project (August 31st, 2014). The test case is a freeway located in the southern part of the Grenoble area. The freeway is being equipped with innovative traffic sensors which communicate in a wireless fashion with a control center located in the urban area.

DEWS researchers are currently addressing the case when control actions are computed in a control center located far from the traffic system and then transmitted, through a wireless communication channel, to the actuators placed along the road (i.e. on ramp traffic lights in the ramp metering control illustrated in Figure A1.5). More specifically, we assume that the communication network is a dynamical system with peculiar features and the transmitted information may be affected by time delays and packet loss. The macroscopic model named METANET is chosen to describe the freeway system in terms of traffic flow evolution. METANET is a second order model that enables to describe the dynamics of traffic speed, which is required to deal with problems of emissions and fuel consumption. We propose to adopt a control strategy based on model predictive control (MPC) nature using a buffer to compensate time delays, so that the designed traffic networked control scheme provides performances significantly close to those of the ideal case (i.e. no delay). Further, in order to reduce computational load, a modified version of the control strategy is proposed, in which the length of the control horizon of the predictive control algorithm, and, consequently, the buffer length, is updated according to delay estimation. A simulation analysis of the different networked control strategies is provided, along with the comparison with a conventional MPC equipped with an hold mechanism.

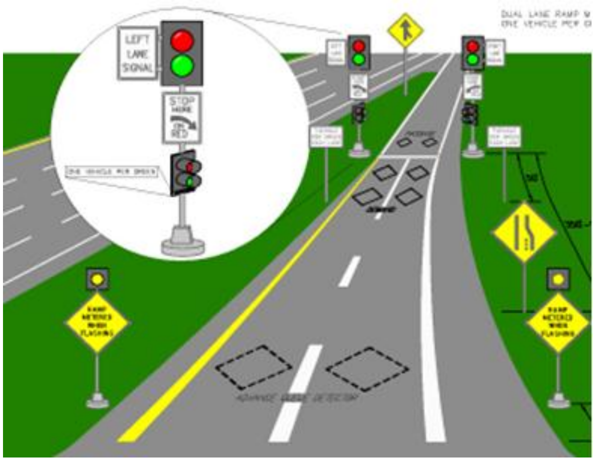


Figure A1.5: On-ramp metering control.

# A2: Energy

## Mining Ventilation Control

In the context of the HYCON project, we conducted a research on ventilation automation on behalf of Boliden, a leading European metal mining company, using as test case one of its mines located in Garpenberg, Sweden (see Figure A2.1). At Garpenberg, polymetallic ore is mined. Its main constituents are zinc and silver, but the ore contains also lead, copper and gold. Overall, more than one million tons of ore are processed at the concentrator every year. One supporting process associated to ore extraction in a mine is the ventilation in tunnels, needed for oxygen supply of the personnel and for the combustion process of vehicles. Mining ventilation is an interesting example of a large scale system with high environmental impact where advanced control strategies can yield major improvements. More specifically, as much as 50% or more of the energy consumed by the mining process may go into ventilation (including air heating). Indeed, an important objective of a modern mining industry is to satisfy environmental specifications during ore extraction and crushing, by minimizing energy consumption or and/or pollution. The mine electric consumption was 4% of total industrial electric demand in the United States in 1994 (6% in 2007 in South Africa) and 90% of it was related to motor system energy. It is estimated that the savings associated with global control strategies for fluid systems (pumps, fans and compressors) represent approximately 20% of the total manufacturing motor system energy savings. During a visit to the mine, we argued that re-configurability and wireless interconnection should have been key components in the design of an advanced ventilation control. Re-configurability is related to the variable topology of the mine (mobile process industry): after all accessible ore has been retrieved from a mine level, the extraction rooms are filled and a new level further down along the decline (which is a spiraling tunnel used by the trucks to reach the surface) is bored. All equipment, including ventilation, has to be moved and re-configured in the new level. While making re-configurability easier, the necessity of wireless networks also derives from blasting and drilling operations in the extraction rooms, making the wiring infeasible in these areas. Wireless networks can also be used for improving the efficiency of other processes that are of importance in operating a mine, e.g., equipment (trucks and ventilation system) maintenance, people and equipment localization, voice communication and security. As depicted in Figure A2.2, the actual control architecture is characterized by:

- no automatic control, but maximum ventilation power during ore extraction;
- no continuous monitoring of air quality;
- no wireless sensing;
- no localization system.

Figure A2.1: Mine site at Garpenberg, Sweden.

DEWS researchers proposed in [WDIS+10] a wireless control architecture as shown in Figure A2.3, where we introduced networked sensors in the access tunnels and in the extraction rooms. The sensors placed in the access tunnels can make use of the existing wired connections, while those in the extraction rooms have to be wireless, due to the blasting activities. The exchange of sensor measurements and control signals can be then carried thanks to wired links as well as wireless communication.

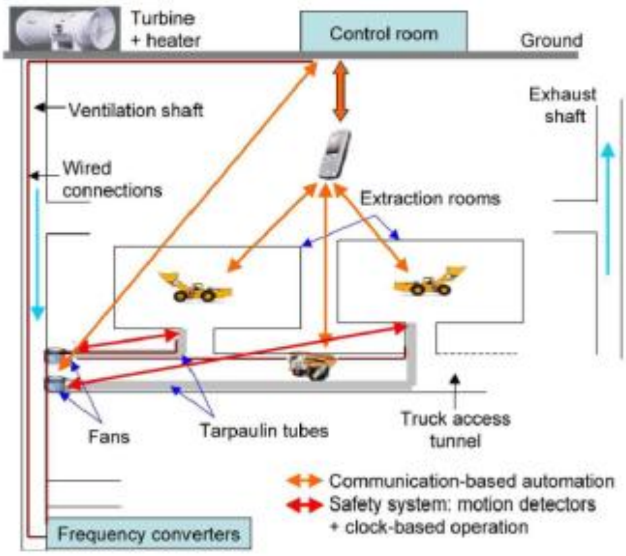


Figure A2.2: Mine ventilation process and actual control.

