ZigBee-based Remote Patient Monitoring

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Abstract. This paper describes a developed continuous patient monitoring system based on the ZigBee protocol. The system was tested in the hospital environment using six sensor devices in two different modes. For electrocardiogram transmission and in the absence of hidden-nodes, the system achieved a mean delivery ratio of 100% and 98.56%, respectively for star and 2-hop tree network topologies. When sensor devices were arranged in a way that three of them were unable to hear the transmissions made by the other three, the mean delivery ratio dropped to 83.96%. However, when sensor devices were reprogrammed to transmit only heart rate values, the mean delivery ratio increased to 99.90%, despite the presence of hidden-nodes.

Keywords. Remote patient monitoring, eHealth, ZigBee, HM4All.

Introduction

Healthcare systems across the European Union face a common challenge: rising health care costs [1]. According to the World Health Organization, health care costs are presently primarily driven by technological change, which accounts for 50-75% of growth in costs. Other perceived causes, such as increasing older population ratio and people's growing expectations, accounts for, approximately, 10% of cost growth [2, 3].

Emerging standard communication technologies specifically designed for low-cost, low-power consumption, such as IEEE 802.15.4 [4] and ZigBee [5], have the potential to provide high quality of patient care without considerably increasing costs. However, whereas devices based on these protocols are well-suited for personal health care applications, their use in a healthcare facility to monitor several patients poses several difficulties, mainly because these protocols were primarily designed to operate in extremely low duty-cycle scenarios.

This paper describes HM4All, which stands for Health Monitoring for All, a ZigBee-based patient monitoring system developed to overcome some of the shortcomings from present ambulatory patient monitoring systems, such as obtrusiveness and high cost. Additionally, it provides results from its evaluation in a real hospital environment and presents actions being taken towards its improvement.

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1. HM4All description

HM4All comprises wireless medical sensor devices, ZigBee networking devices, a ZigBee-to-IP gateway and Web-based applications, as in Figure 1 [6-9]. Data generated by a wearable sensor device are transported by ZigBee routers and coordinator to a ZigBee-to-IP gateway. Then, data are stored in the data server and made available to monitoring centers or wireless portable devices carried by health care providers.

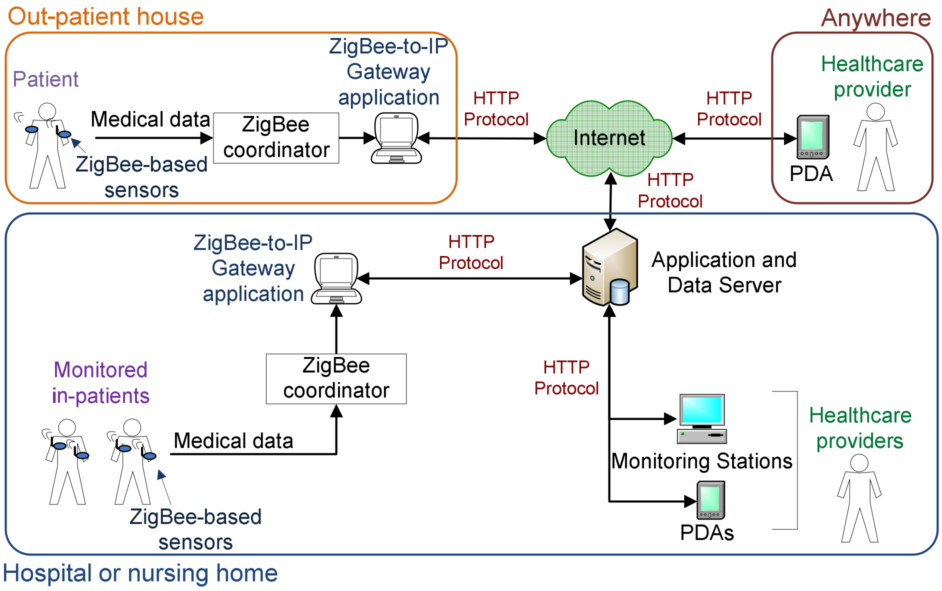

Figure 1. HM4All conceptual diagram.

