

Master Thesis

Energy Efficient Active Sensor Selection
Scheme for U-healthcare in WBAN

Hyeok Soo Choi (최혁수)

Division of Electrical and Computer Engineering

(Computer Science and Engineering)

Pohang University of Science and Technology

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U-Healthcare에 사용되는 WBAN 센서들의
효율적인 에너지 사용을 위한
Active 센서 선택 기법

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By

Hyeok Soo Choi

Division of Electrical and Computer Engineering
(Computer Science and Engineering)
Pohang University of Science and Technology

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Approved by

Major Advisor: James Won-Ki Hong
co-Advisors: Nazim Agoulmine and Hui Wang

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최 혁 수

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ABSTRACT

The number of people over the age of 65 has significantly increased in all countries over the last few decades. With this current trend in population, chronic diseases are becoming the world's leading cause of death and disability for the elderly. Chronic diseases debase quality of life because chronic diseases require frequent hospital visits. Another major reason for injury and hospital admission among elderly is accidents such as falling that occur in the home. To address these social problems, one possible solution is a Ubiquitous Healthcare (U-Health) smart home. The U-Health smart home can support remote medical care that can act as a substitute for hospital visits from the elderly. The U-Health smart home can also provide continuous health monitoring, which can support early diagnosis and treatment to reduce health care costs.

Today, Wireless Body Area Network (WBAN) is considered a key element to provide health care services anywhere, anytime in the U-Health smart home and will play an important role to enhance quality of life for elderly in the future. Therefore, research about WBAN is necessary before developing the U-Health smart home.

Medical sensors that organize a WBAN should be as small as possible because they must not cause any activity restriction or behavior modification to the user. A small-sized sensor implies that its energy resource such as a battery

should also be small. The amount of energy available in the wireless medical sensor is limited since it is proportionate to the size of battery. This restricted energy is the most important characteristic and most important problem of WBAN. Therefore, enhancing the WBAN's lifetime through efficient energy consumption is necessary.

In a WBAN, each medical sensor monitors different vital signs such as temperature, blood pressure, or ECG. Data collected by the medical sensors is transmitted to the coordinator. However, this data is not identical to the information needed to determine whether or not the elderly person has a specific disease. Only some of the data is necessary to make a decision. However, in existing systems, even though the data is not needed, medical sensors are always activated and continuously transmit data to the coordinator. This configuration causes high energy consumption in all medical sensors and reduces seriously their operational time.

For efficient energy consumption in the WBAN, it is necessary to select only the most appropriate sensors that have the highest impact on the coordinator's decision at a particular stage.

Since, it is necessary to identify the set of symptoms to monitor at a particular stage and what is the importance of each symptom in the detection of a disease, it is important to find the relationship between symptoms and diseases, and we propose to use mutual information to define the information gain. Based on this information gain, we propose a way of selecting the most appropriate sensors to activate. We validate the proposed WBAN system by implementing a prototype system based on version 2.31 of NS-2.

Contents

1 Introduction.....	10
1.1 Motivation.....	10
1.2 Problem Statements	11
1.3 Outline of this Dissertation	14
2 Related Work.....	15
2.1 Smart Home	15
2.2 Medical WBAN	17
2.2.1 Comparison between medical WBAN and WSN	18
2.2.2 Media Access Control for WBAN.....	21
2.2.3 Medical Sensors	22
2.3 IEEE 802.15.4 Standard.....	23
3 Postech U-Health Smart Home Project	26
3.1 Autonomic U-Health Smart Home Architecture	26
3.2 Elderly Health Monitoring System.....	30
4 Proposed WBAN Sensor Scheduling.....	33
4.1 Proposed Approach	33
4.2 Sensor Selection Criterion	36
4.3 Case Study: Calculation of Information Gain.....	41
4.4 Evaluation of the Operation Cost.....	45
4.4.1 Energy Consumption of Successful Transmissions.....	46
4.4.2 Energy Consumption of Unsuccessful Transmissions.....	48
4.5 Information-based Sensor Scheduling	49

5 Evaluation	52
5.1 Simulation Environments	52
5.2 Simulation Results	56
5.2.1 Energy Consumption.....	57
5.2.2 Validation Time	59
6 Conclusions	61
6.1 Summary.....	61
6.2 Contributions	63
6.3 Future Work	64
References	65

List of Figures

Fig. 1. Presentation of a Medical WBAN	17
Fig. 2. Data rate and power consumption	20
Fig. 3. IEEE 802.15.4 superframe structure	25
Fig. 4. Autonomic U-Health smart home framework	28
Fig. 5. Overview of U-Health care system	31
Fig. 6. A prototype of WBAN	34
Fig. 7. Relationship between mutual information and entropy.....	38
Fig. 8. Relationship between mutual information and entropy.....	40
Fig. 9. SD and BI	54
Fig. 10. Communication processes	54
Fig. 11. Beacon frame structure	55
Fig. 12. Disease schedule.....	56
Fig. 13. Total energy consumption.....	57
Fig. 14. Energy consumption at sensors	57
Fig. 15. Energy consumption of CB-WBAN and IB-WBAN with variations of validation time.....	60
Fig. 16. Latency of CB-WBAN and IB-WBAN with variations of validation time	60
Fig. 17. Trade-off between energy saving and latency	60

List of Tables

Table I. Characteristics of Medical Sensors.....	23
Table II. Probabilities of symptoms and diseases	42
Table III. Probabilities of symptoms and diseases.....	44
Table IV. Key parameters of the simulation.....	52
Table V. Relationship between disease and symptoms	56

1 Introduction

This chapter provides a brief introduction to the current trend of the society toward a higher proportion of dependent elderly. The motivation of our work is the use of technologies and more precisely the concept of U-Health smart home as a solution to reduce costs related to health and safety management of elderly allowing them to stay in their home as long as possible. The specific part of the U-Health Smart Home, the Body Wireless Network is particularly as it is a key part of the system.

1.1 Motivation

The number of people over the age of 65 has significantly increased in all countries over the last few decades and is expected to double worldwide by 2025 [1]. With this current trend in population, chronic diseases are becoming the world's leading cause of death and disability for the elderly. Chronic diseases debase quality of life because chronic diseases require frequent hospital visits. Another major reason for injury and hospital admission among elderly is accidents such as falling that occur in the home [2]. To address these social problems, one possible solution that is focusing the interest of many governments, industries and research centers is a Ubiquitous Healthcare (U-Health) smart home. The U-Health smart home is a concept of home that embed appropriate technologies to support remote monitoring and medical care that can act as a substitute for hospital visits from the elderly as well as reducing elderly visits by expensive nurses. Because chronic diseases require long-term treatment, the U-Health smart home enhances quality of life and provides elderly patients who prefer to live in their own house with an independent lifestyle away from hospitals. The U-Health smart home can also support continuous health monitoring. This

continuous monitoring enables early diagnosis that can lead to early treatment and reduce health care costs. Also, this continuous monitoring can find correlations between health and lifestyle [3]. The U-Health smart home for elderly people has been an area of rapid growth in recent years because many elderly people are concerned about their health and governments willingness to reduce the health system cost in the future.

In parallel to this growth of interest in U-Health Smart Home, advances in low power electronics and semiconductor technologies have been steady these last decades and is leading to the development of more and more smaller-sized medical sensors. These medical sensors are aimed to be attached on/in the bodies of the elderly without any activity restriction and are capable of monitoring a human's health state. Also, the advancement in wireless technologies is enabling more and more efficient data exchange among small portable devices at different ranges. Combining these two technologies, a new type of wireless network called Wireless Body Area Network (WBAN) has emerged as the network of all wireless devices that can be installed on a human body and could communicate. In the health domain, the WBAN consists on a set of medical sensors implanted in or on the user's body to monitor the state of his or her health and equipped with communication board/antenna to forward the information to a medical system to display, store and process the data to detect any medical anomaly.

Today the medical WBAN is considered a key element to provide health care services anywhere, anytime and will play an important role to enhance quality of life for elderly in the future. Therefore, research about WBAN is necessary before developing the U-Health smart home.

1.2 Problem Statements

Wireless medical sensors that organize the WBAN are attached on/in the

patient's body. These medical sensors should be as small as possible because they must not cause any activity restriction or behavior modification to the user. A small-sized sensor implies that its energy resource such as a battery should also be small. The amount of energy available in the wireless medical sensor is limited since it is proportionate to the size of battery. Also, once medical sensors are installed, changing or recharging their batteries is inconvenient. Especially in case of implant medical sensors, it is impractical; therefore, any such battery ought to work for at least several years in a user's body. This restricted energy is the most important characteristic and most important problem of WBAN. Therefore, enhancing the WBAN's lifetime through efficient energy consumption is necessary and is a crucial design challenge.

Patients will be then monitored through the set of sensors that are installed on or in their body constituting the WBAN while remaining in their home. For that, the home itself will be equipped with a number of technologies to interact with the WBAN to collect the medical information to detect abnormal health situations. Such a home is called U-Health Smart Home.

The design of the WBAN necessitates a careful approach in term of communication as they are the main consumers of the sensor's energy [4]. WBAN are usually composed of a set of sensors communicating with a particular node playing the role of a coordinator and serving as a gateway to the home server directly or via another network i.e. WLAN. In this context, the energy problem is more critical to the sensors than to the coordinator.

Most existing WBAN systems are configured based on the following principles.

- Medical sensors are configured according to the communication needs such as duty cycle to save energy.

- Communication is triggered by medical sensors and sensed data is sent to the coordinator regularly.
- The coordinator gathers all data from medical sensors and determines whether or not there is an abnormal condition in the human's health based on that data.

To determine whether a human is affected by a specific disease, it is not necessary to check every symptom; only some of them need to be checked. This means that the entire data collected by medical sensors is required by the U-Health smart home for diagnosis in any given situation. However, medical sensors are not intelligent enough to determine whether a data is requested to identify a symptom or not in a given situation. That is why the medical sensor in the existing WBAN systems are activated and sampling rate configured based on the decision of the coordinator decisions. By doing so, the sensors do not it to send data when not necessary and could therefore extend their lifetime.

We can therefore enumerate the research questions that are addressed in this thesis:

- Is it possible to define an alternative communication approach reducing the energy consumption while not missing important information that is necessary to detect health anomaly?
- What symptoms are relevant to a specific disease?
- Which symptom has the most information to determine whether or not the elderly person is infected with a specific disease in a given situation?
- How much sensing and communication energy is needed to accomplish the diagnosis?

1.3 Outline of this Dissertation

The organization of this thesis is as follows. Chapter 2 describes issues related to the smart home, WBAN, and IEEE 802.15.4 to better understand the context of this thesis. In chapter 3, we introduce the concept of U-Health smart home project at POSTECH and highlight the challenges of the WBAN design as part of the U-Health Smart Home that are addressed in this research work. The following chapter 4 presents the proposed solution in term of designing an energy efficient solution to detect health anomalies. In chapter 5, we give the evaluation details of the proposed WBAN system. Finally, chapter 6 concludes this thesis with a summary, contributions, and future work.