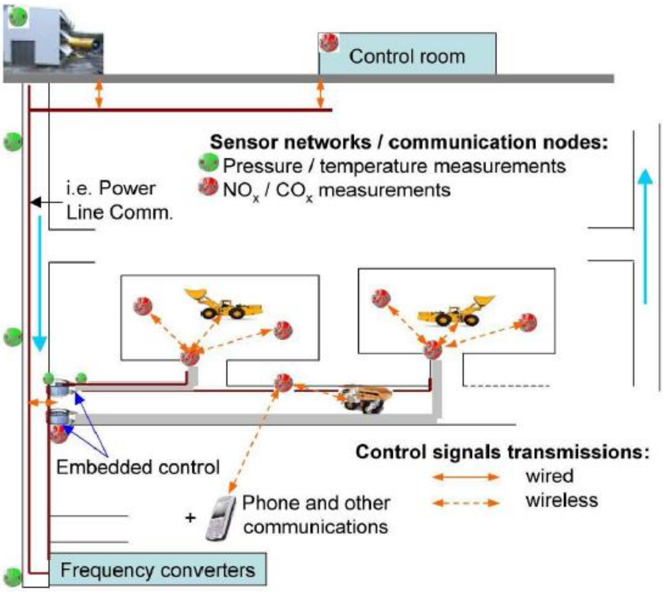


Figure A2.3: Proposed automation architecture.

The objective of the proposed control system is the regulation of turbine and heater to provide suitable air flow pressure at the ventilation fans in the tunnels, and the regulation of ventilation fans to ensure air quality in extraction rooms. We focused our attention on the control of air quality, addressing the following control specifications:

**Safety:** the gas concentrations cannot enter an unsafe set (a red alert zone), given by standard air quality for humans.

**Comfort:** the gas concentrations may enter, only for a bounded amount of time, a yellow alert zone where safety air quality for humans is satisfied but may be uncomfortable.

The non-idealities introduced by the multi-hop network have been modeled by means of a communication delay. Inspired by assume-guarantee reasoning, we considered a threshold controller and modeled the closed loop system as a hybrid system. Because of the hybrid nature of the problem (e.g. number of trucks in an extraction room, continuous dynamics of the gas concentration and of the airflow model), it is hard to exhaustively verify on the model whether the specifications above are satisfied for any discrete and continuous disturbance. To overcome these difficulties, we used abstraction techniques and model checking algorithms.

## Smart building automation

The increasing need to improve the efficiency of energy usage is pushing towards the design of green, energy efficient buildings, eventually leading to buildings whose net energy consumption is zero, as shown in Figure A2.4. The term green building (also known as green construction or sustainable building) refers both to a structure and to the practice of designing structures that are environmentally responsible and resource efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Buildings, both residential and commercial, consume significant amount of energy and account for approximately 20% of world energy use, as depicted in Figure A2.5. In a highly developed and industrialized country such as the United States, the shares of buildings in the energy consumption is even bigger reaching more than the 40%, as shown in Figure A2.6.

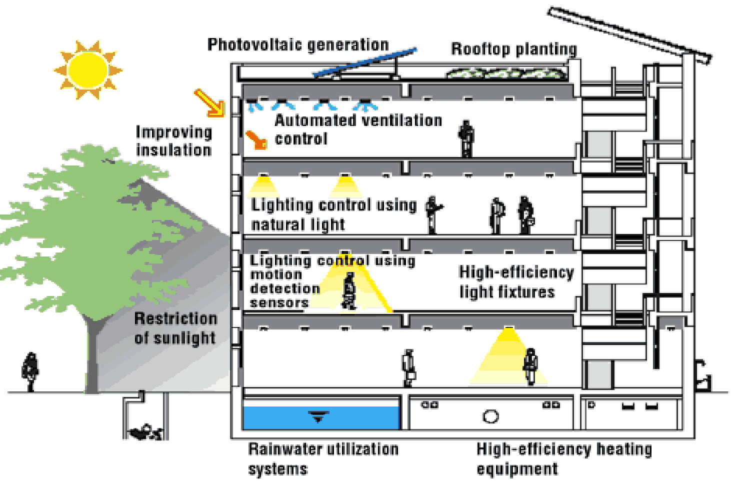


Figure A2.4: Control of a green building.

With growing environmental awareness and uncertainty in global energy markets, energy-efficient buildings are appealing for consumers, corporations, and government agencies alike. Moreover designing and deploying building control systems is becoming increasingly difficult. It is expected that the design of future generation energy efficient buildings will rely on control algorithms that are capable of fine-tuning energy consumption.

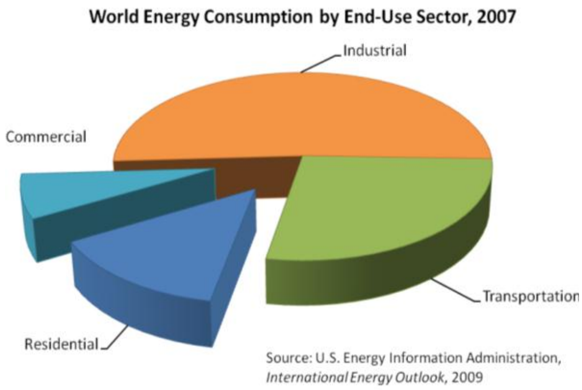


Figure A2.5: World energy consumption.

