A Robust, Adaptive, Solar-Powered WSN Framework for Aquatic Environmental Monitoring

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***Abstract*—The paper proposes an environmental monitoring framework based on a wireless sensor network technology characterized by energy harvesting, robustness with respect to a large class of perturbations and real-time adaptation to the network topology. The fully designed and developed ad hoc system, based on clusters relying on a star topology, encompasses a sensing activity, a one-step local transmission from sensor nodes to the gateway, a remote data transmission from the gateway to the control center, data storage in a DB and real-time visualization. Hw and Sw modules have been either carefully selected or designed to guarantee a high quality of service, optimal solar energy harvesting, storage and energy awareness. A monitoring system integrating the outlined framework has been deployed in Queensland, Australia, for monitoring the underwater luminosity and temperature, information necessary to derive the health status of the coralline barrier. At the same time, acquired data can be used to provide quantitative indications related to cyclone formations in tropical areas.**

***Index Terms*—Adaptive communication protocol, distributed environmental monitoring systems, energy harvesting, wireless sensor networks (WSNs).**

I. Introduction and Motivation

DISTRIBUTED environmental monitoring with wireless sensor networks (WSNs) is one of the most challenging research activities faced by the embedded system community in the last decade [1], [2], and [3].

Of particular complexity are those applications involving an aquatic environment, e.g., for the possible water infiltrations in the unit, algae deposits on the sensor, communication inefficiency due to RF reflections and a contained elevation of the antenna w.r.t. the water surface.

The aim of this paper is to present an aquatic monitoring framework based on WSNs that is scalable, adaptive with respect to topological changes in the network, power-aware in its middleware components and endowed with energy harvesting mechanisms both at the gateway and sensor nodes. The proposed framework addresses all aspects related to environmental monitoring: sensing, local and remote transmission, data storage, and visualization.

The WSN has been deployed at Moreton Bay, Brisbane, Australia, to deliver temperature and luminosity data of the marine ecosystem at different depths. However, this initial sensor configuration can be simply extended by adding application-related sensors and actuators. Data cover scales of time and space, information that has, until now, been unavailable due to cost, technical feasibility, or a combination of the two.

The developed system leads to the following outcomes:

- ability to monitor the marine environment at multiple scales simultaneously so that it is possible to validate biological models for these ecosystems;
- a significant improvement in the prediction of the occurrence of ecological phenomena such as toxic algal blooms and climate-related loss of species and overall biodiversity;
- availability of precious and timeliness data for the development of risk-based and early warning systems (e.g., hurricanes formation) to underpin management response and the longer-term sustainable management of coastal marine resources.

The structure of this paper is as follows. Section II reviews the principal applications presented in the literature w.r.t. energy harvesting, adaptation to topological changes and robustness. Section III presents the Hw components of the embedded system as well as the adaptive energy harvesting and the advanced storage modules. Section IV introduces the application Sw with a focus on the *ad-hoc* robust protocol. Section V briefly presents the real-time data storage and visualization system. Finally, Section VI discusses the problems encountered during the deployment and the acquired data both at application and sensor level.

II. Relevant Applications: A Review

Deployments of WSNs rarely address adaptability to environmental changes and energy-aware issues; such a limitation affects lifetime and QoS of the monitoring system.

The work of [4] presents a star-based topology for seabirds habitat monitoring (the gateway collects data from the sensor nodes and forwards them to a remote control station for further processing). A solar-energy scavenging mechanism has been envisaged only at the gateway level, leaving sensor nodes battery powered. Since the communication refers to the sensing unit-gateway and gateway-base station segments, the gateway must be always on. No adaptation schemes have been reported.

The work in [5] proposes a system for monitoring volcanic eruptions; no energy harvesting solutions have been included for the gateway and the three sensor units. Although the transmission protocol is based on a traditional scheme involving packet retransmission, a large number of packets went lost due to weather conditions and the presence of obstacles.

A more complex WSN architecture is proposed in [6]; there, a multihop WSNs for wildland fire monitoring is proposed.

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All units are battery-powered without energy-harvesting mechanisms. The limited adaptation ability of the system requires human intervention at the software level for new node addition.

The work in [7] presents a WSN for studying rare and endangered species of plants in the Hawaii Volcanoes National Park. Units, equipped with cameras among other sensors, are battery-powered; no energy-harvesting mechanisms are envisaged. A multihop protocol, which implements a synchronization mechanism and an adaptive routing strategy, has been considered.

The work in [8] proposes a WSN for tracking Zebras. Each unit is equipped with a GPS sensor. Acquired data are periodically collected by a data mule installed on a manned mobile base station. Unfortunately, such an approach is not effective for applications requiring a large WSN or not allowing a data mule. Solar panels recharge the units' batteries.

A WSN designed to detect the cane toad in northern Australia is presented in [9]. The WSN units acquire acoustic data, locally process them, and transmit data to a gateway which, in turn, sends the frog "presence/absence" information to the control center. Neither energy-harvesting, power-aware solutions, nor sophisticated energy management policies have been reported.

The work in [10] represents one of the major efforts in the WSN field. The application refers to the development of a WSN to identify mobile targets within a surveillance application. The 70 units also manage occurrence of failures by periodically rebuilding the routing paths. No energy-harvesting solutions have been considered; conversely, an effective duty cycle mechanism is envisaged for keeping under control power consumption.

In [11], the authors present a system to monitor a crop field with temperature and humidity sensors. The application is based on a low duty cycle and implements a multihop protocol to forward data from sensor nodes to a gateway, which is connected by a WiFi link to a base station. Routing tables are periodically rebuilt to provide robustness; some sensorless units are deployed and act as communication relays.

The work in [12] considers a system to measure soil moisture and monitor grass conditions; units are equipped with solar panels. WSNs are also used to study cattle behavior, as shown in [13] and [14], adopting units equipped with GPS and solar panels to track animals' movements. All data are sent to a gateway placed in the paddock.

In all of the above deployments, wherever adopted, the considered energy-harvesting mechanism is based on an on–off charging scheme. While effective in optimal sun conditions, its efficiency drastically falls (the charging does not occur) when an insufficient radiation is available (e.g., in presence of a partly cloudy sky, mist, morning and late hours, or dust on the solar panel). Differently, for an effective solar energy harvesting in adaptive radiating situations, a maximum power point tracker (MPPT) scheme must be addressed which adapts online the solar cell working point with the solar radiation to maximize charging efficiency.

At the same time, an energy harvesting mechanism impacts on the network topology and, in turn, on the communication protocol. In fact, units need to be switched off when batteries are exhausted and must be activated once energy is back. This start/restart mechanism needs both Hw and Sw modifications to be effective and a robust-power aware-communication protocol.

