

Developing residential wireless sensor networks for ECG healthcare monitoring

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Accepted Version

Dey, N., Ashour, A. S., Shi, F., Fong, S. J. and Sherratt, R. S.
ORCID: <https://orcid.org/0000-0001-7899-4445> (2017)
Developing residential wireless sensor networks for ECG
healthcare monitoring. IEEE Transactions on Consumer
Electronics, 63 (4). pp. 442-449. ISSN 0098-3063 doi:
10.1109/TCE.2017.015063 Available at
<https://centaur.reading.ac.uk/73898/>

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Published version at: <http://ieeexplore.ieee.org/document/8246822>

To link to this article DOI: <http://dx.doi.org/10.1109/TCE.2017.015063>

Publisher: IEEE

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Title: Developing Residential Wireless Sensor Networks for ECG Healthcare Monitoring

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Publication: IEEE Transactions on Consumer Electronics
Publisher: IEEE
Volume: 63
Issue: 4
Date: Accepted 16 November 2017
pp.: not yet assigned
DOI: not yet assigned

Abstract

Wireless technology development has increased rapidly due to its convenience and cost effectiveness compared to wired applications, particularly considering the advantages offered by Wireless Sensor Network (WSN) based applications. Such applications exist in several domains including healthcare, medical, industrial and home automation. In the present study, a home-based wireless ECG monitoring system using Zigbee technology is considered. Such systems can be useful for monitoring people in their own home as well as for periodic monitoring by physicians for appropriate healthcare, allowing people to live in their home for longer. Health monitoring systems can continuously monitor many physiological signals and offer further analysis and interpretation. The characteristics and drawbacks of these systems may affect the wearer's mobility during monitoring the vital signs. Real-time monitoring systems record, measure, and monitor the heart electrical activity while maintaining the consumer's comfort. Zigbee devices can offer low-power, small size, and a low-cost suitable solution for monitoring the ECG signal in the home, but such systems are often designed in isolation, with no consideration of existing home control networks and smart home solutions. The present study offers a state of the art review and then introduces the main concepts and contents of the wireless ECG monitoring systems. In addition, models of the ECG signal and the power consumption formulas are highlighted. Challenges and future perspectives are also reported. The paper concludes that such mass-market health monitoring systems will only be prevalent when implemented together with home environmental monitoring and control systems.

Index Terms

Zigbee, electrocardiography, electrocardiogram, monitoring, wireless communication, transceivers, ECG monitoring system

I. INTRODUCTION

Electrocardiogram (ECG) is a vital diagnosis device to detect heart disease abnormalities. Cardiovascular disease affects the cardiovascular system, specifically the blood vessels and the heart. Strokes and heart attacks are the most common cardiovascular diseases in the general public that require continuous monitoring. ECG is the most broadly used cardiovascular disease monitoring technique that measures the electrical activities of the heart. An ECG system is a non-invasive monitor for evaluating the heart electrical activity, for measuring the regularity/rate of heartbeats, and for identifying any damage to the heart. The ECG includes the placement of electrodes on the human body surface at convenient places. Such electrodes are linked to the ECG monitoring device via cables to detect and amplify the electrical impulses of the heart, where heart conditions change the ECG characteristic.

A clinical ECG device may be used for short-term monitoring, but it is often large and the attached electrodes reduce the flexibility/mobility of the wearer. For long-term monitoring, a portable Holter monitor device can be used to detect the heart arrhythmias. Recently, wireless ECG monitoring systems are implemented [1, 2]. Bluetooth and Zigbee are the main wireless transmission protocols used in the ECG wireless monitoring systems.

The development of remote ECG Monitoring Systems (MSs) through telecommunication networks have become an important research topic. Such systems facilitate remote monitoring of people wearing portable devices equipped with Wireless Sensor Networks (WSNs) for ECG monitoring [3] as part of the Smart Home concept [4]. The ECG signals are transmitted to a local hub and then sent to an ECG server that can be used in hospitals for further analysis offering long-distance heart health monitoring. New developments in mobile devices, biosensors, and wireless equipment further the online MSs. In addition, MSs can provide automatic alerts to a physician based on the intelligent ECG processing, which in turn can assist the wearer depending on the detected anomalies.