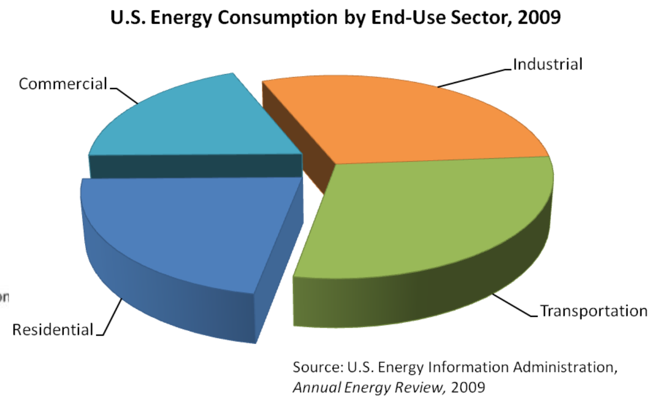


Figure A2.6: U.S. energy consumption.

Building automation can be regarded as a special case of process automation, with the process being the building indoor environment and its closer surroundings. The process consists of numerous sub-processes, both discrete and continuous. The most complex processes are present in the Heating-Ventilation-Air-Conditioning (HVAC) domain. Since HVAC processes involve large (thermal) capacities, changes in system parameters occur only gradually. Quick transients typically only have to be detected when optimizing system behavior. Since the process behavior is slow, requirements on controller response times are relaxed compared to industrial control applications. Despite the general absence of high-speed control loops, HVAC control is not without challenges. It has to deal with disturbances, which change over time as a function of load, weather conditions, and building occupancy. These influences are of stochastic nature and therefore not exactly predictable, although certain assumptions can be made. In large buildings, the HVAC system can be decomposed into three groups of subsystems, which are depicted in the schematic diagram in Figure A2.7. This architecture implies the existence of three levels of controllers acting with growing hierarchical importance from the terminal units to the central plant.

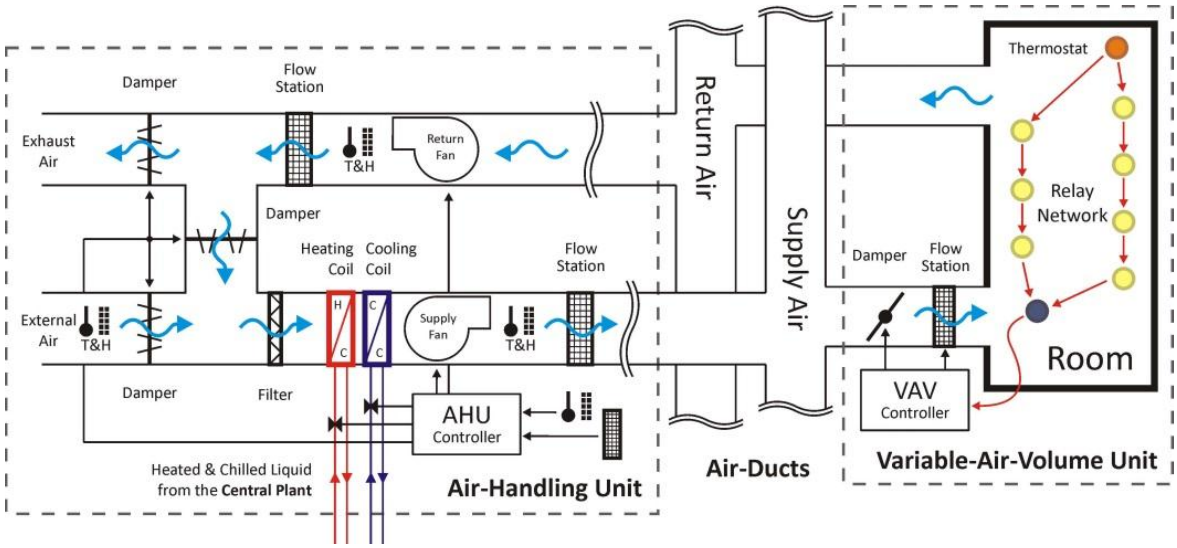


Figure A2.7: HVAC scheme.

In smart buildings, Wireless Sensor and Actuator Networks (WSANs) determine the observable and controllable variables available to the building manager and have to be systematically designed, located and monitored to achieve effective control and diagnosis, high reliability and low maintenance costs. Wireless multi-hop networks play a dual role in the realization of smart buildings since, if on one hand they introduce additional problems during the design phase, on the other hand they offer a rich palette of possibilities to the designer. In particular, multi-hop WSANs have very desirable characteristics for this application. The benefits of distribution are manifold, such as increasing robustness and reducing latencies in control loops, avoiding single points of failure, reducing the risk of performance bottlenecks and allowing for subsystems to be out of service due to failures or scheduled maintenance without affecting other parts.

Today, the design and installation of HVAC systems is based on experience from previous designs. Due to the scale and heterogeneity of control systems for large buildings, the design of the control algorithms and communication networks for HVAC systems is very challenging for designers without the help of automated procedures. DEWS researchers believe that building automation, and in particular HVAC system control, is an interesting and promising application field for the methodologies developed for Networked Embedded Control Systems in research area M1. We aim at exploiting our methodologies for co-designing control algorithms in an HVAC system and protocol configuration (e.g. topology, scheduling, routing) of a WSAN deployed in a smart building. The existence of a formal mathematical framework for modeling a (wireless) networked control system allows exploiting optimization techniques with the final goal of minimizing the total energy consumption, while satisfying constraints such as peak power consumption, transmission power and communication bandwidth usage of the wireless nodes, network latency, robustness to packet losses, and fault tolerance. Moreover, the methodologies developed in M1 allow detecting malfunctions of network devices at the application level of the ISO/OSI protocol stack without modifying the communication protocol. By dynamically reconfiguring the control algorithms using on-the-fly fault detection algorithms it is possible to avoid "out-of-service" of the networked control system even in case of partial malfunctions and maintenance interventions.

