August 2013
Master's Degree Thesis

A Priority-based Reactive Routing Protocol for Wireless Body Area Networks

Graduate School of Chosun University

Department of Computer Engineering

Christian Henry Wijaya Oey

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무선 인체 네트워크를 위한 우선순위 기반 리액티브 라우팅 프로토콜

August 23, 2013

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Christian Henry Wijaya Oey

A Priority-based Reactive Routing Protocol for Wireless Body Area Networks

Advisor: Prof. Sangman Moh, PhD

A thesis submitted in partial fulfillment of the
requirements for a Master’s degree

April 2013

Graduate School of Chosun University

Department of Computer Engineering

Christian Henry Wijaya Oey

오이 크리스티안 헨리 위자야의 석사학위논문을 인준함

위원장 조선대학교 교 수 정 일 용(인)

위 원 조선대학교 교 수 강 문수.(인)

위 원 조선대학교 교 수 모 상만(인)

2013 년 5 월

조선대학교 대학원

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한 글 요 약

무선 인체 네트워크를 위한 우선순위 기반 리액티브 라우팅 프로토콜

오이 크리스티안 핸리 위자야

지도 교수: 모상만

컴퓨터공학과

대학원, 조선대학교

전 세계적인 노인 인구의 급속한 증가와 건강 관리 비용의 상승으로 최근 건강 및 의료 분야가 크게 부각되고 있다. 무선 인체 네트워크(WBAN)는 인체 내부 및 주변에 장착된 소규모 센서로 구성되며, 인체 기능과 상태를 모니터링하는 것을 목적으로 한다. 생물학적 영향을 최소화하는 것이 WBAN의 가장 주요한 요소이므로, 온도 상승을 고려한 라우팅 프로토콜의 설계가 매우 중요하다. 온도 상승을 고려한 몇몇 라우팅 프로토콜들이 제안되었으나, 그들 모두는 프로액티브 라우팅 기법들이다. 본 논문에서는 리액티브 라우팅 기법에 기반을 두고 온도 상승을 고려한 라우팅 프로토콜을

제안한다. 주요 목표는 온도 상승을 억제하고 전송률을 증가시키기 위해 중요 노드에 우선순위를 두는 것이다.

본 논문에서는 두 단계의 연구 결과가 기술된다. 첫째, 온도 상승 측면에서 프로액티브 라우팅과 리액티브 라우팅을 비교한다. 비교 분석 결과에 따르면, 리액티브 라우팅이 프로액티브 라우팅보다 우수한 성능을 나타내며, 최대 온도 상승은 27.87% 감소시키고 평균 온도 상승은 43.75% 감소시킨다.

둘째, 비교 분석 결과를 반영하여, 온도 상승을 고려한 새로운 리액티브 라우팅 프로토콜을 제안한다. 제안 프로토콜은 노드의 패킷 전송률을 제어하기 위하여 라우팅 계층과 응용 계층 사이의 크로스 레이어 설계로 이루어진다. 기존의 온도 상승을 고려한 프로토콜인 TARA와 비교하여, 제안 프로토콜은 온도 상승률이 50% 감소한다. 또한, 중요 노드에 우선순위를 부여하면 중요 노드의 전송률이 약 35% 향상된다.

ABSTRACT

A Priority-based Reactive Routing Protocol for Wireless Body Area Networks

Christian Henry Wijaya Oey
Advisor: Prof. Sangman Moh, Ph.D.
Department of Computer Engineering
Graduate School of Chosun University

The rapid growth of the elderly population in the world and the rising cost of health care impose big issues in healthcare and medical monitoring. A wireless body area network (WBAN) is comprised of small sensor nodes attached inside, on, or around a human body, the main purpose of which is to monitor the functions and surroundings of the human body. Since the reduction of bioeffects is one of the top priorities in WBANs, the temperature-aware design of a routing protocol is very important. There are already several temperature-aware routing protocols have been proposed for WBANs. However, all of them are using proactive routing approach. In this thesis, we propose a routing protocol for WBANs which is based on the reactive protocol approach. It aims to lower the temperature rise of the network and to give priority to vital nodes so that they are able to increase their throughput.

There are two steps taken in this thesis. First, we compare the generic proactive and reactive routing protocols in terms of temperature rise. We prove that the reactive protocol achieves a better performance than the proactive one. The reactive protocol achieves 27.87 % lower maximum temperature rise and 43.75 % lower average temperature rise compared to those of the proactive one.

Based on this result, we propose a new routing protocol for WBANs which is based on reactive approach, temperature-awareness, and cross-layer design between routing and application layers to control node's packet rate. The proposed protocol is compared to the existing temperature-aware routing protocol called TARA and it achieves around 50 % lower temperature rise rate. The throughput of vital nodes in the network is compared before and after the priority mode is enabled. The result shows that, after the priority mode is enabled, the throughput of vital nodes increases by around 35 %.

I. INTRODUCTION

According to the Department of Economic and Social Affairs of the United Nations Secretariat, the elderly population (persons of age 60 years and over) in the world in 2010 was 759 million and projected to be 1,198 million in 2025 or 15% of world population [1]. Since the people belonging to this age group are susceptible to various health issues, they tend to require more frequent healthcare treatment. However, it is considered inconvenient and costly if they have to periodically do medical check-up in healthcare facilities which are located far from their home, not to mention the fact that they are much less mobile than younger ones. Moreover, the cost of health care for the elderly is more expensive than that for other aged groups. Since most of health care expenditures are intended to serve elderly people, this situation could become a big challenge in the future if not taken seriously, given the limited resources.

Besides the health care cost issue, the traditional health monitoring system imposes the problem of inaccuracy. Usually, patients are monitored only at a certain point of time and the next monitoring occurs after a considerable period of time. This would lead to incomprehensive health diagnosis. For example, a healthy patient might be diagnosed to have high blood pressure whereas, in fact, that misdiagnosis is caused by exhaustion after he walks into the clinic. Therefore, a non-intrusive, ambulatory, continuous, yet economical health monitoring system needs to be developed to achieve a better and complete picture of health diagnosis and reduce the cost of health care.

Currently small and intelligent sensor devices can be attached to or even implanted into the human body, thanks to the advancement of microelectronics and micro-electromechanical systems (MEMS). These battery-powered devices gather

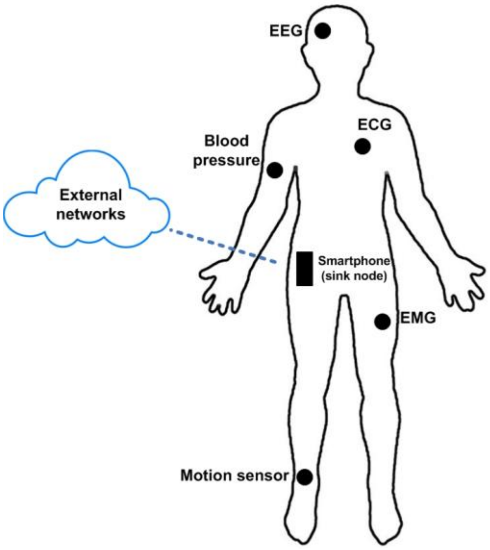


Figure 1. A general example of WBANs.

patients' vital signs and send it to medical workers, e.g. physicians and nurses, for further examination and analysis. There might be more than one sensor device attached to the body. The wired connections between devices for collecting data are not effective, troublesome, or even impossible for daily use. As a solution, the sensors are equipped with wireless transceivers so that they can communicate wirelessly to transmit the sensed data. This type of network is called Wireless Body Area Networks (WBANs) or sometimes also called Body Area Networks (BANs); hereafter WBANs. Since WBANs are actually a subset of Wireless Sensor Networks (WSNs), WBANs inherit the typical challenges and issues of WSNs.

According to the IEEE 802.15 Task Group 6 [2], Body Area Networks are defined as "a communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics/personal entertainment and others." By this definition, WBANs can be used in many application areas.

However, current studies in WBANs are mostly focused on medical applications since this is the main purpose and the reason for developing WBANs.

