A Framework for the Effective Deployment of Wireless Dynamic Sensor Networks

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***Abstract*—Deployment of wireless sensor networks is a key activity for the enhancement of the state-of-the-art wireless networking systems. In this paper, we present an architecture scheme capable to integrate several heterogeneous modules in a complete and inexpensive wireless dynamic sensor network system. The system can manage a high rate of data gathered from mobile units and can provide precise information in both real time and through a back end service. A real-world implementation of this system is proposed together with some in field performance measurements.**

Keywords-Wireless Sensor Network; ZigBee; Performance measurements.

I. INTRODUCTION

Wireless Sensor Networks (WSN) do represent a growing technology that finds application in different fields like environmental control, interaction among people or computers, remote activation of systems. Such networks can be composed of several units like sensor nodes, actuator nodes, gateways possibly connected to a wide area network like the Internet, and one or more clients. A particular application of WSN is composed of mobile elements, thus introducing a more dynamic scenario that can be defined as Wireless Dynamic Sensor Network (WDSN). The mobility of sensing devices requires a rapid network reorganization and the search of alternative route paths to keep a constant association of single elements to the network. Specific protocols for WDSN help the process of creation, self-organization, route discovery and management of this type of networks [1][2].

The implementation of new services dedicated to WDSN require the integration of several components and technologies to collect, transmit and elaborate data. The data generated or used by units like sensors or actuators are often exchanged through a variety of basic transmission systems mainly based on serial protocols. This data bundle is usually not complex, thus the data preparation preceding the transmission can rely on the resources provided by compact units like micro controllers. As far as the creation of a distributed network, the ZigBee protocol [3] is an international multi hop standard protocol designed with the aim of allowing a straightforward setup and management of a WDSN. The ZigBee protocol allows the creation of different network configurations, from single sink topologies up to a full mesh disposition, and several dedicated devices are nowadays available on the market to develop tailored systems. Although the interconnection among modules is provided by standard protocols, a specific design for the actual implementation of a WDSN system is always required.

There are several emerging applications of WDSN exploiting the integration of modules useful in smart cities [4], smart health [5][6][7], and smart home [8] environments. Among the other proposals, we cite the implementation of an intelligent traffic control system to avoid traffic jams, an infrastructure to manage a bike sharing service, and a framework for the supervision of agricultural cultivation or animal farms. Some of these examples are further analyzed in the Section VI. In the next section II, we focus the attention on our proposal for a framework for the deployment of a complete WDSN capable to integrate in a single transmission system heterogeneous sensors having different characteristics. Section III introduces the proposed architecture scheme, while Section IV provides some details about the current implementation. Section V reports the results of first experiments, before the final considerations presented in Section VII.

II. WDSN TECHNOLOGIES AND PROTOCOLS

The composition of electronic devices in an integrated system requires a shared method to exchange data among the involved units. Simple yet effective communication between two electronic devices can happen by means of Universal Asynchronous Receiver Transmitter (UART) protocol. Transmissions are asynchronous, that means an external clock signal is not required and the number of wires or I/O pins is minimized. The lack of a clock entails a shared configuration between the pairing devices. As a first rule to be shared, the *baud rate* specifies the data communication speed, that is anyway limited to 115200 bits per second. Data are then transmitted in frames and a basic parity bit check mechanism increases the communication reliability. Although simple, the protocol is so common that many electronic components always offer a pair of UART Tx and Rx pins.

Although the UART is a simple and useful protocol, it is not conceived to address multiple communications on a single channel. In the years between 1980 and 1990, Philips developed the I^2C (*Inter Integrated Circuit*) protocol to manage several units by using a single pair of input and output lines, named SCL for *Signal clock* and SDA for *signal data* [9]. The data exchange is still serial and happens on this single bus at predefined baud rate ranging from 100 kbit/s