# A3: Advanced monitoring and control

The methodological research activity and especially the one in M2 is strictly related to various application domains in which wireless sensors and actuators networks provide the key support for advanced applications. In particular, the following application areas are of interest for A3:

- Environmental monitoring and control
- Precision agriculture
- Wireless networks in manufacturing plants
- Structural monitoring
- Homeland security
- Home automation
- Support to new arts

Although research activities have been done in all these areas, in year 2010 specific projects on the application areas "Environmental monitoring and control" has not been carried out.

Besides all the activities to support the development of applications and prototypes, illustrated in the description of the most recent projects in the remainder of this section, DEWS researchers performed international coordination activities on application domains of relevant interest. The COST Action IntelliCIS: "Intelligent Monitoring, Control and Security of Critical Infrastructure Systems" falls in this context and is summarized below.

The main objective of the Action is to develop innovative intelligent monitoring, control and safety methodologies for critical infrastructure systems, such as electric power systems, telecommunication networks, and water distribution systems. This is an interesting action, that brings together expertise from different fields in order to develop methods for managing and protecting critical infrastructures, especially those of major interest for the society.

DEWS is especially committed in WG3, which deals with telecommunications networks and is particularly targeted to i) investigate security models as they apply to various networks (e.g., wireless, optical), ii) design methodologies for intelligent management, monitoring and control of communication systems, iii) develop network security models and use them to enhance network security, iv) develop resource allocation and Quality of Service provisioning methodologies, v) investigate similarities and connections with transportation systems. DEWS is contributing with original work on developing and implementing security mechanisms in wireless sensor networks (see internal project WINSOME), and on designing routing and topology control for wireless networks in critical applications.

## Precision Agriculture

A detailed monitoring of environmental parameters which are critical for a particular cultivation can permit the optimization of production and the improvement of quality. At the same time through this monitoring it is possible to detect precisely pathologies or criticalities. As a result, an effective irrigation and a proper and selective dispensing of chemical treatments (e.g. fungicides) is possible, so lowering the presence of chemicals in foods while reducing costs. In this report the project entitled "Monitoring technologies for the support of cultivation of grapevine and the production of wine" is briefly described.

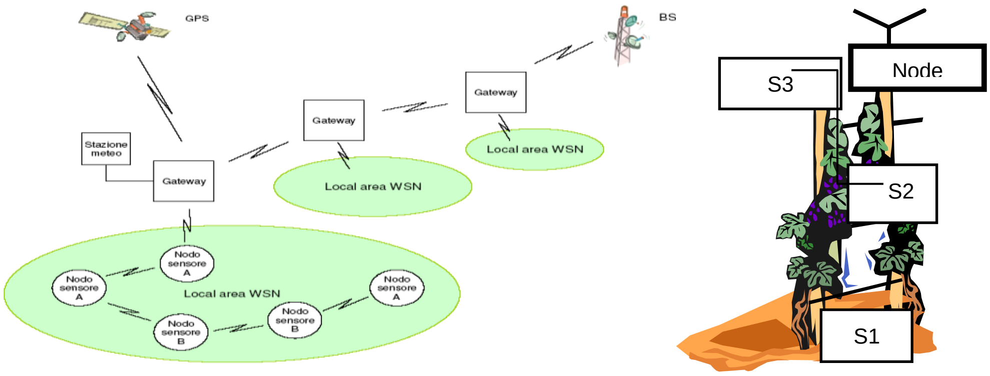


Figure A3.1: Network topology for precise agriculture.

The impressive development of Internet of things allows connecting with an ever increasing continuity and reliability sensors and actuators to local area networks and, through them, to potentially convey the data around the world. In such a context a crop can be equipped with networks of sensors/actuators, and through their administration by the farmer, it is possible to make maximally efficient the agricultural production, allowing the production to reach quality objectives otherwise difficult to achieve. One area of agricultural production in which this kind of methods are being tested since four years is the cultivation of vines for the production of high quality wine. In this context, networks of sensors/actuators (often wireless) have been deployed in Italy (Chianti area) and in France, collecting statistical data showing that a proper use of these innovative technologies can lead to increases in production capacity and in product quality. However, it is straightforward that these actions have focused on experimental areas that historically operate in the wine sector, with internationally recognized expertise and results. Indeed, to produce quality wine we cannot rely solely on technology but it must be accepted by those who holds the know-how and dominates the complex and delicate process of high quality wine production, so that the technology exploitation can be maximized. In this project the equipment of a vineyard with networks of sensors that collect a series of chemical and microclimatic parameters and which make such data available to growers is proposed. This will make it possible to provide to professionals in that sector, which already have significant expertise and sensitivity in managing the process of cultivation and production, a new tool that enables them to further improve the quality of their product, reducing costs and preserving the environment. Monitoring in this context aims a number of objectives: (i) improvements in productivity, (ii) improved quality, (iii) optimization of resource use (e.g. water), (iv) minimization of environmental impact (use of pesticides, herbicides, etc.), (v) cost reduction (automation of operations, optimization of interventions). To be most effective, monitoring of weather should be performed on two different spatial scales: (a) macroclimatic monitoring , which measures the weather of the entire cultivated area, (b) microclimatic monitoring, which performs measurements at much shorter distances and with a spatial resolution much higher in the cultivated area. Each crop has special monitoring requirements, related to the different sensitivity of individual plant species to various climatic parameters and the specificity of the threats caused by them. Viticulture, as a first phase of the wine production process, is one of the crops most valuable in terms of economics in general in Italy and in the Abruzzo region. The specific requirements for monitoring applied to winemaking can be summarized as follows.