Typically, the performance of Zigbee and Bluetooth are relatively similar, however, the use of Zigbee is more common environmental control systems and home monitoring systems. Zigbee is also currently in numerous applications including elderly people monitoring, who suffer from heart diseases and/or diabetes and other real-time

monitoring systems. While there are many personal medical devices that use Bluetooth, this paper focuses on and emphasizes the reliability and mass-market deployment advantages of merging medical WSNs, primarily ECG monitoring, into home control networks, and thus focusses on Zigbee based home health monitoring.

Chapter II discusses home health monitoring, Chapter III presents the topic of wireless ECG monitoring and Chapter IV presents the challenges and future directions for home healthcare monitoring. The paper concludes in Chapter V.

II. HOME HEALTH MONITORING SYSTEMS USING ZIGBEE

Wireless communication enabled healthcare systems offer light weight intelligent sensing at low cost, ideal for consumer mass market penetration. Recently, advancements in medical sensors, networking, and physiological data processing have enabled new devices and services. Ubiquitous health monitoring is emerging to support personal healthcare, physicians' diagnosis and to provide a first aid response in cardiac arrest cases.

A. Monitoring System Architecture

For monitoring a cardiac arrest, a portable device can be attached to the person that consists of a wireless enabled processor to transmit the sensed ECG signal from the body. Typically, the ECG signal, heartbeat, and pulse rate of the wearer are all sensed. Thus, for any detected abnormalities, action can be taken by issuing an alert message to the physician or the nearby hospital. To enable communication out of the house, to the hospital, cellular communication or an Internet connection can be used to assist the wearer in the cardiac arrest case [5].

B. Mathematical Model of ECG Signals and Zigbee-based ECG Monitoring

Typically, the sensors' characteristics can be modeled using [6]:

$$G(x_i, \eta_i) = s(x_i, \eta_i), \quad (1)$$

where G is the sensor's output, x_i is the sensing position, and η_i represents the characteristic parameter. In addition, one of the applied methods is to model the physiological signals, including the ECG signal, using the Fourier transform, which can be used represented as:

$$ECG(t, f) = \frac{1}{2\pi} \left| \int e^{-j2\pi f\tau} b(\tau) f(\tau - t) d\tau \right|^2, \quad (2)$$

where $ECG(t, f)$ is the output sensed signal, and $f(\tau - t)$ is the sliding window function along $b(\tau)$. Afterwards, the Personal Radiation Detector (PRD) can be used to detect the abnormality difference of the person compared to 'normal' conditions or can be learnt over time. The difference between the current signal and reference signal is found, where a large PRD value potentially indicates a serious condition that the wearer may be suffering from. The processed ECG output signal is then feed to the house hub via Zigbee for further processing. Typically, the foremost objective of the Zigbee network is then to be able the house hub to have high coverage throughout the house, directly or via mesh networking. Thus, the Zigbee operation and battery characteristics models become an active research area.

C. Zigbee Design

Zigbee is a typical open technology that can handle low-power/low-cost demands of the wireless networks through short-range radio. It is used mainly in Radio Frequency (RF) applications that entail long battery life, secure networking, and only requires a relatively low data rate. Zigbee mesh networking topology may provide more extensive range as well as high reliability, through the use of multiple home hubs, when available.

The Zigbee Alliance developed the Zigbee specifications for several applications in sensor networks and control for low cost connectivity and low power for devices that operate on batteries. The main Zigbee characteristics are based on the IEEE 802.15.4 standards [7]. Similar to any equipped device using batteries, Zigbee requires the sleep and shut down ability. In Zigbee nodes, the battery usage has several advantages, including increases the Zigbee device flexibility, low-cost, and batteries make Zigbee appropriate for scalable network with low duty cycle. The Zigbee devices' battery power consumption occurs through the reception/transmission time. Meanwhile, the IEEE 802.15.4 standard uses an enormously low duty cycle. Thus, in Zigbee networks, the wireless device is in sleep mode most of the time offering a long battery life, typically for many years, dependent on the device operation [8].