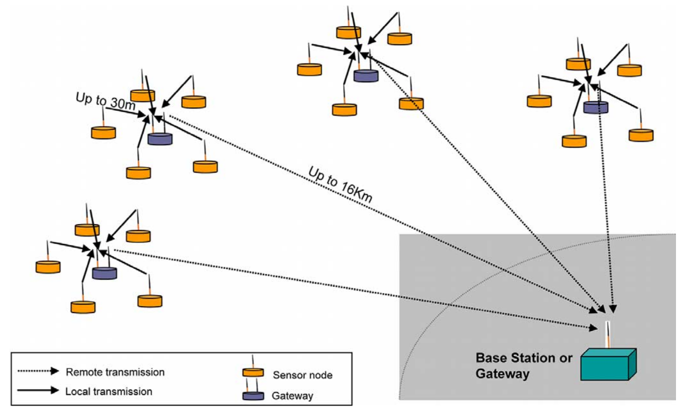

Fig. 1. Network architecture.

It immediately arises that a credible deployment requires units and gateways to be equipped with MPPT-based energy-harvesting mechanisms as well as a communication protocol robust w.r.t. perturbations affecting the QoS and adaptive w.r.t. changes in topology as we do in this paper.

III. Designing the System: Hardware Aspects

A. Network Infrastructure

In its simplest architecture the proposed WSN is characterized by a cluster topology ruled by a cluster head (here acting as a gateway); the cluster constitutes the core of a more sophisticated hierarchical architecture obtained by adding other clusters to the network (Fig. 1).

Gateways forward the collected information to the base station. A multihop approach at the gateway level would constitute a different option for conveying data to the base station which was not requested in the considered application by marine biologists.

Communication at the cluster and the gateway level may use the same transmission protocols (e.g., the *ad-hoc* TDMA-base protocol presented in Section IV) or may differentiate themselves based on application needs (e.g., through a FDMA acting at the gateway communication level).

At the cluster level, a traditional hierarchical TDMA-based solution would be particularly appealing for simplicity and energy efficiency, but surely it is not adequate in a situation where the network topology is subject to a continuous change and it might suffer from intracluster frequency interference. While the latter issue can be solved by considering the frequency allocation mechanism proposed in [15], the former requires design of an *ad hoc* TDMA-based protocol able both to deal with adaptation in the network topology and to increase the robustness to communication errors and to permanent or transient faults of the units, yet keeping in mind energy savings aspects. Such a protocol will be presented in the next section.

Each sensor node [see Fig. 2(a)] is composed of five main modules: control unit and data processing, signal acquisition and conditioning, local transmission radio, energy-harvesting mechanisms, and energy storage. The gateway [see Fig. 2(b)] is a sensor node unit augmented with a long-range communication ability which allows remote transmission to the base station.

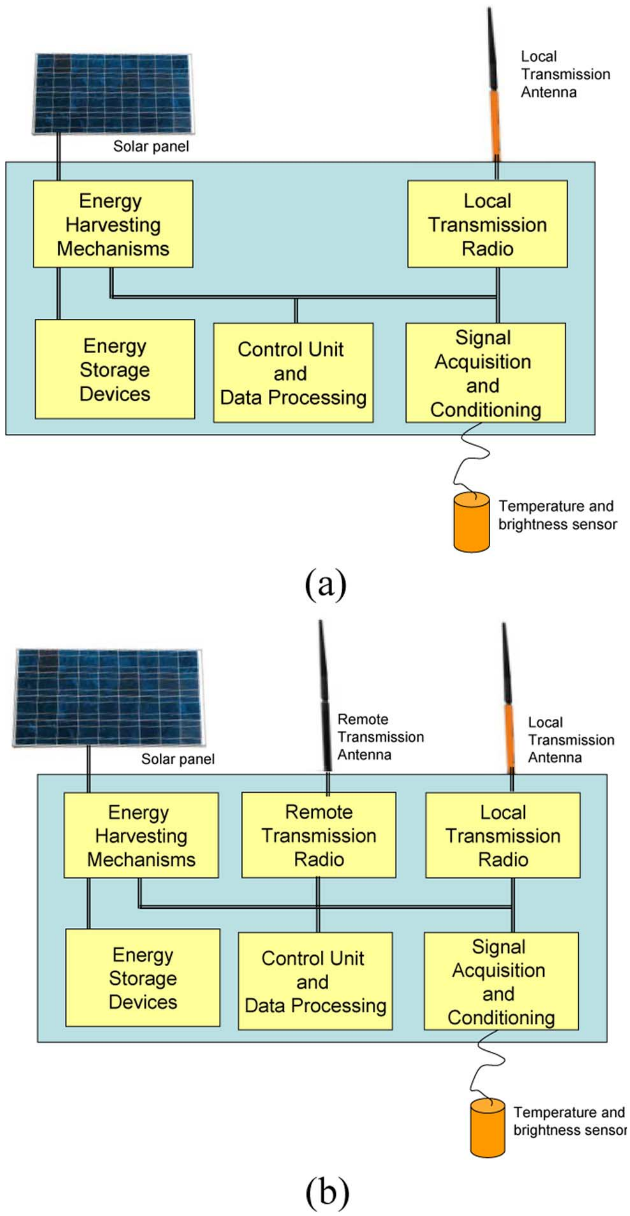

Fig. 2. (a) Sensor node architecture. (b) Gateway architecture.

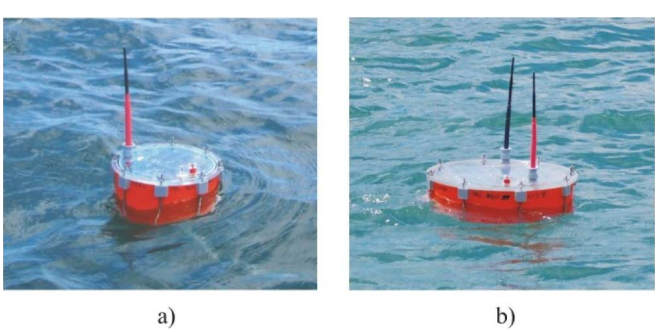

Fig. 3. (a) Sensor node. (b) Gateway.

Both nodes and gateways, fully designed both in terms of hardware and software components by our group, are inserted into waterproof buoys (see Fig. 3); underwater sensors (developed at the University of Queensland) live outside the buoy.