Macroclimatic monitoring - integrated monitoring of: (a) air temperature, (b) direction and speed of wind, (c) rainfall intensity; in order to: (i) report in near real time the approaching of frosts, (ii) create statistical maps of the risk of icy conditions, (iii) create historical maps of macroclimatic conditions for the preparation of estimates of the maturation process and the addressing of harvesting operations (quality improvement), (iv) develop estimates of the amount of water fallen on the cultivation in order to manage selectively watering operations (optimization of resources) and make assessment of the risks associated with excessive release of water.

Microclimatic monitoring - integrated monitoring of: (a) solar radiation, (b) humidity, (c) soil moisture, (d) moisture of the leaves, (e) soil pH, (f) concentration of CO in air, (g) concentration of iron in the soil (h), concentration of herbicides in soil.

There are several classes of end-user that might be interested in the type of information that can be extracted from the base of raw data collected. Among them there are farmers, associations and public agencies operating in the agrifood industry sector, public bodies operating for the protection of health, and organizations concerned with intellectual property protection.

# Distributed network architecture for monitoring systems

The advanced features of a monitoring system, both in terms of richness of information acquired in the environment and of timeliness in the development and delivery to a user, cannot disregard the availability of a capillary communications network. For ease of installation, maintenance and reconfiguration, the network must necessarily make use of wireless technologies. In this context both short-range communications systems (e.g. Wireless Sensor Networks, WSN, and solutions for radio frequency identification - RFID) and systems that provide connectivity on a geographic scale (e.g. mobile systems) are available. The combination of these network components ([PTGD+09a], [TPGD+09a], [TPGD+09b], [TDRP+11], [TPTA+11]), together with the use of proper protocol solutions (e.g. self-configuring networks with low energy consumption on some nodes) and of advanced software architectures (embedded operating systems, distributed databases, localization features) leads to the definition and advanced implementation of service platforms characterized by: i) modularity, ii) flexibility, iii) sustainability, iv) pervasiveness, v) ease of usage and of maintenance. All these functions are largely absent in traditional monitoring systems. Based on these considerations, in this project the network architecture for wireless coverage of a cultivated area consists of wireless sensor nodes for the pervasive monitoring, each affiliated with one (or more) gateway(s). The measuring stations must be differentiated, i.e. equipped with different configurations of sensors optimized according to the measuring point, in order to reduce the complexity and cost of each station. Gateways should be able to organize a network among themselves so as to ensure the transport of data collected through the cultivated area up to the first point of access to the communication network infrastructure. WSN components can be reviewed as a set of homogeneous elements, whose goal is mainly to collect useful data for environmental monitoring. The distance between adjacent nodes can vary from a few tens to a few hundred of meters (depending on the technology and on the requirements of energy autonomy of individual nodes). In such networks there is a Base Station, that is an element that is responsible, on a local basis, of the collection, storage and processing of data collected by sensor nodes in the interested area to make them accessible to an infrastructured network, which is in turn responsible of onward transmission to the remote control center. The sensor nodes are equipped with an interface with the whole range of planned sensors and they have to manage sampling in accordance with the physical quantities under observation. It is also necessary to equip sensor nodes with software modules that can implement the geographic positioning of nodes, which allows to tag collected data with their coordinates for the purpose of enabling targeted activities. This is particularly important in the "precision farming" which aims to optimize the interventions (irrigation, fertilization, pest control, harvest) by planning, in a geographically selective mode, all operations on the basis of data provided by the monitoring system. The ability to automatically obtain the location of the nodes can make the network deployment easier and cheaper, especially in those cases where the system must be moved periodically as affected by crop rotation in soils.

Upon completion of the technological framework provided in the preceding paragraphs, it is interesting to consider the use of RFID for traceability in food processing field, with the aim of responding to the needs of:

- checks to ensure local and typical productions (geographical area protected designation of origin etc.);
- anti-sophistication checks.

Therefore, in this scenario, cultivation is the first step in a transformation process (e.g. grapes into wine and derivatives) which coincides with the path to be traced. The most basic tracking application should provide for the labeling of the harvest with a tag that identifies the source and allows to automate the tracking operations that follow the raw material, including information from more diverse farms along the different stages of the chain processing or distribution. An evolution of this basic application may leverage the added value brought to the agricultural production activities from the monitoring system described in the preceding paragraphs, one of the peculiarities of the environmental monitoring is indeed its capability to assess the quality of production, linking it to the environmental conditions which accompanied the process of maturation.

