

An Energy Efficient Protocol Architecture for m-Health Systems

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Abstract—Contemporary technologies as implemented in the field of health care have provided the everyday clinical practice with a plethora of tools to be used in various settings. However, from all established and emerging applications, priority will be given to those amongst them that target problems pertinent to efficiency in health care delivery that is also associated with increased costs tantalizing contemporary National Health Systems (NHS) not only in Europe but globally. In this field, WSN4QoL is a Marie Curie project which involves academic and industrial partners from three EU countries, which aims to propose new Wireless Sensor Networks (WSNs)-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

e-Health, according to *Health Information and Management Systems Society (HIMSS)* is defined as “the application of Internet and other related technologies in the healthcare industry to improve the access, efficiency, effectiveness, and quality of clinical and business processes utilized by healthcare organizations, practitioners, patients, and consumers to improve the health status of patients”. Recently a sub-segment of e-Health has emerged. This field is called m-Health, where m indicates the use of mobile communications and one of the definitions provided by Professor Robert Istepanian is “the use of emerging mobile communications and network technologies for healthcare” [1]. In 2010, the m-Health Summit of the Foundation of the National Institutes of Health came up with yet another definition this time shifting the weight of implementation to the devices: “the delivery of healthcare services via mobile communication devices” [2]. In the current document the terms e-Health and m-Health will be used interchangeably as the focus of the project lies in the field of wireless and mobile communications.

m-Health is not a surrogate for the clinician. It does provide the means to extend the reach of the provider beyond a face-to-face patient encounter, with the advantage of expanding the delivery of limited resources and expertise. For instance, using electronic images and pictures, diagnoses may be made from a remote location, either within or outside the facility. The m-Health Systems Architecture includes several dimensions

that can be materialised according to the specific environment: (i) Internet: access to information and sites with adequate access privileges per user category (doctors, nurses, administration, etc.) or universal access to public content such as education material with epidemiological characteristics (e.g., information on human papillomavirus or immunodeficiency virus, tuberculosis, etc.). (ii) Extranet: secure, remote connections between predefined participants (links between primary, secondary and tertiary health care levels) even including e-commerce (enterprise resource planning ERP systems). (iii) Intranet: communications infrastructure within the enterprise, which may facilitate and deliver access to internal and core data systems to all participants in the healthcare delivery chain. (iv) Core Data Systems: function-based systems that support the key processes of the enterprise. These may be financial, clinical or administrative systems. Included in this group are systems such as the electronic health record (EHR), Diagnostic Support Systems (DSS), admission and appointment systems, financial patient accounting systems as well as the internal infrastructure systems. (v) Telecommunications: the physical and technical layer that enables the connections and interchange of information through all available media: wireless, fiber, cable, satellite, and any other new and emerging means. Voice and email are interchangeable on some of the new devices. Recording, storing and transmitting this information falls within the boundaries of m-Health. (vi) Hardware: computers, pagers, personal digital assistants (PDA's), PC tablets telephones, servers and a plethora of vital signs capturing sensors to be used in conjunction with the DSS provide the physical support for this infrastructure.

The m-Health environment is provided by the relatively seamless interaction of these layers permitting the exchange of information and transactions. The rapid development of new technologies is also reflected in the adoption of many tools from all telecommunication fields, often significantly less expensive than the prior generations.

New technologies are easily integrated into existing scenarios when they address issues not yet resolved under the current implementations. Contemporary m-Health reality consists of an amalgam of sensors targeting to measure or assess an individual's vital signs or even to track his/her location in case

of an emergency as is often the case with elderly suffering from senile dementia. These sensors come into the form of portable (or wearable) devices for enhanced user acceptability.

The individuals who require continuous monitoring are not a rarity. Unfortunately they represent quite a significant percentage of the population and, as our planet ages (Europe is considered a rapidly ageing continent), the numbers are going to exponentially increase [3]. A typical case of monitoring will require a belt that could be worn round the chest with incorporated sensors measuring heart and respiration rates and ambulatory electrocardiogram (ECG) recorder (event triggered). The signals have to find their way into the treating physician's computer in order to be assistive to further diagnosis and treatment. Today's implementations feature the combination of short range communications (hence constituting a Personal Area Network, PAN) and long range communications for fulfilling their primary target, i.e., patient (remote) monitoring.