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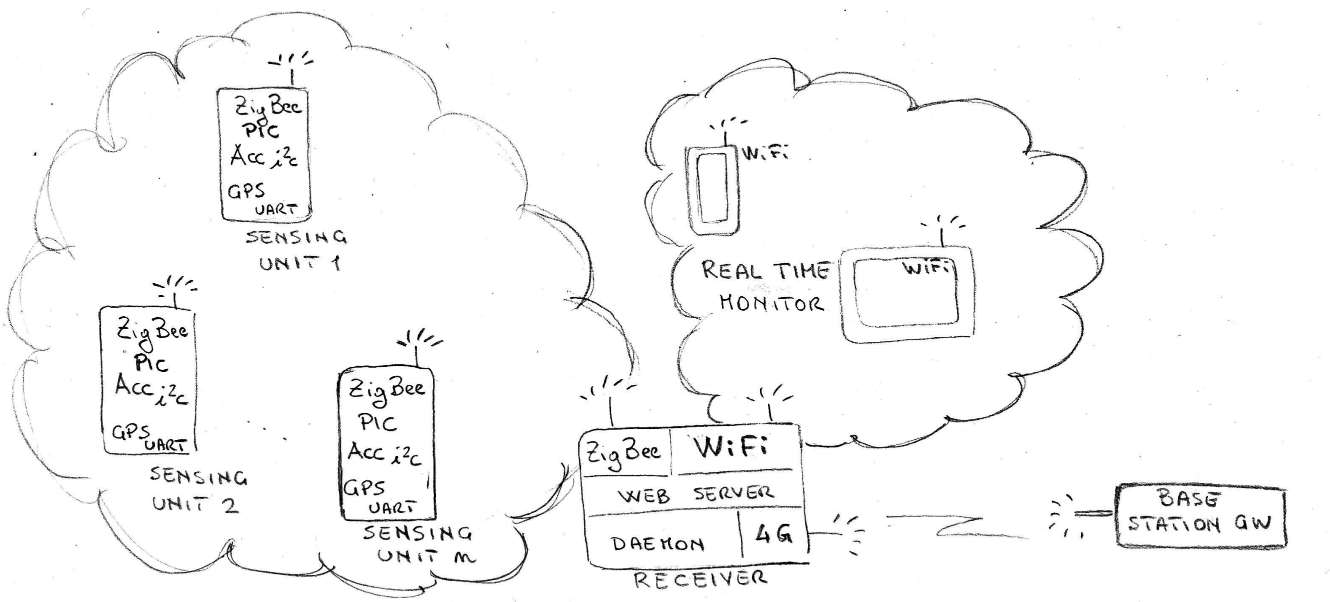

Fig. 1: The architecture scheme

up to 3.4 Mbit/s in the more recent components. All the I^2C units are identified by a unique address, thus connection of multiple units to a single collector is allowed. Despite the possibility to manage even more complex configurations, the usual setup is composed of a single master and multiple slaves. As a basic assumption, both SCL and SDA lines are kept to the high logic level thanks to pull up resistors. The master is responsible for managing the SCL clock line and for starting the communication by lowering the SDA line. Both read and write operations are allowed on the bus. Following a master write of the slave address, the involved slave can eventually take control of the SDA line if a read operation is required. SDA transitions are allowed only when the SCL is low, while SDA data are considered valid when the SCL is high. The ninth bit of each sequence is always considered as an acknowledgement. At the end of each procedure, the master raises up the SDA lines to stop the communication.

