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A. De Paola, M. Ortolani, G. Lo Re

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Wireless Sensor Networks for Marine Environment Monitoring

Orazio Farruggia, Fabrizio Foderà, Alessandra De Paola, Marco Ortolani, and Giuseppe Lo Re
Dept. of Computer Engineering, University of Palermo
Viale delle Scienze, ed. 6 – 90128 Palermo, Italy
email: {farruggia, fodera, depaola, ortolani, lore}@dinfo.unipa.it

***Abstract*—This work reports on the experience gained in the context of the development of a system of wireless sensor networks for marine environment monitoring, as a part of the GeoGrid project.**

The proposed system employs a monitoring network composed of commonly available motes, equipped with sensors for monitoring water quality in restricted marine environments. Those lower-end nodes communicate among each other whenever possible, but rely on higher-performance nodes implementing the Data MULE paradigm for delivering information to the remote base station in the not so uncommon event of a disconnection in the network.

This paper describes the hardware and software architecture of the employed nodes, and the operations of the resulting hybrid network, and gives some details on the testbed deployment.

***Index Terms*—Wireless Sensor Networks, Data MULE, Environmental Monitoring.**

I. Project Scope and Motivation

WIRELESS Sensor Networks [1] have attracted more and more attention in the recent past not only within the academic world, but also from industrial actors, that have customized the proposed theoretical solutions in order to adapt them to specific real-world scenarios. Applications to different areas have been proposed, ranging from environmental and structural health monitoring, to location estimation, just to name a few [2], [3]. Their key feature is represented by the possibility of a pervasive, and relatively inexpensive deployment, and by the adaptability to mutable operating scenarios.

Environmental monitoring is one of the fields where the benefit of applying such technology is more evident; for instance, wireless sensor nodes can enable monitoring of inhospitable sites, where human intervention is discouraged or infeasible. Similarly, assessing the eco-sustainability of projects involving soil or water management requires constant and pervasive monitoring, which is usually difficult to obtain with traditional technologies. In this context, the GeoGrid Project [4], developed at the University of Palermo, has proposed the design of a system for the acquisition of environmental data through low-cost sensors. The developed framework aimed to build a distributed georeferenced digital library of land and marine data in order to study environmental dynamics; such knowledge base will be made available to different kind of users (environmental engineers, data analysts, and so on) via a cluster of networked computers, organized according to the grid computing paradigm.

The present work deals with a specific aspect of the whole project, regarding the design of a prototypal system for marine environment monitoring. Commonly available wireless nodes have been equipped with specialized sensors in order to monitor water quality in restricted marine environments; in particular, we describe here the development of a proof-of-concept system that includes the deployment of floating sensor nodes in a salty water lagoon in the South of Italy. Measurements include the position of each probe, obtained via GPS, as well as water temperature, pH value, and salinity.

The testbed for our proof-of-concept system was composed by a set of floating buoys containing the mentioned sensor nodes; buoys are not constrained to fixed positions, rather they will follow sea currents, so that the overall sensor network will likely be at most partially connected. This infrastructure was enhanced by adding higher-level mobile wireless nodes, whose motion is predictable and controllable (they are placed onboard of dinghies, used to conduct other sets of experiments), and will act as collection point for data coming from lower-level nodes, according to the MULE paradigm, and will provide connectivity to the whole system, at the cost of an increased latency.

The reminder of the paper is structured as follows. Section II provides a high-level description of the overall system, while Section III gives more details about the implemented routing, and MULE protocols. Section IV describes the two types of employed sensor nodes, and their equipment. Finally, Section V reports our conclusions.

II. Description of the Proposed System

Our prototypal system employs a heterogeneous network of mobile wireless sensor nodes, deployed with varying density in the sensor field. This requirement is imposed by the peculiar considered scenario, where the position of the nodes is heavily influenced by sea currents, according to motion patterns that cannot be easily predicted nor controlled. The use of different types of nodes, on the other hand, was a deliberate architectural choice aimed at coping with the dynamics of the environment.

An effective match between the designed architecture and the specific appplication domain under consideration, was possible only after an intensive preliminary analysis of the considered scenarios phase that highlighted the main requirements in terms of node deployment density, node maximum allowable cost and radio ranges, as well as transmission rates, latency, and reliability.