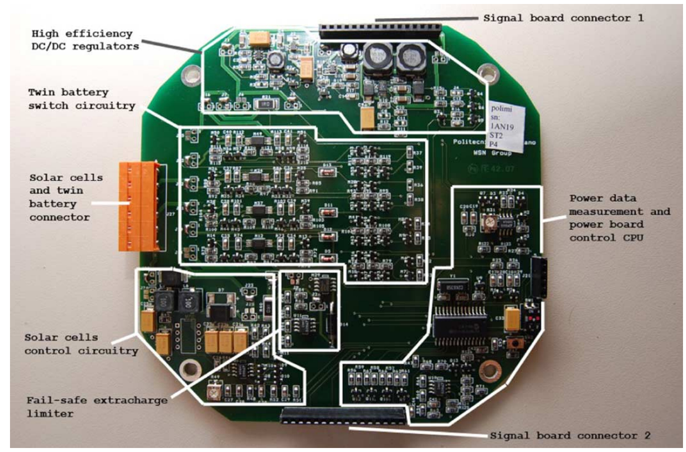

Fig. 4. Power board: main subunits.

Energy is granted by two 0.5-W and eight 0.5-W polycristalline solar cells for nodes and gateway, respectively, with a tandem battery solution as a means of storage.

One dipole omnidirectional antenna is present on nodes for communicating to the gateway which, differently, mounts two omnidirectional antennas: one to communicate with the local cluster network and the other for establishing a radio link to the ground control station. Details regarding the Hw and the Sw will be given in the sequel.

B. Units

Nodes and gateways have been designed to be interchangeable, with the unique HW difference associated with the presence of the radio link module for the gateway.

A buoy electronics is composed of two circular boards stacked vertically and linked through connectors. The lower one is responsible for the unit power management and storage, and the upper is responsible for managing processing, signal conditioning, and radio communication.

The lower board contains a solar cell control circuitry, a battery control circuitry, an high-efficiency dc/dc power supply module, and an energy-management CPU that controls the power flows. The PCB of the board is given in Fig. 4, where subunits have been outlined.

C. Energy Harvesting and Storage

Energy generation, storage, data acquisition, dc regulation, and cold starting activities are coordinated by a dedicated 8-bit microcontroller, which operates independently from other subsystems (and is housed onto the upper board). The microcontroller executes a relatively simple embedded C code at the extremely low-power-consumption 32-kHz clock frequency. In addition, the microcontroller acts as a hard failure watchdog for higher level subsystems by simply toggling down their power supply once failure conditions are detected.

The energy-harvesting module is composed of a CPU and a controlled step-up dc/dc converter based on the MPPT circuit suggested by the authors in [16]. The MPPT optimally harvests solar energy by adapting the working point of the solar cell to maximize energy transfer from the cells to the batteries. The system supersedes existing energy-harvesting methods by harvesting energy even when the cell is not directly exposed to the optimal radiation or the solar radiation is low, as it happens in outdoor applications where the panel surface may become dusty or covered with water and/or marine salt or clouds change the intensity of the solar radiation.

The power extracted by the MPPT circuit is then directed to the storage mean, here designed as a special twin-battery system.

The basic idea behind this energy storage solution is to separate in time the charge and the discharge phases of the batteries, i.e., the system allows the batteries to be charged and discharged at separate intervals of time. With this solution, we solve one of the major drawbacks in small solar-powered devices, namely, the partial charge/discharge suffered by batteries during the day/night cycle: during the day, solar power is conveyed to batteries (charge phase), while during the night no solar power is present and batteries provide power to the sensor units (discharge phase). It is a common practice (as we did) to employ batteries with an energy capacity larger than the solar-cell daily energy production and daily system energy consumption in order to being able to store energy and permit the system to supply power even in case of bad weather. For this reason, under normal weather conditions, batteries are partially charged and discharged every day.

Unfortunately, chemical batteries cannot withstand a prolonged set of partial charge/discharge cycles since many secondary chemical effects arise: forcing a battery into a prolonged partial charge/discharge cycles condition causes a severe reduction of battery nominal energy capacity and, as a consequence, severe limitations to performance (sometimes this effect is referenced to as the "memory effect" of chemical batteries). One way to solve this undesired phenomenon is to separately perform full discharge and full charge cycles.

We employed two identical battery packs and implemented a very straight idea: while one battery pack powers the system (and thus is under discharged), the other is under charge. Once the former is discharged, an embedded circuit allows the battery packs to be inverted. In this way, one battery pack is always in charge while the other is always being discharged.

A special *ad-hoc* battery switching unit has been designed and developed. The unit is able to connect the two battery packs either to the output of the MPPT converter or the input of the dc/dc regulators in response to dedicated commands coming from the control CPU. Moreover, the unit is able to completely disconnect both battery packs from the output of the MPPT circuit and/or from the input of dc/dc regulator whenever the energy control CPU issues such a command.

This point is particularly important since it the basis of a simple but effective threshold-based energy-management procedure. In particular, when the voltages of both batteries are below a user-defined *warning* threshold, the units disconnect themselves from the network but continue to acquire sensorial data. Such data are temporarily stored in a memory buffer and are sent to the gateway once enough energy is available to reconnect the unit with the network. Moreover, when the voltage of the batteries drops under a user-defined *critical* value (i.e., in the case of exhausted batteries), the unit is switched off (and

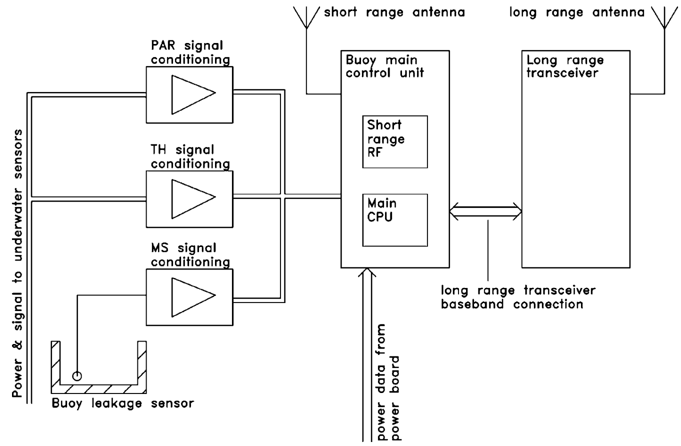

Fig. 5. Signal board block diagram.

batteries wait to be recharged). Of course, more advanced energy-management schemes, e.g., those envisaging a forecast of the energy consumption, can be considered.

On the contrary, if an overcharge condition occurs on the battery pack under charge, the battery is disconnected from the MPPT circuit and posed in an idle state (the system is powered by the other battery pack), while generated power is automatically redirected to a special wasting unit.

In commercial WSN units, a lack of energy coincides with switching them off; no mechanisms are, to the best of our knowledge, nowadays available to grant a new restart of the unit when energy is available. Since this is a main issue to grant a credible deployment, we developed a nontrivial circuit and procedures to grant a cold restart for the units when both battery packs are in a deep discharge state. By solely relying on solar cells (i.e., without any external maintenance intervention), the circuit acquires energy, stores it in a battery, and waits to have enough energy before powering the unit modules.