Two wireless sensor devices were developed: a single channel (3-lead) electrocardiogram (ECG) sensor device and an axillary temperature sensor device. Both sensor devices are based on the JN5139-M00 wireless module [10]. The amount of data generated by each sensor device is shown in Table 1.

Table 1. Amount of data generated by sensor devices.

Sensor	Sampling rate or period	Sampling size	Data generated
ECG (single channel, modified Lead I)	200 Hertz	12 bits per sample	2400 bps (raw data) or 1200 bps (2:1 compressed data)
Heart rate	3 seconds (*)	1 byte	1 byte every 3 seconds (*)
Axillary temperature	1 minute (*)	1 byte	1 byte every minute (*)
Battery level	3 minutes (*)	1 byte	1 byte every 3 minutes (*)

(*) Configurable

ZigBee coordinators/routers are based on the JN5139-M02 high-power module [10] and use the same electronic printed circuit board. The devices contain a Universal Asynchronous Receiver / Transmitter (UART) serial communication interface port used for firmware update and connection to the ZigBee-to-IP gateway. All ZigBee-based devices are based on v1.0 and use private application profiles; see Figure 2.

The ZigBee-to-IP gateway is a graphical user interface (GUI) based application developed in C# language. It validates and processes data frames received from a ZigBee coordinator and sends processed data to the Application Server application through a Hypertext Transfer Protocol (HTTP) connection. Additionally, it contains a user interface where sensor data are exhibited and recorded. The Application Server software comprises a Web server application based on Java servlets and uses the Apache Web server and the MySQL database. This application collects physiologic data from ZigBee-to-IP applications and sends data to remote clients.

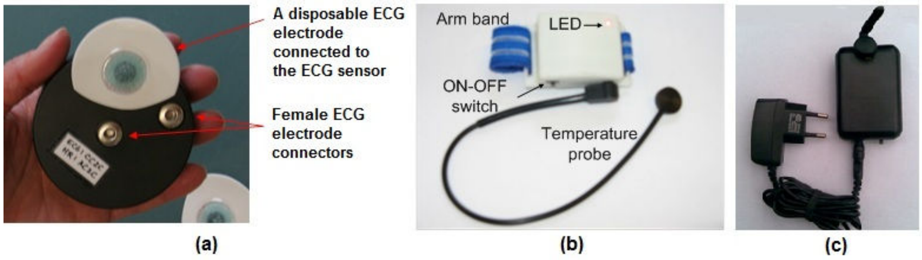

Figure 2. Developed devices: (a) ECG sensor, (b) axillary temperature sensor and (c) router/coordinator.

Applications that run on clients provide a user interface that allows care givers to: a) visualize in real-time patients' vital signs and ECG waveform (Figure 3); b) access historical patient data records; c) configure individual alarms; and d) execute management functions.

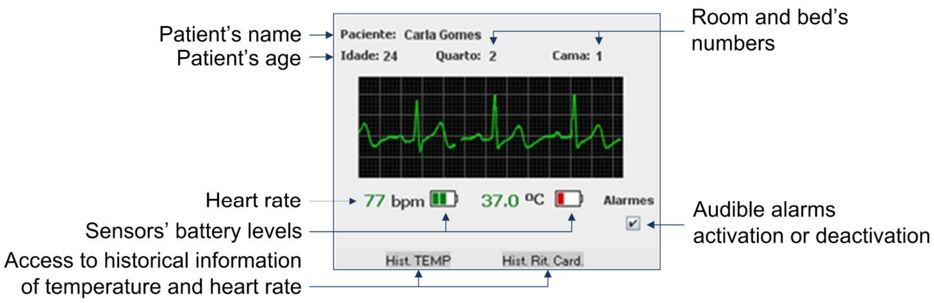

Figure 3. Monitoring window (data presented was previously recorded for testing purposes).