Among the available technologies to exchange data on an average distance range, ZigBee is gaining momentum as the leading solution providing multiple configurations, with tens of cheap devices available on the market. ZigBee is a registered trademark managed by an alliance of companies that produce both components and systems. Physical and MAC layers are compliant with the IEEE 802.15.4 standard protocol. Transmission among the devices happens worldwide in the 2.4GHz frequency band, as well as the 868MHz band available, mainly in Europe, for scientific and medical experimentations. Depending upon the unit power, transmission can range from about 10 meters up to several kilometers in the open space. In a ZigBee network a specific device can be configured as either *coordinator*, or *router*, or *end-device*. For each network there is only one coordinator responsible for the initialization and the setup of operational parameters. One or more routers act as intermediate nodes and rely on the Ad Hoc Distance Vector (AODV) protocol to relay data from other nodes towards the coordinator. Finally the end-devices have limited functionality and are usually battery-powered. They limit themselves to sending collected data to the routers or the coordinator, but they cannot relay any data. To better manage the limited amount of energy available, a particular *beacon* can be either enabled or disabled. In the most simple situations the routers are not power constrained, so the beacon is not enabled and they can be always active to wait for data from end-devices. When the routers have to limit their energy consumption, they can alternate between a sleep and an active state. In this case, a beacon is generated to alert the adjacent devices. According to the 802.15.4 standard, 3 topologies can be set up with zigBee, as it will be explained in the following. In the *star* topology, several end devices are connected to a single coordinator, with no need for ZigBee routers. Although this represents the simplest solution, the coordinator can become a bottleneck for the network as it represents a single traffic sink, so this kind of configuration can be adopted when the number of end devices is restrained, or when the transmissions are infrequent. In the *tree* topology the network can be extended with the introduction of the ZigBee routers. The end devices are called children and can connect either to ZigBee routers or to the coordinator, that act as parent nodes in the hierarchy. The coordinator can be connected to both ZigBee routers and end devices. This configuration allows for a wider network extension, but it does not offer redundancy in case of node failure. Notice also that albeit considered in the standard 802.15.4 protocol, zigBee does not support the cluster tree configuration. The last solution is the *mesh* topology. In this configuration, one coordinator, several routers and end devices build up a multi hop network. The range of the network can be extended, and alternative paths may be available in case of node failure. On the downside, the configuration and the management of this topology are more complex and introduce overhead with respect to the previous

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solutions.

The most recent update to version 3.0 is an effort to unify the various ZigBee proposals in a single standard.

III. Architecture scheme

The architecture we propose is sketched in Figure 1. It is composed of multiple *sensing units*, at least one *receiver* capable to collect data, *monitor units* and one *base station* potentially connected to the Internet.

Sensing units are identified by their unique code number so that data can be differentiated. The update frequency can be configured according to the particular application. All data are collected at the receiver station and the wireless technology is responsible to manage the correct synchronization among the units for an effective radio transmission. Sensor modules are composed of a dedicated control unit, one or more active sensors, and a transmitter. The control unit relies on a micro controller and is in charge of synchronizing the data collection and to send the bundle of data to the receiver. Sensor modules can be heterogeneous and usually provide data through different protocols.

The receiver collects wireless data and makes them ready for presentation and further computations. It is equipped with a powerful aerial to guarantee the reception of data coming from even remote sensor units. The receiver station can also be provided with additional wireless modules for short or long range data forwarding. A short connection can be useful to provide a real time visualization of data, whereas a long range connection offers the chance to reach a more powerful base station capable to store the data, make off line computations or share data on a wide area network.

Monitor units are mainly intended to be real time devices that can provide a quick view of the current situation. They connect to the receiver station and can visualize all sensed data at a glance. To ensure the widest level of interoperability, the receiver station should make available legacy technologies for a straightforward network connection. Specific applications can be developed to enhance the presentation of data.

Finally, the receiver unit can send data to a distant base station for more complex applications. As the receiver unit and the base station can often rely on a greater availability of energy resources, they can be equipped with more powerful radio devices capable to cover longer distances. The base station should be close to an Internet access point to widen the number of applications that can make use of collected data.

We now present some implementation details related to the introduced architecture modules.

IV. Implementation

We made a complete implementation prototype of a system based on the architecture described above. In order to verify the architecture feasibility, most of the modules are designed starting from inexpensive components and configured to be interfaced with electronic devices available on the market.