The last module of the board is composed of dc/dc regulators whose duty is to power the system. We employed four NiMH-cell battery packs with 4.8-V nominal voltage (different unit modules would require different voltages for powering). In particular, we generated three dc powering buses at 3.3 V for the main control unit, 5 V for the radio link, and 7.5 V for UQ underwater sensors.

D. Sensor Control and Processing Units

The upper board contains underwater-sensors signal conditioning, a long-range radio transceiver, a short-range radio transceiver, and unit main control CPU. Fig. 5 shows a schematic diagram of the board.

The signal acquisition and conditioning module is composed of a photosynthetic active radiation (PAR) signal conditioning, a thermal (TH) signal conditioning, and a moisture (MS) signal conditioning. The device deals with analog acquisition of the physical quantities to be monitored (e.g., temperature or brightness as well as humidity sensors) and the subsequent signal conditioning phase. *Ad hoc* solar radiation and temperature sensors have been developed by the University of Queensland for this application since effective off-the-shelf underwater sensors were absent on the market. The module provides an electronic

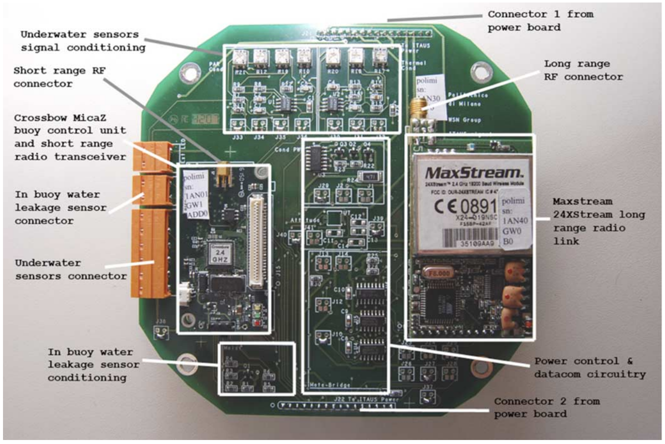

Fig. 6. Signal board main modules.

interface commanded by the control unit; it performs traditional signal filtering before an analog-to-digital conversion, and it allows underwater sensors to be turned on and off for energy awareness. Moisture sensors have been employed to detect possible leaks in buoy sealing O-rings or defective sealed connectors and thus alarm for electronics failure or buoy sinking. A moisture sensor signal was placed also in the underwater sensor housing for the same reasons.

The upper board is given in Fig. 6.

The main control unit is a Crossbow MPR2400 (MicaZ) unit (see [17]), which has an 8-bit microcontroller and acts as main CPU. We considered MicaZ for their large market availability and academic usage, the possibility to use the open source TinyOS operating system, and contained power consumption of the unit.

E. Local and Remote Transmission Radios

In the proposed framework, we used the Chipcon CC2420 (MicaZ) low-range radio module for cluster communication, which allow us to easily cover a 2800-m^2 area (30-m radius). However, nowadays, we would have opted differently for radio modules able to fully support the Zigbee communication protocol [18], for example, modules provided by Jennic Wireless Microcontroller [19] or Freescale [20].

The long-range transceiver is a MaxStream 2.4-GHz Xstream Radio Modem (see MaxStream [21]), able to provide 50 mW @ 2.4 GHz of RF power at the long-range antenna. Since power consumption of this module is particularly high (being around 0.75 W in transmission), the main control unit switches it on and off at fixed intervals of time to communicate with the ground station. Once not in the transmission phase the radio is posed in a low power sleep state and its dc/dc power supply is switched to burst mode control to save further energy as presented above. Data to be broadcast are provided to the radio modem by the main control CPU through its serial communication line.

IV. Designing the System: Software Aspects

A high-level description of the tasks carried out by units and gateway is provided in Fig. 7. In more detail, a time interrupt periodically wakes up the unit that acquires sensorial data, transmits the data to the gateway in its TDMA slot, and then goes to sleep waiting for the next interrupt. The gateway collects data from units (augmented by its own data) and forwards them to the base station at the end of the unit's TDMA schedule.

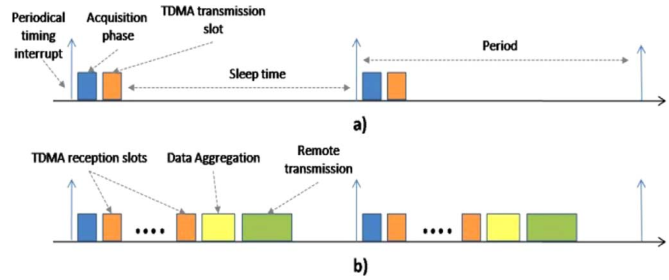

Fig. 7. SW phases over time. (a) Sensor unit. (b) Gateway.

Communication can be corrupted by noise, and the network topology can change unpredictably due to removal or introduction of nodes or lack/availability of energy.

Moreover, only simple power-aware routing algorithms can be considered due to the limited energy stored in batteries or supercapacitors.

In the considered framework, robustness and efficient energy management are thus two fundamental elements of the local transmission protocol for the wireless sensor network.

Several routing algorithms are present in the literature. The carrier sense multiple access (CSMA) avoids message collisions by listening to the channel before each transmission; it is very simple and easy to implement but, unfortunately, the approach is not power-aware (the energy consumption of the radio in the receiving mode is comparable to the one in transmission and the radio must be kept on).

In self-organization medium access control (SMAC) [22], all nodes select a transmission frequency to communicate with adjacent nodes. Unfortunately, the most common off-the-shelf sensor units (e.g., MICA units Xbow [17], Jennic Wireless Microcontroller [18], and T-Mote Sky Moteiv [23], just to name a few) cannot simultaneously receive more than one frequency (no FDMA), and the overhead introduced by the SMAC protocol is not justified for the topology we are considering (i.e., the creation of virtual clusters, which is typical of SMAC, is useless in the considered application). Eavesdrop And Register (EAR) [22] is an effective protocol for both managing fixed and mobile units, but it is overdimensioned for the proposed network (EAR introduces routing mechanisms which are not required here). A hybrid TDMA-FDMA ([24]) allows us to combine TDMA and FDMA approaches by transmitting more data in the allocated time frame with a frequency modulation; again, it cannot be implemented on MICA Z.

A TDMA solution [24] is particularly interesting when units can transmit at a predefined time slot, hence allowing for an efficient management of the radio module. Unfortunately, TDMA is not specific for WSNs and is not power-aware oriented (in a traditional TDMA, the radio module of the gateway remains active for all available time slots even when less sensor nodes are available).

To reduce the power consumption of the WSN, we implemented a duty cycle for the radio module and an ad hoc communication protocol; we verified that power required for other phases, e.g., acquisition and processing, were negligible.