2. Communication reliability evaluation

The communication reliability of HM4All was evaluated in the hospital environment employing nonbeacon-enabled star and 2-hop tree networks comprising six ECG/HR sensor devices that operated in two different modes: ECG mode where ECG waveform samples are transmitted, and HR mode where only HR values are transmitted.

As shown in Table 2, in the absence of hidden-nodes, a nonbeacon-enabled star network comprising six sensor devices operating on ECG mode achieved a delivery ratio (DR) of, approximately, 100%. However, the DR decreased for the nonbeacon-enabled 2-hop tree network. It was due to the traffic duplication on the router and to the inability of routers to interrupt the backoff part of the CSMA-CA mechanism to receive incoming packets, an implementation option adopted by Jennic (the stack implementer).

Table 2. HM4All communication reliability test results for nonbeacon-enabled networks on channel 26.

Network configuration	Test duration (hour)	Delivery ratio (%)
ECG traffic, star network, no hidden-nodes	5.1	100
ECG traffic, 2-hop tree network, no hidden-nodes	16.7	98.56
ECG traffic, star network, 50% of hidden-nodes	2.8	83.96
HR traffic, star network, 50% of hidden-nodes	10.2	99.90

In presence of 50% of hidden-nodes (sensor devices were positioned in such a way so as to prevent three of them to sense the transmissions made by the other three), the DR dropped significantly. As shown in Table 2, devices operating in ECG mode under the presence of hidden-nodes contended often, resulting in a mean DR of 83.96%. When these sensors were reprogrammed to send only HR traffic, which involves sending smaller and less frequent messages, the communication performance improved significantly, with the network achieving a mean DR of 99.90%.

3. Future work

To improve the communication reliability of HM4All, all devices are being redesigned to operate based on the CC2530 communication module [11]. As verified through laboratory tests, the CSMA-CA mechanism implemented by Texas Instruments allows receiving incoming packets during the backoff, which will prevent a significant percentage of messages from being lost during contention periods. Moreover, the use of the ZigBee PRO feature set will allow implementing the ZigBee Health Care Profile required for local interoperability.

It is important to note that the early system was developed between 2008 and 2010 with a currently outdated version of the ZigBee protocol, and is now being updated to feature the most recent version. Whereas a more frequent update of the employed protocol would have occurred naturally in a commercial product, the academic nature of the developed system (essentially, available resources) hampered this aspect.

An internal synchronization mechanism, defined at application level, is being developed to avoid hidden-node collisions. The use of periodic beacons is avoided because they are not allowed in mesh networks based on the ZigBee PRO feature set. The network devices will synchronize to the network coordinator, which will serve as the reference node. The centralized multihop lightweight time synchronization protocol (LTS) [12] is being considered. The main challenges refer to the presence of mobile wearable sensors, which result in intermittent connections, and the increase of network traffic. Considering that a single pair-wise synchronization involves the exchange of three packets, $3n$ packets will be required to synchronize a network of n nodes [13]. The additional traffic implies additional energy consumption and may increase contention between devices.

Finally, the system is being expanded to feature other sensors to complement current monitoring capabilities. Information from additional sensors could be combined to better assist physicians. This would increase the number of practical applications of this system to different healthcare scenarios.

4. Concluding remarks

This paper presents HM4All, a patient monitoring system based on the ZigBee protocol, tailored for the simultaneous monitoring of multiple patients in a clinical setting. This system has been implemented and tested in a real hospital scenario, from which it was possible to obtain relevant information regarding its communication performance in the hospital environment.

Several critical aspects of the employed architecture and support communication platform have been identified and the major difficulties exposed. Based on this information, the paper also discusses some of the future work that is required to improve the system, providing clear guidelines for ongoing research in this field. Despite the challenges, major progress has been achieved in recent years, and the future of wireless sensor networks for real-time monitoring of patients both in the clinical and domestic settings offers great potential.

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