## Structural Health Monitoring

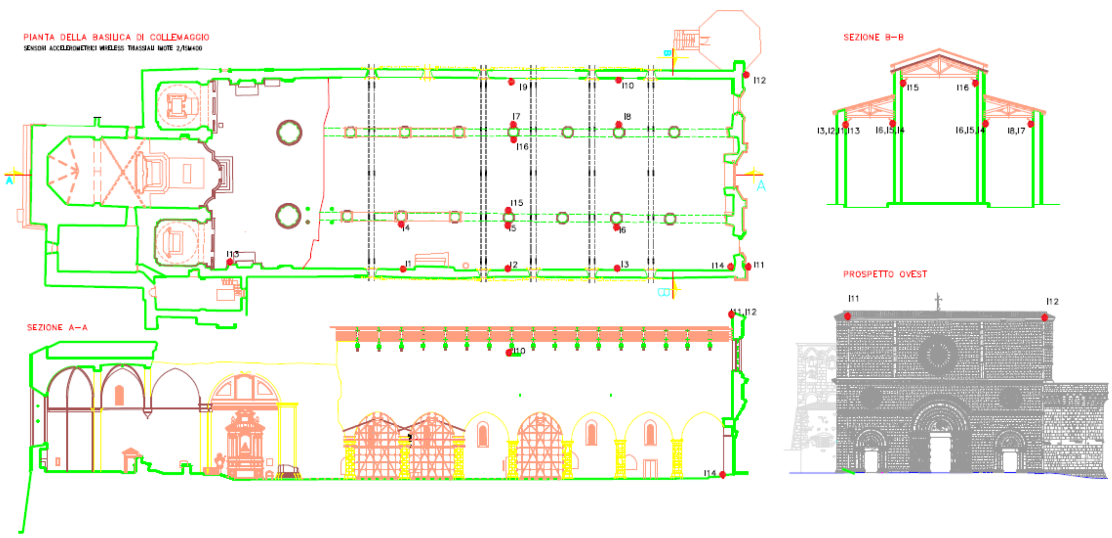


Figure A3.2: Network topology for structural health monitoring of "Basilica di Collemaggio", L'Aquila, Italy

Structural health monitoring systems have a key role in building maintenance and their post-disaster assessment [FGFC12]. Traditional systems are made up of grids of sensors deployed along the building and communicating with a central processing unit via a cable connection.

In the last years, Wireless Sensor Networks (WSN) emerged as a possible attractive alternative solution. Indeed, the replacement of cables with wireless connections along with the use of modern sensors allows to obtain significant benefits in terms of cost, size, ease of installation and invasiveness (key issue in the case of historical buildings) [ACGG+11].

From the network hierarchy viewpoint, sensor nodes measure the structural response and send their data to a so-called "sink node", which collects all data from the whole network. Modern sensor nodes have limited maximum power at the antenna (due to technical and economic requirements), so the available radio range may often end up to be under-dimensioned for the structural monitoring of large constructions; however, thanks to multi-hop routing techniques, connectivity can be extended well beyond the radio range of the single transceiver. The sink node usually forwards received data towards external networks (it plays the role of a gateway). This network unit will be connected to a public network (e.g. to the public land mobile network through the GPRS data service) in order to allow the forwarding to the query messages to the sensor network and to gather the data collected.

Our first goal is to exploit the potential of this paradigm for the implementation of an efficient monitoring system. One of the most representative building of the city of L'Aquila, the Basilica of Collemaggio, will be the first challenging scenario we are going to face. In this scenario, we will try to take advantage of all the features mentioned above, creating a system able to efficiently acquire and transmit data [CFFG+12].

Our research activity will then be oriented to the optimization of data processing. First of all we will try to implement a distributed processing within the network: the development of appropriate techniques for distributed computing, will allow to exploit the processing capabilities of the nodes in order to obtain a local data processing. Besides an optimization of the communication (and therefore of energy consumption), the distribution will be the first step towards a real-time processing of data.

It is well know that one of the major limitations of wireless motes is their limited performance. Therefore, our idea is to use configurable hardware devices (e.g. FPGA) for the creation of hw/sw mixed service based architecture, with processing services directly implemented in hardware. In practice, we want to combine the mote processor with a set of ad-hoc developed co-processors specifically designed for the implementation of various processing modules.

The final result will be an efficient monitoring system able to support heterogeneous services. This result is very important, because in the medium to long term we intend to address three of the major current challenges of civil engineering: structural model updating, damage detection and seismic early warning.

A monitoring system that allows accurate measurements could be the basis for an efficient model updating action. This is extremely important for structural design: only the gradual correction via experimental data allows to obtain a truly reliable model.

The ability to get a long term monitoring action, combined with the integration of environmental effects correction techniques, will allow to implement appropriate damage detection mechanisms. In this way it will be possible to characterize the state of buildings and implement appropriate preventive action with regard to seismic risk.

Finally, the major challenge will be to take advantage of smart sensors for the implementation of seismic early warning mechanisms. In a single-station local approach, our goal is to specialize some of the network nodes as sentinels that will be able to raise an alarm in few - but often vital - seconds before the arrival of high energy seismic waves. This will be the basis for the development of efficient emergency management mechanisms (e.g. automatic security procedures for hospitals, data centers, power plants, gas distribution network ecc.).

# Homeland security

Maximum attention is paid to the issue of homeland security and, in particular, on how the technologies of heterogeneous and cooperative networks can provide a significant contribution in monitoring and control of land and/or sensitive perimeters ([PGS09], [PPS09], [PPS11]). As an example you can refer to the port areas, recognizing that this scenario presents most of the typical application domains of homeland security.

Indeed, in a port area the following needs, sometimes mutually dependent, are present:

a) to secure the port area inside and around its perimeter, which has a part on the sea and a part on the ground and which provides, respectively, the transit of vessels, vehicles and people;

b) to enable the safe harbor activities, often dangerous being characterized by the coordinated movement of vessels, objects and vehicles;

c) to minimize emissions into the atmosphere and water in order to reduce the environmental impact;

d) to increase the efficiency of logistics management;

e) to activate measures aimed at reducing the phenomenon of counterfeiting and smuggling of goods.

Each of the above application contexts is characterized by specific rules and, in this framework, is open to the use of innovative technologies. To prove the topicality of the issues outlined above and the urgency to deal with it, it is useful to mention the project Imcosec (Improve the supply chain for container transport and integrated security Simultaneously - www.imcosec.eu), started on 1 April 2010, which the EU has entrusted the task to identify and describe gaps in security and efficiency of transport logistics. The project is funded through the 7th European Framework Programme (FP7) and brings together different agencies, including the BIC (Bureau International des Containers) and, for Italy, the Politecnico di Milano, and will propose processes, procedures and technologies to help to smooth the transport chain between a port and its hinterland. The first objective is to draw a road map that allows to carry out demonstration activities of the efficiency of the proposed solutions.