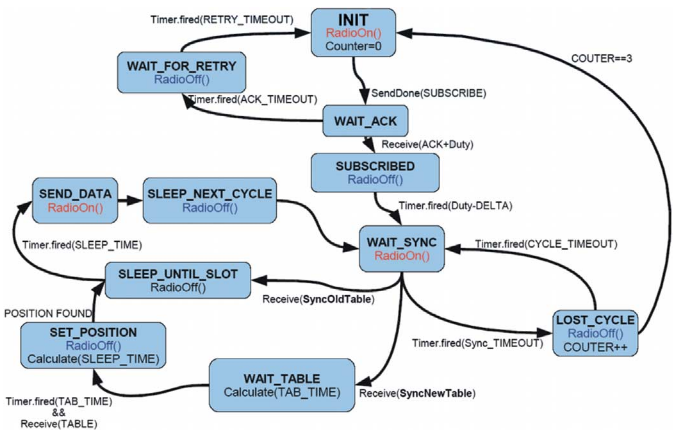

Fig. 8. FSM of the sensor node protocol.

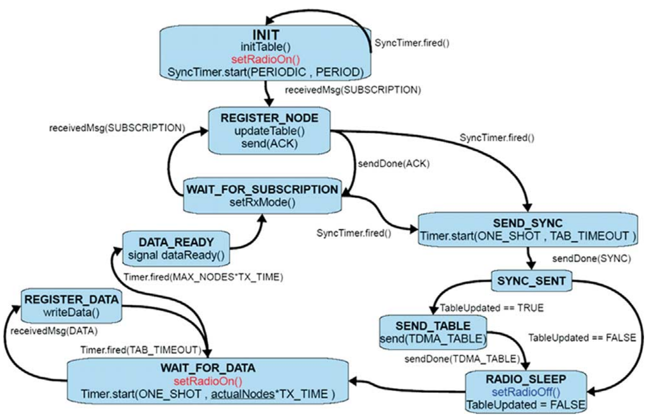

Fig. 9. FSM of the gateway protocol.

A modified TDMA protocol was suggested which faces power-aware and network scalability aspects and, at the same time, allows for a plug-and-play insertion/wake-up and harmless removal of units. We emphasize that the suggested ad hoc transmission protocol was developed to guarantee both robustness w.r.t communication and faults at the unit level (either permanent or transient) and adaptability to changes of the network topology. What is suggested here is a solution that was proven to be effective in a real deployment, but it does not necessarily represent the unique communication mechanism to be considered for this type of applications. We suggest the WSN designer to consider a protocol which trades off performance and simplicity (and, hence, energy savings).

What we have proposed can be formalized through the finite-state machines (FSMs) of Figs. 8 (units) and 9 (gateway). The protocol acts will be detailed more as follows.

A. Sensor Node

Each sensor node starts from the INIT state. In this initial state, the node has no information about the state of the gateway and its transmission time slot. The sensor node turns on the radio in a transmission (TX) mode and sends a SUBSCRIBE message to the gateway to signal its presence and be included in the gateway TDMA table. Once the message has been sent, the unit commutes onto the reception (RX) mode and waits for an acknowledge (ACK) message from the gateway. If the ACK message does not arrive within ACK_TIMEOUT seconds, the sensor node turns off the radio, sleeps for RETRY_TIMEOUT seconds, and returns to the initial INIT state.

If the sensor node receives the ACK message, the gateway has registered the sensor node as belonging to the network and modified the TDMA table accordingly. Moreover, in the ACK message, the gateway provides the unit with its sleeping time (DUTY_DELTA) before waking up for the next synchronization phase (which is the first phase of each TDMA cycle). After DUTY_DELTA seconds, the sensor node moves into the WAIT_SYNC state and turns on the radio in the RX mode. If the SYNC message does not arrive within SYNC_TIMEOUT seconds, the unit moves into a LOST_CYCLE state, turns the radio off, sleeps for CYCLE_TIMEOUT seconds and wakes up again in the WAIT_SYNC state. If a unit misses three consecutive SYNC messages (the number is an application parameter), it disconnects itself from the network and starts again from the INIT state. When the sensor node receives the SYNC message moves to the SYNCHRONIZED state. The gateway includes in the SYNC message the information whether a new TDMA table is arriving (due to a network topology change in the previous TDMA cycle) or not (no change happened). In the case of a new TDMA table, the sensor node moves to the WAIT_TAB state and waits the TAB message from the gateway for TAB_TIMEOUT seconds. If the TAB message does not arrive the unit disconnects itself from the network and moves into the INIT state. When the TAB message arrives a unit becomes aware of its own transmission time slot, computes the sleeping time (SLEEP_TIME) and sleeps until the next transmission (SLEEP_UNTIL_SLOT state). If the SYNC message does not anticipate arrival of a new TDMA table the unit moves in the SLEEP_UNTIL_SLOT state.

After SLEEP_TIME seconds, each sensor node turns on the radio and transmits its own data (a message). Then, it turns off the radio and sleeps (SLEEP_NEXT_CYCLE) up to the next synchronization phase.

B. Gateway

The gateway starts in the INIT state, turns on the radio, and waits for a SUBSCRIBE message from sensor units. This approach is not power-aware for the gateway that may remain in the RX mode for a long time. On the contrary, this limitation is compensated by the power-aware mechanism in sensor units presented in the previous subsection. The gateway requires a higher energy capability, as already pointed out when discussing its radio link activity.

When the gateway receives a SUBSCRIBE message, it activates a timer that will generate an interrupt after PERIOD seconds, moves into the REGISTER_NODE state, updates the TDMA table with the registered unit, and sends back the ACK message. Afterwards, the WAIT_FOR_SUBSCRIPTION state sets the radio in the RX mode and waits for subscription of other units.