Fig. 1. A specimen of the developed sensor buoy.

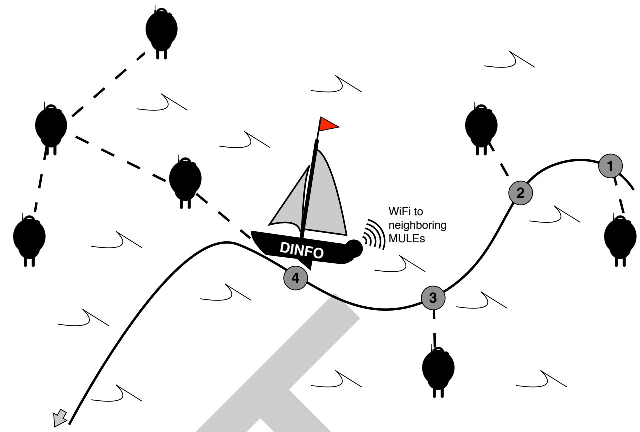

Fig. 2. An example of the deployment scenario.

In particular, the system is composed by 20 floating sensor nodes, equipped with the proper sensors, and contained inside a buoy as depicted in Figure 1. The actual task of sensing the required quantities is demanded to such nodes, but given the operating conditions (in particular, the mentioned unpredictability of the nodes' trajectories, and the limited range of the onboard radios) full connectivity cannot be expected for the resulting network. The basic sensor network was thus enhanced through the addition of 5 *micro-server* nodes. Those are characterized by a higher computational capability, larger memory and transmission range; they have the possibility of organizing themselves into a connected network, whose main task is to gather data from lower-end nodes, and forward it to the remote base station. It is worth noting that the presence of at least one micro-server is sufficient to guarantee the system's functionality, as they operate according to the MULE (Mobile Ubiquitous LAN Extensions) paradigm [5], whose data gathering strategy relies on the presence of mobile entities able to physically transfer information from one part of the network to another, thus enabling data transfer between faraway, possibly not connected nodes.

This strategy exploits nodes' proximity in order to plan data trasfers, and to reduce the required transmission power; this is in fact one of the main advantages of the MULE-based communication scheme in terms of energy saving. Secondarily, the mobility of the nodes, exploited through the MULE paradigm, favors the design of a simpler network infrastructure.

In our architecture, two different classes of nodes are employed, identified as *Sensing nodes*, and *MULE nodes*; the former perform the actual sensing of the environmental quantities, whereas the latter (formerly indicated as micro-servers) deliver the measurements to the remote data collecting devices.

MULE nodes can actively move towards each of the floating sensing devices and, once a connection is established, gather the stored data. Data may then either be wirelessly exchanged with other similar micro-server (if any is present within the transmission range), and then be quickly made available at the remote base station, or it may be physically carried back to destination. Figure 2 exemplifies how that is possible: MULE nodes are actually carried by dinghies that were already used in the chosen testbed environment in order to collect water samples; as they wander across the deployment field, the onboard MULE node will get in touch with nearby sensing nodes and collect their measurements. Moreover, one sensing node that has previously fallen within hearing range of other similar nodes, may have already collected their data, so that it is not necessary that the MULE directly contacts all sensing nodes. The details of the communication paradigms will be explained in Section III.

The MULE strategy represents an alternative to two traditional approaches; the former one requires a large number of low-cost sensor nodes, with short transmission range, so that the resulting network is characterized by a high node density; whereas the latter one considers heterogeneous networks, where higher-layer nodes with longer transmission ranges act as base stations, collect data from lower-end nodes, and retransmit them over potentially long distances. A drawback of MULE-based architecture is an increased latency for the overall transmission, caused by the unpredictable delay in the data exchange phase between the MULE nodes and the sensing nodes. In our particular scenario, however, some latency was deemed acceptable, as no real-time constraint was present.

III. Design Choices

The present section highlights the most relevant choices made during the design phase of the project; they regarded the network architecture, and the routing protocol to be adopted in order to achieve the most efficient use of the available hardware resources, while still effectively gathering the requested measurements.

A. Node Interaction

In the proposed architecture, node interactions are heavily influenced by the difference in hardware characteristics between common sensor nodes and MULEs; while the former nodes have tighter constraints on energy consumption, as they are limited by their available resources, the latter are equipped with independent energy sources. An effective interaction may in fact result into a prolonged lifetime for the entire network; this reciprocal influence may be analyzed by observing the *MULE discovery* phase, and the *data transfer* phase.