Generally, the power consumption is a function of the battery, duty cycle, processing, reception windows, electronic components and systems of the network, battery energy of the Zigbee network. For one node in the Zigbee network, the main energy consumption components are included in the battery total power consumption [9] as:

$$P_C = P_t + P_r + P_s + P_{id} , \quad (3)$$

where, P_C is the total power consumption, power consumption owing to the transmitted signal and the received signal are P_t and P_r respectively. During the sleeping mode, the power consumption is represented by P_s while P_{id} represents the power consumption due to the idle/sleep state at which zero packets are received/transmitted. The battery lifetime can be calculated in hours based on the following expression:

$$BT = \frac{L_c}{L^n} , \quad (4)$$

where, BT represents the battery life time in hours, the battery capacity is L_c in mAH, and the load current is L in mA, where, n is the Peukert's exponent ranging from 1 to 1.3. These mathematical models have been used to calculate the battery life time of the Zigbee device [10].

D. Evaluation of Zigbee Medical Sensor Networks

In clinical diagnosis, measuring and monitoring several physiological parameters is an essential process. Such parameters are measured using attached biomedical sensors to the person. The significant parameters to the physician include the pulse rate, blood pressure, ECG and temperature. However, these measurements are performed using analogue equipment resulting in a low degree of flexibility as the wearer is tied to the monitoring device. In addition, information sharing and backup become impossible due to the analogue equipment, where the sensors are connected to monitor devices through wires.

A potential problem arises due to wires tending to restrict mobility. Thus, for the sensor data, a wireless network system leads to greater elasticity for the user. Using computers remotely allows for personal healthcare monitoring since the wearer is coupled to a biomedical sensor network. In addition, smart signal processing techniques are used to process the sensed signal locally before communication to the hub, rather than transmitting large amounts of raw data to a hub. Interesting engineering tradeoffs exist between the required power for local processing of sensed data, vs. the wireless power required to transmit larger amounts data for remote processing.

A typical sensor network consists of one/more Body Area Networks (BANs) and one/more interconnected hubs [11]. The received information at a hub may then be passed on via a home backbone network. Finally, the information is displayed at the connected terminals to the network [12]. This monitoring system has the prospective of instant diagnosis, ECG monitoring, and in-home monitoring. The wireless sensor nodes all run on batteries which forms the need to require power efficient wireless network systems.

The IEEE 802.15.4/Zigbee standard is considered a promising wireless standard that provides low power consumption and great flexibility for wireless networks. It offers low cost, small hardware, and can have many devices in one network.

E. Operation of Sensor Nodes through Zigbee

Unicast, broadcast, anycast, and multicast are the four data transmission methods to categorize the communication nodes. Broadcast and multi-cast are one-to-many transmission as they can convey information to numerous receivers. Nevertheless, unicast transports packets only to a single hub, thus, have less traffic overhead. On the other hand, anycast is an innovative network routing methodology wherein the information from a sender is directed to the nearest topology hub.

Sensor node operation is as follows [13]. Once a sensor unit obtains the vital signs, such as the ECG signal and heart rate, it notifies the Zigbee unit to examine the existence of a route to a hub. In the case of available route, the Zigbee unit will transmit the information packets to the hub. Else, the Zigbee unit encapsulates a message into a frame which is broadcasted to the adjacent router nodes. Regarding the data receiver, once the Zigbee unit collects the information packet, it records route in the updated routing table. In the case of collecting more than one information packet by the Zigbee unit, the extra data received may be deleted, or collected for diversity reception.