2 Related Work

In this chapter, we introduce the state of art on various relevant technologies to our area of interest. This chapter is divided into three parts. In the first part, we introduce the motivation of the U-Health Smart Home and current issues related to its development. In the second part, we provide an overview of the existing WBAN systems and introduce the current open issues with WBAN design. Finally, we introduce the main specifications of the IEEE 802.15.4 protocol for media access control that is used in our proposed WBAN system.

2.1 Smart Home

A ‘smart home’ can be defined as a residence equipped with information and computing technology [5] in order to ensure occupants’ comfort, convenience, security, and health care. Currently, many smart home projects are proceeding with different purposes, and many researchers have become increasingly interested in various aspects related to this concept. In this section, we pay more attention towards the U-Health Smart Homes which has some specificities comparing to the general area of smart homes.

Many smart home projects have been launched to address the health care problem. Among them, we can mention first the MavHome project [6][7]. This project aims to design a smart home that acts as an intelligent agent of the inhabitants. The home is equipped with sensors that can record occupants’ interactions with appliances and the role of the agent is to predict occupants’ movements in the home. Another project presented in [8][9] propose also a smart home aiming at providing health care of inhabitants. In [8], the authors propose a prediction model in a smart home system that can be used for identifying occupants’ health condition over time. Similarly, in [9], the authors propose an

agent-based smart home where agents run a prediction algorithm that can identify common activities of occupants and anomalous activities that may indicate a health accident. In [10], authors developed a wireless body sensor system to monitor a patient's physical activities in the smart home and to classify different human movements.

Several researchers have studied home-based telemedicine systems. The TOPCARE project [11] developed a home care platform and telecommunication structures for bringing cooperative health care services to the patients' homes. In [12], the authors developed a telemedicine system using home automation sensors to detect the activity level of patients. Bed, chairs, and other furniture are equipped with sensors to monitor patients and detect any abnormal health state. If this system detects any abnormal state then it triggers an alarm that may result in an automated connection with a medical center or doctor. In [13], the authors present the concept of home based e-health which includes both telemedicine and smart home design.

The main goal of the CodeBlue project [14][15], which started at Harvard University, is to develop a wireless communications infrastructure for critical medical care environments. This project also developed medical sensors such as ECG, Pulse Oximeter, and motion activity sensors based on Micaz [16] and Telos [17] mote platforms. Using this infrastructure, the project enhanced first responders' ability to assess patients on the scene. There have been similar efforts to develop wireless communication infrastructure and wireless medical sensors for home-based care. Authors present in [18][19] a ubiquitous mobile health environment based on a Wireless Body Area Network. In [18], the authors propose a scanning algorithm that allows dynamic discovery and installation of mobile devices. In [19], authors developed a system incorporating diverse medical sensors communicating via wireless connections and live transmission of measured vital signals over public wireless networks to health care providers.

These examples of research into medical smart homes aims to enable elderly people to maintain their independent lifestyles away from hospitals and to avoid expensive health care costs through early detection of disease.

2.2 Medical WBAN

To provide U-Health care service in a smart home, a user's bio information is necessary anywhere, anytime in the home. Therefore, with the advancement of small sized medical sensors and wireless communication technology, a new type of network has emerged called a Wireless Body Area Network (WBAN). A medical WBAN is a very small sized network, which consists of several medical sensors implanted in or around the user's body. This term was first used by K. Van Dam et al. [20] and several studies have since been done in this area.

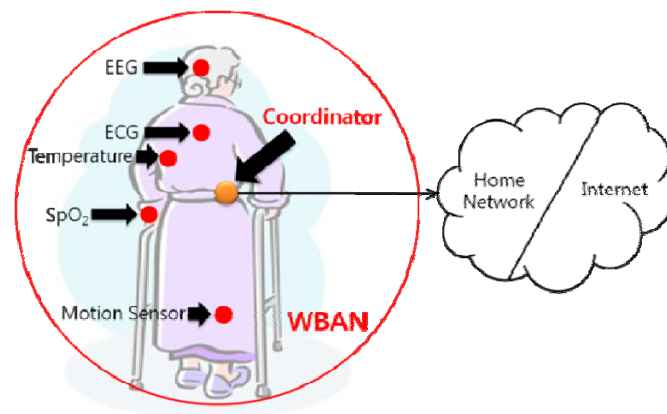


Fig. 1. Presentation of a Medical WBAN

As shown in Fig. 1, a medical WBAN consists on a set medical sensors and one coordinator installed on a human body. Medical sensors installation can be complex and sometime need to be done by a specialist. In this context, the most important constraint is their limited energy supply, indeed medical wireless

sensors need a battery to work properly. Once medical sensors are installed, changing or recharging their batteries is uncomfortable or sometime impractical. At the same time, in order to make users comfortable, the size of medical sensor should be as small as possible which means always smaller battery and therefore less energy. In this situation, energy efficient wireless medical sensors and efficient energy usage these sensors is a very important issue. Hence, in case of implant medical sensor, when the battery is exhausted, the patient will require surgery to replace the sensor. In this case, the cost of the surgery cost is more expensive than the cost of the sensor. Therefore, implanted medical sensors must work for at least several years. For the coordinator, the situation is a little bit different, since usually the coordinator has a bigger battery and can be reloaded more easily. This coordinator is less constrained than medical sensors in terms of energy. Therefore, increasing network lifetime is a crucial challenge in WBAN design involving using relatively more energy from the coordinator than the medical sensor. Each medical sensor measures the human body's signals and transmits them to the coordinator. The coordinator gathers this bio information and transmits it to the U-Health system server (or directly to the health centre or hospital), which can store and analyze the bio information. This coordinator also has responsibility to manage all the medical sensors on/in the body.

2.2.1 Comparison between medical WBAN and WSN

A Wireless Sensor Network (WSN) is usually comprised of a large number of sensor nodes, which can cover ranges of up to hundreds of meters. Each sensor node measures ambient conditions and transmits them to the sink node through many intermediate nodes. Because of its similarity, WBAN can use some wireless technologies in WSN. However, this does not always apply because WBAN has different requirements and characteristics. These differences create new technical challenges and opportunities. The followings are a comparison of WBAN and WSN.

- **Network Size:** A conventional WSN operates in wide area such as a battlefield. Unlike a WSN, a WBAN operates on/in the body and its communication range is about 2 meters. This restricted communication range enables low transmission power that reduces energy consumption of nodes and decreases interference among adjacent nodes. The range between the coordinator sensor and the home gateway or U-Health System may be bigger i.e. 10 meters.
- **Sensor Size:** Because medical sensors are attached on/in the body, the sensors should be designed to take into account human comfort. This makes small sensor size more important. Smaller sensors imply smaller resources such as smaller batteries, smaller antenna and smaller storage.
- **Sensor Type:** Generally, in a WSN, the type of sensor is homogeneous and each sensor monitors the same target. Therefore, a WSN can use an efficient aggregation rule to reduce energy consumption. However, the type of sensor in a WBAN is heterogeneous and each medical sensor monitors a different target.
- **Data Rate:** Generally, sensors in a WSN are homogeneous and have similar data rate. Unlike a WSN, data rate in a WBAN varies significantly from few Kbps to few Mbps depending on application type. Fig. 2 shows that data rate and power consumption depend on application type [21]. Applications sensing continuous data like ECG require a high data rate, but applications sensing discrete data like body temperature require a low data rate. In the WBAN, integration between the various types of applications is needed.

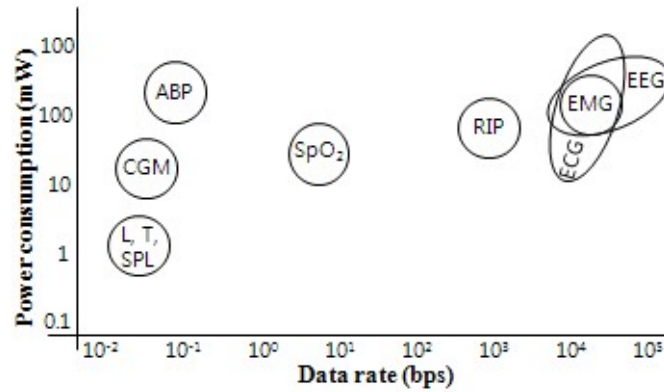


Fig. 2. Data rate and power consumption

- Architecture:** Sensors in a WSN are distributed in a wide area and measured data are transmitted to sink nodes through many intermediate nodes. Every sensor acts both as a sensor to sense data and a router to route the data. Therefore, energy-efficient routing algorithms are necessary. Due to the WBAN's small coverage range, a WBAN forms a simple master-slave architecture and star topology. A slave node is a medical sensor and a master node is a coordinator that acts as a router. Medical sensors measure the human body's signals, and then transmit them to the coordinator directly. Direct communication between medical sensors and the coordinator can make the routing algorithm simple. Therefore, in the WBAN, we do not need to worry about energy consumption at the routing layer.
- Latency:** Some WBAN sensors require low latency and delay guarantee to operate accurately. And if the state of a person's health is abnormal or if there is an emergency, latency becomes a more important factor. Therefore, traffic should be treated differently depending on traffic type to support emergency states. If the traffic is an emergency traffic, it has high priority and should be delivered more quickly. A dynamic changing

duty cycle and sampling rate depending on human health state can also be considered to provide both efficient energy consumption and QoS in an emergency.

2.2.2 Media Access Control for WBAN

A Media Access Control (MAC) layer provides a channel access control mechanism to avoid collisions and to maximize throughput. Many MAC protocols have been studied because an efficient MAC protocol can reduce a node's energy consumption. MAC protocols can be categorized as one of two types: contention-aware protocols and schedule-based (contention-free) protocols.

The typical contention-aware MAC protocols are Sensor-MAC (S-MAC) [22] and Timeout MAC (T-MAC) [23]. S-MAC sets the sensor to sleep during transmissions of other nodes to reduce energy consumption in listening. However, idle listening will increase when network traffic is low. T-MAC extends S-MAC and introduces an adaptive duty cycle that allows the sensor to sleep when there is no traffic for a certain time. However, T-MAC has a synchronization overhead and high latency problem.

Unlike contention-aware protocols, schedule-based protocols provide a contention-free scheme by assigning time slots to every node. The typical schedule-based MAC protocols are μ -MAC [24] and DEE-MAC [25]. μ -MAC uses application layer knowledge in the form of flow specification to reduce energy consumption. DEE-MAC reduces energy consumption by making the idle nodes sleep to reduce idle listening using synchronization at the cluster heads. But, μ -MAC and DEE-MAC are not appropriate in frequently changing networks. Z-MAC [26] is a hybrid protocol. It combines the strengths of CSMA and TDMA, but it also retains their weaknesses.

Recently, some MAC protocols for WBAN were proposed in

[27][28][29][30]. Authors of [27] proposed a TDMA-based low duty cycle MAC protocol to support streaming of large amounts of data such as ECG and EEG. This protocol takes advantage of its static nature and has almost no idle listening. [28] proposed an adaptive MAC protocol to support a diverse range of applications with throughputs ranging from few Kbps to few Mbps. [29] proposed a priority-guaranteed MAC protocol for WBAN to support heterogeneous service requirements. [30] proposed a real-time on-demand MAC protocol to support pervasive healthcare such as monitoring vital signs and drug delivery.