A. Sensing unit

The sensing unit prototype is pictured in Figure 2. It is based on the PIC16F87-I/P micro controller acting as a control unit. This Peripheral Interface Controllers (PIC) provides an internal clock up to 8MHz, and supports both UART digital communication and I^2C peripherals. Two different sensor modules are connected to the control unit: a) a Global Position System (GPS) UART sensor that includes the PIC receiver serial line; b) a 3D accelerometer and magnetometer LSM303DLHC sensor based on the I^2C protocol, linked to the specific PIC input line. The magnetometer provides raw data that can be used to calculate the sensing unit position as well as the pitch, roll and heading. The PIC serial line output is instead connected to a wireless module supporting the ZigBee protocol. To provide a high rate of samples, all sensor modules are set to a refresh rate of 5Hz. The control unit executes a

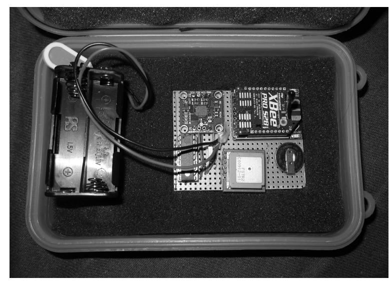

Fig. 2: The sensing unit prototype

routine coded in low level programming language. The routine enters a loop starting from the data read from the sensing units. Data read from each sensor module are composed of 5 samples that get stored in the local PIC memory. A unique code number is appended to all the samples to let the sensing unit be identified; the composed data bundle is eventually sent across the serial output to be processed by the transmitting unit. To ensure the correct management of the data processing phase, all units are set to a baud rate of 38400. Frame composition

ID 6 byte	s	Acc – 80 bytes	s	GPRMC sentence 68 bytes

Fig. 3: Sensing unit frame composition

is depicted in Figure 3 as a plain text sentence of 156 bytes. Every set of data ends with a one byte separator. As the current configuration sends 5 sentences per second, the load is of 6240 bits/sec for each sensor.

The radio communication is ensured by a ZigBee module. In order to provide a wide range coverage, a powerful Xbee Pro S2B international module from Digi is installed on the sensing unit. Although this international version limits the power consumption to 10mW, a good aerial allows for a broad radio coverage, as reported by the comparative experiments presented in the following section.

B. Receiver

The receiver is implemented on a Raspberry Pi mini computer running a dedicated image that initializes the USB port for the interconnection with the radio receiving module and to enable an access point service through a Wi-Fi dongle. The data collection from sensors is ensured by a high gain ZigBee receiver module connected to the main unit through one of the available USB ports. As a result, data are received on the serial line and they are processed by a dedicated daemon that makes the necessary calculations to obtain the instant position, pitch, roll and heading of each sensing unit. A special script arranges such data in a XML file, with a single element for each sensing unit. These data can be immediately accessed in real time from nearby devices like tablets or smartphones via a dynamic web page always accessible from the receiver. Data on the web page are refreshed at the same rate of the data provisioning, that is 5 samples per second in the current configuration. Furthermore, a $4G$ internet key can send the data bundle to a distant base station for data storage, elaboration and presentation on a wide area network.

V. PERFORMANCE MEASUREMENT

We have developed a complete system to test the application. Two different configurations for sensing modules are available: the former with an external 5dB gain, 2.4GHz omnidirectional aerial, capable of long distance coverage, the latter with a more compact and simpler wire aerial. Power on sensing modules is ensured by 6V 2500mAh batteries. The receiver benefits from a high gain omni-directional external aerial and exploits the power of a battery connected to a recharging system. We tested the coverage of both these configurations, as well as the batteries duration on the sensing units. The actual measures are presented in table I. The first row reports the maximum distance before packet loss occurs. The radio coverage of sensing units equipped with external aerial is far greater than that ensured by internal wire aerial. As far as the battery consumption, the difference between the two configurations is neglectable. We then estimate the energy consumption to send a single bit through the ratio $\frac{MaxPower}{(lifetime)\times frameL}$, with the lifetime expressed in seconds. Considering a bit rate of 6240 bits/s in our current configuration, we calculate a $3.51e-5$ mA consumption per bit sent.

TABLE I: PERFORMANCE MEASUREMENTS

	EXT. AERIAL	INT. AERIAL
DISTANCE [m]	3076	412
LIFETIME [hh:ss]	3:10	
ENERGY/BIT [mA]	$3.51e-5$	

A mobile monitor can exploit the web based system active on the receiver sensor to show the real time measurements, with a refresh rate of $200ms$. A screenshot is shown in Figure 4.