The limitations and challenges for the research community are: (i) Power autonomy: the more the supported functions and the longest the time of monitoring, the greater the energy demands will be. Increased size of batteries is not an option as it will lead to weightier products drastically reducing both usability and user satisfaction. (ii) Ubiquitous tracking for patients with senile dementia: indoor operation can be proven somehow problematic with the classical outdoor positioning technologies (e.g., GPS), while the user requirement should be strictly followed. (iii) Security: sensitive data are connected to individual's health condition. A major inhibitor of these applications is the difficulty in convincing patients.

In agreement with the above issues, the on-going WSN4QoL project [4] involves the design of pervasive Wireless Sensor Networks (WSNs) specifically suited to meet healthcare application requirements. This paper aims to present an efficient protocol stack architecture to support the new WSN4QoL's solutions. 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 WSN4QoL's objectives. Section III overviews our reference system architecture, while Section IV describes the networking technologies designed to support the solutions proposed and Section V presents energy efficiency results measured from a WSN deployment in realistic conditions. Finally, Section VI concludes the paper.

II. WSN4QoL DESIGN CHALLENGES

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 dynamic, since the links 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 [6]. (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 and performance-guaranteed 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, robust 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 wireless body area network (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 (GW), 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 and fully distributed people localization.

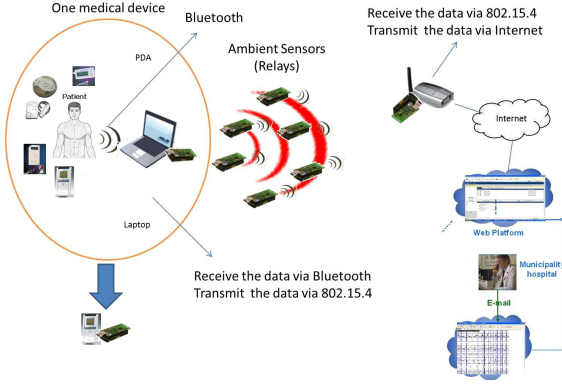


Figure 1. Reference Healthcare 3-tiers System Architecture.

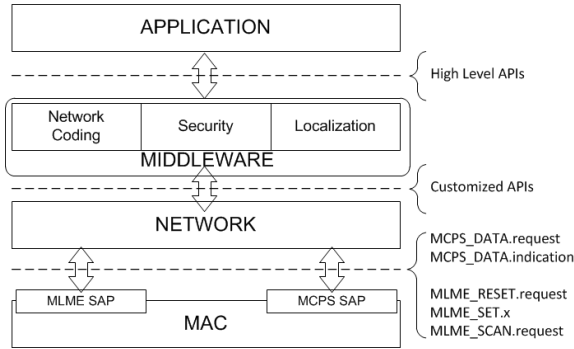


Figure 2. Communication Protocol Stack on top of the IEEE 802.15.4 standard. Basic interfaces and roles of each layer are also shown.

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 Application Programming Interfaces (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], [11]) aim to exploit intrinsic properties of the biometric data in order to provide energy efficient tele-monitoring solutions. These techniques can be implemented exploiting the APIs offered by the middleware.

IV. PROTOCOL STACK

A. MAC Layer

In the frame of WSN, the standard de-facto for communication is IEEE 802.15.4 and among the options offered by this standard [12, Chapter 2], in WSN4QoL we have chosen to refer to the Non Beacon Enabled Mode (NBEM), i.e., the fully asynchronous mode. This choice is motivated by the fact that mobile nodes usually have a variable duty cycle and, 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-power mode, 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. Once assumed IEEE 802.15.4 at the MAC layer, the most widely referred network layer on top of that is ZigBee. In this sense, we refer to the basic features of that standard in order to customize it to our healthcare scenario and special requirements.

Networking problems in medium-and-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 pre-planned 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. Each synch packet is the starting point of a superframe composed of an active and an inactive period¹. 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 already to evident energy savings. It is worth stressing that synch packets are not IEEE 802.15.4 beacons. Unlike beacon frames, it is not mandatory for these packets 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 (and this would not be allowed by the 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 a 16 bit long address, assigned according to some policy, and used 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 [14] and briefly recalled in next section.

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 [14].

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. ENERGY EFFICIENCY

A. Network Coding

To achieve efficient measurements reporting through the ambient relay network the most viable solution is the application of NC techniques. Figure 3 illustrates a scenario in which two nodes A and B are mobile sources, a relay node C is fixed and the residential gateway D is the destination of the measurements reports.