Currently, one of most acceptable MAC protocols for an energy efficient wireless personal area network (WPAN) is 802.15.4 [31]. Based on 802.15.4, there are many U-Health systems [32][33][34]. In this paper, we chose the IEEE 802.15.4 standard as the communication protocol for our WBAN system and we develop our own communication model based on this standard. A more detailed investigation of IEEE 802.15.4 is given in section 2.3.

2.2.3 Medical Sensors

A fundamental element of WBAN is medical sensors. There are two types of medical sensors: wearable medical sensors and implanted medical sensors. Depending on the type of medical sensor that organizes the WBAN, the characteristics of the network traffic and requirements of WBAN can vary. Therefore, investigating the characteristics of the medical sensors is important before designing the WBAN. Table I shows the data transfer characteristics of medical sensors [35][36].

Table I. Characteristics of Medical Sensors

Type	Application	Sampling frequency (Hz)	Accuracy (bit)	Data rate
Wearable Medical Sensor	ECG	100-1000	12	10-100kbps
	EEG	256	12-16	10-50kbps
	Pulse oximetry	60	16	1-2kbps
	Glucose	0-50	16	1-2kbps
	Body temperature	0-1	12	120bps
	Motion sensor	0-500	12	30-50kbps
Implanted Medical Sensor	Cardiac output	30-50	16	500-100bps
	Insulin pump	-	-	50-100bps
	Cochlear	-	-	100kbps

In the case of implanted medical sensors, heat generated by the sensors can have a negative effect on humans. To void this negative effect, a low specific absorption rate (SAR) for the radio is needed. Some medical sensors are sensitive to the latency. These kinds of sensors require minimum delay to operate accurately.

2.3 IEEE 802.15.4 Standard

The traditional IEEE 802.11 standard was designed without considering the energy issues related to small portable devices. Therefore, the IEEE 802.15.4 is designed for extremely low power consumption and low data rate among inexpensive portable devices [37]. Currently, this protocol is extensively employed in different areas of applications and is considered as a communication standard for Wireless Personal Area Networks (WPAN) and WBAN. In [38], this protocol is used in the context of home automation network; in [39], it is used for

industrial applications, and in [40][41], it is used for a health care network.

The most fundamental element in the IEEE 802.15.4 system is the device. The device can be categorized as either a Full Function Device (FFD) or a Reduced Function Device (RFD). The FFD can operate in three modes: network coordinator, coordinator, and device, while the RFD can operate only in device mode. Also, FFD can communicate with both FFD and RFD, while RFD can only communicate with FFD. The IEEE 802.15.4 system should contain at least one FFD device defined as the network coordinator. The network coordinator initiates the network, stores information about the network and bridges to other networks. An RFD is suitable for applications which are simple sensors and do not require complex operations like routing. This RFD can be implemented using limited resources but can consume less energy than FFD. In our WBAN system, the network has one FFD as a coordinator, and other medical sensors are RFDs. This configuration affects the network topology. Possible topologies in the IEEE 802.15.4 are star, peer to peer, and cluster tree topology. In our case, we use a WBAN in star topology as we want the medical sensors to send directly the information to the coordinator. There is in this case no energy consumed at the routing level since each medical sensor is configured to know exactly who the coordinator is and how to reach it in one hop. Another benefit of the star topology in the WBAN system is that the coordinator can be used with a rechargeable power supply [42]. In [43], the star topology configuration of the IEEE 802.15.4 is considered for a WBAN system and its performance is analyzed. When an FFD activates for the first time, the device establishes its own network, and then becomes the network coordinator. Other medical sensors are RFD and can communicate only with the network coordinator.

In the IEEE 802.15.4 protocol, there are two kinds of operation modes: beacon enabled and non-beacon enabled mode. A beacon frame is broadcasted periodically from the coordinator and it contains information, which is necessary

to build the network. In [38], parameters of the beacon frame are analyzed and optimal parameters suitable for the smart home environment are proposed. In this work, we focused on the beacon enabled mode because it is more suitable for the star topology of the medical WBAN.

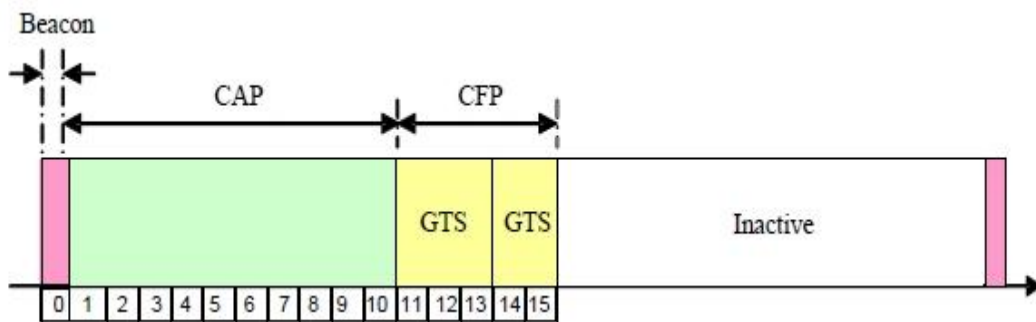


Fig. 3. IEEE 802.15.4 superframe structure

The superframe structure of IEEE 802.15.4 in the beacon enabled mode is illustrated in the Fig. 3. In this mode, the superframe is bounded by the beacon frame and can have both an active and inactive portion. During the inactive portion, the coordinator may enter in an extremely low power mode [44] and the network can save more energy. Communications between the coordinator and devices occur in the active portion. This portion is divided into 16 equal time slots and there are two kinds of communication periods: Contention Access Period (CAP) and Contention Free Period (CFP). The CAP starts immediately after the beacon frame and finishes before the CFP. In this period, devices should compete with other devices using a slotted CSMA/CA communication mechanism. Several papers analyzed the performance of CSMA/CA in the IEEE 802.15.4 protocol [45][46][47]. The CFP starts immediately after the CAP and finishes before the inactive portion. The network coordinator can allocate up to seven time slots called Guaranteed Time Slots (GTS) in the CAP. Device(s) that require dedicated bandwidth or real time applications can be allocated one or more GTS [48][49] which impact the performance of the system.

3 Postech U-Health Smart Home Project

In this chapter, we introduce the U-Health smart home project which is being developed at Postech University. This chapter is divided into two parts. In the first part, we provide an overview of the autonomic U-Health smart home architecture. In the second part, we illustrate a behavior of the U-Health Smart Home supporting the elderly inhabitant health monitoring.

3.1 Autonomic U-Health Smart Home Architecture

The cost of computing systems has increased rapidly because of their growing complexity and their large deployment in the society and the industry. In the 1990's, computing system expenditures came mainly from hardware and software acquisitions while human administrator expenses were proportionally lower. Nowadays, the situation has inversed and the human administrator cost is much higher while the hardware and software cost has significantly decreased. If there is no change in the present trend, human expenses will eventually overwhelm equipment costs in the near future and will make it an unsustainable situation [50]. The main goal of the autonomic computing system [51][52], which started at IBM, is to overcome the high complexity of management systems. Autonomic computing systems are self-managing systems that continuously check and analyze their current status to adjust to ever-changing circumstances. The autonomic system manager defines high-level goals or policies instead of controlling the system directly. The autonomic system takes its own decisions based on the high level predefined goal or policy by the human administrators but this later doesn't intervene in the day to day operations. Using this new paradigm, of autonomic computing systems, the high complexity of management systems will be controlled automatically reducing the human interventions and the

associated cost.

This concept of autonomic computing plays also a very important role in the smart home since it is envisioned that the smart home will be a complex computing system deploying numerous ICT. Smart home systems will be composed of a number of small and large computing systems (computers, sensors, network equipments, appliances, etc) that interact together to gather data from different sources, and analyze it to understand what is the situation of the smart home as well as the inhabitants. The smart home should be designed to be an autonomic computing system that is able to take autonomously proper actions in order to ensure occupants' comfort, convenience, security, and health care in the case of U-Health smart home.

At Postech, we are developing a U-Health smart home using the autonomic concept. In this project, we aim to build an autonomic system that monitors occupants' health and detects their health anomalies anywhere, anytime.

Fig. 4 shows the autonomic U-Health smart home framework in our project. To achieve this goal, we have defined a framework for the U-Health Smart home that defines four logical layers. Each layer presents the functional requirements of the autonomic U-Health smart home to achieve specific goals.

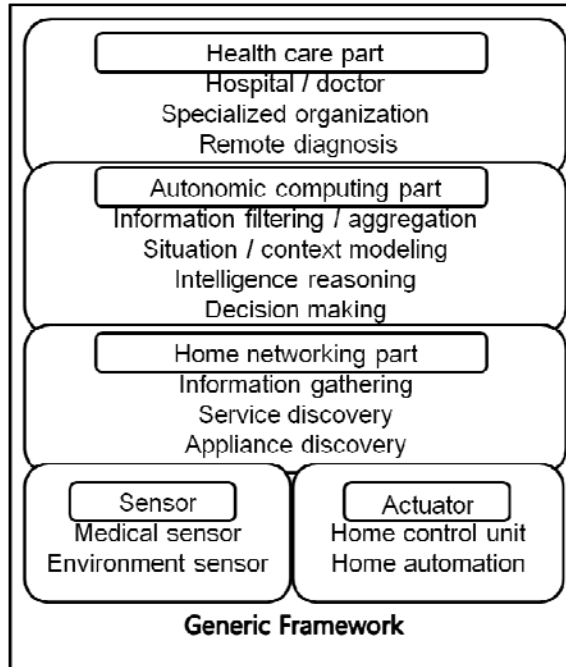


Fig. 4. Autonomic U-Health smart home framework

The lower layer consists of two main components: the sensors and actuators. These components are physical hardwires that allow the U-Health smart home to collect data from the environment and from the inhabitants as well as to perform some actions on them. Sensors can be of two types: environment sensors and medical sensors. Environment sensors are those devices installed at various locations in the smart home to collect environmental data such as temperature or humidity while medical sensors aims to be installed on/in the occupant’s body to collect vital data such as ECG, blood pressure, or SpO2 in case of intrusive monitoring. Actuators are those devices installed in the smart home to control its appliances or other additional systems. Their functions include on/off for appliances, open/close for windows, or open/close for doors. We have also installed an LED path on the floor of the smart home to prevent occupants from falling at the night, as falls are the second major cause of injury and hospital

admission for the elderly.