If a SUBSCRIBE message arrives, the gateway moves into the REGISTER_NODE state and registers the new sensor node. Then, after PERIOD seconds from the subscription of the first node, the gateway moves to the SEND_SYNC state, sets the

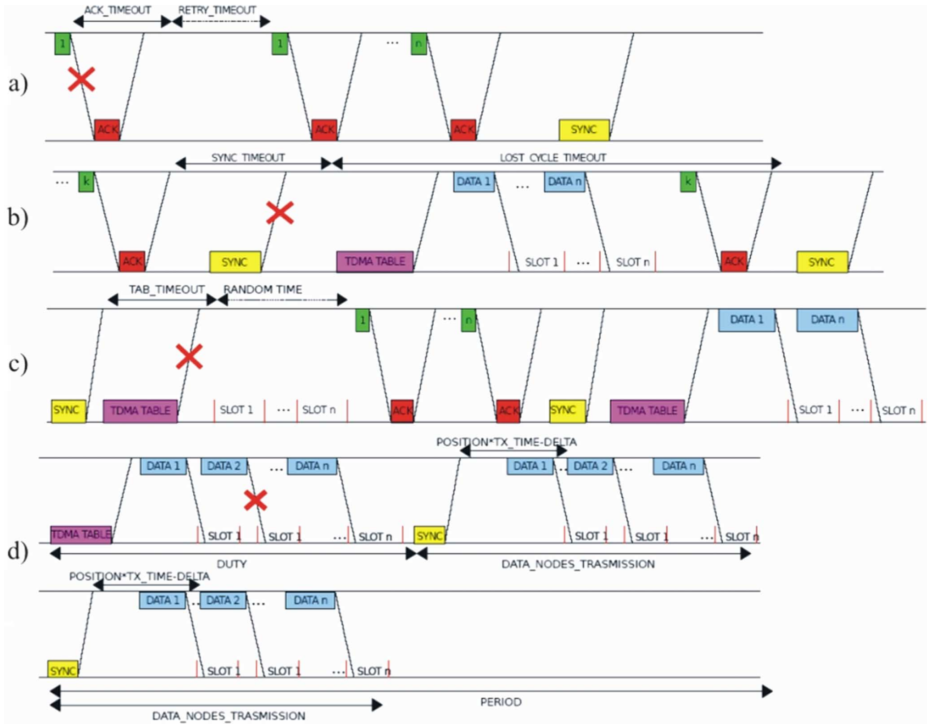

Fig. 10. Robustness to transmission errors. (a) Loss of the SUBSCRIBE message. (b) Loss of the SYNC message. (c) Loss of the TABLE message. (d) Loss of the DATA message.

radio to a TX mode, broadcasts the SYNC message (that contains information regarding the necessity to send a TDMA table or not) and activates the TAB_TIMEOUT timer.

In the case of TDMA table transmission, the gateway ends in the SEND_TABLE state, broadcasts the updated TDMA table, turns off the radio, and moves to the RADIO_SLEEP state. When the gateway does not need to send a new TDMA table, it simply moves into the RADIO_SLEEP state.

When the TAB_TIMEOUT timer generates an interrupt, the gateway moves into the WAIT_FOR_DATA state, sets the radio to RX mode, and waits for the data messages coming from the registered nodes.

Each time a message arrives, the gateway moves to the REGISTER_DATA state, stores received data in a specific memory location, and returns to the WAIT_FOR_DATA state.

After CURR_NODES*TX_TIME seconds (i.e., the sum of all of the time slots of the registered nodes), the gateway gains the DATA_READY state, which means that all data have been collected by the sensor nodes in this TDMA cycle. Then, the gateway returns to the WAIT_FOR_SUBSCRIPTION state to allow registration of new sensor nodes.

C. *Robustness Issues*

Robustness is a key aspect in a WSN design to reduce the effect of perturbations that might affect the local transmission phase. With this goal in mind, we designed the TDMA protocol to be robust both w.r.t. transmission errors (e.g., one or more messages did not reach the recipient) and topology changes (e.g., nodes or gateway are momentarily not reachable).

In particular, the suggested TDMA protocol is robust w.r.t. transmission errors causing the loss of the SUBSCRIBE message [see Fig. 10(a)], loss of the SYNC message [Fig. 10(b)], loss of the TDMA table [Fig. 10(c)] for units, and loss of a DATA message for the gateway [Fig. 10(d)]. In the case of loss of the SUBSCRIBE message [Fig. 10(a)], the unit relies on a retry mechanism that keeps sending the subscription in next cycles up to the final accomplishment. If the unit does not receive the SYNC message, it waits for RETRY times (in our case, we set $\mathrm{RETRY} = 3$) and, in case of a negative commitment, returns to the INIT state. Once the TDMA table is not received due to a transmission error [Fig. 10(c)], the unit disconnects itself from the WSN not to interfere with others; afterwards, the unit moves to the INIT state. If the DATA message does not reach the gateway [Fig. 10(d)], the protocol passes to the next TDMA slot (of the next node) without affecting the whole data acquisition of the TDMA cycle: to guarantee robustness to message losses the reception of DATA at the gateway is a nonblocking operation.

The power-aware TDMA protocol is able to manage those situations where the gateway activates after the units [Fig. 11(a)] or, while the network is synchronized, the gateway switches off before sending the SYNC message [see Fig. 11(b)] or the TDMA table [see Fig. 11(c)].

The protocol does not require the gateway to be active before the nodes thanks to the registration phase which, periodically, activates the subscription phase [a SUBSCRIBE message sent and an ACK received, see Fig. 11(a)]. As explained above, when the node does not receive the SYNC message, it waits it for RETRY times and then, after an unsuccess, moves into the INIT state. As such, if the gateway switches off when the network is synchronized, all nodes, after having waited for the SYNC message for RETRY times, will move into the initial free configuration characterized by the INIT state [Fig. 11(b)]. Consequently, once waking up, the gateway will find units ready to

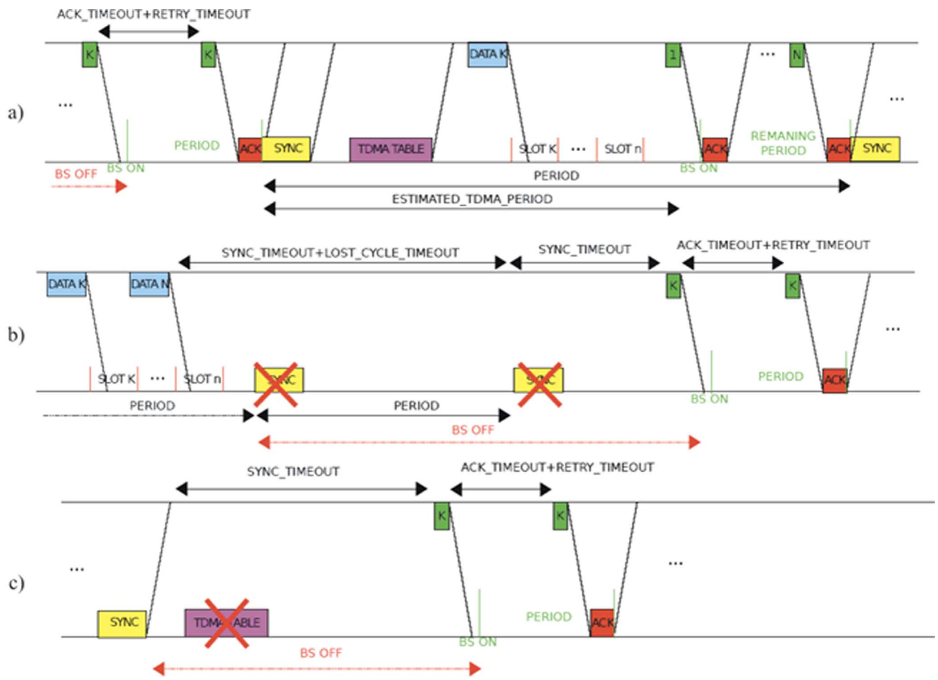

Fig. 11. Protocol robustness to gateway faults. (a) The gateway switches on after the sensor nodes. (b) The gateway temporarily switches off while the network is synchronized. (c) The gateway switches off before sending the TDMA table.