A WBAN consists of one or more sensor devices positioned on, in, or around the human body. The sensor devices sense and collect data from the human body and then transmit the data to a central device called sink that can be in the form of a smartphone or PDA. After collecting all information, this sink then forwards the data to the medical workers through external networks. A general example of WBANs is shown in Figure 1.

A. Research Objectives

Despite the promising applications for healthcare systems, WBANs also impose several challenges in network design and implementation. As the devices are attached to the human body, a careful design must be made to protect human tissue from heat caused by the radiation and device operation. Human safety becomes the most important factor in WBANs. Another challenge is that in general medical monitoring applications, there are nodes that are considered important. They are nodes that are monitoring physical vital signs, which are blood pressure, respiratory rate, pulse rate, and temperature. Because they are important, there should a mechanism to prioritize these nodes in terms of data delivery.

In this thesis, we propose a routing protocol for WBANs called “Priority-based reactive routing protocol” that mitigates those two challenges mentioned above. Namely, a routing protocol for WBANs that achieves a lower temperature rise rate compared to an existing routing protocol and prioritizes the throughput of the so-called priority nodes in the network. This protocol takes the reactive routing protocol approach, which has been proven to achieve better performance in terms of temperature rise compared to proactive protocol approach, and uses temperature as the indicator to control node’s packet rate which in turn, provide higher priority to the priority nodes.

B. Thesis Layout

We first study the existing temperature-aware routing protocols proposed for WBANs in literatures. Actually, there are routing protocols other than temperature-aware routing protocols proposed for WBANs. However, in this thesis, we focus only on temperature-aware routing protocols since temperature is considered as the most important parameter for designing a routing protocol for WBANs. In chapter II, first we discuss the challenges in designing a routing protocol for WBANs and then several temperature-aware routing protocols along with its strengths and weaknesses are discussed.

In chapter III, we will discuss the preliminary work of this thesis. The preliminary work compares the performance of generic proactive and reactive routing protocol in terms of temperature rise. This work is done in order to seek the feasibility of using the reactive routing protocol approach to design a routing protocol for WBANs. We perform the evaluation using simulation in MATLAB.

The proposed routing protocol is presented in chapter IV. The proposed routing protocol takes Ad-hoc On demand Distance Vector (AODV) routing protocol as its basis and adds important functionalities such as temperature awareness and packet rate control in order to adapt to WBANs requirements. The proposed routing protocol is compared against an existing key WBANs routing protocol, TARA, in terms of temperature rise rate. The result shows that the proposed routing protocol achieves a slower temperature rise rate, which is good for applications in WBANs.

Then, we increase the throughput of the vital nodes in the network using a packet rate control mechanism, a cross-layer based approach. The result shows that after the packet rate control mechanism (or later we call it priority mode) is enabled, the vital nodes achieves higher throughput compared with that before the packet rate control mechanism is enabled. The thesis is finally concluded in chapter V.

II. RELATED WORKS

Generally, a routing protocol can be defined as a set of rules to successfully deliver data from source to destination node. Designing a routing protocol for a specific environment is not a trivial work as it is influenced by many challenging issues and factors that must be overcome to achieve a particular design objective. As mentioned earlier, WBANs which are regarded as a subset of WSNs, inherits the typical challenges and issues of WSNs. However, WBANs have more specific requirements due to its placement in the human body. It must put the human safety as the top priority in the design over the other requirements such as packet delay or packet drop rate. In this chapter, there are two things that we are going to present. First, we cover the design issues that need to be considered when designing a routing protocol in WBANs with emphasis on bioeffects as the differentiating factor from typical WSNs. Second, the existing temperature-aware WBANs routing protocols that tries to mitigate the bioeffects are covered.

A. Challenging Issues

1. Bioeffects

The unique characteristic of WBANs is that the nodes are located inside, on, or around the human body. The node operation will produce heat and cause temperature rise in its vicinity. When the node’s power consumption is very low or the node is not actively sending data, it might not generate significant heat. However, when the node is operating continuously, transmitting and receiving the data in a considerable period of time, the heat generated by the node cannot be neglected. This concern becomes even bigger when dealing with in-vivo sensor nodes (i.e., implanted inside the human body). The human body has a thermoregulatory mechanism to balance the heat around the body. However, when the heat received rate is larger than the thermoregulatory mechanism rate, the temperature will rise and, in turn, damage the human tissue.

Lazzi [3] conducted a study about the thermal effects of bioimplants. There are two main sources of temperature rise when sensor nodes are implemented in the human body. They are the power dissipated by the implanted sensor nodes and the electromagnetic fields induced in the human body. The power dissipation itself can be divided into three sources: the power dissipated by the implanted microchip, by the implanted telemetry coil, and by the stimulating electrodes. When the node operates, it will consume energy and there is some energy portion which is dissipated. The dissipated energy will convert into heat and increase the temperature of its vicinity. The longer the node operates and transmitting receiving data, more energy will be dissipated and turned into heat.

The sensor nodes implanted inside the human body can be safely assumed to be using a wireless system to transmit and receive the data. The human tissue will absorb the radiation energy and convert it into heat, which then will increase the temperature. The well known parameter used by most international standards regarding the electromagnetic safety toward human body is the specific absorption rate (SAR). It can be defined as a measure of the rate at which energy is absorbed by the body when exposed to a radio frequency electromagnetic field, expressed in W/kg. By looking at its unit, we can also say that SAR shows the power dissipated per unit mass of tissue. The value of SAR is determined by these four factors: tissue density, conductivity, and electric field amplitude at a point of location in human tissue. Therefore, based on where the SAR value is calculated, the value can be different depending on those factors. However, the IEEE standard recommends the value of 1.6 W/kg averaged over 1 gram of tissue as the acceptable value of

SAR. This value is also adopted by FCC (Federal Communications Commission) to regulate the SAR level of mobile phones sold in the United States. Another commission, The International Commission on Non-Ionizing Radiation Protection (ICNIRP) defines the upper limit of 2.0 W/kg for 10 grams of tissue. The study in [4] translates these SAR values into temperature rise, and the maximum values of possible temperature increase in the human head and brain are 0.31℃ and 0.13℃ for the FCC standard and 0.60℃ and 0.25℃ for the ICNIRP standard. The study in [5] also indicates that a temperature rise of 0.1℃ is high enough to trigger intense human body thermoregulatory responses.

The effects of these factors actually can be reduced by a good hardware design. A node and its antenna can be engineered and designed to consume as low energy as possible, which therefore reduce the temperature rise. In addition, a properly designed routing protocol used in the network also plays an important role on reducing the bioeffects and this is what the routing protocols presented in this paper are trying to accomplish.

2. Other Issues

In this part, the other issues related to the design of routing protocols in WBANs are presented.

- **Network topology:** There are two main types of network topology depending on how many hops the data traverses from the source node to the sink node: single-hop and multi-hop topology. A single-hop topology means that every sensor node is directly connected to a sink node while in the multi-hop topology, the data transmitted from the sensor nodes to the sink node will traverse through one or more intermediate nodes before reaching the sink node. In case of single-hop, no routing protocol is needed since all sensor nodes are one hop away from sink node. However, due to the lossy nature of the human body, it is not always possible to have a direct communication between the source node and the sink node. It is more likely that the data will go through intermediate nodes before reaching the sink node. Moreover, Natarajan et al. [6] conducted an experiment to investigate the reliability between the two topologies. The packet delivery ratio parameter is used to measure reliability. It turned out that the multi-hop topology is more reliable than single-hop topology. Based on the reasons above, we can conclude that for WBANs, multi-hop topology is the best choice.

- **Packet delivery delay:** The packet delivery delay in WBANs also plays an important role. As the typical applications of WBANs are in the medical area, the packet usually must be delivered from the source node to the destination node within a certain period of time or deadline, otherwise it is useless. How to reduce the delay as low as possible while maintaining the temperature level becomes the challenge in designing a routing protocol in WBANs.