The second layer of the framework is the home network part. Data generated by various sensors must be delivered to the smart home gateway in which an autonomic system should perform the MAPE (Monitoring, Analysis, Planning and Enforcing) autonomic loop as introduced by IBM [50][51]. Once the analysis of the situations and planning of actions finalized, the autonomic system may issue command messages to the numerous actuators in the home of on the inhabitant body. To do this, sensors and actuators are connected and form a wire/wireless network. In our U-Health smart home project, there are two kinds of wireless networks: a Wireless Sensor Network (WSN) and Wireless Body Area Network (WBAN). A WSN consists of various environment sensors and some appliances that are equipped to communication with them. A WBAN is a very small sized network that consists of heterogeneous medical sensors implanted in/or the occupants' body. A coordinator in the WBAN can communicate directly with some nodes in the WSN. And the WBAN can be included into the WSN as a subset. For these wireless networks in the smart home, several wireless technologies such as ZigBee, Bluetooth, or Ultra Wide Band (UWB) can be used. Some actuators to control appliances are connected with power lines and can communicate with the smart home server using Power Line Communication (PLC). Through these wire/wireless networks, the various parts of the framework exchange information.

The third layer is the autonomic computing part. Data generated by environment sensors and medical sensors are transmitted to the smart home gateway through the home network. In this layer, the data are filtered and aggregated and saved in a database. The smart home autonomic system interprets the data and transforms it into knowledge. Based on this produced knowledge and as set of predefined policy rules, the autonomic system may be able to take decisions on its own. These decisions can connect with service providers in the

fourth layer and provide various services for occupants' comfort, convenience, security, and health care.

The framework's fourth layer is the health care part. In this layer, doctors or hospitals provide health care services and define the goals of the U-Health smart home.

3.2 Elderly Health Monitoring System

The main goal of our U-Health smart home project is to provide the following health care services to the elderly: 1) Monitor health condition of elderly inhabitant at anytime and anywhere in their home, 2) Detecting a disease or abnormal situation in their health while they are at home, 3) Transmitting data collected at the home to the health care service provider such as a doctor or hospital in order to support remote medical care or emergency visit should be given.

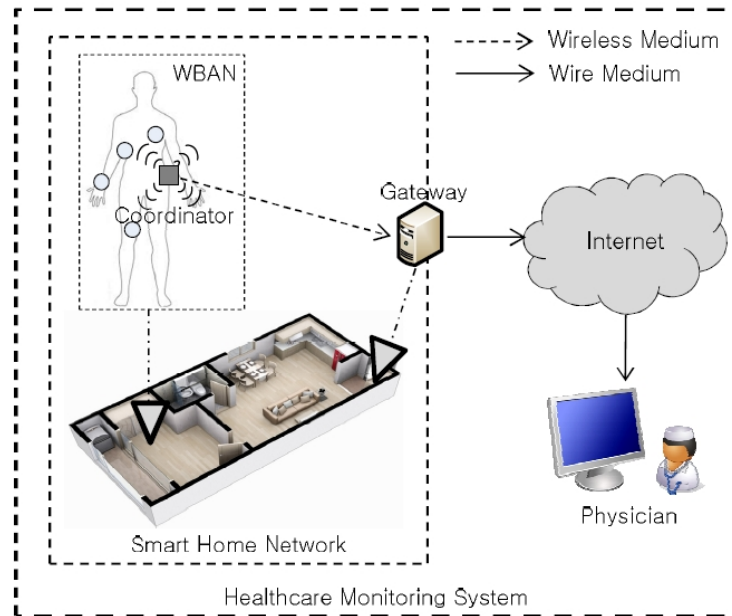


Fig. 5. Overview of U-Health care system

Fig. 5 shows an overview of U-Health care system being developed in the project. The system is composed of one home gateway connected to the home network serving as a host for the autonomic system as well as a gateway to the Internet. The role of this gateway is to gather all the information generated in the home including the health state of the elderly occupant and which is connected to the Internet in order to transmit this data to the health care service provider. At the starting of the system, the gateway first discovers all the controllable devices in the smart home, e.g. controllable appliances, environment wireless sensors, and medical wireless sensors.

The monitoring system of the elderly health status is based, as previously mentioned, and based on a set of wireless medical sensors using ZigBee technology. To reduce the energy consumption of these sensors and elongate their

lifetime, the communication is limited to a short range and not the directly to the home gateway which maybe far away from the place where the elderly is staying. To provide comfort for the elderly occupant and support pervasive communication, medical sensors on/in the body transmit sensed data using ZigBee, which is wireless communication technology. However, medical sensors do not transmit the data to the home gateway directly, but instead to the coordinator located on the elderly person. Using the coordinator in this way saves the medical sensors' energy However, since the coordinator has to transmit the entire medical data, its consumption will be much higher however the coordinator is also more accessible (e.g. carried on a belt) hence it has more processing capabilities and could analyze the collected data and take local decisions before forwarding the date to the gateway as it will be detailed in the following.

4 Proposed WBAN Sensor Scheduling

4.1 Proposed Approach

The solutions proposed to extend the lifetime of the system and reduce the human intervention to change the medical sensors batteries or the sensors themselves are based on the nature of their activities. Indeed, in the real world, people go to a hospital to see a doctor when they suspect they have a health problem or when they are feeling bad. Doctors follow a rational process that is first to examine one or several fundamental vital sign(s) to confirm the symptoms of any disease. This first phase has the following benefits: 1) The symptom indicates clearly the indication of a disease, 2) It is a cost effective phase since this phase helps to reduce the domain of possible diseases to investigate, 3) The test causes little pain to the elderly and helps to give a fast first diagnosis,.

The criteria for selecting a type of vital sign to measure in order to check for a symptom can differ depending on the doctor or situation, but the important thing is that no one checks all possible symptoms at the same time. A doctor checks the symptoms of an elderly patient step by step. If the results of first examination are positive then the doctor may conclude that the patient's health is fine (absence of the disease) or suspect a different disease. If the results are negative then the doctor would then check other symptoms related to the disease to make sure the elderly is infected with the disease. We inspired from this doctor's methodology in the real hospital.

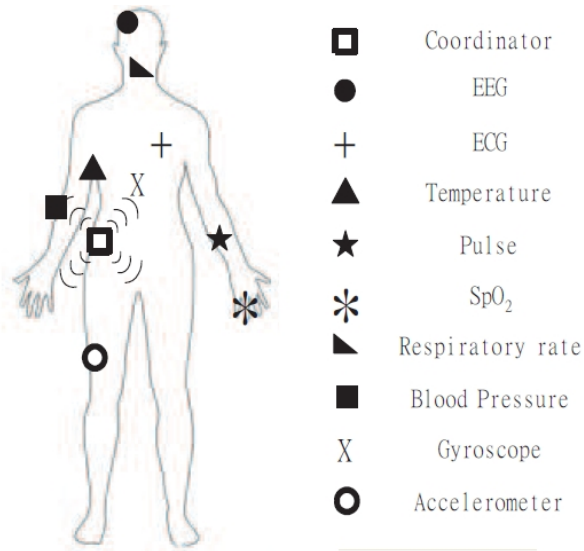


Fig. 6. A prototype of WBAN

Fig 6 shows a prototype of a WBAN installed on an elderly body. The WBAN architecture is based on a star topology around a coordinator as previously mentioned. Each medical sensor monitors different vital signs such as temperature, blood pressure, or ECG which can indicate a symptom such as high fever, hypertension, or abnormal ECG signals, respectively. Data collected by the medical sensors is transmitted to the coordinator. However, this data is not identical to the information needed to determine whether or not the elderly person has a specific disease. At each stage, only some of the data is necessary to make a decision. In existing systems, even though the data is not needed, medical sensors are always activated and continuously transmit data to the coordinator. This is the case because medical sensors cannot themselves determine what are the investigated symptoms and at which stage the doctor is in his investigation. This configuration causes high energy consumption in all medical sensors and reduces seriously their operational time. Like the doctor's approach in the real world, the aspect of the energy saving is relevant to finding proper symptoms related to a

suspected disease. In other words, it is necessary to select only the most appropriate sensors that have the highest impact on the coordinator's decision at a particular stage.

Since, it is necessary to identify the set of symptoms to monitor at a particular stage and what is the importance of each symptom in the detection of a disease, it is important to find the relationship between symptoms and diseases, and we proposed to use mutual information to define the information gain. Based on this information gain, we proposed a way of selecting the most appropriate sensors to activate. More details about the mutual information and sensor selecting algorithm will be presented in section 4.2. There is indeed a trade-off between information gain and operating cost (energy consumption) to solve in order to select the set of medical sensors to activate at a particular stage. Both information gain and operating cost are important elements when designing the WBAN. To balance these two objectives, we propose to use a utility function that integrates both objectives. More details about the operating cost function and utility function will be presented in 4.4 and 4.5, respectively. We also propose a communication protocol between the medical sensors and the gateway on the top of ZigBee protocol that enforce the results of the information-based sensor selection algorithm. More detailed explanations regarding this communication mechanism will be presented in 4.1.

We use the following notation in our formulation of the medical sensors scheduling problem in the WBAN:

- Superscript t denotes time. We consider discrete times t that is nonnegative integers.
- Subscript $i \in \{1, \dots, m\}$ denotes the sensor index; m is the total number of sensors in a WBAN. As a specific type of network topology, WBAN is deployed on the elderly body on a small scale. The position of each node

on the body remains static. We assume that each medical sensor is identified by the particular index.

- Subscript $j \in \{1, \dots, n\}$ denotes the diagnosis index; n is total number of diagnoses being evaluated. Here, we also assume that each exact diagnosis is identified.
- The diagnosis state vectors at time t is denoted as $D^{(t)} \in R^{|n|}$. For a multi-diagnosis decision problem, this is a concatenation of individual diagnosis state $d_j^{(t)}$, which is a theoretically described diagnosis with symptom values formed on the basis of real clinical cases.
- The measurement of sensor i at time t i.e., the symptom is denoted as $e_i^{(t)}$. Also, $E^{(t)} \in R^{|m|}$ will be used to denote the corresponding vectors for time t .

4.2 Sensor Selection Criterion

A disease is an abnormal condition affecting the body of an organism. It is often construed as a medical condition associated with specific symptoms. It may be caused by both external factors and internal dysfunctions [53]. A symptom is a shift from normal function or feeling which is noticed by a patient, indicating a disease or a health anomaly [54]. In the U-Health smart home, symptoms can be observed by monitoring vital signals of the elderly using medical sensors. In order to reduce energy consumption in the WBAN, we propose a mechanism by which only the medical sensors that have a high impact on the coordinator's knowledge of given health situation of the monitored patient are activated.

To define this information gain, we propose to use mutual information in this thesis.

Mutual information [55][56] measures the dependency of different random variables, or represents how much one random variable tells us about other random variables. If two random variables X and Y have high mutual information then we can predict a lot about one from the other. If two random variables X and Y are independent then the mutual information is zero and knowing one does not give any information about the other.

Given two discrete random variables X and Y, the mutual information is defined as (1)

$$I(X; Y) = \sum_{y \in Y} \sum_{x \in X} p(x, y) \log \left(\frac{p(x, y)}{p(x)p(y)} \right) \quad (1)$$

Where $p(x, y)$ is the joint probability density function of random variables X and Y, and $p(x)$, and $p(y)$ are the marginal probability density functions of random variables X and Y, respectively.