Periodically, the sensor unit can sample the vital signs/ECG signals and buffer the data. Once the buffer becomes full, the Zigbee unit creates a DATA message from the condensed data for transmission. Afterwards, periodically the Zigbee unit checks the Acknowledgement (ACK) message derived from successful reception. Once the Zigbee unit obtains an ACK message, it may delete the acknowledged data, while if within a timeout, the ACK message is not received, the Zigbee unit checks its DataReceiver list.

III. WIRELESS ECG MONITORING SYSTEM

Vital signal monitoring is considered the most effective procedure for remote/continuous personal health tracking. Trends in proactive healthcare are leading to the implementation of wearable sensor devices in modern tele-medicine, which in turn is enabled due to the vast progress in mobile computing, low-power microprocessors embedded with wireless technology and sensor technologies that offer accurate ubiquitous health monitoring [14]. ECG monitors are employed in several hospitals for diagnosing and monitoring the status of person's health by measuring cardiac activity. The wireless ECG MSs acquire, amplify, processes and transmit the wearer's ECG signal over wireless connection. Sensor-based incorporated systems are able to sense, process, and communicate the medical information to the involved parties, including the physicians and the emergency services' agents [5, 15].

A. EEG Sensors

Recently, wearable health monitoring devices play a vital role in tele-healthcare. Such devices ranging from pulse monitors, portable ECG monitors, fall detection, activity monitors [16], through to implantable sensors. Typically, the ECG is equipped with electrodes (ECG sensors) attached to lower/upper chest to quantify the cardiac activity based on short samples of the electrical activity of the heart between the different electrode pairs. Several bio-monitor systems are used to provide continuous monitoring of several physiological parameters. These systems are engaged to detect, to process and to record the signals.

An ECG signal is acquired by gauging five electrical potential between several points of the human body through an amplifier connected to the body through attached leads to electrodes [17]. Electrodes detect the electrical currents that extend through the body due cardiac cells repolarisation and depolarisation. The typical cardiac monitoring system involves 3-leads that are connected to 3-electrodes to the wearer for forming an Einthoven's triangle. Electrodes are located on different sides of the heart to measure the activity of the heart muscles as well as the voltage between the electrode pairs, which is often presented in graph form.

B. ECG Communication Procedure

Advanced monitoring systems primarily use wireless technology to connect to the sensor devices. This may form several nodes into a Wireless BAN (WBAN). Zigbee, Bluetooth, and WiFi are typically used wireless communication standards. Typically, the WLAN is used for communication in the home to the primary hub, typically Internet enabled.

Zigbee, is different than Bluetooth as it can easily be used in implementing complex home networks up to 65,536 devices. It is used in several biomedical devices implementation [18, 19].

C. Personal Healthcare Monitoring Systems

Personal healthcare monitoring systems typically involve several devices for monitoring the person's status, including ECG, vital signs and blood pressure [20]. These systems may use wireless monitoring technologies to support the healthcare. Several studies have been conducted to implement wireless monitoring systems for improving the healthcare of people [21-23]. Typically, Bluetooth, WiFi, RFID (Radio Frequency Identification) and Zigbee have been used for wireless communication. TABLE I includes a comparison between these various technologies in terms of several metrics.

TABLE I
COMPARISON BETWEEN WIRELESS TECHNOLOGY STANDARDS CHARACTERISTICS

Symbol	Bluetooth	Zigbee
Battery life	Days-years	Days-years
Number of connected devices	Not defined Typically <14	Up to 66,029
Coverage (range)	Up to 100m	Up to 75m
Data rate	1Mb/s (2Mb/s for BLE5)	249 kb/s
Topology	Star/Mesh	Star/Cluster/Mesh

In terms of data reliability including power consumption, scalability, and interference; Bluetooth has superior performance against interference compared to Zigbee and Wi-Fi. However, Bluetooth is inefficient in public congested places, including hospitals, clinics, train stations, schools, which affect the service quality of the BAN. Moreover, Zigbee has superior scalability compared to the Bluetooth as it can connect up to 65,536 sensors at a time in the BAN.