- **Energy consumption:** WBANs design for human use must be noninvasive and ambulatory. Thus, it must have a fewer and smaller node which also implies a smaller energy capacity. Because of this, one has to consider the tradeoff between the energy capacity and energy consumed by the processing and communication operations in order to use energy efficiently.

- **Path loss:** In WBANs, sensor nodes might be placed on the body, e.g. chest, back, wrist, or inside the body, e.g. pacemaker for regulating heart beating. The wireless transmission between these nodes must propagate through the human body, and compared to free space medium which has path loss exponent of 2, the human body is an extremely lossy environment. The path loss exponent in human body ranges from 4 to 7 [7], a value relatively much higher than the condition in free space which means that the signal power will be severely degraded.

- **Reliability:** Reliability in the data delivery in a network can be measured by Packet Delivery Ratio (PDR) and Bit Error Rate (BER). PDR represents the ratio of the number of packets received by the receiver to the number of packets generated by the sender, while BER represents the ratio of the number of error bits to the number of bits generated by the sender. Reliability is very important in medical applications. An error in data transmission from the sensor node to sink node could be fatal and could lead to mistreatment.

- **Data aggregation:** Because energy consumption for communication is much higher than that for computation [8], data aggregation might be considered as a way to save energy. Data received from different sources is combined and fused before being transmitted to the next hop node. Whether this technique is used or not, energy consumption must be considered as there is a tradeoff between energy consumption and network load. When data aggregation is not used, it means the packet size sent to the next hop node will be larger.

- **Quality of Services:** In every application, Quality of Services or QoS must be carefully considered. Each application has its own requirements: maximum delay, data rate, packet loss, bit error rate, etc. When these requirements are not met, there might be issues for the applications. For

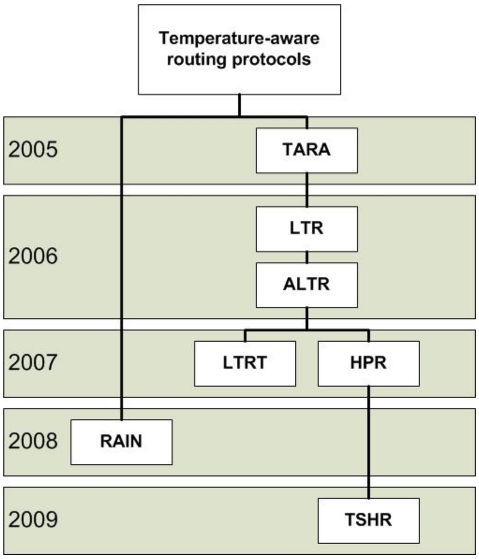


Figure 2. Taxonomy of temperature-aware routing protocols in WBANs.

example, an electrocardiogram used for monitoring heart rate in the middle of surgery must provide a real time measurement of heart rate of the patient. If it exceeds the acceptable delay or latency value, then it becomes useless.

B. Existing Temperature-aware Routing Protocols

Ullah et al. [9] conducted a comprehensive survey in WBANs. They surveyed WBANs on PHY, MAC, and network layers and classified routing protocols based on their strategies: temperature-aware, cross layer, and clustering. In this chapter, however, we are going to present routing protocols temperature-aware routing protocols only, taken from the survey in [9] and add other temperature-aware protocols that have not been included yet. These protocols are intended to be applied in the in-vivo sensor nodes. The taxonomy of temperature-aware routing protocols in WBANs is shown in Figure 2.

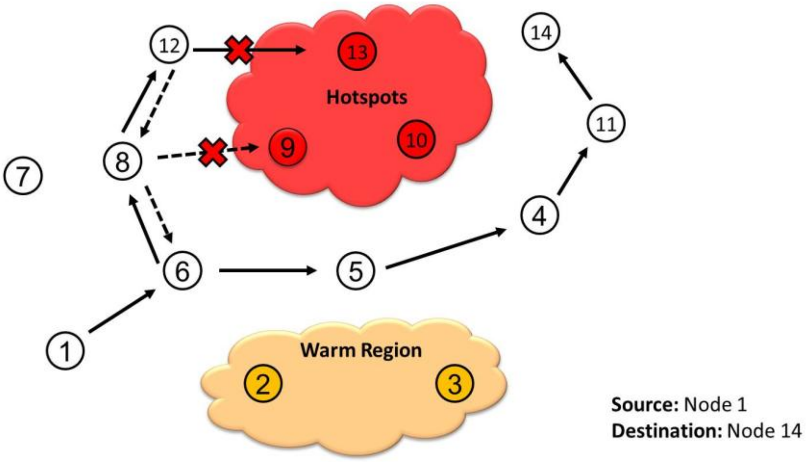


Figure 3. An example of TARA [10].

1. TARA (Thermal-Aware Routing Algorithm)

TARA or Thermal-Aware Routing Algorithm [10] is known as the first protocol that introduced temperature as a routing protocol metric. As explained in the previous section, TARA also considers two sources as the major sources of heat: antenna radiation and power dissipation of node circuitry. However, since nodes are small in size and expected to be as simple as possible, it is assumed that there is no temperature sensor inside the node to measure the temperature. Therefore, the temperature is measured by observing sensor activities, from antenna radiation and power dissipation of the node circuitry.

The general operation of this protocol is as follows. In the setup phase, each node exchanges neighborhood information, create its own neighbor list, and collect the number of hops information, so that every node knows how to reach the sink node. Next, in the data forwarding phase, the nodes having data to send will forward the packet to the next hop until it reaches the sink node. A node whose temperature exceeds a predefined threshold value will be marked as a hotspot node and any

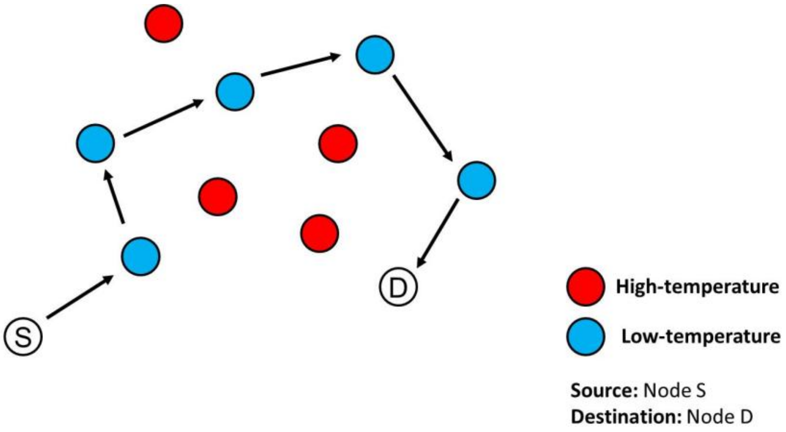


Figure 4. An example of LTR [11].

packet having a hotspot node as its destination node will be buffered until the estimated temperature drops. If the buffered packet period exceeds the timeout period, it will be dropped.

When the hotspot node is an intermediate node, the packet will be routed through different path and thus avoiding the hot spot area. This strategy is called withdrawal strategy, which operates as follows. If the next hop node is a hotspot node, the node will check into the forwarding set of this route whether there is any other available next hop node to send the packet to. Should there is no more available next hop nodes, the packet will be forwarded back to the previous node. This previous node will try to forward the packet using an alternative path or might again forward it back to its previous node. The information about hotspot nodes is carried by the packet when the withdrawal strategy is used. A sample of how TARA works is shown in Figure 3.