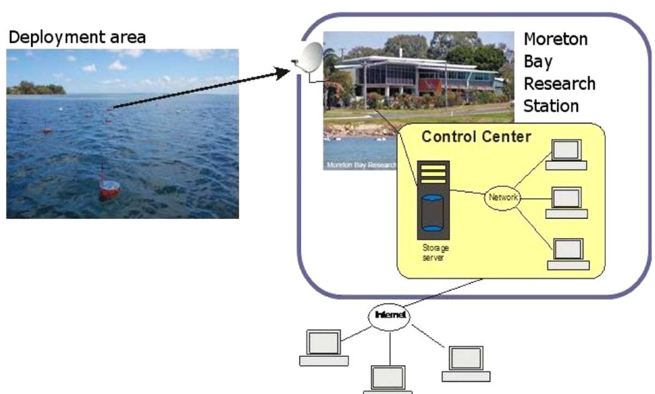

Fig. 12. Overview of the system.

be connected [Fig. 11(a)]. If the gateway switches off before sending the TDMA table [Fig. 11(c)], the units disconnect from the network and move to the initial registration phase.

V. Designing the System: Data Storage and Presentation

Measurements acquired by units and transmitted by the gateway finally achieve the control center for data storage and aggregation (see Fig. 12).

In particular, measurements and their timestamps are stored in a database based on a multithreaded, multi-user SQL DBMS MySQL Server 5.0 running on a Linux OS. In addition to the application measurements, we also stored the status of the network, defined as the "connected, not connected, not registered" label for each unit, the voltage of the batteries, the input power coming from the solar panel, the humidity level, and the possible presence of water within the buoy.

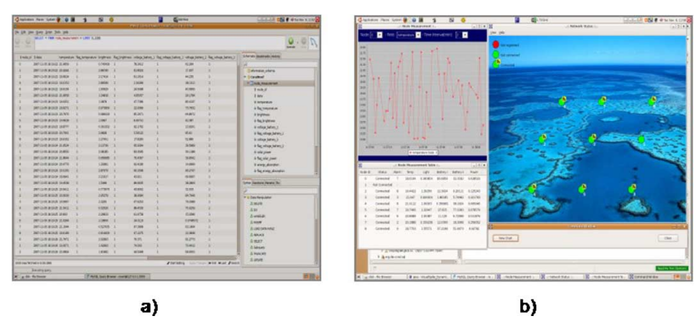

Fig. 13. Database and graphical interface at the base station. (a) Database. (b) Graphic interface.

Operators easily query the database at the control station or remotely, through the internet thanks to a proprietary SW application (see Fig. 13 for two views of the system). In particular, users may inquire for temperature, brightness, status of the batteries for a specific node or for all connected nodes by specifying the time interval of interest. Moreover, an immediate graphical user interface provides the state of all the nodes in the network and, for each connected node, the most recent measurement acquisitions (temperature and brightness), and information about its state (status of the batteries, solar power absorption, and alarms) both numerically and graphically.

VI. Deployment at Moreton Bay

The proposed framework has been deployed on the Australian Coral Reef at Moreton Bay, Brisbane, Australia. The developed WSN is composed of nine units (immediately scalable up to 70 in a plug-and-play fashion) and a gateway; devices are inserted in buoys anchored to the coral reef (see Fig. 14 for a top inside view of a unit). The distance between gateway and base station

Fig. 14. WSN unit.

Fig. 15. Final deployment at Moreton Bay, Brisbane, Australia.

TABLE I
POWER-AWARE TDMA PROTOCOL PARAMETERS

Protocol Parameter	Aim	Value
PERIOD	Time of the duty cycle	30s
TX_TIME	Time of each TDMA time slot	0.142ms
TAB_TIMEOUT	Time allotted to the gateway for sending the TDMA TABLE	2s
ACK_TIMEOUT	Time allotted to the gateway for sending the ACK message	1s
SYNC_TIMEOUT	Time allotted to the gateway for sending the SYNC message	4s
LOST_CYCLE_TIMEOUT	Time between the SYNC_TIMEOUT and the reception of the next SYNC message	25s
RETRY_TIMEOUT	Time the sensor node waits to re-send the SUBSCRIBE message RETRY_TIMEOUT = PERIOD/2 + U(0,10)	Random

was about 1 Km; units were deployed in a pseudolinear configuration as per Fig. 15.

The sampling frequency of the temperature and the brightness sensors is 1 Hz; acquired measurements are averaged (to reduce acquisition noise) and sent to the gateway every 30 s. Each DATA message is composed of 24 bytes with 14 bytes of payload. Table I shows the considered transmission parameters chosen for the application.

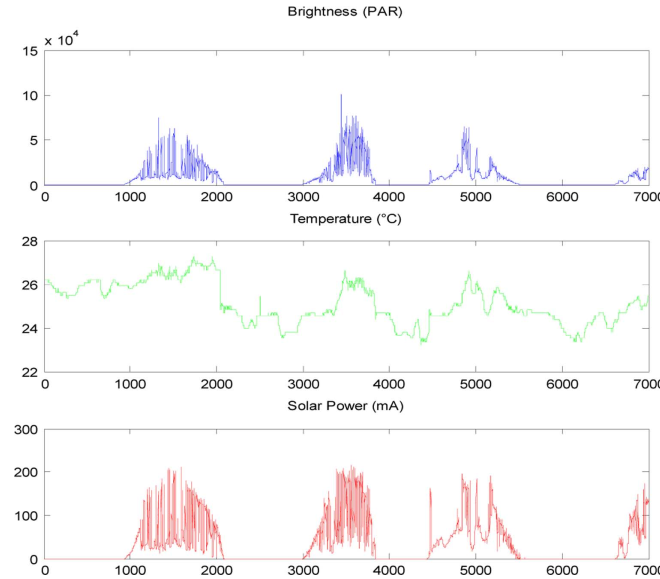

Fig. 16. Node 1: Brightness, temperature, and solar power w.r.t. time (7000 samples between 2007-11-18 20:06:03 and 2007-11-22 09:20:27).

