Towards a credible WSNs deployment: a monitoring framework based on an adaptive communication protocol and energy-harvesting availability

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Abstract—The paper proposes an environmental monitoring framework based on WSNs oriented towards a credible deployment. Here, credible has to be intended as an energy-aware system, robust with respect to perturbations affecting the normal operational life that adapts itself to face a change in the network topology. The developed proposed system encompasses the sensing activity, a local transmission from sensor nodes to the gateway, a remote data transmission from gateways to the control center and subsequent data storage in a DB and visualisation. The system has been tested on a first prototypical WSN deployed to monitor the Australian coral reef barrier.

I. INTRODUCTION

Environmental monitoring with wireless sensor networks (WSNs) is one of the most challenging research activities faced by the intelligent and distributed measurement community in last decades [1]. The need to have pervasive and accurate monitoring systems pushes the research towards the realisation of credible deployments able to survive in harsh environments for long time. As a consequence, basic research issues have to be integrated with technological constraints requiring multidisciplined competences.

In recent years some deployments of WSNs have been suggested in the literature both addressing the adaptability to environmental changes and energy-aware issues; in both cases limitations arise which either prevent a long lifetime or/and the QoS of the application.

For instance, [2] and [3] present a star-based topology for seabirds habitat and volcano monitoring, respectively (the gateway collects data from the sensor nodes and forwards them to a remote control station for further processing). The first perception that energy scavenging is a fundamental aspect for a credible deployment has been pointed out in [2], where simple solar harvesting mechanisms have been envisaged (only at the gateway level, leaving sensor nodes battery powered).

In the proposed WSN thirty-two sensor units are deployed for four weeks while the authors estimate in six months the lifetime of the network. In [3] a system for monitoring volcanic eruptions has been suggested; no energy harvesting solutions are provided neither for the gateway nor for the three sensor nodes. The deployment of the proposed WSN (involving the gateway and three sensor nodes) was active only to collect 54 hours of infrasonic signals. A more complex WSN architecture is proposed in [4] where a multi-hop WSNs for wildland fire environment Monitoring is proposed. The limited adaptation ability of the presented monitoring system requires human intervention for introduction of new nodes, which are battery powered.

It immediately arises that a credible deployment requires sensor nodes and gateways to be equipped with energy harvesting mechanisms. In this direction, since the maximum power density obtainable from a modern solar cell is about $5 - 20mW/cm^2$ (outdoor, sun at the zenith) whereas all other sources provide an energy gain far below $1mW/cm^2$ [5], solar energy is the most adequate energy supply mechanisms for most of outdoor applications. In this direction, [5] and [6] suggest to use commercial silicon solar cells and an on-off charging scheme based on the solar power. While the system is effective in optimal sun conditions, the efficiency drastically falls (the charging mechanism goes off) when a direct strong light is not granted (e.g., in presence of a partly cloudy sky, mist, morning and late hours, etc). To grant an effective energy harvesting for the most relevant energy source it is therefore necessary to consider a Maximum Power Point Tracker (MPPT), a circuit which continuously monitors, forecasts the light conditions and consequently adapts the solar cell working point to maximise energy transfer to accumulation means. The system allows the unit for harvesting energy even if the cell is not directly exposed to the optimal radiation, as it happens in outdoor applications where the panel surface may become dusty or covered with water. We implemented, in our units, the adaptive mechanism for tiny solar cells suggested in [7]. In turn, consideration of energy harvesting aspects implies that units need to be disconnected from the network for lack of energy and reconnected once energy goes back to a sufficient level. These adaptation aspects have an immediate impact on the network node clustering and the local communication protocol.

In its simplest architecture a WSN is characterised by a star topology with sensor nodes sending their measurements directly to the gateway (single-hop transmission). More sophisticated architectures would involve a hierarchical structure for the network (e.g., see Figure 1) with nodes locally organized in clusters, each characterised by a star topology. Gateways forward the collected information to a second level gateway; a multi-hop approach would constitute a different option.
Moreover, the limited energetic resources present in the sensor nodes (e.g., batteries or supercapacitors) require simple power-aware routing algorithms able to guarantee a reduced and optimised access to the radio module.

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

Several routing algorithms are present in the literature. In SMAC (Self Organization Medium Access Control) [9] all nodes select a transmission frequency to communicate with adjacent nodes. Unfortunately, the most common off-the-shelf sensor units (e.g., MICA units [10]) cannot receive simultaneously more than one frequency (no FDMA) and the overhead introduced by the SMAC protocol is not justified for the topology we are considering. Eavesdrop And Register (EAR) [9] is an interesting protocol able to manage both fixed and mobile sensor nodes but its use would be overdimensioned for the proposed network. A Hybrid TDMA-FDMA [11] allows us for combining TDMA and FDMA approaches by transmitting more data in one time slot acting on different frequencies. Again, the FDMA cannot be considered on MICAz units. The Carrier Sense Multiple Access (CSMA) avoids message collisions by listening the channel before each transmission; the approach is not power-aware (the energy consumption of the radio in the receiving node is comparable to the one in transmission and the radio must be kept on). The TDMA approach [11] is particularly interesting in applications where sensor nodes transmit at predefined time slots hence granting an efficient control of the radio module. Unfortunately, TDMA is not specific for WSNs, it does not support adaptation to topological changes 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).

