PROJECT PERIODIC REPORT

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1.1 Summary description of project context and objectives

Monitoring systems are common place wherever a building or a structure is built and an invaluable tool where surveillance and hazard detection are needed over time. Production plants, bridges, tunnels and other transportation structures, as well as building for public and private dwelling, are all provided with heterogeneous, collaborating devices capable of *sensing* the current condition of the structure, *report* information to data collection and elaboration points, and sometimes even *enact* needed maintenance, repair or other suitable actions. The clear advantages of using these systems, which include greater safety and reduced maintenance costs, have increased the demand for even more pervasive and sophisticated monitoring tools. *Wireless sensor networks (WSNs)* have recently provided the right technology for enabling cable free systems for structural health monitoring. These networks of collaborative sensor nodes are easily deployable, can be embedded into structures, and through wireless communications they ease data reporting. However, the solutions that have made it to the market are in practice still expensive, typically single-hop (i.e., not pervasive), they require personnel for data retrieval, are as reliable and robust as the wireless technology they deploy, and are scarcely adaptable to context and to the evolving needs of the end users. Perhaps the most important reason preventing the extensive use of WSN-based monitoring systems is that the *lifetime* of the network, i.e., the duration of the services it provides, is severely limited by energy resources: The sensor nodes are powered by short-lived batteries whose replacement or recharge is expensive, if even possible.

The **GENESI** project has the ambitious goal of bringing WSN technology to the level where it can provide the core of the next generation of **systems for structural health monitoring** that are **long lasting**, **pervasive** and totally **distributed** and **autonomous**. This goal requires embracing engineering and scientific challenges never successfully tackled before. Sensor nodes will be redesigned to overcome their current limitations, especially concerning energy storage and provisioning (we need devices with virtually infinite lifetime) and resilience to faults and interferences (for reliability and robustness). New software and protocols will be defined to fully take advantage of the new hardware, providing new paradigms for cross-layer interaction at all layers of the protocol stack and satisfying the requirements of a new concept of *Quality of Service* (QoS) that is application-driven and truly reflects the end user perspective and expectations.

Here are the main objectives of the proposed research:

- Develop *long lasting* sensor nodes by *combining* cutting edge technologies for energy generation from the environment (*energy harvesting*) and green energy supply (*small factor fuel cells*).
- Achieve *robustness* and *energy efficiency* through the integration of low power radio front ends, radio triggering circuit, and energy-efficient, fault tolerant, robust to interference, adaptive protocols and algorithms.
- Define *models* for energy harvesting, energy conservation in super-capacitors and energy availability through fuel cells for enabling nodes to predict when energy will be available, and how much of it.
- Design new *algorithms* and *protocols* that dynamically allocate sensing and communication tasks to the sensors so that end user requirements are met given the currently available resources.
- Design *communication protocols* for large scale heterogeneous wireless sensor/actuator networks with energy-harvesting capabilities. Designing protocols which overcome limits of existing technology in terms of configurability, power consumption, scalability, and fault tolerance.
- Define distributed *mechanisms for context assessment* and *situation awareness* enabling a node to collaboratively determine the status of the environment in its particular region of the network and whether something new and important for the application has happened. Context knowledge and situation awareness are essential to a node for determining strategies for energy management, task allocation and optimized routing.

- Develop machine learning-based mechanisms for predicting environmental behavior and its possible changes. These mechanisms are crucial for maintaining the quality of real-time feedback and control as well as for early warning of potential failures and damages.
- Bring the *end users into the research cycle* from the get go. Gather requirements from their experience, receive continuous feedback through all the research phases, design with them experiments for testing the GENESI technology on the field, and finally assist them on the exploitation of the developed monitoring systems.

All these objectives coincide with those of the third challenge of the ICT theme, and in particular with the target outcome "Engineering of Networked Monitoring and Control Systems" of Objective ICT-2009.3.5.