To better understand the concept of mutual information, we need to present the entropy and conditional entropy. Entropy $H(X)$ measures the amount of uncertainty about a random variable X, and conditional entropy $H(Y|X)$ is regarded as the amount of remaining uncertainty in Y after X is known.

Given random variable X, the entropy $H(X)$ is defined as (2)

$$H(X) = - \sum_{x \in X} p(x) \log p(x) \quad (2)$$

Given random variables X and Y, the conditional entropy $H(Y|X)$ is defined as (3)

$$\begin{aligned} H(Y|X) &= - \sum_{x \in X} p(x) \log p(x) \\ &= - \sum_{x \in X} \sum_{y \in Y} p(x, y) \log p(y|x) \end{aligned} \quad (3)$$

Using equations (2) and (3), we can complete the following equation (4):

$$\begin{aligned} H(X, Y) &= - \sum_{x \in X} \sum_{y \in Y} p(x, y) \log p(x, y) \\ &= - \sum_{x \in X} p(x) \log p(x) - \sum_{x \in X} \sum_{y \in Y} p(x, y) \log p(y|x) \\ &= H(X) + H(Y|X) \end{aligned} \quad (4)$$

Using equations (1), (2), (3), and (4), we can represent the relationship between mutual information and entropy. (See fig. 7)

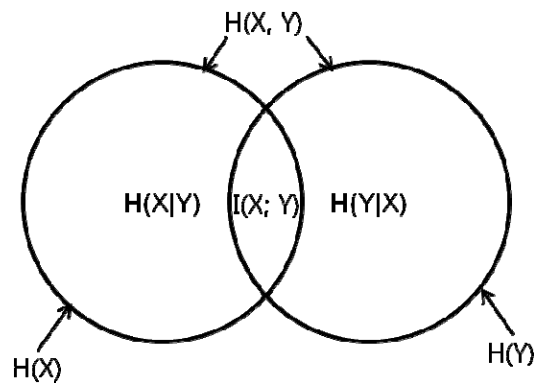


Fig. 7. Relationship between mutual information and entropy

In the U-Health smart home, there are two uncertainties: diseases and symptoms. Let X is the disease and Y the symptom in Fig. 7. We cannot measure the disease X directly, but we can predict parts of disease $I(X; Y)$ if we know about symptom Y . We can reduce the amount of uncertainty as much as $I(X; Y)$. This reduced part $I(X; Y)$ from previous uncertainty $H(X)$ is the information gain that is provided by Y to know about X . Remaining uncertainty about X after learning about Y can be expressed as conditional entropy:

$$H(X|Y) = H(X) - I(X; Y)$$

To calculate the mutual information between a disease and a symptom, the following knowledge is necessary: the joint probability density function and the marginal probability density function of the disease and symptom. Obtaining the joint probability functions is not possible in practice, but we can derive this function from conditional probability between disease and symptom using Bayes' theorem (See equation (5)). It is easier to obtain the conditional probability function than the joint probability function from hospitals because a person goes to a hospital with specific symptoms to check for diseases and they could have or not these diseases.

$$p(x, y) = p(x | y) p(y) \quad (5)$$

Therefore, to save the energy of the WBAN, the coordinator will only activate the medical sensors which help to obtain the higher information gain for the targeted disease (6):

$$\arg \max_{i \in A} (I(D; e_i)) \quad (6)$$

The WBAN coordinator selects first the set of medical sensors based on equation (6) that provide the highest mutual information the selected diseases to monitor. After receiving data from these medical sensors, the coordinator decides

if the collected knowledge is good enough to achieve a diagnosis. If not, the coordinator may select another sensor to activate to increase the information gain. In this case, the amount of mutual information does not equal the amount of information gain. Therefore, the coordinator should consider mutual information between symptoms that have already been measured as well as mutual information between the disease and symptom to find a medical sensor that maximizes information gain.

Fig. 8. Relationship between mutual information and entropy

Fig. 8 shows an example scenario. In this scenario, D is the disease to diagnose and $S1$, $S2$, and $S3$ are symptoms related to the disease. Sensor1, sensor2, and sensor3 are medical sensors that are capable to collect data to detect symptoms $S1$, $S2$, and $S3$, respectively. The amount of mutual information between the disease and each symptom is as follows:

$$I(D; S1) > I(D; S2) > I(D; S3)$$

The coordinator selected sensor1 as the first medical sensor to activate according to equation (6) and activate it. The dash lines in Fig. 8 represent the

information gain obtained by the measurements of sensor1. Even though $I(D; S2)$ is bigger than $I(D; S3)$, it is obvious that S3 will provide more information gain to the coordinator's knowledge about the disease because of the high dependency between S1 and S2. In this case, the coordinator should also consider the mutual information between symptoms that have already been considered as well as the mutual information between the disease and symptoms.

Therefore, the current knowledge can be expressed as $p(D | e_{i \in B})$, where $B \subset \{1, \dots, i\}$ is the subset of medical sensors whose corresponding symptom has already been monitored and incorporated. The coordinator logic is then to choose which sensor, reflecting the largest dependency on the disease D , to query among the remaining unincorporated set $A = \{1, \dots, m\} - B$. We can finally express i the new optimization function that is (7):

$$\arg \max_{i \in A} \left(I(D; e_i) - \sum_{j \in B} I(D; e_i; e_j) \right) \quad (7)$$

4.3 Case Study: Calculation of Information Gain

In this section, we will show how we calculate the information gain based on results of section 2.2. Let us assume that Table II contains information about diseases and symptoms received from a hospital and specialized health organizations. Based on this information, we need to calculate first the information gain between symptoms and a disease here the flu. There are four symptoms that can be measured: high temperature, cough, phlegm, and high blood pressure. Each number in Table II represents the probability of apparition of these symptoms as well as the join probability with the flu.

Table II. Probabilities of symptoms and diseases

Item	Notation	Value
$p(\text{flu})$	$p(D)$	0.00001
$p(\text{high temperature})$	$p(e_1)$	0.0001
$p(\text{cough})$	$p(e_2)$	0.0001
$p(\text{phlegm})$	$p(e_3)$	0.0001
$p(\text{high blood pressure})$	$p(e_4)$	0.0001
$p(\text{flu} \text{high temperature})$	$p(D e_1)$	0.02
$p(\text{flu} \text{cough})$	$p(D e_2)$	0.015
$p(\text{flu} \text{phlegm})$	$p(D e_3)$	0.01
$p(\text{flu} \text{high blood pressure})$	$p(D e_4)$	0.001

We want to use this information to configure the U-Health Smart home coordinator. Let us consider the following situation:

- The coordinator wants to check whether or not an elderly person in the home is infected with the flu.
- At the beginning, the coordinator has no information about the patient's symptoms.

In this case, the coordinator calculates the mutual information between the flu and symptoms according to equation (1) and equation (5). The following shows an example of how to calculate the mutual information between the flu and a high temperature. Characters marked in bold are information received from the hospital.

$$\begin{aligned}
I(D; e_1) &= p(D, e_1) \log \left(\frac{p(D, e_1)}{p(D)p(e_1)} \right) \\
&= p(e_1) \cdot p(D | e_1) \cdot \log \left(\frac{p(e_1) \cdot p(D | e_1)}{p(D)p(e_1)} \right) = 0.00022
\end{aligned}$$

We can calculate other mutual information in the same way using the information provided in Table III. The following are the results of this calculation:

- $I(D; e_1) = 0.000022$
- $I(D; e_2) = 0.00001575$
- $I(D; e_3) = 0.00001$
- $I(D; e_4) = 0.00000067$

The WBAN coordinator selects e_l because more mutual information implies more information gain when the coordinator has no information about the patient's symptoms. Then, the coordinator sends a request message to the corresponding medical sensor with the symptom e_l . After receiving data from the medical sensor, the coordinator's knowledge can be interpreted as $p(D | e_{i \in B})$, where $B \subset \{1\}$ is the subset of medical sensors whose symptoms have already been gathered and incorporated. If the coordinator wants more measurements, it should select the next symptom to monitor based on equation (7). To calculate equation (7), the coordinator needs additional data about the symptoms and diseases that can be also provided by hospitals. The required data are shown in Table III where each number is assumed value related to the probability of the symptoms.

Table III. Probabilities of symptoms and diseases

Item	Notation	Value
$p(\text{cough} / \text{high temperature})$	$p(e_2 e_1)$	0.5
$p(\text{phlegm} / \text{high temperature})$	$p(e_3 e_1)$	0.3
$p(\text{high blood pressure} / \text{high temperature})$	$p(e_4 e_1)$	0.001
$p(\text{flu, cough} / \text{high temperature})$	$p(D, e_2 e_1)$	0.015
$p(\text{flu, phlegm} / \text{high temperature})$	$p(D, e_3 e_1)$	0.005
$p(\text{flu, high blood pressure} / \text{high temperature})$	$p(D, e_4 e_1)$	0.00001

In equation (7), to calculate the mutual information with the three parameters, the following equations are needed:

$$\begin{aligned}
 I(D; e_i; e_j) &= I(D; e_i) - I(D; e_i | e_j) \\
 I(D; e_i | e_j) &= H(D; e_j) + H(e_i; e_j) - H(D; e_i; e_j) - H(e_j) \\
 &= \mathbf{p}(e_j) \cdot \mathbf{p}(D; e_i | e_j) \cdot \log\left(\frac{\mathbf{p}(D; e_i | e_j)}{\mathbf{p}(D | e_j)\mathbf{p}(e_i | e_j)}\right)
 \end{aligned}$$

According to equations (1), (5) and (7), we can calculate the information gain (IG). The following shows an example of calculating the information gain between the two diseases flu and a cough.

$$\begin{aligned}
IG(D; e_2) &= I(D; e_2) - I(D; e_2; e_1) \\
&= 0.00001575 - I(D; e_2) + I(D; e_2 | e_1) \\
&= \mathbf{p}(e_1) \cdot \mathbf{p}(D; e_2 | e_1) \cdot \log\left(\frac{\mathbf{p}(D; e_2 | e_1)}{\mathbf{p}(D | e_1)\mathbf{p}(e_2 | e_1)}\right) \\
&= \mathbf{0.0001} \cdot \mathbf{0.015} \cdot \log\left(\frac{\mathbf{0.015}}{\mathbf{0.02} \cdot \mathbf{0.5}}\right) = 0.00000085
\end{aligned}$$

We can calculate other mutual information following the same approach using the data provided in Table II and Table III.

4.4 Evaluation of the Operation Cost

Most of the operation cost in medical sensors is communication cost. The low-rate wireless personal area network (LR-WPAN) standard, called IEEE 802.15.4, has been specified to provide ultra-low complexity and power for low-data-rate wireless connectivity among inexpensive moving devices. The IEEE 802.15.4 standard is used in many medical wireless sensors and we are also using it in this work.