The specific aim of this project is to maximally exploit wireless technologies to increase efficiency and resiliency of security related systems and functionalities in this challenging scenario.

# Home automation

The aim of "Casa+" project is to help people with Down syndrome to get their own autonomy by increasing the awareness of their means and always keeping the safety. To achieve these goals we will assist those people with technological support in doing the every-day actions in and outside the house. The plan is to give to the house itself the ability to control and help its guests by using some devices able to check lighting system, water system, ect, and to interact with people living in the house. The project is totally consistent with the Sue Buckley research fund vision (sue-buckley.org/): *"Our vision is a world where all young people with Down syndrome are offered the opportunities that they need to achieve their individual potential..."*.

All projects' activities can be subdivided into three main categories:

***Home Living:*** We want to help guests to use the house's facilities in the best way, in order to do this we need to localize each guest in the house and customize the house action to the particular user. Just to give an example: if someone gets out of a room without switching off the light, the house will remind the guest, calling with is name, that if there is no one left in the room there is no need to keep the light on, and if the user doesn't get the message, than the house takes care of it.

The project also plans to help guests in cooking providing an interactive cookbook that will guide them through the recipe giving the needed actions and timing.

***Communication:*** The house has two multi touch computers installed. By using these devices guests can surf the web though a scalable and customizable browser and also share with each other their multimedia contents such as photos, movies, songs, etc.

***Follow Me:*** This is about a tracking system, made though a specific device or a smartphone, with geo-fencing capabilities. Thanks to a web interface it is possible to define a safe area/path and since the user stays in this area no one is aware of its position. As the user goes out of the safe area, its position is shown on the web interface and an alarm message is sent to the assisting personal. The user can also call the assisting personal in case of emergency by pressing an alarm button.


Figure A3.3: Casa+ network topology.

The project will provide new tools based on ICT technologies that could enable the completion of existing educational protocols or activate new ones.

The expertise of DEWS in the field of home automation, in particular regarding heterogeneous wireless sensors/actuators networks, is proving to be essential for the CASA+ project.

This ability to introduce interesting new elements in the context of home automation through a wise insertion of wireless components is also a key element of a recently funded project, aiming at innovating the home automation context, entitled SMILING (SMart In home LIviNG: Innovative technologies for sensing and automation in Home Automation).

The project aims at creating a "laboratory" for the transfer from research to the industries involved in developing technologies of advanced automation and sensors, in the field of home automation. These technologies will allow the development of innovative products and the delivering of new services to improve housing quality and energy efficiency of homes. The laboratory will consist of three operating units distributed in south-central Italy. The coordinator will be in the Marche area (Fabriano, AN), while other places involved will be located in Abruzzo (L'Aquila - DEWS) and in Campania (Napoli). The two involved universities, Università Politecnica delle Marche, as leader, and Università degli Studi dell'Aquila - DEWS, will provide its expertise and research findings in order to upgrade the product offerings of many SMEs in those territories that are currently operating in the fields of mechanics, electronics, mechatronics, information technology, furniture and systems for energy production and management. The distributed laboratory will perform three main functions: will serve as a demonstrator of the innovative proposals coming from the involved research centers, will stimulate and support, in both technical and management levels, the creation of new high tech enterprises, and will be support new enterprises in carrying out tests and as a meeting and exchange point.

## RF Sounding: a System for Generating Sounds from Spectral Analysis

The contamination between scientific knowledge and artistic components is too often limited to chance, mainly stemming from the convergence on the same research group of technical and artistic interests. In this scenario we are mainly interested in the integration of wireless communications and audio waves, being both characterized by the same propagation medium, even if with substantially different propagation modes.

RF Sounding is an open space installation which comprises both artistic and technological innovations; its aim is to provide the user, while entering a specifically defined area, with awareness of radio frequency signals characterizing the cellular networks band. Indeed, radio signals are shifted, with proper elaboration, to the audible band and the result is spread all over the specific area through a certain number of loudspeakers [GRT10].

For this procedure we have been inspired by the eternal metaphor of the impossible human dream to fly, thus the limitations of our senses which are capable of feeling audio waves (sounds) but (maybe luckily) are not capable of directly feeling radio frequency (RF) waves are highlighted. The translation is the starting point for a more complex and exciting musical composition [Rin10a], [Rin10b].

The aim of this project is twofold. Indeed, from one side we want to increase end users knowledge of the strength of the power emitted by their cellular phones with respect to the electromagnetic fields produced in the environment, on the other hand we want to provide for an artistic and interactive installation that can also be remotely joined through a web interface.

The main project comprises a hexagonal area that is equipped with gate sensors, a subwoofer, six loudspeakers, a receiving antenna for RF sensing and six sensor nodes for localization. The RF signals gathered by the antenna and the localization data coming from the sensor network are sent to a spectrum analyzer and an elaboration unit in order to process sound and spatialization algorithms (see Figures A3.4 and A3.5).

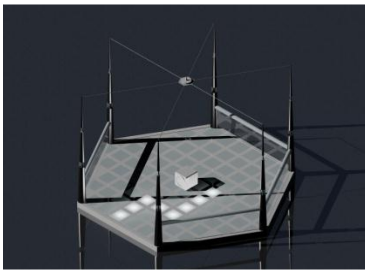

Figure A3.4: RF Sounding: axonometric view.