The process of MULE discovery allows nodes to detect the presence of a MULE node within its transmission range. Each MULE node periodically transmits beacon packets announcing its presence within a limited radio range; this technique is feasible thanks to the presence of an independent energy source. Sensor nodes, on the other hand, adopt a low duty cycle (`LISTENING` phase) while waiting for the reception of a beacon, and switch to a fully operational regime (`DATA TRANSFER` phase) for data exchange, once the presence of a MULE has been detected.

In order to ensure stability in successive radio communications, the system was designed so that MULE nodes are equipped with actuators able to partially control their motion. A MULE node, after getting within hearing range of sensing node, having followed motion patterns independent of its control and mainly influenced by marine streams, may partially modify its trajectory so as to ensure proximity to the sensing node for a time sufficient for data transfer to be completed. In such scenario, there is clearly a strong dependence between lost packets due to errors in the radio channel, and the relative distance between MULE and sensing node. The `DATA TRANSFER` phase was thus designed so that it may be completed within a time slot, also minimizing data losses; this allows for a reduction of necessary retransmissions, that results in a shorter overall transfer time, and implicitly in lower energy consumption. Finally, the retransmission strategy was modeled according to an Automatic Retransmission Request (ARQ) protocol that ensures efficiency through the use of an adaptive transmission window, and synchronization with the MULE nodes. The adaptive window exploits information about link quality available to the sensor node through the radio device management module of TinyOS (the sensor nodes' operating system).

B. Opportunistic Routing

In order to efficiently collect from sensor nodes the measurements relative to the main physical, chemical, and biological parameters of waters, and to the related environmental parameters, a specific routing protocol has been designed. The proposed protocol takes energy saving into account by reducing the number of nodes that a MULE node has to visit in order to collect all the necessary information. The reference paradigm is *opportunistic routing*, whose main feature is that path selection is based on identifying potential destinations at transmission time, as opposed to using pre-computed routes; this choice is motivated by the high variability of the considered operating environment, that prevents the routing protocol from acquiring information suitable to determine sufficiently steady routes. Opportunistic routing in the proposed system is based on location information, available on nodes thanks to their GPS module; such information is used to determine the next hop in the path towards the destination. In our case, there is no pre-fixed destination, as the system makes use of MULE nodes to collect data, so the goal is to spread the sensed data among nodes in the same geographical area, and to provide some redundancy. Collected information may also be conveniently encrypted so that authentication can be provided about the id and position of the source node.

C. Choice of the MAC Layer

Among the different MAC protocols analyzed during our preliminary study, the most suitable with respect to the specific design requirements appeared to be B-MAC [6], a random access protocol, able to adapt to extremely mutable environments. B-MAC provides a set of control primitives for the access to the transmission medium that allow to decouple the actual Link Layer from the underlying medium access policy, thus making it possible to to define novel ad-hoc MAC protocols. One of those primitives is Low-Power Listening (LPL), by which the channel polling used in B-MAC is indicated.

The use of this kind of protocol has allowed for the realization of the network architecture described here. LPL assumes that nodes are in the *sleep* state for most of the time, and awaken periodically to sense the channel. This phase lasts only a short time, so that if no activity is detected, the node switches back to the sleep state.

The listen phase is actually preceded by a broadcast message by which each node advertises the boundaries of the time interval to which its data must be referred. Only after such a message is sent, nodes start sensing the channel in order to wait for request messages from their nearby neighbors. Request messages contain the indication of the time interval of interest. In the event that some requests are received, a node transmits all the information it has stored, beginning with the more recent one, so that its neighbors, also owning part of the information, have a chance to quickly go back to a sleep state. The preamble of sent messages must cover all of the link's polling period, so that any potential receiver is bound to notice the communication, just by hearing it. The importance of this process is evident when considering that the awakening time of each node within the reference interval is determined via a random algorithm; moreover, potentially busy nodes may also trigger the sender to delay the forwarding.

The main benefit of such an approach is in the possibility of using very short sampling periods; oh the other hand, this implies that a longer preamble likely increases the access latency. This operating mode is specifically suitable for our domain, where nodes have to spend most of their time in the sleep state, and will need to be waken up by MULE nodes, or other neighbors, in order to update their information.

