A Protocol Architecture for Energy Efficient and Pervasive eHealth Systems

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Abstract— **The design of new and more pervasive healthcare systems has been fostered by the increased expectancy of life in the coming years. In this field, distributed and networked wireless embedded systems, such as Wireless Sensor Networks (WSNs), suit well with the requirements of continuous monitoring of aged people for their own safety, without affecting their daily activities. WSN4QoLis a Marie Curie project which involves academic and industrial partners from three EU countries, and aims to propose new WSN-based technologies to meet the specific requirements of pervasive healthcare applications. This paper focuses on presenting a protocol stack architecture designed to support the solutions proposed in that project to enhance energy efficiency.**

I. Introduction

The worldwide population aged over 65 years is projected to increase from 6.9% to 12.0% worldwide, and, in particular, from 15.5% to 24.3% in Europe [2]. Furthermore, the average worldwide life-span is expected to extend another 10 years by 2050 [3]. The growing number of older adults increases the demands on the public healthcare system, and on medical and social services. Recent research [4] has shown that the key is in the exploitation and integration of *sensing* and *consumer* electronic technologies into healthcare common practices, which would allow people to be constantly monitored in their usual living places. More specifically, Wireless Sensor Networks (WSNs) and, particularly, Wireless Body Area Networks (WBANs) technologies are considered as the major research areas in computer sciences and application industries for healthcare provisioning [5].

In perfect agreement with the above issues, the on-going WSN4QoL project [6] involves the design of WSNs specifically suited to meet healthcare application requirements. This paper aims to present an efficient protocol stack architecture to support the new solutions proposed in WSN4QoL. Accordingly, the remainder of the paper is organized as follows. Section II focuses on the main challenges of a WSN-based system design and the main objectives of this project. Section III overviews the reference system architecture assumed in WSN4QoL, while Section IV describes the networking technologies designed to support the solutions proposed. Finally, Section V concludes the paper with some remarks and future on-going research activities.

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II. Challenges of WSNs Design for Pervasive Healthcare

WSNs are distributed networked embedded systems, where each node combines sensing, computing, communication, and storage capabilities. These nodes communicate with one another by forming multi-hop wireless networks, whose topology is, in general, dynamic, since the connectivity among the nodes may vary with nomadic and mobile devices. Because of their wide variety of applications, it is envisioned that, in the near future, WSNs will become an integral part of our everyday lives [5].

Although fundamental research results on WSNs theory and practice have been achieved for many different applications, e.g., traffic monitoring, plant monitoring in agriculture, and infrastructure monitoring, healthcare scenarios pose some unique application-specific challenges and constraints. In particular, the efficient design of a WSNs-enabled pervasive healthcare system is characterized by the following intrinsic differences with respect to "general-purpose" WSNs design, which require special attention [4]. (*i*) The devices have limited available energy resources, as they have a very small form factor. (*ii*) A low transmit power per node is needed to minimize interference and to cope with health concerns. (*iii*) The devices are located on the human body, which can be in motion. WSNs for pervasive healthcare should therefore be robust against frequent changes in the network topology and channel variability. (*iv*) Data mostly consists of medical information, hence, high reliability and low delay/latency are required. (*v*) Stringent security mechanisms are required to ensure the private and confidential character of data. (*vi*) Context-awareness through cooperative localization in outdoors and indoors is crucial to enable a prompt reaction in case of emergency.

Along these lines, the main research objective of WSN4QoL is to provide fundamental research advances, proof-of-concepts, and real-life implementations on the enabling technologies for a winning use of WSNs-based systems in pervasive healthcare applications. More in detail, the research objectives of WSN4QoL include: (*i*) To design a protocol stack architecture, which can accommodate a variety of protocols, algorithms, sensor devices for pervasive healthcare applications. (*ii*) To develop energy-efficient

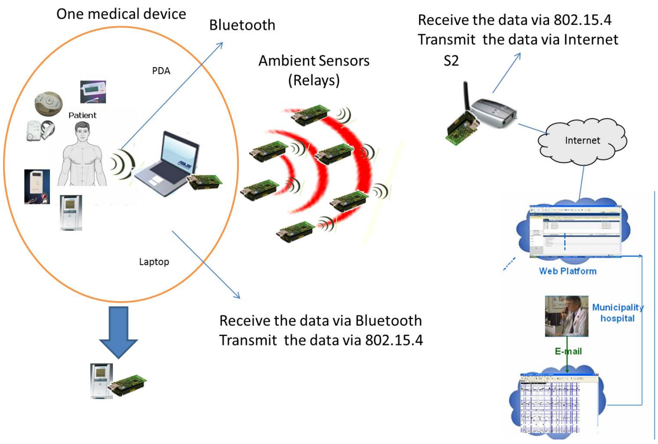

Fig. 1. Reference Healthcare 3-tiers System Architecture.