IEEE 802.15.4 devices can work in two different modes: beacon mode and non-beacon mode. In this contribution, we adopted the beacon mode as the coordinator requires controlling the medical sensors. We therefore consider two different cases for packet transmission: successful packet transmission and

unsuccessful packet transmission. Thus, the total energy consumption of a sensor, derived from [57], can be expressed as

$$E(\cdot) = E_s(\cdot) + E_u(\cdot)N_u(\cdot)$$

where E_s and E_u denote the energy consumption for successful packet transmission and unsuccessful packet transmission, respectively. N_u is the expected number of packet failures.

4.4.1 Energy Consumption of Successful Transmissions

To save energy, a medical sensor is in sleep mode most of the time. It is programmed to “wake up” at regular times to process the beacon frame broadcasted by the coordinator. If it finds its address in the beacon frame, it performs a measurement encapsulates it in a packet and sends it to the coordinator and immediately after switch back into sleep mode to save energy. If there are no transmission errors, the coordinator will receive the packet. Otherwise, the coordinator will request the same data from the sensor at the next beacon cycle.

We assume that the transceiver supports several transmission power levels and each transmission signal power level $P_t(i)$ at sensor i is given by

$$P_t(i) = I_t(i)V_s$$

where $I_t(i)$ is the supply current for $P_t(i)$ and V_s is the supply voltage.

Similarly, the power consumption for reception for the entire sensor has the same expression:

$$P_r = I_r V_s$$

where I_r denotes the supply current for reception. The time interval to transmit or receive a packet is L / R_b where L represents the length of the packet R_b

denotes the transmission rate. The total number of bits in the packet has the following expression:

$$L_{pack} = 8 \times (L_{header} + L_{data}) \text{ bits}$$

Thus, the total energy consumption for successful transmission can be expressed as

$$E_s(i, L_{pack}) = E_{Tx}(i, L_{pack}) + E_{Rx}(L_{Beac}) \quad (8)$$

where E_{Tx} denotes the transmission energy consumption. E_{Rx} denotes the receiving energy consumption. We have

$$E_{Tx}(i, L_{pack}) = P_t(i)L_{pack} / R_b;$$

$$E_{Rx}(L_{Beac}) = P_r L_{Beac} / R_b$$

Substituting it into (8), we have

$$E(i, L_{pack}) = \frac{(L_{pack} I_t(i) + L_{Beac} I_r) V_s}{R_b}$$

4.4.2 Energy Consumption of Unsuccessful Transmissions

In this case, we assume the data packet is received in error. Thus, the energy consumption for unsuccessful transmission is calculated as follows

$$E_u(i, L_{pack}) = E_{Tx}(i, L_{pack}) = \frac{I_t(i) V_s L_{pack}}{R_b}$$

N_u depends on the probability of packet failure P_{PER} . Here, we assume the probabilities of received packets with error P_{PER} for each transmission independent and identically distributed. Retransmissions continue until the coordinator successfully receives the data packet. Thus, the expected number of retransmissions N_u depends on the probability that the received data packet is corrupted, $P_{PER}(i, d, L_{pack})$. Thus, we have

$$N_u(i, d, L_{pack}) = \frac{P_{PER}(i, d, L_{pack})}{1 - P_{PER}(i, d, L_{pack})}$$

where $P_{PER}(i, d, L) = 1 - (1 - P_{BER}(i, d))^L$. IEEE 802.15.4 uses O-QPSK modulation due to $f_c = 2.4\text{GHz}$ and the bit error rate is expressed by

$$P_{BER}(i, d) = Q\left(\sqrt{\frac{2E_b(i, d)}{N_0}}\right)$$

where $E_b(i, d)$ denotes the energy per bit and N_0 denotes the noise spectral density. The energy per bit in mJ is given by

$$E_b(i, d) = \frac{10^{\frac{P_r(i, d)}{10}}}{R_b}$$

where $P_r(i, d)$ is the expected received power in dBm and the distance from the sensor and the coordinator is d . Thus, the signal to noise ratio is given by

$$\frac{E_b(i, d)}{N_0} = 7.6007 \times 10^{\frac{P_r(i, d) + 94}{10}}$$

where N_0 was derived in [58] for the IEEE 802.15.4.

The average received power $P_r(i, d)$ is expressed as

$$P_r(i, d) = P_t(i) - (P_L(d_0) + 10 \alpha \log \frac{d}{d_0}) dBm$$

where $P_t(i)$ denotes the transmission power in dBm , $P_L(d_0)$ represents the expected path loss in dB from the sensor to reference distance d_0 and α is a path loss exponent [59]. The reference path loss $P_L(d_0)$, can be evaluated empirically as

$$P_L(d_0) = 10 \log_{10} \left(\frac{(4\pi d_0)^2 L}{G_T G_R \lambda^2} \right) dB$$

where G_T and G_R denote the transmitter and receiver antenna gains, respectively. L denotes the system loss factor not related to propagation and λ denotes the wave length related to the carrier frequency f_c by $\lambda = c / f_c$. Here $G_T = G_R = L = 1$.

Finally, the operation cost function can be expressed by

$$\sum_{i \in V_t(t)} [E_s(i) + E_u(i)N_u(i)] \leq C$$

4.5 Information-based Sensor Scheduling

A utility function is defined as a relation between utility and each data reading of a sensing node. The utility function can be expressed as

$$U : I \times T \rightarrow R$$

where $I = \{1, \dots, K\}$ are sensor indices and T is the time domain. Each sensor operation is also assigned a cost. Thus, the information-based sensor scheduling problem aims to maximize the value of collected information given a certain quantity of energy. It is expressed as follows:

$$\max \sum_t \sum_{i \in V_s(t)} U(i, t)$$

subject to

$$\sum_t \sum_{i \in V_s(t)} C_s + \sum_t \sum_{i \in V_t(t)} C_t + \sum_t \sum_{i \in V_r(t)} C_r \leq C \quad (9)$$

where C_s is the sensing operation cost, C_t is the transmission cost, C_r is the reception and aggregation cost and C is the total cost of the resources usage in the WBAN. We assume that each measurement operation in a sensor results in the transmission of a packet and therefore all costs are expressed in unit costs per packet. We have already calculated the information gain and operating cost in sections 4.2 and 4.4, respectively. We can easily show that the equation (9) is a constrained optimization problem aiming at maximizing the utility over a period of time by determining the sets of sensors V_s , V_t , and V_r .

In order to obtain the optimal solution, the optimization problem of the information-based sensor tasking service is reformulated as an unconstrained optimization problem by utilizing the Lagrangian duality method. Thus, the objective function is augmented with a weighted cost functions as follows:

$$\begin{aligned}
& F(p(D|\{e_i\}_{i \in B} \cup \{e_j\})) \\
&= \alpha \cdot \xi \cdot (p(D|\{e_i\}_{i \in B} \cup \{e_j\})) - (1 - \alpha) \cdot \rho(e_j)
\end{aligned}$$

where $p(D|e_{i \in B})$ denotes the coordinator's current knowledge, B denotes a subset of medical sensors whose corresponding symptom has already been processed, ξ denotes the information utility of including the symptom e_j from sensor $j \in \{1, \dots, m\} - B$, ρ denotes the communication cost as well as other resources associated with the provision of e_j , and α is the relative weight between the information gain and operating cost. In particular, we could exploit the flexibility to obtain ξ by calculating either the total information gain of the knowledge state after including the new symptom or just calculating the increase in the information gain. Based on the above objective function, the criterion for choosing which sensor to activate has the following form:

$$\text{Find } v = \arg \max_{j \in A} F(p(D|\{e_i\}_{i \in B} \cup \{e_j\}))$$

5 Evaluation

In this chapter, we explain the conducted simulation scenarios and results.

5.1 Simulation Environments

We have used in this work Network Simulator 2 (NS-2) [60] to evaluate our proposed WBAN systems. We have modified the version 2.31 of NS-2 code to support our information-based sensor tasking algorithm. Key parameters of this simulation are listed in Table IV.

Table IV. Key parameters of the simulation

Item	Contents
MAC protocol	IEEE 802.15.4
Routing protocol	NOAH (No Ad-Hoc routing Agent)
Traffic pattern	CBR
Link layer type	LL
Initial energy	300(J)
Rx / Tx energy consumption	100 (mW) / 300 (mW)
Idle mode energy consumption	100 (mW)
Sleep mode energy consumption	15 (mW)
Number of medical sensors	7
Validation time	300, 400, 500, 600, and 700 (s)
macSuperframeOrder	6
macBeaconOrder	12
Simulation area	2 (m) X 2 (m)
Simulation time	24 Hours

We created eight wireless sensor nodes: one sensor as the WBAN coordinator and seven sensors as the medical sensors. The coverage of sensors was set to 2 meters. Each medical sensor is directly connected to the WBAN coordinator in a star topology for data transmission and beacon reception. For this direct communication, we used the NOAH (No Ad-hoc routing Agent) routing protocol. Using this routing protocol, we fixed the routing table between medical sensors and the coordinator. In the IEEE 802.15.4 protocol, there are two types of operation modes: beacon enabled and non-beacon enabled modes. We used the beacon enabled mode to control the medical sensors using the beacon frame. The coordinator periodically broadcasts the beacon frame in the beacon enabled mode. Also, in this protocol, there are two kinds of communication periods: Contention Access Period (CAP) and Contention Free Period (CFP). Each medical sensor uses CAP to transmit the sensed data to the coordinator in our simulation. To build a superframe structure, there are two key parameters: SO (macSuperframeOrder) and BO (macBeaconOrder):

- SO determines the Superframe Duration (SD) with the following equation:

$$SD = aBaseSuperFrameDuration \cdot 2^{SO}$$

- BO determines Beacon Interval (BI) having following equation:

$$BI = aBaseSuperFrameDuration \cdot 2^{BO}$$

In this simulation, we used the values 6 and 12 for the SO and BO, respectively. Fig. 9 highlights the impacts of SO and BO on the IEEE 802.15.4 superframe structure.