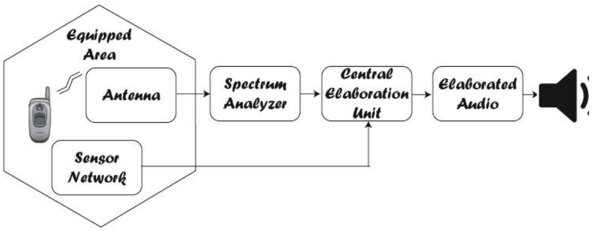


Figure A3.5: RF Sounding: dataflow diagram.

A first prototype has been successfully realized and presented as full paper and demo to various international scientific conferences [RPAG10], [RPGA+10], [RPGL10]. It has been also approved by various Italian contemporary music composers. With respect to the general project the spectrum analyzer is replaced by a GSM engine (Siemens TC35), the localization algorithm is achieved through an active target and sound spatialization is simplified in stereophony.

The active localization is achieved through the use of Crossbow Crickets and a proper developed algorithm. These nodes establish a network where a certain number of anchors (called Beacons) send to a Listener (the node to be localized) both RF and an ultrasonic signals. By computing the time difference of arrival of the two signals, the Listener is able to estimate its distance from each Beacon.

The sound produced by loudspeakers is depending on BSs channel frequencies and Rx powers, as well as user position in space. The sound is elaborated in real time on a laptop that receives data from the listener and the TC35. A proper implementation of Open Sound Control (OSC) protocol has been developed to guarantee these connections. Since we want to represent the different perspectives of reality that can be enjoyed only by flying, the demonstration space is divided into small spaces (corresponding to possible user's positions and thus perspectives) and for each of these positions short musical pieces are developed. They differ from one position to another only for a certain sound characteristic (e.g. timbre) and the larger the distance between two points, the higher the difference between the pieces. Moreover, each piece of music lasts for no more than 30 seconds and can be smoothly interrupted by moving from one position to another. It also moves from the additive synthesis of RF signals (translated to the audible band) to a more complex and changing sound by the exploitation of variables evaluated by means of localization data (distance, speed, permanency, etc.). A proper use of some resonant filters (with moving formant) as well as frequency modulation technique and randomicity assures the completeness of each single micro-piece.

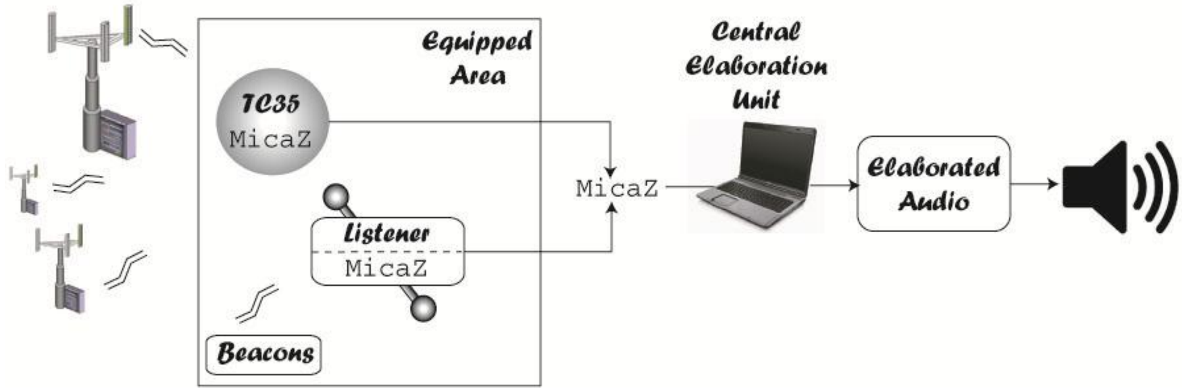

Figure A3.6: Dataflow of the realized prototype.

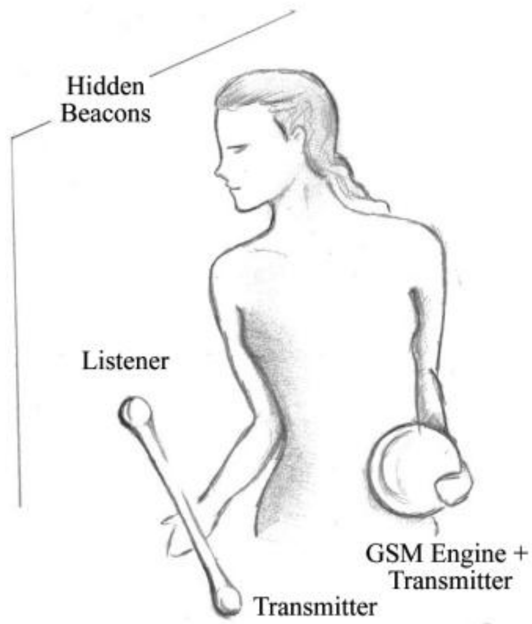

Figure A3.7: Prototype from users point of view.

# Publications

**2012**

[BPDB12a] A. Borri, G. Pola and M.D. Di Benedetto. A symbolic approach to the design of nonlinear networked control systems. *Hybrid Systems: Computation and Control* 2012, pp. 255-264, I. Mitchell and T. Dang (Eds.), 2012.

[BPDB12b] A. Borri, G. Pola and M.D. Di Benedetto. Symbolic models for nonlinear control systems affected by disturbances. *International Journal of Control*. To appear, 2012.

[CFRS12] M. Colizza, M. Faccio, C. Rinaldi, and F. Santucci. A Methodology to Design an Advanced Framework for Efficient Modelling and Testing of MANETs. In *Proc. of IEEE Wireless Telecommunications Symposium (WTS'12)*, London, April 2012.

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