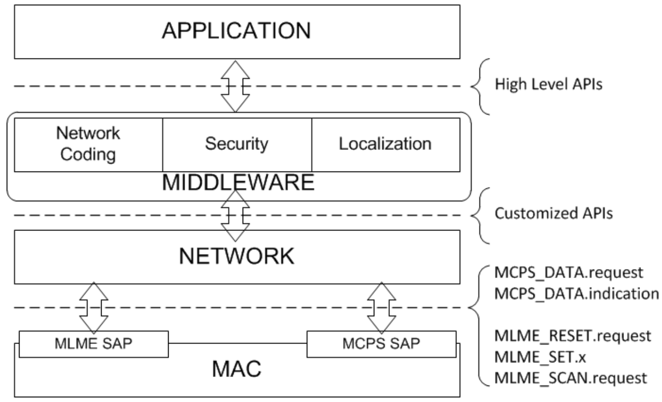

Fig. 2. Communication Protocol Stack on top of the IEEE 802.15.4 standard. Basic interfaces and roles of each layer are also shown.

and performance-guarantee cooperative protocols and Network Coding (NC) schemes for WSNs-enabled pervasive healthcare applications. (*iii*) To propose advanced distributed localization protocols and algorithms specifically suited for the scenarios (e.g., indoors) envisaged by WSNs-enabled pervasive healthcare applications. (*iv*) To conceive effective, efficient, and resilient security solutions for the proposed algorithms and protocols. (*v*) To implement and assess the performance of the protocol stack in a WSN testbed. (*vi*) To integrate the proposed solutions in real devices and validate them in real-working environments.

III. System Architecture

Similar to other work in literature (e.g., [7], [8]), the reference system architecture proposed in this project is as depicted in Figure 1. It is a three-tiers architecture, where at the lowest tier a Bluetooth-enabled WBAN connects sensors to a local collector (i.e., a hub), which can be a portable embedded PC or a PDA. The hub needs to communicate with WBAN devices through a Bluetooth radio module and then send measurements reports towards a residential gateway, through a ZigBee/IEEE 802.15.4-based multi-hop WSN. The gateway is able to perform local computation and forward data to the public IP-based network towards the professional caregivers for real-time analysis. The scope of the WSN4QoL project is focused on the efficient data transmission over the multi-hop WSN network, as well as to support real-time people localization in a fully distributed way.

Consequently, by focusing on the WSN part of Figure 1, i.e., the ambient network linking the hub collector worn by the patients to the GW, Figure 2 shows the proposed communication protocol stack. Moving from the bottom, the protocol stack is composed of the following entities, further detailed in next section. (*i*) *IEEE 802.15.4 MAC Layer*. This layer is responsible for the access to the wireless medium for transmission and reception of the frames for both mobile patients and fixed relay nodes. (*ii*) *Network Layer*. This layer is responsible for the end-to-end communication between the mobile nodes and the GW, as well as for the organization of the network. As it will be detailed next, the proposed solution is partially inspired by the ZigBee standard, thus the APIs provided by this layer will result from their customization. (*iii*) *Middleware Services*. This layer represents an interface between the underlying protocol stack and the application layer, and is the core of the novelties introduced in the WSN4QoL project. (*iv*) *Application Layer*. This last layer mainly focuses on gathering measurements from the sensors and data compression. For instance, at this layer, compressed sensing techniques (e.g., [9], [10]), aiming to exploit intrinsic properties of the biometric data in order to provide energy efficient tele-monitoring solutions, are implemented exploiting the APIs offered by the middleware.

IV. Protocol Stack

A. MAC Layer

Figure 3 shows an architectural overview of an open source IEEE 802.15.4-2006 MAC implementation for the TinyOS 2 operating system [11]. While this figure abstracts from the majority of interfaces and some configuration components, it illustrates one important aspect, namely how access to the platform specific radio driver (PHY) is structured. For the purpose of explanation, the MAC can be subdivided into three sub-layers. For more details the reader can refer to [12, Chapter 2].