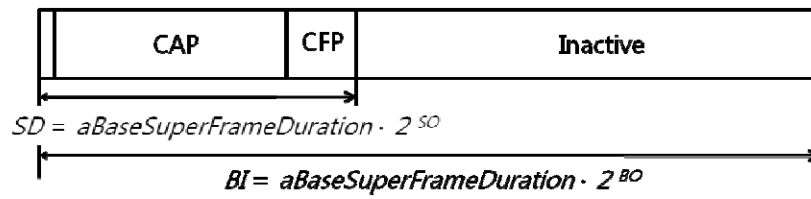


Fig. 9. SD and BI

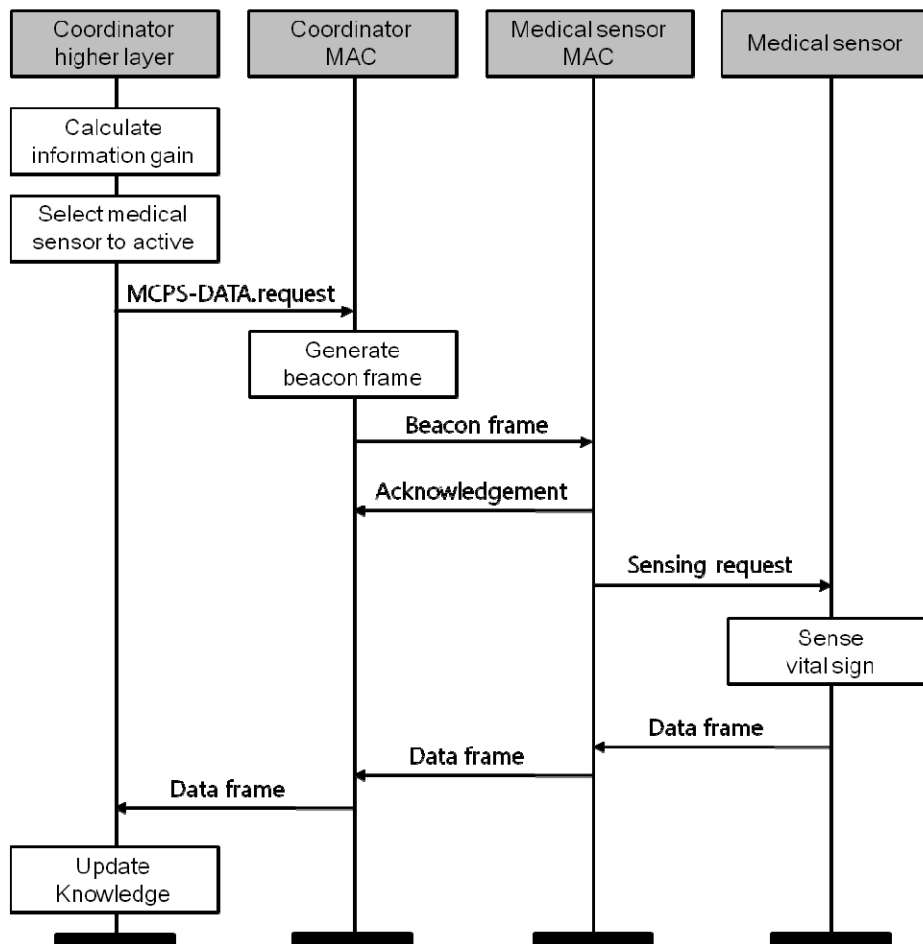


Fig. 10. Communication processes

When the WBAN coordinator requires measurements to detect a particular disease, it calculates the information gain that the knowledge of each symptom will provide and selects accordingly the corresponding medical sensors to activate according using the proposed information-based sensor selection algorithm. This information about the selected medical sensor is delivered to the MAC layer of the coordinator. In this MAC layer, when the coordinator builds a beacon frame, it sets the selected sensor's address(s) into the pending address fields as illustrated in Fig. 11. This beacon frame is broadcasted to the WBAN. The entire medical sensors always wake up just before a beacon frame's arrival and check whether the beacon frame's pending address field contains their own address. If true, the corresponding medical sensor collects data about the target vital sign and transmits it to the coordinator. If the pending address field does not contain the sensor's own address, the medical sensor goes immediately back into the sleep mode until the next beacon frame's arrival in order to save energy. The same cycle is repeated at each beacon cycle. This process is highlighted in the Fig. 10.

Octets:2	1	4 or 10	2	variable	variable	variable	2
Frame control	Beacon sequence number	Source address information	Superframe specification	GTS fields	Pending address fields	Beacon payload	Frame check sequence
MAC header			MAC payload				MAC footer

Fig. 11. Beacon frame structure

To evaluate our WBAN system, we assume five diseases and their related symptoms. Each disease has three corresponding symptoms. For example, disease 1 (D1) is identified by symptom1 (S1), symptom2 (S2), and symptom4 (S4). The remaining relationships between diseases and symptoms are listed in the Table V.

Table V. Relationship between disease and symptoms

Disease	Symptom		
D1	S1	S2	S4
D2	S2	S3	S5
D3	S2	S5	S7
D4	S2	S3	S6
D5	S2	S4	S6

Our simulation lasted for 24 hours. This simulation time consists of three phases: part1 (from 0 to 9 hours), part2 (from 9 to 16 hours), and part3 (from 16 to 24 hours). To evaluate our WBAN system, we predefined the occurrence of diseases all along the simulation period. During part1 and part3, several diseases are occurring according to the predefined schedule. During the second part of the simulation, no disease occurs.

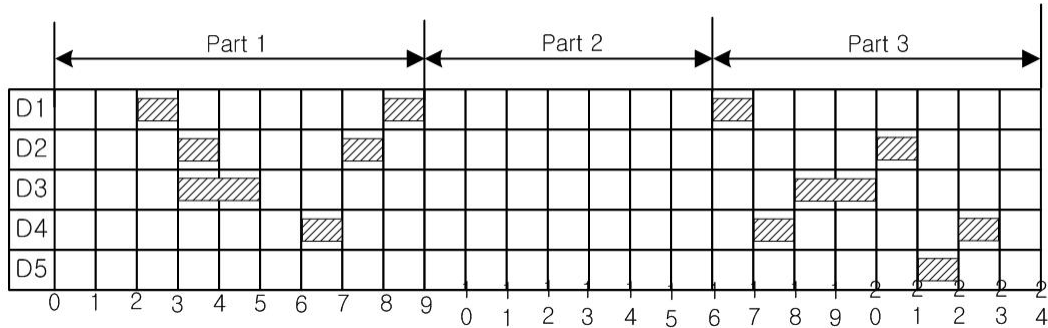


Fig. 12. Disease schedule

5.2 Simulation Results

In the section 1.2, we presented highlight the fact that existing WBAN system

are designed according to the communication needs of medical sensors such as a duty cycle. We will call this type of networks, CB-WBAN, (Communication-Based WBAN) while we'll call, WBAN designed according to our proposal IB-WBAN (Information-Based WBAN). In this section, we will explain the simulation results for these two approaches with regard to energy consumption and latency. All simulations were executed three times and the results are presented as averages.

5.2.1 Energy Consumption

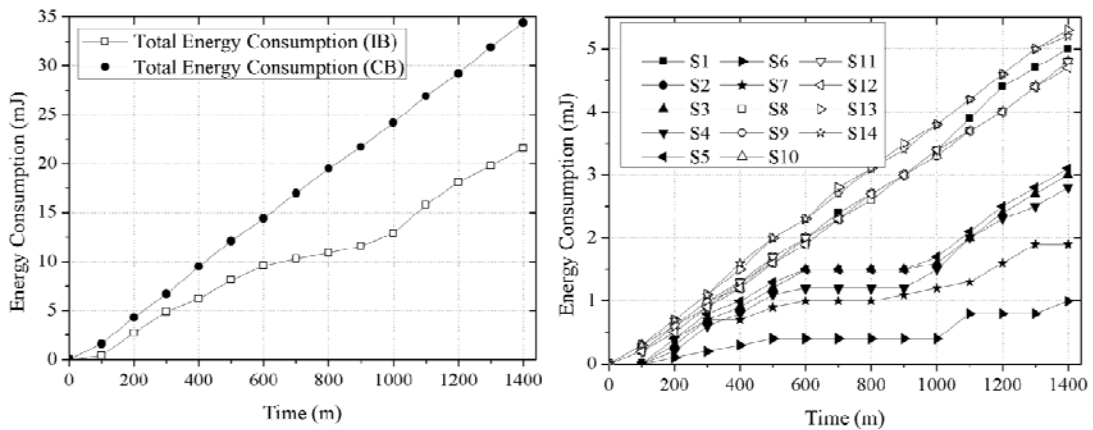


Fig. 13. Total energy consumption

Fig. 14. Energy consumption at sensors

Fig.13 shows the total energy consumption of CB-WBAN and IB-WBAN during one day. As shown in this figure, IB-WBAN allows energy savings of about 30% compared to CB-WBAN by the end of the simulation. CB-WBAN's energy consumption rate is constant from start to finish because this approach

cannot recognize a user's health state, while IB-WBAN's energy consumption rate changes according to the user's health state. Especially in the part2 (from 540 minutes to 960 minutes), a lot of energy is saved because most of the medical sensors except those that cause the highest information gain for each disease are not activated.

Fig. 14 shows more detailed information about the energy consumption of CB-WBAN and IB-WBAN. Each line represents a medical sensor's energy consumption over time. Sensors (from S8 to S17) belong to the WBAN that uses the communication-based approach. The other sensors (from S1 to S7) belong to the WBAN that uses the information-based approach. The energy consumption rate of the CB-WBAN sensors is constant. Their results are similar to each other because these sensors operate continuously, regardless of the user's health state.

In the information-based approach, the coordinator initially calculates mutual information and selects one medical sensor per disease. The chosen sensor is that one that will result in the highest information gain related to the specific disease. These medical sensors are activated firstly when the coordinator has no information about diseases. We call these medical sensors a compact subset. In our experiments, S1 and S2 are selected as a compact subset. This compact subset (S1 and S2) is activated firstly when the coordinator wants to check a disease and it operates in a way similar to the communication-based approach. For this reason, the graph of compact subset resembles the one belonging to the CB-WBAN sensors.

The energy consumption rate of the sensors belonging to IB-WBAN with the exception of the compact subset (S1 and S2) changes according to the user's health state. Especially in part2 (from 540 to 960 minutes), a lot of energy is saved. Because there is no symptom in this period, checking the compact subset is enough to determine the user's health state. Therefore, these medical sensors (S3

to S7) are not activated in this period. However, in part1 and part3, the medical sensors that are correlated with the disease are activated and consume energy for transmitting the sensed data to the coordinator.

5.2.2 Validation Time

The knowledge stored in the coordinator is only valid for a limited time period. Because a user's health condition changes dynamically, information that has passed certain time limit cannot be trusted. We will call this period of validity the validation time. In this section, we present the impact of the validation time with regard to energy consumption and latency.

Fig. 15 shows the energy consumption of CB-WBAN and IB-WBAN with variations of validation time. As shown in this figure, when the validation time decreases, energy consumption increases, because a short validation time means that the coordinator needs to update its knowledge more often. That requires more frequent measurement about same vital sign and medical sensors consume more energy. In this figure, we can also see that CB-WBAN consumes more energy than IB-WBAN in all cases.

Fig. 16 shows the latency of CB-WBAN and IB-WBAN with variations of validation time. As shown in this figure, when validation time decreases, latency also decreases because a short validation time forces the coordinator to maintain more recent information about the user's health state. This graph also shows that there is trade-off between energy saving and latency.

Fig. 17 shows more detailed information about the trade-off between energy saving and latency when the validation time is fixed at 600 (s). When the size of compact subset is identical to the number of medical sensors, its network works in a way that is similar to the communication-based approach and that produces similar results. In this figure, we can see that when the performance of energy

saving increases, the performance of latency decreases, and vice versa with variations of compact subset's size.