PERIOD is inversely proportional to the sampling frequency, while the TX_TIME time must be long enough to guarantee transmission of one DATA message by the CC2420 transceiver radio at a 250-kpbs effective rate. TAB_TIMEOUT, ACK_TIMEOUT, and SYNC_TIMEOUT have been fixed experimentally by considering the geographical deployment of the sensor units and by taking into account flight-time, distance between units and gateway, computational time, and possible clock skews. LOST_CYCLE_TIMEOUT, which is the time between the SYNC_TIMEOUT and the reception of next SYNC message, can be easily computed as PERIOD-SYNC_TIMEOUT-1 s (guard time).

A. *Critical Aspects of the Deployment*

In the case of marine monitoring, the buoy is one of the most important issues since watertightness must be guaranteed. In turn, this implies that physical connectors between the electronic boards, which remain inside the package, and external elements (i.e., sensors and antenna) must be watertight. To further reduce the water infiltration risk, magnetic switches have been considered to activate the electronics: units can be enabled/disabled without any physical connector with the buoy inside.

Fixing elements such as screws, hooks, cables, and the anchorage bolt must be made with special steels able to resist in the marine water.

We included inside the buoy some utility sensors such as humidity and water to detect as quick as possible the possible formation of water or water infiltrations (the sensors allowed us for detecting water infiltration in the gateway during the first deployment). Temperature within the buoy was controlled by a thermal exchanger, which is a metallic steel closure placed on the bottom of the buoy in direct contact with the sea.

A further critical aspect was the anchorage system and its interaction with high/low tide and waves.

Buoys have been anchored with a mooring cable to a reinforced concrete block at the sea bottom. Waves induce severe

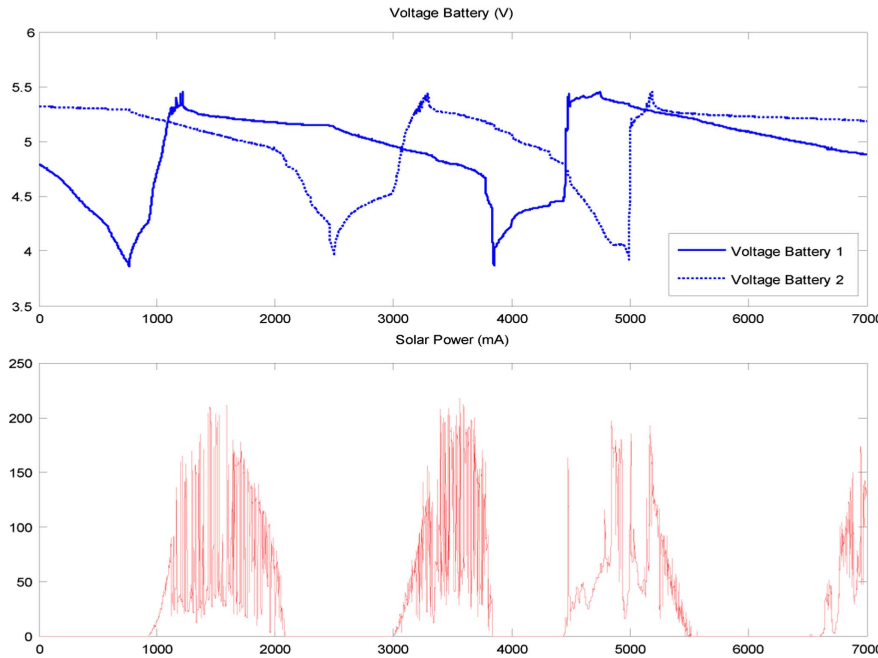

Fig. 17. Node 1: Voltage batteries, and solar power w.r.t. time (7000 samples between 2007-11-18 20:06:03 and 2007-11-22 09:20:27).

flutters on the buoys which impact on the mooring cable (which could break causing the loss of the buoys) or affecting the sensors. Moreover, when the distance between adjacent buoys is not adequate, the mooring cables may get twisted causing possible tears. For this reason, we used elastic mooring cables able to absorb the strong swinging the waves can induce on the buoys. Moreover, we used a specific hook (between the buoy and the mooring cable) to maintain horizontal the buoy even in case of strong streams.

There is another problem which affects the measurements: the formation of algae on the sensors which affect the data acquisition process. Calibration can be envisaged to reduce this loss in accuracy effect but a periodic cleaning of the sensor (e.g., once per year) is required.

As a last issue, the deployment of units needs to be adequately signaled with signaling buoys and a permission for the deployment needs to be released by the competent authority.

B. Current Results and Discussions

Here, we present and discuss the measurements acquired by a node in four days acquisition campaign (from 2007/11/18 20:06:03 to 2007/11/22 09:20:27). In particular, Fig. 16 presents the temperature, the brightness, and the solar power generated by the solar panels, while Fig. 17 shows the state of the batteries.

The behavior of the brightness and the solar power follows the classic day/night cycle. As expected, both brightness and incoming solar power assume the zero value during the night (e.g., samples in the [0, 960] interval for day one) then they rise in the morning (interval [960, 1260]) and afternoon (interval [1800, 2100]). Even the temperature follows the day/night seasonality with dynamics depending on the thermal inertia of the water.

Fig. 17 shows the state of the batteries and the solar power in the acquisition period. At the beginning of the experiment Battery 1 is active; its voltage decreases w.r.t. time up to sample 900. Battery 2, in the same period, suffers from self-discharge phenomena causing a reduction of the voltage even when the battery is not used.

When the voltage of the Battery 1 decreases below 4 V (at sample 900), the energy-harvesting mechanisms module switches between the two batteries and activates Battery 2 (and Battery 1 goes under charge). Between samples 900 and 1200, Battery 1 is recharged by the solar energy. When the battery is fully charged (the voltage overcomes 5.5 V), it is disconnected from the energy-harvesting module to prevent overcharge (sample 1200). When a battery is inactive, it suffers from self-discharge phenomena, as can be seen between samples 1200 and 2600. Battery 2 is used up to sample 2600; afterwards, batteries switch: Battery 1 becomes operational and Battery 2 under charge.

VII. Conclusion

We presented a WSN-based framework for marine environment monitoring. All aspects of the environmental monitoring system such as sensing activity, local transmission (from sensor nodes to gateways), remote transmission (from the gateway to the control center), data storage, and visualization, have been designed and implemented. A power-aware and adaptive TDMA protocol for the local transmission that guarantees robustness and adaptability to network changes in terms of topology has been proposed while the deployment has been designed to be credible and robust.

Differently from what has been proposed in the literature, each unit of the WSN is endowed with adaptive solar-energy-harvesting mechanisms and tandem batteries for optimizing energy storage and prolonging battery lifetime. Finally, the proposed framework has been deployed with success at Moreton Bay, Brisbane, Australia, to monitor the water conditions of a segment of the Australian Coral Reef.

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