Basically, TARA tries to avoid the hot spot area by observing the neighboring nodes' temperature and detour the packet using the withdrawal strategy. This strategy causes high delay and low network lifetime since the packet will be

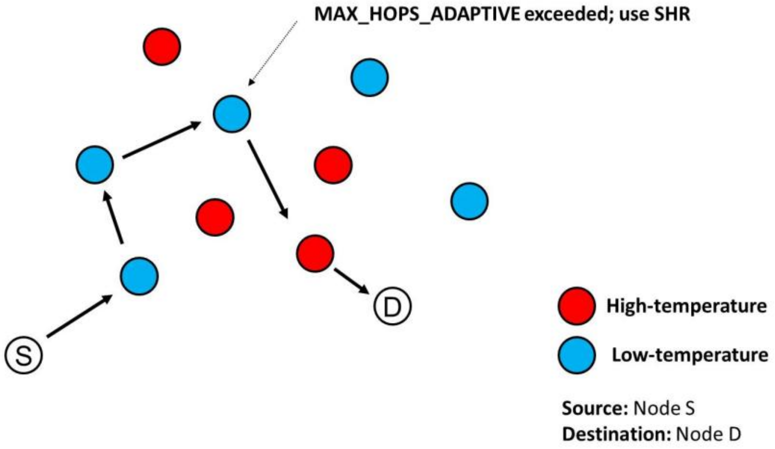


Figure 5. An example of ALTR [11]

roaming around the network for some considerable amount of time. However, this withdrawal strategy, which avoids the hotspot nodes, will balance the load in the network since hotspot nodes are considered as high load nodes, i.e., nodes that already served a lot of packets.

2. LTR (Least Temperature Routing)

LTR or Least Temperature Routing protocol [11] is developed based on TARA protocol. The setup phase is similar to that of TARA, every node communicates with its neighbors and gather information about their temperature by observing their activities. The improvement lies on how the packet is forwarded in the network. Unlike TARA that buffers the packet if the destination node is a neighboring node, LTR forward the packet directly to the destination node. And as its name implies, in LTR, each node tries to forward the packet to the "coolest" neighbor since the beginning of transmission from the sender node. There is also a packet discarding mechanism, in which a parameter named MAX HOPS is defined and if the received packet's hop count exceeds this value, the packet will be drop.

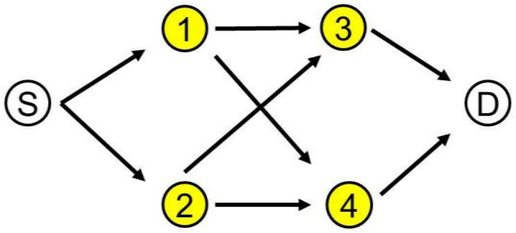
The purpose of this mechanism is to prevent a packet from going around the network too far. Another mechanism to reduce unnecessary hops and loops is also presented. If the "coolest" neighbor has been recently visited, the packet will be forwarded to the "second coolest" neighbor. To support this mechanism, a list of recently visited nodes within some time window is included in the packet. Figure 4 shows a sample of how the LTR protocol works in the network.

3. ALTR (Adaptive Least Temperature Routing)

ALTR or Adaptive Least Temperature Routing [11] is the adaptive form of LTR. A new parameter named MAX HOPS ADAPTIVE is presented by this protocol. Each time a packet is received by a node, its hop count value is examined. If the value is lower than MAX HOPS ADAPTIVE, then the packet is routed in the same way as LTR. However, as shown in Figure 5, if the value is greater than MAX HOPS ADAPTIVE, instead of being dropped, the packet is routed using shortest hop algorithm. ALTR also introduced a mechanism called "proactive delay" to reduce the temperature rise at the cost of the packet delivery delay. If a node receives a packet and has no more than two outgoing neighbors such that its coolest neighbor has a relatively high temperature, the node delays the packet by one time unit before forwarding it to the coolest neighbor.

4. LTRT (Least Total-Route Temperature) Routing

This protocol, named LTRT or Least Total-Route Temperature [12], is basically a hybrid between the LTR protocol and shortest hop routing algorithm. This protocol uses temperature as its metric, and then using shortest hop algorithm, it calculates the route with the lowest temperature metric.



Weight of Nodes:
Node 1 = 1
Node 2 = 2
Node 3 = 3
Node 4 = 4

Path 1-3-D = 4 ← best route
Path 1-4-D = 5
Path 2-3-D = 5
Path 2-4-D = 6

Figure 6. An example of LTRT [12].

The algorithm of this protocol is briefly described as follows. First, every nodes collects the temperature information from its neighboring nodes and then build all possible routes to the destination. Then, it assigns temperature as weight to each intermediate node and builds a weight graph. On this graph, it applies the Djikstra’s algorithm to solve the single source shortest path (SSSP) problem of the weight graph. The result is a path which has the lowest temperature metric. A sample of this graph is shown in Figure 6. That being said, since the beginning, LTRT tries to look at the end- to-end connection perspective, instead of the connection between two directly connected nodes only. It tries to select the least temperature route from every possible route.

5. HPR (Hotspot Preventing Routing)

Hotspot Preventing Routing or HPR algorithm [13] is an improvement of LTR and ALTR. In LTR and ALTR, reducing the network average temperature does not necessarily mean preventing any node having a very high temperature. However, HPR not only prevents the formation of hotspot nodes in the network but also prevents the packets from taking suboptimal paths, and thus reducing the average network delay. This protocol achieves both objectives of preventing hotspots and reducing delay by means of the shortest hop algorithm and a threshold value.

There are two phases in HPR: setup phase and routing phase. In setup phase, nodes exchange information about the shortest path and initial temperatures, and building a routing table based on that information. In routing phase, first, nodes use shortest hop algorithm as long as no hotspots appear in the path. A hot spot is dynamically determined using a threshold value that is derived from both average temperatures of neighboring nodes and nodes' own temperature. If the next hop node's temperature exceeds the sum of the temperature of the sender node and threshold, then the packet will be forwarded to the "coolest" neighbor. Similar to LTR, HPR uses MAX HOPS parameter, which drop packets that exceeds this threshold value, and a list of recently visited nodes to prevent any routing loops.

This protocol differs from its predecessors on how it defines when a node is marked as a hotspot. The previous protocol uses a predefined temperature threshold value and if a node exceeds this value, it is marked as a hotspot. However in HPR, the threshold value is dynamically calculated by each node considering neighbors' temperature and its own.

6. TSHR (Thermal-aware Shortest Hop Routing)

TSHR or Thermal-aware Shortest Hop Routing [14] is an improvement of HPR. It is almost similar to HPR that has two phases - setup and routing phase - and makes use of threshold. The difference is that in TSHR, there are two kinds of threshold introduced: fixed threshold and dynamic threshold. Fixed threshold is a threshold value that is applied for all nodes, while dynamic threshold is a threshold value that is specific to each node and set based on the temperature of the node and its neighbors. The dynamic threshold is used to mark a node as a hotspot. If the next hop node temperature exceeds this dynamic threshold, the sending node will look for another coolest node which has not been visited by the packet. On the other hand, the fixed threshold is used every time a node is going to transmit a packet. It compares the next hop node temperature to the fixed threshold and if it exceeds the threshold, the packet will be buffered until the next hop node temperature is below the threshold. The fixed threshold implies the maximum node temperature allowed in the network. Another difference is that no packets are dropped in TSHR. If the hop count exceeds the maximum hop threshold, then the packet is forwarded using shortest hop algorithm.

7. RAIN (Routing Algorithm for network of homogenous and Id-less biomedical sensor Nodes)

RAIN [15] stands for Routing Algorithm for network of homogeneous and Id-less biomedical sensor Nodes. The main difference between RAIN and the above routing protocols is that in RAIN, the nodes are id-less. It is argued here that the overhead of id maintenance is very high and in sensor networks, how to get the sensed data from network is more important than knowing node id itself. That is why the approach of using id-less network is proposed.

The word id-less here does not mean it really does not use node id at all. It uses, instead of a static id, a temporary id. This id is generated during setup phase of protocol operation. Each node has a random number generator that generates random number between 1 and (2^{16}-1) which will be its node id during operational lifetime. Since this protocol does not maintain global addressing, it relies on local addressing and coordination. Each node needs to know only its neighbors id; thus, there might be two identical node ids in two different localities in the network. Nonetheless, this does not affect the network performance.