IV. The Prototypal Nodes

Several hardware platforms are commonly available nowadays for wireless sensor nodes, and they are basically characterized by four elements: one or more sensors for the quantities to be measured, a transceiver for data communications, a control and processing unit, and an autonomous energy source. In the context of the GeoGrid project, the chosen hardware belongs to the two already mentioned categories:

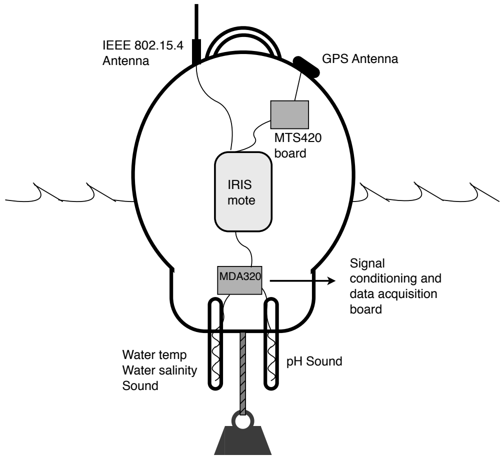

Fig. 3. Scheme of the prototypal buoy containing the processor unit, the radio modules, and the sensors.

- *Sensing Nodes*: devoted to sensing the characteristic quantities for the marine environment under consideration;
- *Data MULE Nodes*: devoted to collecting, and aggregating the information gathered by the sensing nodes.

The prototypal sensing node consists of a floating buoy containing one wireless node equipped with the required sensors, as depicted in Figure 3. The peculiar operating environment obviously required an ad-hoc design both for the electronics, and for the packaging itself. A preliminary requirement analysis phase identified the Iris Mote as a suitable device, also because of its characteristics, such as a larger transmission range, and double memory than traditional sensor nodes belonging to the *mote* family; moreover, its transceiver is ZigBee compliant, and implements the IEEE 802.15.4 standard. The prototypal MULE node required less customization, as the chosen hardware (the Stargate micro-server nodes) are already equipped with the interface required by the present project. Both hardware configurations are described in detail in the remainder of this section.

A. Sensing Nodes

The Iris mote has been chosen as the sensing device for our architecture. It is equipped with an Atmel RF230, IEEE 802.15.4 compliant, ZigBee-ready radio transceiver with

Fig. 4. The sound with water temperature and salinity sensors.

a transmission range of a few tens of meters, and a datarate of 250 kbps. Its processor is based on the Atmega1281 micro-controller, and is equipped with 512 Kbytes of Flash memory. Finally, the sensor set may be augmented by exploiting its I2C, and UART interfaces that allows for external peripherals to be connected. A picture of such a node, and its characteristics, are reported in Table I.

The sensor board had to be customized to meet the specific requirements of our system; the final module consisted of a set of transducers integrated into one board that can be directly plugged into the sensor node; in particular, the following sensors were considered:

- bi-axial accelerometer (±2g range);
- barometric pressure sensor (300-1100 mbar range);
- visible light sensor (400-1000 nm spectral response);
- water temperature;
- relative humidity sensor;

moreover, our board is equipped with a 16-channel GPS receiver, able to compute a 2D localization within a 10 m range.

In order to integrate those external transducers we used an MDA320 data acquisition board, and exploited its 8 ADC input channels, and 8 digital I/O channels.

The project required that we measured geo-referenced data; thus the node position was acquired through a GPS sensor, and correlated with the measurements relative to water temperature, pH value, and salinity. Salinity, in particular, is measured as a function of temperature, and conductivity. A sound by Hannah Instruments (Figure 4) carrying both sensors was integrated ; the sound acts as a variable resistance, and generates a voltage measurement with a non-linear characteristic through which the desired measure may be computed.

TABLE I
THE SENSING NODE.

Sensor Type		Characteristics		
Iris mote		**Processor**	**Model**	Atmel ATmega1281
			Memory	Flash 512 Kbyte
				RAM 8 Kbyte
			Current draw	8 mA *Active mode*
				8 μA *Sleep mode*
		Radio	**Model**	Atmel RF230
				(ZigBee compliant)
			Current draw	16 mA *Rx mode*
				10 mA *Tx mode*, -17dBm

TABLE II
THE DATA MULE NODE.