Alternatively, we could have considered the ZigBee protocol [12]. Unfortunately, this off-the-shelf protocol does not support a fine management of the radio module, which is autonomously managed by the protocol itself. To reduce the transmission/reception power consumption of the WSN units we require to access the radio module with the lowest admissible frequency and simplify the protocol by minimizing the size of the message and the volume of message exchange.

What we propose is a modified TDMA method by including power-aware and network scalability issues. In particular, the suggested power-aware TDMA provides an efficient radio management both of the sensor nodes and the gateway (the gateway only listens the messages of the sensor nodes connected to the network). A robust registration phase has been included in the developed protocol to allow an efficient insertion/removal of sensor nodes to the network.

The designed power-aware TDMA can be formalized through the finite state machines of figures 2 (sensor nodes) and 3 (gateway). The protocol acts as follows.

![Hierarchical Topology](image)
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 sensor node commutes the radio to the reception (RX) mode and waits for an 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 in the network and modified the TDMA table accordingly. Moreover, in the ACK message, the gateway signals to the node the amount of time (DUTY_DELTA) it can sleep (turning off the radio) up to the next synchronization phase (which is the first phase of each TDMA cycle). After DUTY_DELTA seconds, the sensor node passes to the WAIT_SYNC state and turns on the radio in RX mode. If the SYNC message does not arrive within SYNC_TIMEOUT seconds, the sensor node moves into the LOST_CYCLE state, turns off the radio, sleeps for CYCLE_TIMEOUT seconds and finally wakes up again in the WAIT_SYNC state. If a sensor node misses three consecutive SYNC messages, it disconnects itself from the network and starts from the INIT state.

When the sensor node receives the SYNC message, it passes 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 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 is not arrived at the end of the timeout, the sensor node disconnects itself from the network and passes to the initial INIT state. When the TAB message arrives, each sensor node identifies its own transmission time slot and computes the amount of time (SLEEP_TIME) it can sleep up to the next transmission (SLEEP.UNTIL_SLOT state). If the SYNC message does not signal the arrival of a new TDMA table, the sensor node passes directly to SLEEP.UNTIL_SLOT state.

After SLEEP_TIME seconds, each sensor node turns on the radio and transmits its own 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 a sensor node. This approach is not power-aware for the gateway that may remain for long time in RX mode. On the contrary, this limitation is compensated by the power-aware approach of sensor nodes that minimize the energy consumption of the radio in the registration phase. This approach is also justified by the fact that the gateway has higher energy capabilities (larger solar panels) than sensor nodes due to the augmented energy needed by the radio link for the remote transmission.

When the gateway receives a SUBSCRIBE message, it activates a timer that will fire after PERIOD seconds, moves into the REGISTER_NODE state, updates the TDMA table with the just registered sensor node and sends back the ACK message. When the gateway reaches the WAIT_FOR_SUBSCRIPTION state it sets the radio in RX mode waiting for subscription of other sensor nodes. If a SUBSCRIBE message arrives, the gateway returns to the REGISTER_NODE state and the registration of the new sensor nodes is the same per the first one.

After PERIOD seconds from the subscription of the first node, the gateway moves to the SEND_SYNC state, sets the radio to a TX mode, broadcasts the SYNC message (that contains the information regarding the necessity to send a TDMA table or not) and activates a TAB_TIMEOUT timer. Then, in case of TDMA table transmission, the gateway reaches 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 achieves directly the RADIO_SLEEP state.

When the TAB_TIMEOUT timer generated 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 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 new sensor nodes for registering to the network.
C. The power-aware TDMA protocol: Robustness issues

As presented in Section II, robustness is a key aspect in the local transmission phase. With this goal in mind we designed the suggested TDMA protocol so as to be robust both to error transmissions (e.g., one or more messages did not reach the recipient) and to topology changes (e.g., one node or the gateway is momentarily not reachable; node fault).

In particular, the suggested power-aware TDMA protocol is robust w.r.t transmission errors that can cause the loss of the SUBSCRIBE message from a sensor node (see Figure 6.a), loss of the SYNC message by a sensor node (see Figure 6.b), loss of the TDMA table by a sensor node (see Figure 6.c) and loss of a DATA message by the gateway (see Figure 6.d). In case of loss of the SUBSCRIBE message (Figure 6.a), the node unit relies on a retry mechanism that keeps on sending the subscription in the next cycles up to the final accomplishment. On the contrary, if the node unit does not receive the SYNC message, it retries the reception for RETRY times (in our case we set RETRY = 3) and it returns to the INIT state. When a node unit waits the TDMA table and a transmission error corrupts the transmission (Figure 6.c), it disconnects itself from the WSN since it would be not aware of the new transmission order. After the disconnection, the node unit returns in the INIT state. If the DATA message does not reach the gateway (Figure 6.d), the protocol changes over the next node without affecting the whole data acquisition of the TDMA cycle.