In this protocol, a mechanism to prevent a node from sending a duplicate packet is implemented. The algorithm will check whether or not the received packet id is already in the queue. If it is, then the packet will be dropped. Hop counts check is also implemented to prevent packets from going around the network uselessly. This protocol deals with nodes temperature by using probability to send a packet to next hop nodes. Each next hop node is assigned a probability value that is inversely proportional to the estimated temperature of the nodes. This way, the “coolest” neighbor node is likely to be chosen as the next hop node.

Another main mechanism implemented in RAIN is Status Update, a mechanism implemented to mitigate “Energy Hole” problem in the network. The “Energy Hole” problem occurs when the nodes around the sink become depleted of energy very fast due to receiving and forwarding packets coming from the network. To mitigate this, the sink node will broadcast a status update to its neighbors which contains packet-id of the received packets by the sink node. This will prevent neighbor nodes from forwarding multiple copies of the same packet to the sink node, thus saving a lot of energy.

8. Comparison and Discussion

The ultimate objective of the temperature-aware routing protocols is to reduce the temperature rise caused by the node's operation. All protocols here are intended for in- vivo sensor nodes, that is, the nodes implanted inside the human body. In this section, we discuss the advantages and disadvantages of each protocol and how a routing protocol in WBANs should be designed. The comparison between protocols is shown in Table 1.

TARA is the first routing protocol that introduced temperature as a routing metric. The first advantage of TARA compared to SHR (Shortest Hop Routing) protocol is

Table 1. Comparison of temperature-aware routing protocols in WBANs.

Routing protocol	Routing approach	Application area	Packet discarding mechanism	Routing decision	Addressing scheme	Link Model
TARA	table-driven	in-vivo nodes	not available	per-hop basis	global-id	bi-directional
LRT	table-driven	in-vivo nodes	available	per-hop basis	global-id	bi-directional
ALTR	table-driven	in-vivo nodes	not available	per-hop basis	global-id	bi-directional
LTRT	table-driven	in-vivo nodes	not available	end-to-end basis	global-id	bi-directional
HPR	table-driven	in-vivo nodes	available	per-hop basis	global-id	bi-directional
TSHR	table-driven	in-vivo nodes	not available	per-hop basis	global-id	bi-directional
RAIN	table-driven	in-vivo nodes	available	per-hop basis	local-id	bi-directional

that it achieves a better performance in terms of reducing the maximum and average temperature rise. The SHR protocol only cares about how to send the packet to the destination node using as short route as possible without considering any other factors. While it achieves a low packet delivery delay, it suffers from high temperature rise since the same nodes will always be used for a particular route. On the other hand, the TARA protocol concerns about the temperature of the nodes and using the withdrawal strategy, it will avoid hotspot nodes by sending back the packet to the previous node and tries another available route. This mechanism will reduce the average temperature rise of the network and limit the maximum temperature to the predefined threshold value. Nevertheless, as the trade-off, the withdrawal strategy introduces high delay because the packet will be detoured arbitrarily using another route as long as there is an available next hop node.

The second advantage of TARA is reducing the traffic congestion in the network by means of load balancing. TARA calculates the temperature of neighboring nodes by observing the nodes’ activities, that is, how many packets are transmitted and received by the nodes. It means that the more number of packets are transmitted and received by a node, its temperature will rise. Therefore, while TARA tries to distribute the temperature in the network, in the same time the load of the network is also distributed and thus, resulting in less traffic congestion.

As explained previously, the packet delivery delay plays an important role in routing protocols in WBANs. The drawback of TARA, which introduces delay due to the withdrawal strategy, is trying to be solved by the LTR protocol. Unlike TARA, if the next hop node is the destination node, the packet is forwarded immediately, no buffering mechanism. There is also no withdrawal strategy in LTR, which means there is no packet sent back to the previous node, and a list of recently visited nodes is also maintained to prevent routing loops. Moreover, since the beginning, LTR tries to send the packet via the coolest neighbor. However, there is a packet discard mechanism to prevent a packet roaming around too long in the network.

The ALTR protocol is an adaptive form of LTR. The adaptive form here means, the general mechanism is the same with LTR but a different threshold called MAX HOPS ADAPTIVE is introduced. When the hop count of the packet received by a node exceeds this threshold, the packet is forwarded to the destination node using shortest hop algorithm. By means of these mechanisms, LTR and ALTR achieves a better performance than TARA in terms of packet delivery delay and average temperature rise in the network. In addition, while LTR still introduces packet drop due to the packet discarding mechanism, ALTR achieves a comparable performance with SHR in terms of percentage of packet drop during the simulation.

Another disadvantage of LTR and ALTR is that there is no guarantee that during the transmission from sender to destination, the packet will always be transmitted toward the direction of destination node. A packet may be sent to a wrong direction away from the destination node because LTR and ALTR only concerns about the nodes temperature. Moreover, in ALTR, the packets might be transmitted through the hotspots after exceeding MAX HOPS ADAPTIVE which will result in temperature rise.

These disadvantages are trying to be mitigated by the next protocol, LTRT. Looking at the end-to-end connection perspective, LTRT transmit the packet through the path or route having the lowest temperature level. Therefore, the packet will always be transmitted toward the direction of the destination node, no sending back the packet to previous node. Using this algorithm, LTRT achieves a lower average temperature rise and lower packet delay compared to LTR and ALTR.

Nevertheless, the average temperature rise metric that is used by LTR, ALTR, and LTRT is not appropriate for WBANs applications. The reason is that the average temperature rise does not reflect the individual node's temperature. The average temperature level may appear to be low while actually there are nodes who already exceeds the safe temperature level. These nodes that are already above the safe temperature level are hazardous for human health. Therefore, the metric maximum temperature rise, which is used by TARA, is more appropriate to be used in WBANs because it shows the maximum temperature rise that exists in the network.

The HPR protocol provides a better approach in dealing with temperature rise in the network. It considers the maximum temperature rise as the metric, not average temperature rise, and also it uses a dynamic threshold based on node's own temperature and its neighbors. HPR achieves a better performance compared to TARA and SHR in terms of maximum temperature rise, average delay, and packet drop especially in high packet arrival rate environment. Unlike TARA that tries to withdraw the packet back to previous node, HPR tries to bypass the hotspot nodes by sending the packet to the coolest next hop node.

The TSHR protocol did some modifications on HPR protocol. Besides the dynamic threshold that is used by HPR, TSHR added one more temperature threshold called fixed threshold that is applied to every node before it transmit the packet. This threshold defines the maximum temperature allowed for a node to participate in the routing process. Different from HPR, in TSHR there is no packet discarding mechanism. If the next hop node is a hotspot, the packet will be buffered until the temperature drops below threshold. While this provides a low packet drop rate, it suffers from higher network delay compared to HPR.

As for the last protocol, RAIN protocol offers a unique characteristic. In contrast with the previous protocols, RAIN does not use global id for each node, it uses local-id instead, which is generated randomly. This approach is developed to deal with the possibility of id-less network deployment in the future. This is a clear advantage of RAIN compared to the other protocols. The comparison in simulation is done with C-FLOOD, a flooding algorithm, and RAIN achieves a better performance in terms of maximum temperature rise, energy consumption, packet delivery ratio, and average packet delivery delay.

From the explanation above we can see that all routing protocols presented here have the same method to estimate node’s temperature. They calculate the temperature by observing the node’s activities, how many packets are transmitted and received by the nodes. They also use distributed algorithm in the sense that each node has the capability to decide the route; it does not depend on one node to decide the route.

However, after observing the advantages and disadvantages of each routing protocol, we can find some rooms for improvement in routing protocols for WBANs in the future. Table 2-1 shows that all protocols use proactive or table-driven routing approach, which means that each node maintains a routing table to be used in the routing decision. However, the reactive or on-demand approach is also worth considering to be implemented in the routing protocol in WBANs especially for applications that transmit data periodically, e.g. every 30 minutes or every hour. This way, each node does not have to maintain routing table when there is no data traffic, thus, reducing the routing overhead. For a resource-limited environment such as WBANs, this approach needs to be considered.