1.2 Expected final results

The GENESI project has the ambitious goal of overcoming once and for all the barriers that make current monitoring systems unfit for indispensable applications by providing technology with virtually infinite lifetime, that is truly pervasive, is robust and can automatically adapt to application requirements and demands. We will develop a new generation of large-scale, heterogeneous, energy-efficient, situation-aware wireless sensor networks for structural health monitoring and control that are able to autonomously operate for several decades performing in-situ reasoning and evaluation of potential failures invisible to current monitoring.
This goal will be achieved by the following results:

- Newly designed and built node prototypes, integrating cutting edge technologies developed within the project, each of which has scientific merit per se:
  - Fuel cells for low power small factor devices;
  - Radio triggering technology to wake up the transceiver of a given node only when it has to receive a packet addressed to it. This technology will eliminate the energy toll required by idle listening;
  - Multi-source energy harvesters, optimized to work at the best operational point.
- Newly designed and implemented cross-layer optimized networking protocols, exploiting the enhanced GENESI nodes hardware capabilities for optimized system performance. These protocols will operate based on and adapt to application driven QoE (Quality of Experience) requirements. The objective will be to maximize the QoE perceived by the final user while exploiting the spottier energy resources of an heterogeneous wireless sensor network with energy harvesting. Specific contributions will include dynamic task allocation and selective node activation, MAC and routing protocols designed to account for harvested energy and radio triggering capabilities, protocols and algorithms to ensure fault tolerance and robustness to failures, communication unreliability and malfunctioning nodes. Solutions will account for nodes heterogeneity and will be optimized for the nodes resources.
- Newly designed collaborative sensing and learning mechanisms including adaptive distributed sampling scheduling, sensor fusion, outlier detection and learning having cross layer interaction with the networking protocols. Adaptive distributed sampling is one of the mechanisms ensuring energy efficiency and data quality in the network. By designing a mechanism which distributes the sampling load based on energy level of the nodes and which enforces cooperative sampling by taking advantage of the spatio-temporal correlation between neighbouring nodes to reduce the frequency of the sampling, network lifetime can be extended without loosing on the data quality. Limited knowledge of the individual nodes about their observation area will be extended when neighbouring nodes fuse their observations and collectively make a decision. Compared to centralized approaches, this in-network cooperative decision will speed up the decision making and enables situation-awareness. The collaboration between nodes in determining events of interest will enhance reliability and quality of the decision made. Adaptive learning mechanisms are used to cope with inherent uncertainty and error in the sensed data, dynamic nature of the network, and lack of prior knowledge about events influencing the structural health. The ultimate result will be

- Improved sensor data quality (cooperative sensing);
- Enhanced network lifetime (adaptive distributed sampling)
- Being aware of potential structural health deterioration whenever and wherever first invisible indications are sensed (in-network sensor fusion and distributed event detection);
- Quality aware operation of the sensor networks (adaptation).

- Integrated node platform, communication protocols, distributed data processing and learning and reasoning mechanisms to guarantee autonomous, reliable operation of the network for decades.
- Newly developed tools to support ease of deployment and of configuration of large scale heterogeneous monitoring and control systems for critical infrastructures.

The GENESI technologies will be integrated with traditional structural monitoring technologies and data management systems to map the GENESI networks to the needs of the structural health monitoring market segment. Extensive testing of each designed component and of the overall system will be performed by means of in situ experiment designed and performed in close collaboration with the end users.