As follows, different studies that have been conducted for ECG monitoring systems based on these wireless technologies. Bluetooth-based monitoring technology has been used in several applications. Ekström [24] designed a wireless sensor structure for patient monitoring with high flexibility, free mobility, and the ECG sensor's consistency. This system includes a Personal Digital Assistant (PDA) to transmit ECG sensor's signal. Besar *et al.* [25] developed an ECG based MS. This monitoring system used Data Acquisition unit (DAQ), processing unit, ECG sensor, and a transceiver. Through Bluetooth, the ECG signal was transferred to the server for supplementary analysis.

Moreover, the WiFi-based monitoring technology has been employed in several applications. A wireless monitoring system has been developed by Yu and Cheng [26] based on Bluetooth and WiFi. It was designated to obtain the wearer's physiological signals for further transmitting them through Bluetooth to a server. A control center, mobile devices, monitor unit, and a web page communicated through WiFi. In order to increase mobility, Bluetooth may be combined with WiFi networks. Noimanee *et al.* [27] designed a monitoring system that included a video camera, an ECG transceiver to send the biosignals through Zigbee/IEEE RF unit, and a WiMAX transceiver to send the ECG signals. In the case of detecting an ECG abnormality, the ECG sensor will direct the signals to the video camera that is near to the patient to be monitored by physicians. Of course, physicians may not be available at the time.

RFID-based monitoring technology also has a significant role in home healthcare. Ishihata *et al.* [28] proposed an implantable RFID chip to store the person's information and to track the location. Trappey *et al.* [29] proposed a RFID-based mobile intelligent medical system that consisted of location broadcasting RFID application and an identification system to reduce the data entry redundancy/error, and to provide intelligent decision making. Teaw *et al.* [30] developed a wireless sensor structure for monitoring of vital signs, such as heart rate, respiration rate, blood pressure, and body temperature. In addition, the system tracked the patient's location through RFID tags to alert their relatives when required. A bar code printed on the wrist bands can be used to monitor the patients in hospitals. In addition, Want [31] proposed to replace the bar codes by RFID tags to give the ability to store more information. For real-time monitoring, Ogawa *et al.* [32] designed a body matched tags. Such tags have been used also for patients' localization. Cho *et al.* [33] extended the network area coverage for active RFID devices through a mesh type multihop network, while using Zigbee between the hubs and the RFID readers.

Frehill *et al.* [34] proposed a new architecture to measure the patient's signs through a friendly user Interface. Wireless ECG and Pulse-Oximeter sensors were included to share the information. The results established the efficiency of Zigbee to meet achieve the required mobility, power, and data throughput. Park *et al.* [35] implemented a Zigbee Network-based Multi-channel Heart Rate MS for exercise rehabilitation patients. This monitoring system involves a central MS and a wearable Patient's Side Device (PSD). The central MS can simultaneously monitor several patients. A warning signal is generated if necessary and linked with the MS through the Zigbee network. Becher *et al.* [36] designed a Zigbee based system along with Bluetooth to incorporate the patient's ECG, body weight, and pulse. Three cardiovascular wireless sensors are involved to monitor the ECG signal, body weight and pulse. The patient's information is gathered from these sensors through a microcontroller for further data processing which is forwarded to a Zigbee gateway. The Zigbee gateway was used to forward the packets through a Bluetooth transceiver for data analysis.

While many people suffering from medical conditions are housebound, there are medical benefits from being able to go outside. Wang *et al.* [37] presented a Zigbee based home healthcare monitoring wearable system using ECG, fall detection and GPS to monitor people outside.

Home healthcare systems can infer the activity of the person through their location in the home. Yan *et al.* [38] developed an e-health monitoring system based on multisensory data fusion to predict activities and further the decision making process concerning the person's health.

IV. HOME CONTROL AND SMART-HOME SERVICES

Zigbee has been used as the wireless communication protocol for home automation systems, including smart energy control [39-41], home control [42] and environmental monitoring [43]. More recently, the smart home concept [4] has furthered the services to consumers offering accessible displays [44], remote device control [45, 46], and device collaboration [47, 48], through always-on Internet home gateways [49]. Interestingly, the smart-home does enable the control of humanoid-type robots for home automation and perhaps the care of the elderly using robots [50].