Another issue to deal with is in the link model assumption. All routing protocols having been proposed so far assume the link between nodes to be bi-directional, that is, each pair of node is able to transmit data to each other. However, in the real environment, due to node heterogeneity, the link is most likely to be uni-directional. There is no guarantee that if node A can transmit data to node B, node B can also transmit data to node A. This situation also needs to be coped by routing protocols in WBANs. The mechanism to transmit the data using an optimal power level of transmission is also interesting to be explored.

III. COMPARISON OF PROACTIVE AND REACTIVE ROUTING PROTOCOL

As explained in the previous chapter, we know that all existing temperature-aware routing protocols for WBANs are using proactive approach. Therefore, with an assumption that reactive approach will produce a lower temperature rise due to less network activity, in this chapter we would like to seek the possibility of using a reactive approach in designing a routing protocol for WBANs.

Several studies have compared and analyzed routing protocols in general mobile ad hoc networks. For example, Jun et al. [16] provided an expressive analytical model for general routing protocols in mobile ad hoc networks based on probability theory. The mobility and delay were defined using probability and the throughput was then measured afterwards. Abdullah [17] also performed analytical modeling for throughput and delay in wireless multihop ad hoc networks. However, their study focused only on the MAC layer.

Our work in this chapter is based on a study conducted by Xu et al. [18], where generic proactive and reactive routing protocols were modeled using a mathematical model. The word “generic” means that it did not use any specific proactive or reactive routing protocols. That is, the authors defined the general characteristics of both proactive and reactive routing protocols. The protocols were analyzed in network and MAC layer using probability theory to model the broadcast rate and the delay of the network. They were then compared in terms of protocol efficiency, packet delivery ratio, and packet delivery delay. However, this study did not take the temperature rise as a metric for comparison.

A. System Model and Assumptions

- **Topology.** Because this study was only interested in comparing the performance of the routing protocols with regard to the temperature rise, it was assumed that the nodes are located in a grid network topology.

- **Mobility.** The nodes in the network were assumed to be stationary. Although human body movement might cause mobility to the network, particularly for the nodes located in arms and legs, it is safe to assume that for the nodes attached to the torso or head, small mobility occurs relative to the position of the central node (e.g. central node attached to the waist). Therefore, this study assumes that there is no mobility in the network.

- **Link connectivity.** The links between nodes were considered bidirectional. This means that if a node can send data to a particular node, it also can receive data from that node.

- **Node neighborship.** A node is considered a neighbor of any particular node in a network if it is inside the transmission range of that particular node.

- **Traffic model.** In the network, there will be one central node that gathers all the data from all other nodes. This type of network is called a converged-cast network. Data generation in the network will be defined by the probability.

1. Proactive Routing

As the name suggests, every node proactively maintains a routing table to each destination in the network. Upon the activation of a node in a network, the node will broadcast a topology packet periodically informing the other nodes about the routes it knows. After every node receives complete information about the network and how to reach every destination in the network, the network is considered to be converged and ready to operate.

When a node receives a packet, it will read the destination address from the packet header, look up the routing table for the next hop node address, and forward the packet accordingly. In the proactive routing protocol, the route is always available because every node maintains its routing table by periodically exchanging topology updates message. Every time a node needs to send data, it just looks up the next hop destination node in the routing table and sends it accordingly.

In addition to exchanging topology update messages, every node also monitors its connected links, and if the link is disconnected, it will broadcast the topology change updates throughout the network. After all the nodes are informed about the changes, the network can operate as normal again.

2. Reactive Routing

The generic reactive routing protocol works on an on-demand basis. This means that unlike the proactive routing protocol, which always provides the route, the reactive protocol only creates a route whenever there is a need to send data from a source node to its destination node. The nodes that are not involved in the flow of data can be idle or even put into a sleep state. No routing table is maintained in each node. The operation of the reactive routing protocol can be divided into two main parts:

- **Route discovery.** When a node needs to send a packet to the destination node, it will broadcast a route request packet to its neighbors asking for the route. If the intermediate nodes have the asked route, they will reply with a message to the source node along with the route information to the destination node; otherwise, it will again broadcast the request message. After the request message reaches the destination node, the destination node will reply to the source node along with the route. At this point, the route discovery phase is considered complete and the data can be sent from the source node to the destination node.

- **Route maintenance.** As in any sensor network, the link between the source and destination node might be disconnected, causing the flow to be disrupted. In this case, the node, whose link is broken and closer to the source node, will send a unicast route error message to the source node. The source node can again perform the route discovery mechanism.

3. Formulation

- **Temperature Rise**

  The well-known Pennes bioheat equation, as used in [10], is used in this work:

$$\rho C \frac{dT}{dt} = K\nabla^2 T + \rho SAR - b(T - T_b) + P_c + Q_m (Watt/m^3) \qquad (1)$$

where *dT/dt* is the rate of the temperature rise in the control volume and ρ is the mass density of human tissue. The right side shows the factors affecting heat transfer inside the human body. $K\nabla^2 T$ and $b(T-T_b)$ are the heat transfer caused by the conduction and blood perfusion, respectively, whereas Q_m is the heat generated by metabolic heating.

This differential equation was solved using the Finite-Difference Time-Domain method, and the result of the new bioheat equation can be expressed as follows [10]:

$$\begin{aligned} T^{m+1}(i,j) &= \left[1 - \frac{\delta_t b}{\rho C_p} - \frac{4\delta_t K}{\rho C_p \delta^2}\right] T^m(i,j) + \frac{\delta_t}{C_p} SAR + \frac{\delta_t b}{\rho C_p} T_b + \frac{\delta}{\rho C_p} P_c \\ &+ \frac{\delta_t K}{\rho C_p \delta^2} \begin{bmatrix} T^m(i+1,j) + T^m(i,j+1) \\ + T^m(i-1,j) + T^m(i,j-1) \end{bmatrix} \end{aligned} \tag{2}$$

where Tm+1(i,j) is the temperature of the grid at coordinate (i,j) at time m+1, δt is the discretized time step, and δ is the discretized space step.

Looking at equation (2), all variables except for *SAR* and *Pc* were constant. Therefore, only the value of *SAR* and *Pc* need to be found to obtain the temperature. The method for calculating the *SAR* value is explained in the next subsection, whereas *Pc*, was obtained simply by counting the number of packets transmitted and received by a node.

- **Specific Absorption Rate (SAR)**

The nodes in the network communicate with each other wirelessly using an antenna. The antenna produces electrical and magnetic fields. As examined by many researchers, the radiation generated by the antenna will be absorbed by human tissue. As a result, the human tissue will experience temperature rise. The measure of the rate at which radiation energy is absorbed by the tissue per unit weight is called the Specific Absorption Rate (SAR). In many countries, the government regulates the maximum allowable value of the generated SAR of mobile devices, such as handphones. The formula to show the relationship between radiation and SAR [10] can be expressed as

$$SAR = \frac{\sigma |E|^2}{\rho} (Watt/kg) \tag{3}$$

where σ is the electrical conductivity of human tissue, E is the electric field induced by radiation, and ρ is the tissue density. The induced electric field E is directly proportional to the value of SAR.

The node uses a short dipole antenna consisting of a short conducting wire with a length dl. The current given to the antenna is the sinusoidal drive current I. The area around the antenna is divided into two areas: near field and far field. The near field will span as far as $d0 = \lambda/2\pi$, where λ is the wavelength of the radio frequency.

The formula for the SAR in the near field and far field [10] can be written as

$$SAR_{NF} = \frac{\sigma\mu\omega}{\rho\sqrt{\sigma^2 + \varepsilon^2\omega^2}} \left(\frac{I \cdot dl \cdot \sin\theta e^{-\alpha R}}{4\pi} \left(\frac{1}{R^2} + \frac{|\gamma|}{R} \right) \right)^2 \tag{4}$$

$$SAR_{FF} = \frac{\sigma}{\rho} \left(\frac{\alpha^2 + \beta^2}{\sqrt{\sigma^2 + \varepsilon^2\omega^2}} \frac{I \cdot dl}{4\pi} \right)^2 \frac{\sin^2 \theta e^{-2\alpha R}}{R^2} \tag{5}$$

where R is the distance from the antenna to a point on the human tissue, θ is the angle between the observation point and the x-y plane, γ is the propagation constant, ε is permittivity and ω is the frequency.