1.3 Work performed since the beginning of the project and the main results achieved so far

Activity has significantly progressed in all the work-packages (see details in section 2) and the project is generally in line with what originally envisioned. No problems in fully achieving the overall original objectives is currently envisioned, no major delays in achieving technical objectives envisioned for Y3 is currently expected. One significant delay with respect to what originally envisioned regards the start of the second deployment site, due to delays in the construction works. For this reason partners would like to request a minor change in the closure of the technical work-packages, asking to postpone it from M32 to M34. The motivation is to be able to benefit from extensive in field testing activities to refine and enhance system components which could not be tested in the first deployment. The timeline for the integration checkpoint of a first in lab tested complete system is kept the same as originally planned. Major results achieved in the project so far are the following:

- Extensive work has been performed on use cases characterization, node and system requirements. An application-oriented QoS model has been delivered, and node and system architectures have been specified.
- Prototypes of the GENESI platform have been designed, developed, tested and optimized. This inlcudes:
    - A fully integrated wireless sensor node, comprising sensors, 'mote' and power unit. To this end, a GENESI sensor interface layer was designed and developed and a vibrating strain gauge interface board has been designed, prototyped and tested.
    - A smart power unit board hosting multi-harvester (wind and solar) and fuel cells, including serial interface to exchange power information with the main board. It has been integrated in the GENESI node.
    - A radio triggering circuit to selectively wake up the nodes when they need to receive a packet. The wake up technology has been developed, prototyped, characterized, and preliminary tested. Interfacing with the GENESI node is on going.
- GENESI prototype gateway has been developed and is under test, characterisation and validation. It provides for Ethernet and cellular (i.e. 3G) TCP/IP connectivity and GENESI node connectivity (physical) in line with emerged user-requirements
- Communication protocols, models and cross layer optimization has significantly advanced. Specifically, in the second year of the project the following achievements have been reached:
    - We have designed, implemented and extensively evaluated in field energy prediction models which are able to estimate the energy intake both in short and medium term, both in case of solar and wind energy harvesting. Our solution, Pro-Energy has been compared to state of the art solutions such as EWMA and WCMA proving significant improvements in terms of accuracy with which harvested energy can be predicted. For instance considering

a prediction horizon of one hour, Pro-Energy shows a Mean Absolute Percentage Error (MAPE) which is almost one third that of the other schemes;

- We have designed, implemented and evaluated a greedy lazy scheduling algorithm for scheduling node tasks while accounting for available and predicted energy in green wireless sensor networks. The proposed Lazy Scheduling Algorithm is compared to Early Deadline First scheduling of tasks showing that it has superior performance in terms of time of the first deadline miss and number of violated deadlines;
- We have designed and evaluated a scheme, called ENMASSE, for sensor mission assignment, which combines multiple information such as reward and demand of missions, utility offered by a node to the execution of the application mission, as well as energy harvesting, available energy and predicted energy information when deciding which are the missions a node should bid for. ENMASSE is a distributed scheme with the objective to maximize the quality of experience of the final user (based on an expression of the value of missions and of the fit of nodes to missions) over a target lifetime. ENMASSE has been shown superior to SoA such as greedy approaches ('basic scheme'), as well as energy aware and target lifetime aware schemes both in terms of overall QoE (profit), with an increase at least twofold with respect to the other schemes but also in terms of capability to provide a stable profit over the whole network lifetime. We have also analytically modelled the problem showing that ENMASSE achieves performance close to the global optimum.
- State of the art protocols for FEC and routing in energy harvesting enabled WSNs have been implemented and compared. In particular testing of energy harvesting aware routing in the GENESI bridge scenario has been performed by means of GENESI simulator, proving that energy awareness can improve load balancing and increase availability of energy resources for non communication related operations.
- To improve performance in case of coexisting WiFi networks operating on the same band, we have first studied empirically validated models of WLAN operation. A first contribution has been to translate such models which provide a global view of WLAN operation and channel occupation to local view models of the WLAN channel occupation as observed by the nodes. In this way a node can learn the parameters of the model by sampling the channel over time. This information can then be used to adapt the WSN parameters, providing information which can be exploited for dynamic channel selection and for opportunistic channel access within the selected channel. The final MAC protocol is currently under simulation evaluation and will be presented in the next WP4 deliverable. Results provide evidence of the performance impairments that can be caused by a coexisting WLAN (based on a small scale test-bed we have set up, with coexisting WLAN and GENESI WSN), show the simple yet effective model we have derived to allow nodes to learn the WLAN model parameters, and present a simple scheme to perform dynamic channel access. A comparison of the proposed solution with fixed channel operation and the SURF protocols shows our solution is able to achieve over 98% packet delivery ratio while resulting in good latency performance.
- Despite security is not part of the activities funded within the GENESI project, we have combined the experience of La Sapienza GENESI and ARTEMIS CHIRON teams (with the latter project dealing with WSN security) and shown that energy harvesting technologies for sensor nodes may lead to a radical rethinking of the solutions which can be adopted for secure communications in wireless sensor networks. Specifically in the report we describe the design and implementation of a multi-authority CP-ABE based data access control scheme for green wireless sensor nodes. Our access control framework, AGREE, allows nodes to dynamically define and change access policies based on current context, and pushes (most of the)costly CP-ABE encryption operation to periods where thanks to energy harvesting there is an excess of energy available, combining pre-computation and energy harvesting awareness at best.