We finally evaluated the precision of the compass. The accelerometer and magnetometer provide the data that can be used to calculate the pitch, roll, and to compensate the tilt of the compass calculation. We then compared the measurements of the tilt compensated compass with the compass reading received from GPS. We derive such data from a reading batch of 300 samples. A routine active in the receiver unit executes

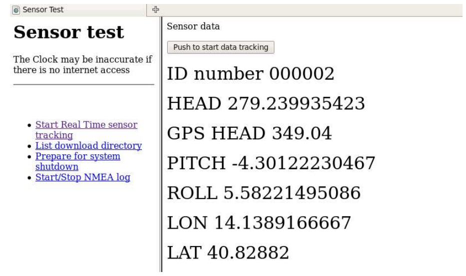

Fig. 4: A screenshot of real time web-based measurements

the required trigonometric computation to get pitch, roll, and tilt compensated compass. We then make an offline difference between the tilt compensated compass and the analog reading from the GPS. We did expect a difference in the precision of these units. The average and the standard deviation of this difference is reported in Table II.

TABLE II: TILT COMPENSATED COMPASS MEASUREMENTS

	AVERAGE	STD DEVIATION
CMP-GPS CMP	65.52	2450.48

VI. RELATED WORK

Many related works have studied and applied the concept of WDSN. In [10] the authors evaluate the benefits and drawbacks of the ZigBee technology when applied to the situation of moving nodes. Among the other features, they highlight the presence of a single ZC (ZigBee coordinator), the limited concurrent associations among nodes (120 in total), the maximum time that a child node can remain without communication with its parent node according to a configurable sleep time set on the end node to limit power consumption. Furthermore, it is reminded that routing tables in ZigBee nodes are refreshed every 10 seconds. A real test composed of several fixed end devices and one moving coordinator is presented as a proof of concept to check the re-association feature.

A similar composition of technologies like Radio Frequency IDentification (RFID), Global System for Mobile communication (GSM), ZigBee and PIC micro controller is presented in [11] with the purpose of enabling a system capable to control the car traffic in congested cities. Special sensors are positioned at street junctions to catch the number of passing vehicles and estimate the congestion so that the red lights duration can be tuned accordingly. Also, the system allows for the interception and monitoring of stolen cars, while the approaching of emergency vehicles can activate the green light at the next junction by exploiting ZigBee radio signaling.

ZigBee is still used to ensure the communication in a proposal for green street lights system [12]. Both sensors and actuators are mounted on street lights: sensors estimate the required level of light; data are then sent to a premise energy and management station that can finally send the most appropriate configuration towards the LEDs dimmer on the lamppost.

A complete system that collects data from moving sensing units is presented in [13]. Several sensors mounted on bicycles and worn by cyclists constitute an example of a wireless

BAN (body area network). Rich information concerning the travelled distance, the air pollution, the traffic intensity, fitness parameters like hearth rate, are conveyed to a back end server either through opportunistically encountered wireless access points, or by exploiting the cellular channel of mobile phones. Sensing units are based on the capabilities of Tmote Invent units. Some metrics are introduced to estimate things like pollution level or safety of paths. A localization system based on distance and magnetometric direction travelled is also compared to the information provided by GPS.

VII. Conclusions

The major contribution of this paper is the implementation of a framework for the deployment of a mobile sensor network that can provide high precision data at high rate. In the proposed architecture, a single controller manages the flow of measurements gathered from two different sensors making use, respectively, of UART-based communication and of the I^2C protocol. Data are then shared in a distributed system through the capability provided by a ZigBee network. A complete framework has been implemented to test both the functionality and the basic performance of such a system. Current implemented sensors provide high rate and precise information about the location of units, so they can find application in many fields. We are planning to increment the number of implemented nodes to create a multi hop network and to verify the impact that dense node coexistence may have on the overall system performance.

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