V. CHALLENGES AND FUTURE DIRECTIONS

Many personal healthcare devices use different wireless technologies, do not have compatible interfaces and often require cable connection. Consequently, it is essential to remove wired connections and develop short-range wireless connections for feasible connectivity between devices. Zigbee over IEEE 802.15.4 and Bluetooth over IEEE 802.15.1 are the two main low power consumption wireless communications that have short range communication protocols to replace cables. Bluetooth is an inexpensive device for short range communication that based on a wireless radio system. While mesh networking is possible, it has primarily been used for point to point communication and to produce small ad-hoc networks. Bluetooth is robust, requires low complexity, low power and low cost [51, 52].

A Zigbee device can offer consistent mesh networking, multi-hop, and self-organization which complements the application software layers quantified by the IEEE 802.15 and Zigbee alliance. Zigbee can provide low power connectivity and low cost for equipment that requires long battery life. However, it does not necessitate high data transfer rates as those empowered by Bluetooth. Zigbee amenable wireless devices can be used to transmit 10-75 meters based on the applications power output consumption requirements and the RF environment [53].

However, up till now, the Zigbee current standards have not considered the reliability of transmitted messages in a multi-hop topology. Thus, Zigbee could be unsuitable for vital signs transmission, particularly, for emergency information messages, including the ECG signal. Especially, these messages are precarious for detecting the patients' disease and for offering significant clues to the insistence level. Consequently, this can be considered as an active research area.

In addition, the energy requests are founded on the application activities that can be proposed as a model to extend battery life time [54]. Additionally, other research studies are directed to improve and optimize the energy of different Zigbee routing procedures.

Developing new protocol for fast rerouting is a challenging research area. An incomplete path could be improved in a short latency to ensure the transmitted vital signs reliability. Consequently, a Zigbee-based unit can be implemented for ECG signal monitoring system using the new routing protocol.

Applying Zigbee devices in healthcare monitoring systems attracts much research. The readings and the ECG signal obtained using the Zigbee wireless network should be compared in contradiction to collected data gathered from static devices, including a thermostat, or a stethoscope for measuring the heartbeat. Nevertheless, the main limitation was the Zigbee transmission/ reception range.

Employing soft computing techniques to develop an integrated Zigbee healthcare platform in ECG monitoring can be considered as a novel active domain. This monitoring system permits patients to move while the monitoring process

and vital signs readings are also recorded. This platform can be supplemented by using a fuzzy logic based diagnosis system. Further research can be directed to ubiquities vital signs processing and monitoring toward portable and intelligent vital signs processing [55].

Research and development has created intelligent smart homes offering a reliable connection to the Internet and cloud services, which also creating home based health monitoring systems, but this paper has presented that the two systems are sadly invariably developed separately. For health monitoring and intervention to be truly ubiquitous and cost-effective, this paper calls for health monitoring to be considered as an integral part of the overall smart home architecture, rather than a separate or as added feature. Such integration will maximize the performance, the reliability and security of the home healthcare monitoring system through the existing home hubs.

VI. CONCLUSION

ECG is useful method for monitoring the heart electrical activity using an electrode array placed at specific positions on the body. ECG monitoring systems support a physician for understanding the patient's condition. Recently, low power, low cost, and flexible Zigbee wireless units have been deployed to sense and to transmit the remote patient ECG signal and vital signs.

This paper has considered the current state of the art in home ECG monitoring, and has noticed that such systems tended to be designed in isolation, as part of their own network, rather than part of more reliable home control systems. This paper proposes that for true mass-market consumer penetration, such home healthcare monitoring systems need to be part of a wider home control system strategy. Such a deployment strategy offers significant benefits in cost reduction through redundancy, improved device integration, reliability and latency of passing important messages.

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