In this scenario, the packet generation and transmission are scheduled based on a time division mechanism mastered by the node C so that collisions are avoided *a-priori*. Nodes A and B broadcast their packets ($PktA$ and $PktB$, respectively) on their timeslots. Node C receives these packets and combine them into $PktC$ computed as $PktC = PktA \oplus PktB$, where \oplus represents the operation of bitwise XOR. Node D can receive directly $PktA$ and $PktB$ or might lose one packet. In the latter case, suppose that $PktA$ is received correctly, by receiving also $PktC$ it can recover the missing information by simply computing $PktB = PktA \oplus PktC$, while in the baseline scenario, the relay C should forward $PktA$ and $PktB$ in two distinct timeslots.

B. Experimental Setup and Results

For the sake of easiness, since the network scheduling enables a partition of the network into multiple single relay

¹The mobile nodes can communicate with a relay only during its active period, so only after having received its synch packet.

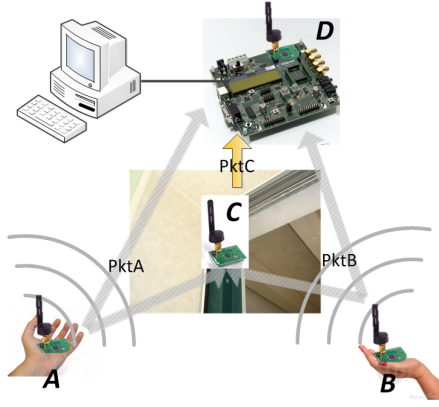


Figure 3. Scenario for efficient communications. Nodes A and B are mobile sources, node C is a fixed relay, node D is the destination (residential GW).

scenarios where the mobile nodes communicate with the relay only in its active portion, two networks, composed by 4 TelosB [15] nodes each, have been deployed as shown in Figure 3 in a real indoor environment, i.e., a residential apartment where, e.g., two persons can live under continuous monitoring. A network was programmed with the NC implementation, while the other with the baseline scenario and the two were running in parallel on two distinct frequency channels, to enable the fairest comparison of the performance. The apartment is composed by 6 rooms, distributed over a total of 60 square meters. The mobile nodes have been configured to send data using 4 different transmission power levels, i.e., 0.6, -0.4, -7.9 and -25.2 dBm. To demonstrate the performance gains of the NC over the baseline relay-only mechanism, 3 different values of the timeslot have been tested, i.e., 200, 400 and 800 ms, resulting in active periods for the relay node of 800 ms, 1.6 and 3.2 seconds, when using Network Coding (four timeslots), and 1, 2 and 4 seconds (five timeslots), when using only relaying, respectively. In each run of the experiments, two persons were carrying out the mobile nodes so that each person represented the source node (A or B) of each network.

Figure 4 presents the energy efficiency computed from the logs of the two scenarios, i.e., with Network Coding and in the baseline relay-only case. The energy efficiency is expressed as bit per Joule and gives an indication of the energy needed to transmit the information from the sources to the destination. As it is evident, NC always outperforms the classical relay-only baseline scenario. This result is as expected since NC enables higher throughput than the baseline scenario, while keeping similar levels of packet loss.

VI. 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 in an energy efficient fashion.

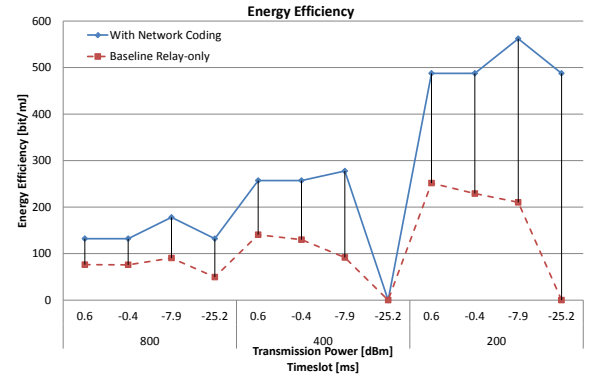


Figure 4. Energy Efficiency of the simple XOR-based NC mechanism.

Future on-going work includes the implementation of the proposed integrated protocol stack in real medical devices and on large scale testbeds, as well as the evaluation of more sophisticated NC schemes, e.g., [16].

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