Table 2. Simulation parameters.

Parameter	Value
Number of nodes	36
Network area	100×100 cm^2
Gap between nodes	10 cm
Transmitting energy	0.3132 Joule
Receiving energy	0.03528 Joule
Payload size	100 bytes
Simulation time	10000 seconds

The second source of heat is the power dissipation of the node. When a node operates, it will consume power but some of the power is converted to heat, which is called power dissipation. As the amount of power dissipated is directly proportional to the amount of power consumed, the amount of power dissipated can be estimated by measuring the power consumption by the node.

The source of the node's power consumption can be divided further into four sources: transmitting power, receiving power, idle power and sensing power. The transmitting and receiving power is the power consumed by the node when it transmits or receives any type of data. In other words, when the antenna operates. The idle power is the power consumed by the node when it is neither transmitting nor receiving but is in standby. The last one, the sensing power, is the power consumed by the node when it senses and gathers information from its environment.

B. Performance Evaluation

To evaluate the temperature rise produced by both proactive and reactive protocols, the simulation program was written in MATLAB using a time-based simulation

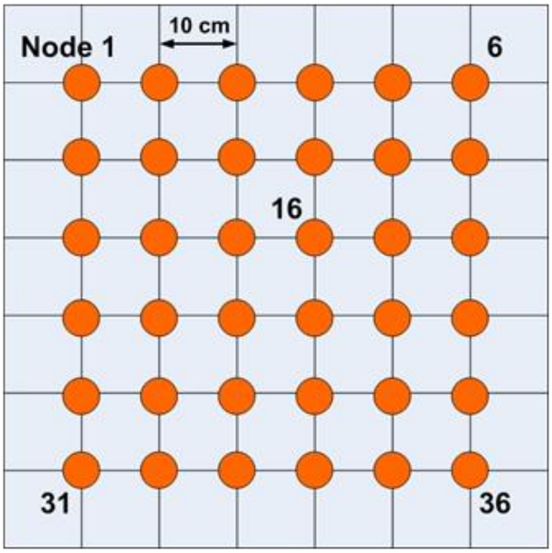


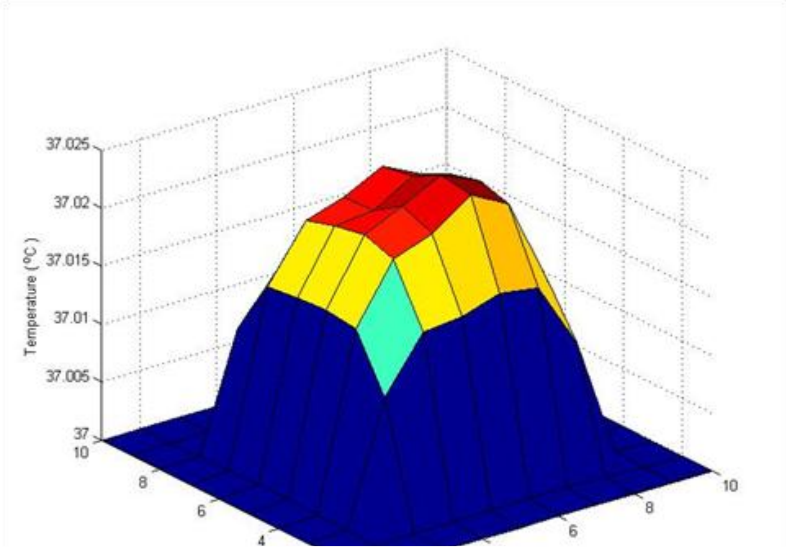
Figure 7. Network topology.

approach. As shown in Figure 7, there are 36 nodes in a grid network of 100 × 100 cm2, and the gap between nodes is 10 cm. Node number 36, located at coordinate (8, 8), was chosen as the sink node, whereas the source nodes are chosen randomly from the rest of the nodes. The source nodes transmit data to the sink node with multihopping and constant bit rate data. The energy to transmit and receive a bit of data is 0.03132 Joule and 0.03528 Joule, respectively. Table 2 lists the simulation parameters. The temperature rise distribution for both protocols was examined and then the temperature of several nodes over the simulation time is also presented.

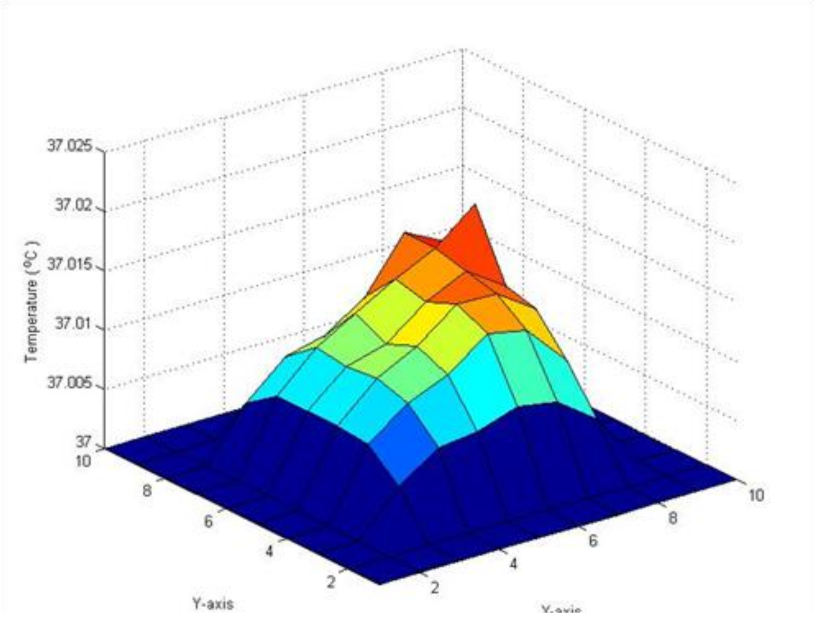
Figure 8 shows the temperature rise distribution of both proactive (a) and reactive (b) protocols. The maximum temperature rise for the proactive and reactive protocol was 0.0244℃ and 0.0176℃, respectively. In other words, the reactive protocol achieves a 27.87% lower maximum temperature rise. For the average temperature rise, the proactive protocol and reactive achieve 0.0064℃ and 0.0036℃, respectively; the reactive protocol is 43.75% lower than the proactive one.

The temperature of the nodes during the simulation time was also monitored and Figure 9 shows some of them. The graphs show that the reactive protocol achieves a lower temperature rise than the proactive one. The proactive protocol achieves a lower temperature rise only on node 36 (Figure 9c), which is the sink node. This suggests that in the reactive protocol, particularly when a link error occurs, the node whose uplink is broken will send a link error unicast packet back to the source node. If the link error occurrence is relatively high, the particular node will need to produce more link error packets, which will in turn affect the temperature rise. On the other hand, the sink node is assumed to be a device located outside the human body and is normally in the form of a PDA or smartphone, which means that the temperature rise does not really become a concern.

The results show that the operation of a reactive protocol achieves a lower temperature rise than the proactive protocol. Therefore, to design a routing protocol for WBANs, the reactive protocol approach is worth considering. However, one also must remember that the design of a routing protocol also depends on its applications. For example, in a critical application, the data packet must be delivered from the source node to the destination node within a certain period of time, otherwise the data is invalid. In this case, one should consider using proactive protocol over reactive one because, as studied in [18]-[20], the proactive protocol achieves a lower packet delivery delay than the reactive one.