Moreover, the power-aware TDMA protocol is able to manage those cases in which the gateway switches off after the sensor nodes (see Figure 7.a), the gateway temporarily switches off while the network is synchronized (see Figure 7.b) and the gateway switches off before sending the TDMA table (see Figure 7.c).

The protocol does not require the gateway to be switched on before the nodes since the registration phase is activated periodically at the nodes up the complete subscription (SUBSCRIBE message sent and ACK message received (Figure 7.a). As explained above, when the node does not receive the SYNC message, it aims at receiving RETRY times and then returns to the INIT state. Thus, if the gateway switches off when the network is synchronized, the nodes will wait for the SYNC for RETRY times and then they will return to the INIT model (Figure 7.b). When the gateway wakes up, the network is exactly in the situation presented in Figure 7.a (the gateway switches on after the sensor nodes). If the gateway switches off before sending the TDMA table (Figure 7.c), the sensor nodes disconnect themselves from the network and return to the initial registering phase.

III. REMOTE TRANSMISSION, DATA STORAGE AND VISUALIZATION

The power-aware TDMA protocol presented in the previous Section is used in the proposed framework to allow the gateway for collecting the sensor node measurements. Once these data are available at the gateway (i.e., after the DATA READY state), it can forward them (together with its own measurement) to the remote center by the radio link. The radio link is thus activated only once in the TDMA cycle and remains off for the rest of the time.

At the remote control center the counterpart radio link listens to the channel for the gateway transmission. Once the message arrives, a software routine is activated to insert the data contained in the payload in the database server (see Figure 4).

Human operators at the control center (or outside the control center through internet) access the database server with a SW application that allows for

- accessing the current and the historical data of the network,
- controlling the status of the sensor nodes in the network,
- controlling the status of the network.

IV. APPLICATIVE CASE: CORAL REEF MONITORING

The proposed framework has been applied to a real monitoring application envisaging a prototypical deployment of the WSN designed for monitoring the Australian Coral Reef. The prototype application aims at monitoring temperature and
lightness in the water at different depths in a circular 2800 m² sea area in Moreton Bay (Brisbane).

The developed WSN is composed of 9 sensor nodes (see Figure 5a) and a gateway (see Figure 5b) that are inserted in buoys anchored to the coral reef and organized in a star topology. The sampling frequency of both the temperature and the lightness sensor is 1 Hz; the acquired measurements are then 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 transmission parameters of the power-aware TDMA that have been experimentally identified for this application.

The technological infrastructure for the processing and the transmission unit in the proposed framework relies on the Crossbow MICAz [10]. This sensor node provides a 7.37 MHz ATmega 128L processing unit (with 4KByte for the RAM and 138 KByte for the program memory) and a CC2420 transceiver radio (single-chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver with a 250 kbps effective data rate).

The technological infrastructure we rely on for the radio link is the MaxStream 2.4GHz Xstream Radio Modem [12]. Thus, the gateway uses the CC2420 radio to communicate with the sensor nodes (local transmission) and the XStream Radio Modem to transmit remotely the data - the measurements received from the sensor nodes together with the gateway measurement - to the control center (remote transmission).

V. CONCLUSIONS

The aim of this work was to develop a “credible” environmental monitoring framework based on WSNs. We designed and implemented all aspects of the environmental monitoring system: sensing activity, local transmission (from sensor nodes to gateways), remote transmission (from gateways to the control center), data storage and visualization. The novel contribution of the paper resides in the design of a power-aware and adaptive TDMA protocol for the local transmission that guarantees robustness and adaptability to network changes in terms of topology (e.g., due to insertion or removal of new nodes caused by energy availability). Differently from the approaches present in the literature, each unit of the WSN is endowed with energy harvesting mechanisms (solar panels).

The proposed framework has been tested with success in the monitoring of the water conditions (temperature and brightness at different depths) of the Australian Coral Reef.

REFERENCES


<table>
<thead>
<tr>
<th>TABLE I</th>
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<tbody>
<tr>
<td>POWER-AWARE TDMA PROTOCOL PARAMETERS.</td>
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<tr>
<th>Protocol Parameter</th>
<th>Description</th>
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<tr>
<td>PERIOD</td>
<td>Time of the duty cycle</td>
</tr>
<tr>
<td>DELTA</td>
<td>Guard time</td>
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<tr>
<td>TX_TIME</td>
<td>Time of the TDMA time slot</td>
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<tr>
<td>TAB_TIMEOUT</td>
<td>Time within the gateway sends the TDMA message</td>
</tr>
<tr>
<td>ACK_TIMEOUT</td>
<td>Time within the gateway sends the ACK message</td>
</tr>
<tr>
<td>SYNC_TIMEOUT</td>
<td>Time within the gateway sends the SYNC message</td>
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<tr>
<td>LOST_CYCLE_TIMEOUT</td>
<td>Time between the SYNC_TIMEOUT and the reception of the next SYNC message</td>
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<tr>
<td>ENTRY_TIMEOUT</td>
<td>Random time the sensor node waits to resend the SUBSCRIBE message</td>
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Fig. 5. a) A sensor node; b) the gateway.
Fig. 6. Protocol 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.

Fig. 7. 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.