Sensor Type		Characteristics		
Stargate		**Processor**	**Model**	Intel PXA255 32 bit
			Memory	32 MB Flash
				64MB SDRAM
			Energy per computation	1.1 nJ/instr.
				1 mJ/beamform
		Radio	**Model**	Orinoco Gold
				(11 Mbps 802.11b)
			Energy per bit	90 nJ/b
			Idle power	160 mA

B. Data MULE Node

MULE nodes represent the gathering and aggregation points for the data sensed by lower-level nodes, besides acting as gateways toward the outer communication network as well. The hardware chosen for this kind of nodes is the Stargate platform; its processor, the Intel PXA255, is a high-end 400 MHz CPU, and can be seamlessly integrated with the mote infrastructure. Those devices may be programmed using standard languages, such as C, as they mount an ad-hoc embedded Linux OS; finally, they are equipped with a WiFi radio module that is used to connected to the remote LAN in the experimentation phases. Table II shows a picture of the sensor board, and its most relevant characteristics.

V. Conclusion

The present work reports a description of a prototypal system for marine environment monitoring. A hybrid network of mobile wireless sensor nodes was designed and deployed in a restricted area of a salty water lagoon, in order to assess water quality through measurements of specific quantities, such as water temperature, pH value, and salinity.

From a networking standpoint, the relevance of such network lies in the study of the interaction between a network composed of standard motes, and a network of higher-performance wireless nodes loosely acting as a backbone. Nodes of both network are mobile, but while the former type of nodes cannot control their movement, the latter type will follow pre-definite trajectories and in fact will actively "seek" floating motes in order to harvest their data.

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Orazio Farruggia received his Laurea degree in Computer Engineering in 2007 from the University of Palermo, Italy. He has since collaborated with the Network Research Group at the Dept. of Computer Engineering of the University of Palermo, and he has participated to research projects at a local and national level, regarding the application of Wireless Sensor Networks to structural, and agricultural monitoring. He is currently the holder of a research grant at a local government agency, where he is studying the application of this technology to lake water monitoring. His current research activities regard the study of sensor network interoperability for environmental monitoring, and of scalable WSNs.

Fabrizio Foderà received his Laurea degree in Computer Engineering in 2005 from the University of Palermo, Italy. He has participated to research projects at a local and national level, during which he worked on the application of wireless sensor networks to environmental monitoring. He is now with Italtel SpA where he is helping as a network administrator for the local network.

Alessandra De Paola received her "Laurea cum laude" degree in Computer Engineering in 2007 from the Univerity of Palermo, Italy. Currently she is attending a granted Ph.D. course in Computer Engineering from the same University. She is member of the Network Research Group at the Dept. of Computer Engineering at the University of Palermo. Her current research activities regard artificial intelligence on distributed systems and networking.

Marco Ortolani received his Laurea degree in Computer Engineering in 2000 from the University of Palermo, Italy, and his Ph.D. degree in Electronic, Computer, and Telecommunications Engineering from the same university in 2004. Since June 2005 he is the holder of a Research Grant on "Optimization and security in Wireless Sensor Networks" and he joined the Network Research Group at the Dept. of Computer Engineering at the University of Palermo. He has participated to several research projects at a local and national level, regarding the development of robust data gathering protocols for WSNs and the application of Wireless Sensor Networks to structural, and agricultural monitoring. His current research activities regard distributed data analysis and networking.

Giuseppe Lo Re received his Laurea degree in Computer Science at the University of Pisa, Italy, and the Ph.D. degree in Electronic, Computer, and Telecommunications Engineering at the University of Palermo, Italy, in 1990 and in 1999, respectively. In 1991, he joined the Italian National Research Council, where he achieved the Senior Researcher position. In 1994 he was a Visiting Scientist at the IBM European Networking Center, Heidelberg, Germany, and in 1999 at the International Computer Science Institute, Berkeley USA. In December 2004, he joined University of Palermo, where he currently is an Associate Professor of Computer Engineering and responsible of the Networking Laboratory at the Department of Computer Engineering. He is author of several papers published in international journals and conference proceedings, in the area of networking. His current research interests are in the area of computer networks, wireless sensor networks, and distributed systems.