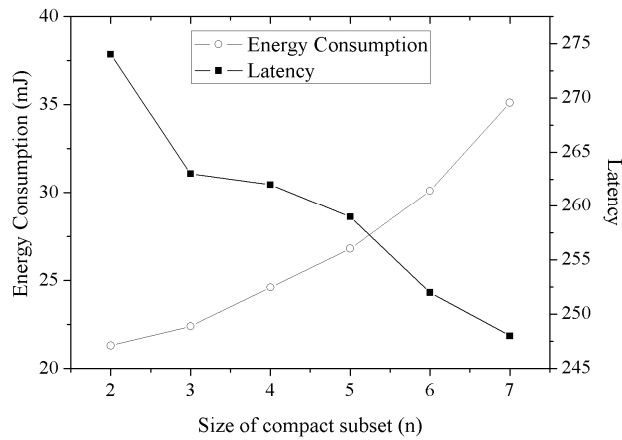
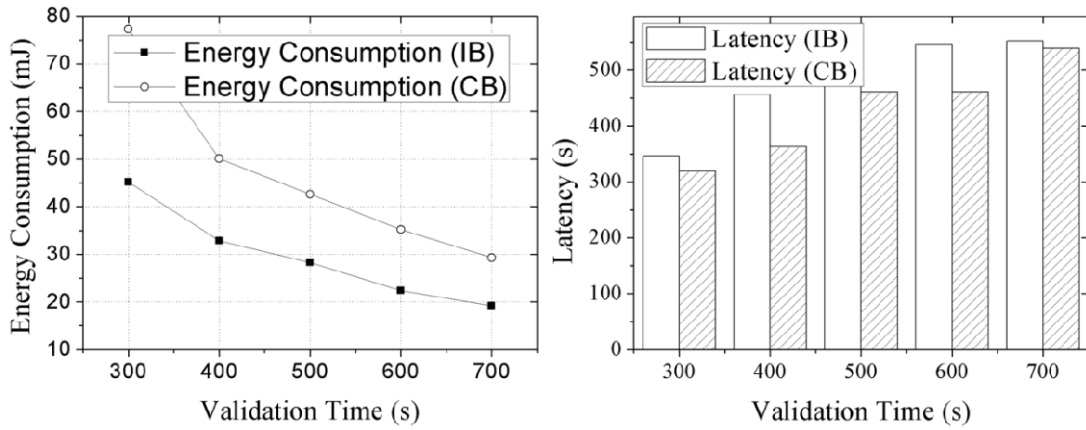


Fig. 15. Energy consumption of CB-WBAN and IB-WBAN with variations of validation time

Fig. 16. Latency of CB-WBAN and IB-WBAN with variations of validation time

Fig. 17. Trade-off between energy saving and latency

6 Conclusions

This section summarizes the overall contents of the thesis and lists a set of contributions. Suggested areas for future work are also discussed.

6.1 Summary

Our aging society is creating a huge challenge for our health care system as well as how we will treat elderly in the future. With this current trend in population, chronic diseases debase the quality of life for more people because these diseases require frequent hospital visits and long term treatment. To solve these problems, one possible solution is the Ubiquitous Healthcare (U-Health) smart home. The U-Health smart home can support autonomic and remote medical care that can be a substitute to costly hospital visits and daily human assistance. The U-Health smart home can also provide continuous health monitoring, which can support early diagnosis and treatment to reduce health care costs.

In this U-Health smart home, the WBAN has key role in providing health care services anywhere, anytime in the smart home and will play an important role in enhancing the quality of life for the elderly in their own home. However, existing remote monitoring solutions using medical wireless sensors have some drawbacks regarding the long term operation. Indeed, since, these devices are uncomfortable for the elderly since they are attached on/in their bodies, to ensure acceptance they need to be as small as possible. Unfortunately, this means also their batteries should be small as well reducing therefore their operational time necessitating human interventions which may be complex. In order to elongate the lifetime of these medical sensors, it is necessary to develop efficient approaches for the WBAN design and communications.

To improve the efficiency of the WBAN, we propose a novel information-based sensor tasking system. This system enables the WBAN coordinator to activate only important medical sensors in a given situation. To do so, we proposed to use the mutual information theory to analyze the value of the data that is gathered by the sensors. Based on mutual information, the coordinator can calculate which medical sensors will result in the highest information gain and therefore only activate these sensors to take the relevant measurements.

The important aspects of the contribution are summarized in the following:

- This thesis presented the characteristics of smart homes, WBANs, and IEEE 802.15.4.
- This thesis provided an overview of the existing WBAN system and its problems with regard to energy consumption.
- This thesis presented the U-Health smart home project which is being developed at Postech.
- This thesis designed an information gain model for when a coordinator selects a medical sensor to activate.
- This thesis designed an operating cost model for when a medical sensor communicates with the WBAN coordinator.
- This thesis proposed a novel information-based sensor tasking system for WBANs to reduce energy consumption without missing important information necessary to detect health anomalies.
- This thesis validated the proposed information-based sensor tasking system for the WBAN by implementing a prototype system based on version 2.31 of NS-2 code.

6.2 Contributions

The concept of a smart home has received a lot of attention from the research community in order to ensure occupants' comfort, convenience, security, and health care. However, the current WBAN system, which is a key component to providing health care service anywhere, anytime in the smart home, has a fundamental problem: a limited energy resource. To extend the lifetime of such system and reduce the energy consumption while maintain a required level of quality of service, we have a proposed a new model for diseases diagnosis and a corresponding analytical model as well as a new communication schema for the WBAN.

Our main contribution in this thesis is the join consideration of medical sensor scheduling at the MAC layer and information gain at the application layer to design a novel communication approach. The information-based sensor tasking system for WBAN in this thesis provides a new approach to detecting health anomalies in the U-Health smart home.

The following are the key contributions of this thesis:

- The problems of the current WBAN system are addressed.
- An information gain model by analyzing the mutual information is presented.
- An information-based medical diagnosis is presented. This approach enables the WBAN coordinator to identify strongly related symptoms for each disease in a given situation.
- Energy efficient sensor selection: Our information-based approach selects medical sensors that maximize information gain. This approach enables the WBAN to reduce energy consumption without missing important information.

- The detailed design of the information-based sensor tasking system for WBAN is described.

6.3 Future Work

In this thesis, we proposed an information-based WBAN system. This system allows energy savings of about 30% compared to existing WBAN systems. However, there is still a need for a more accurate and energy efficient health anomaly detection system.

There are several directions for future works that could benefit this area. Among these directions to enhance the accuracy and reliability of the solution, we can mention:

- The finding of a compact subset of medical sensors by defining more feasible information gain.
- The enhancing of the accuracy of our diagnosis system by using users' health profiles.
- The development of a distributed information-based system to detect health anomalies rather than the centralized architecture around the WBAN coordinator proposed in this thesis.

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Summary

평균 수명의 연장으로 65세 이상의 노인 인구가 급격하게 증가하고 있으며, 2025년에는 그 숫자가 2배에 이를 것으로 예상되고 있다. 노인들은 장기적인 치료를 요구하는 질병을 많이 가지고 있기 때문에 병원에 자주 가야 하는 불편함을 겪고 있다. 뿐만 아니라, 낙상사고 등과 같이 집에서 발생하는 사고가 노인 질병의 상당한 부분을 차지하고 있다. 이러면 문제점을 해결할 수 있는 방법 중 하나는 U-헬스 스마트 홈을 구축하는 것이다. U-헬스 스마트 홈은 집안 어디에서든 노인의 건강상태를 모니터링 할 수 있고, 원격 검진을 통해서 잦은 병원 방문을 대체할 수 있기 때문에, 노인들의 삶의 질을 크게 향상시킬 수 있다.

U-헬스 스마트 홈에서 노인들의 건강 상태를 언제 어디서든 모니터링 하기 위해서 Wireless Body Area Network (WBAN) 이라고 불리는 새로운 형태의 네트워크가 필수적이다. WBAN은 사람의 몸에 부착된 센서들간의 통신을 위한 네트워크로서 2m 정도의 반경을 가진 아주 작은 크기의 무선 네트워크이다. U-헬스 스마트 홈에 있는 WBAN은 사용자의 몸에 부착된 여러 개의 메디컬 센서와 하나의 코디네이터로 구성되어 있다. 이러한 메디컬 센서들과 코디네이터는 사용자의 몸에 부착되기 때문에, 사용자의 활동이나 움직임에 제약을 주지 않게 하기 위해서 가능한 크기가 작아야 한다. 메디컬 센서의 소형화는 센서의 배터리 크기 역시 작아져야 함을 의미한다. WBAN의 센서들은 무선으로 동작하기 때문에, 센서에 부착된 배터리에서만 에너지를 공급받는다. 또한 한번 구축 되면 배터리의 충전 및 교체는 사용자에게 불편함을 주고, implant 센서의 경우에는 배터리의 충전 및 교체가 불가능한 경우도 있다. 따라서 WBAN에 있는 센서들은 작은 크기의 배터리로부터 제한된 양의 에너지만을 공급받기 때문에 효과적인 에너지사용은 필수적이다.

센서 네트워크의 센서들은 통신하는 과정에서 많은 양의 에너지를 소모하게 된다. 특히 WBAN의 경우에는, 네트워크의 크기가 작기 때문에 모든 센서 노드들끼리 직접 통신이 가능하다. 따라서 단순한 라우팅을 가지기 때문에 상

대적으로 Media Access Control (MAC) 단계에서 많은 양의 에너지를 소모하게 된다. 본 논문에서는 WBAN의 생명을 연장시키기 위해서, WBAN 메디컬 센서들을 위한 지식 기반의 에너지 효율적인 스케줄링 기법을 제안하였다. 즉, WBAN의 모든 메디컬 센서들을 active하지 않고, 질병의 유무를 판단하기 위해서 많은 정보를 가지고 있는 증상들을 선택하고, 해당 증상을 센싱하는 메디컬 센서들만 선택적으로 active 시키는 스케줄링 기법을 제안하였다. 우리는 이것을 위해서 mutual information의 개념을 이용해서 주어진 상황에서 특정 질병의 발병 유무를 판단하기 위해서 가장 많은 정보를 가진 증상을 알아내고, 이것을 코디네이터의 스케줄링에 적용시켜서, 해당 증상들을 검사할 수 있는 센서들만 선택적으로 active시켜서 통신에 참가하게 하였다.

제안된 기법은 IEEE 802.15.4 프로토콜을 기반으로 구현하였으며, NS-2를 이용하여서, 에너지 소모 측면, 질병의 유무 판단에 걸리는 시간 측면으로 성능을 평가하였다.

Biography

Name : Hyeok Soo Choi
Birthday: April 5, 1984
Address: RIST Building 4, Rm. 4405
POSTECH, Pohang, Korea, 790-784
E-mail: soodac@postech.ac.kr
soodac@gmail.com
Tel: +82-54-279-5641
Cell: +82-10-2859-2545
Fax: +82-54-279-5699

Education

2009-2011 : MS, Dept. of Computer Science and Engineering, POSTECH, Korea
2003-2009 : BS, Dept. of Informaion and Computer Engineering, University of
Ajou, Korea

Publications: International Conference/Workshop Papers

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Research/Project Experience

1. U-Health Smart Home at POSTECH, 포항공과 대학교.