On the lowest level (dark gray boxes), the *RadioControlP* component manages the access to the radio: with the help of an arbiter component, it controls which of the components on the level above is allowed to access the radio at what point in time. Most of the components on the second level (medium gray boxes) represent the different time intervals in an IEEE 802.15.4 superframe (in the Beacon Enabled Mode, BEM) or the components responsible for the initialization of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) parameters (in the Non Beacon Enabled Mode, NBEM). In either BEM or NBEM, there are components supporting services for channel scanning. The components on the top level (white boxes) implement the remaining MAC data and management services, for example, PAN association or requesting (polling) data from a coordinator. A component

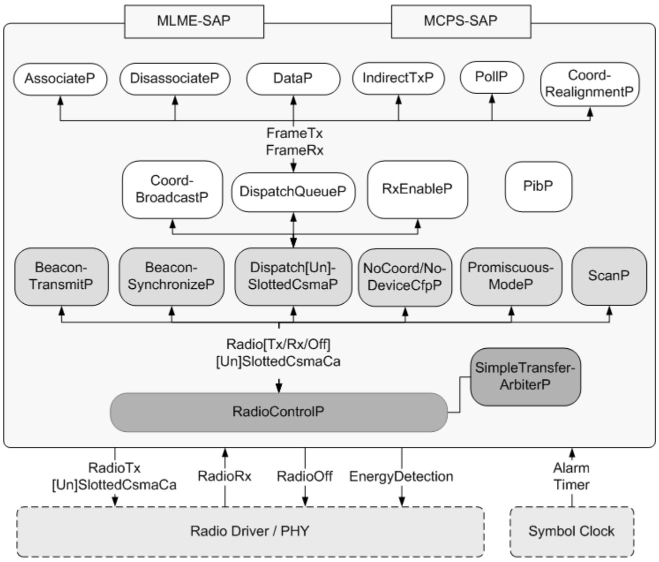

Fig. 3. The MAC architecture: components are represented by rounded boxes, interfaces by connection lines. The radio driver and symbol clock components are external to this architecture.

on this level typically provides a certain MAC MLME/MCPS primitive to the next higher layer, it is responsible for assembling the particular data or command frame and it accepts and processes incoming frames.

Among the options offered by the IEEE 802.15.4 standard, in WSN4QoL we have chosen to refer to the NBEM, i.e., the fully asynchronous mode. This choice is motivated by the fact that mobile nodes usually have a variable duty cycle and that, to achieve efficiency, NC schemes require mobile nodes to transmit data in broadcast. Moreover, in the classical scenario, where patients' data need to be collected at a central station, the asynchronous mode allows for flexibility in accessing the medium only when sensor data are available at the node and a transmission is required. For the majority of the time, the radio interface of these nodes can be kept off or in a low-consumption state, to save the batteries.

Finally, along this line, the basic commands and events offered by the MAC to the upper layer are for packet transmission and reception, and to set some specific parameters, such as the frequency channel and the transmission power, as well as to perform basic channel scan operations.

B. Network Layer

The Network Layer (NWK) is responsible for network management and formation (e.g., association/disassociation, starting the network, addressing, device configuration and the maintenance of the NWK Information Base), message routing and security-related services. In the frame of WSN, the standard de-facto for communication is IEEE 802.15.4 and the most widely referred network layer on top of that is ZigBee. In this sense, we refer to the basic features of that standard to customize it to our healthcare scenario and special requirements.

Networking problems in medium-to-large scale WSNs for remote healthcare patients monitoring can be partially mitigated by considering that the direction of the majority of the traffic flow is upwards (i.e., from the patients to the GW): this leads to the assumption that the ZigBee-like Cluster Tree topology can be our reference network architecture model.

1) Synchronization and Network Formation: Since the asynchronous mode of the IEEE 802.15.4 is chosen, this layer is responsible to keep the synchronization among the fixed relay nodes and regulate the transmissions of the mobile nodes in order to minimize collisions, thus increasing overall energy efficiency. This is achieved by broadcasting synch packets, which are appropriately scheduled. These packets are fundamental to define when a mobile node is allowed to transmit its data, in order to implement the NC mechanisms. Moreover, synch packets are also used by the localization module, since they carry the position of a relay node, which then plays the role of *anchor* for the mobile nodes.

Exploiting these synch packets, the network formation procedure is as follows. (*i*) The GW monitors the background RF noise, by running an energy detection process over all the frequency channels available in the IEEE 802.15.4 standard, then picks a channel, according to a policy aiming to minimize the level of interference. (*ii*) The GW starts sending synch packets on the chosen channel and at a predefined fixed transmission power level. (*iii*) Relay nodes are deployed at known strategic positions, to cover the whole environment (e.g., a house, a hospital) and scan all the channels, waiting to capture any synch packet. (*iv*) Once a relay gets a synch packet, it starts the association process, as like as in the ZigBee Cluster Tree approach: it sends a request to the parent (GW). The parent replies to this request with a response packet containing a time offset that the relay will use to transmit its synch packets to avoid mutual interference. This offset is computed as described in [13]. (*v*) When a relay is not able to receive the synch packets directly from the GW (or the GW cannot accept new associations), the relay will try the association with any other intermediate relay node, from which it is able to receive the synch packets. Then a new association trial is done with the parent relay, as described in the step (*iv*). This allows to form potentially large scale multi-hop networks with different depths [12, Chapter 8].