- Two preliminary solutions for collaborative in-network data processing have been developed, for long linear sensor arrays taking into account lifetime, reliability, data quality, data resolution and abstraction, and latency;
- An improved adaptive sampling approach with a decentralized sampling policy has been developed. Each sensor node decides about its own sampling rate on the basis of environment conditions.
- Design and evaluation of statistic-based outlier detection to detect fast and accurately out of ordinary sensor measurements;
- GENESI simulation framework has been completed, together with abstract models which accurately capture the features of GENESI node and system components.
- Integration of GENESI communication stack, GENESI nodes with interfaces with the identified heterogeneous SHM sensors, and with the smart power unit has been achieved. Interconnection through GENESI GW of the monitoring system with the end users data analysis and decision support systems has also been achieved.
- A first instantiation of the GENESI system is being deployed in field during the excavation phase of Rome underground B1 line from fall 2011.
- First sensor installation at Poya was deployed and further deployment prepared and arranged.
- Significant GENESI results dissemination has been performed, especially in scientific publications (15 accepted), in events where the project was presented to the scientific community (incl. cluster and consultation meetings), in liaison activities with other projects. Moreover, dissemination towards students and potential end-users stakeholders took place.
- 2 patents have been filed regarding the micro fuel cells, and a spinoff company has been started.

1.4 Potential impact and use

The potential impact of the project is multi-fold:

- GENESI has the objective to overcome current barriers of wireless sensor networks enabling long lasting monitoring. Availability of such type of unattended monitoring without the need to charge or replace batteries, limiting the impact and cost of maintenance to the bare minimum, has the potential to make applications which are currently not feasible widely used, increasing the market size for wireless sensor networks. Examples include public and private buildings SHM, monitoring of buildings in seismic areas, where the lifetime of monitoring exceeds current systems significantly.
- Also GENESI enables pervasive monitoring which is not possible today due to the fact it requires extensive use of (expensive) human resources. Consider the case of historical buildings monitoring. Some nations including Italy have such a large number of historic and archeological buildings to monitor, which is not possible to do so as of today (on site monitoring is used), resulting in the fact part of our cultural heritage gets ruined every year. Consider also the case of widespread dike monitoring which is needed in the Netherlands. Again the number of infrastructures to monitor is so large that it cannot be performed without **automatic alarm systems which can last as long as the infrastructure and run unattended**. Availability of such systems is needed for accurate and complete monitoring. Therefore GENESI system is a key enabler for applications which can increase safety of European citizens in multiple application domains, and can help us maintain our cultural heritage at a reasonable cost. (Archeological site monitoring and dike monitoring are two examples which came out of discussions with end users which are indeed interested in exploiting in real application the GENESI system).

1.5 Project references

Project website: http://genesi.di.uniroma1.it/index.php

References of project partners:

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