At the end of the process, the GW and the relays will be out emitting their own synch packets in a non-overlapping and non-colliding way, as exemplified in Figure 4. Each synch packet is the starting point of a superframe composed of an active and an inactive period. The active period is divided into a number of slots, which can vary according to the NC scheme.

Overall, the full network is synchronous and the probability of collisions (so, the need of retransmissions) is minimized, which leads to evident energy savings. It is worth stressing that synch packets are not IEEE 802.15.4 beacons. Unlike IEEE 802.15.4 beacon frames, these packets are not requested to be periodic, in the sense that the duty cycle of the network can be dynamically adjusted. Moreover, to exploit NC schemes and enable their gains, the transmissions from the mobile nodes to the ambient relays are always in broadcast: this would not be easy to achieve in the standard

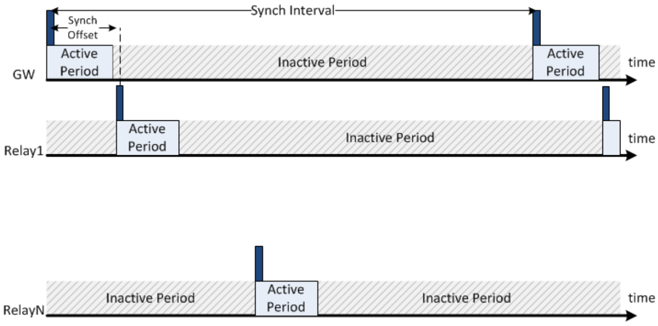

Fig. 4. Network scheduling.

beacon enabled mode of the IEEE 802.15.4.

2) Nodes' Addressing and Routing: Besides the synchronization, the network layer is also in charge of assigning the network addresses to the nodes. In the case of IEEE 802.15.4 radios, there exist worldwide unique addresses, which are 64 bit long, that can be used for the communication with any other device (extended address mode). In ZigBee-based networks a node can receive an address which is only 16 bit long, assigned according to some policy, and used by that node for any communication within the network itself (short address mode).

In our scenarios, the extended address mode is well suited for the mobile nodes, which require flexibility in the communications while they move in the environment. On the contrary, the relays are fixed and form a network with a static topology. Consequently, the short address mode suits well for these nodes. In this case, the ZigBee Distributed Address Assignment Mechanism is a valid option, since it assumes that (relay) nodes are organized into a tree topology. The advantage of using short addresses in this way for the relay nodes is in the fact that they do not need to maintain routing tables to forward incoming data, since simply looking at the destination address, they can decide to forward the packet upwards (to the parent) or downwards (to a child) [12].

C. Middleware

Exploiting the underlying protocol stack, this layer provides key services in the form of a high level application programming interface (API) to the application developers. In particular, the Middleware encompasses three major blocks: (*i*) NC; (*ii*) Distributed Localization; and (*iii*) Security.

The NC entity is in charge of providing efficiency in wireless communications. By means of appropriate combinations of two or more packets coming from the mobile nodes into a single one, a relay node is able to reduce the amount of traffic over the network. A simple binary XOR-based NC scheme can be easily implemented in this protocol architecture, as demonstrated in [1].

The Distributed Localization block deals with the estimation at run-time of the geographical position of a mobile node in the environment. A straightforward *Received Signal Strength* (RSS) and *anchor*-based solution guarantees the necessary accuracy in estimating the position of the mobile nodes in a fully distributed way, by exploiting the transmissions of the relays (synch packets), as demonstrated in [1].

The security block exploits the acknowledgement packets exchanged at the network layer among the nodes to identify potential threats or nodes malfunctioning, and instruct accordingly the lower layers to encrypt frames, taking advantage from the features offered by the IEEE 802.15.4 standard.

V. Conclusions and Future Work

In this paper, the WSN4QoL project elements have been summarized, while particular emphasis has been put on the description of how the designed protocol architecture supports the proposed WSN-based solutions for pervasive healthcare applications. Tests in real working environments of NC techniques and distributed people localization mechanisms implemented on two distinct WSN testbeds have been previously presented in [1] and already gave promising preliminary results, in line with our expectations.

Future on-going work includes the implementation of the proposed integrated protocol stack in real medical devices and on large scale testbeds.

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