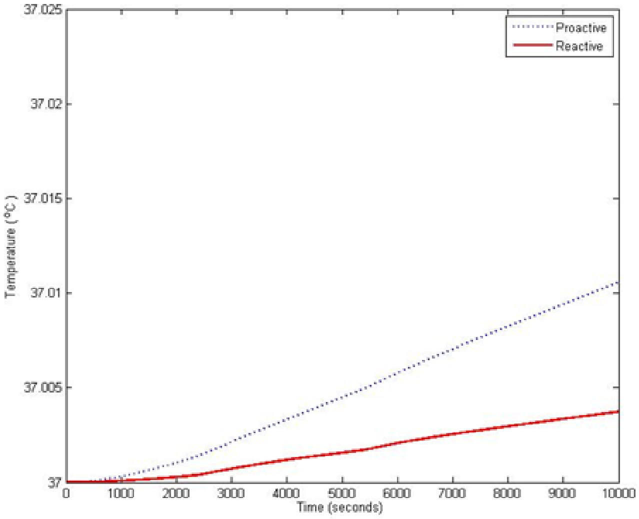


(a) Proactive routing

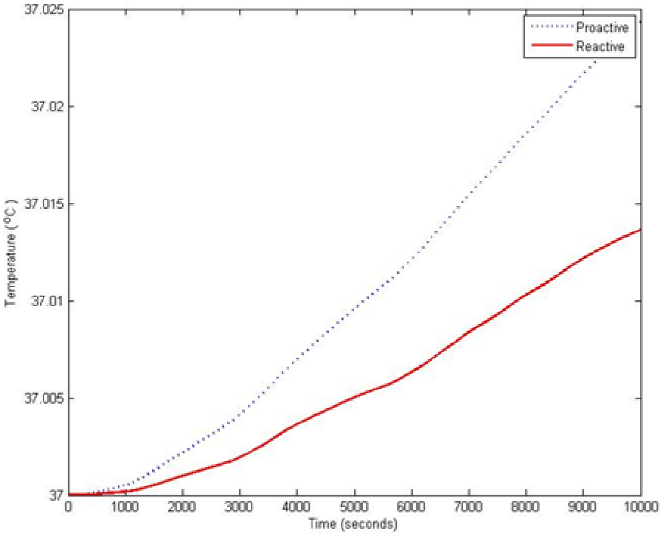


(b) Reactive routing

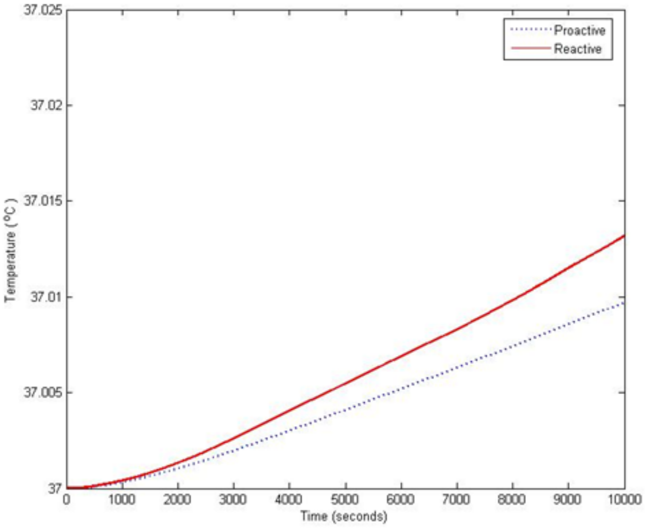
Figure 8. Distribution of temperature rise.



(b) At node 1



(c) At node 16



(c) At node 36

Figure 9. Node temperature over time.

IV. PRIORITY-BASED REACTIVE ROUTING PROTOCOL

We proposed the priority-based reactive routing protocol based on the result of the preliminary work in the previous chapter. The result of the comparison between proactive and reactive protocol in terms of temperature rise shows that the reactive protocol achieves lower temperature rise compared to that of the proactive protocol. Therefore, we decided to use the reactive protocol approach as the basis of the proposed routing protocol.

In principle, the proposed routing protocol enhances the ad hoc on-demand distance vector (AODV) protocol [21] by adding temperature-awareness functionality and priority mode, which is a cross-layer communication with the application layer to control the node’s packet rate. In the following, we explain these two additional functions.

A. Temperature-Awareness

As a routing protocol for WBANs, the awareness of temperature is extremely important. The routing protocol must have the capability to monitor its own temperature and to decide whether or not to continue to operate. With an assumption that there is no dedicated thermometer inside the node, the temperature rise is calculated using the bioheat equation as written in equation (2). Using this equation, a node is able to monitor its own temperature and take any action based on it.

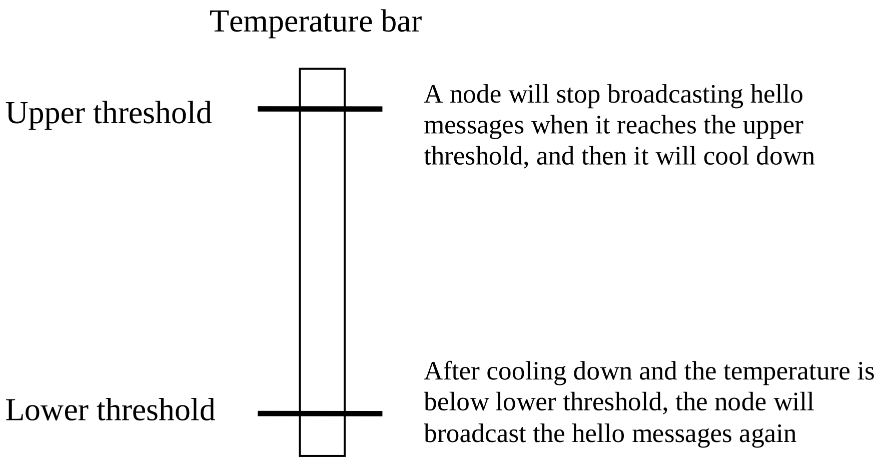


Figure 10. Temperature upper and lower threshold.

In AODV, a node offers connectivity information by broadcasting local hello messages. If, after a certain period of time, a node does not receive a hello message from its neighbor node, the link to that neighbor node will be considered lost and the node will look for another path to the destination node.

In the proposed routing protocol, there are two temperature threshold as shown in Figure 10, namely temperature lower threshold and temperature upper threshold. When a node starts to operate, its temperature will start at the lower threshold. After it is operating, the temperature will rise and when it reaches the temperature upper threshold, the node will stop broadcasting hello messages. This way, the link to this node will eventually be considered lost and the active route will try to look for another path. During this period, as the impact of being considered lost, the node will not receive any data packet and go into cooling down period where the temperature will decrease. When the temperature reaches the lower threshold, the node will broadcast hello messages again and eventually will be appeared available to participate in the routing path. By setting the upper threshold as the temperature

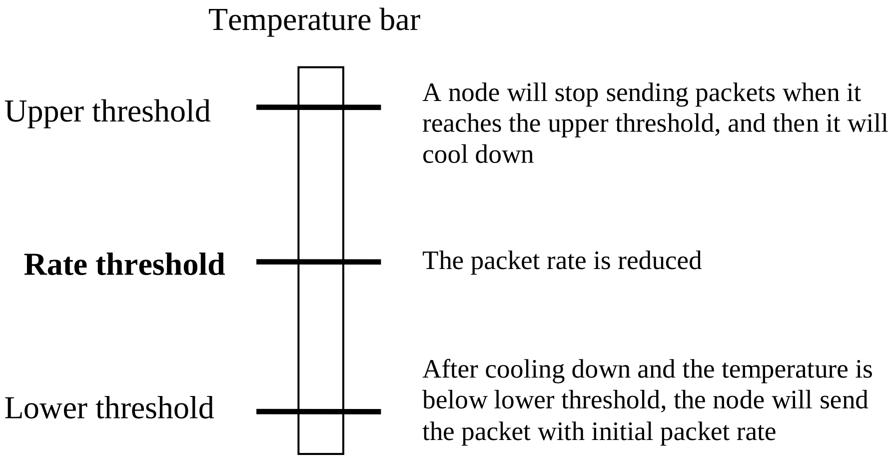


Figure 11. Temperature rate threshold.

safety level, we can guarantee that the node will never reach the temperature level above the safety level, thus safe for the human body.

B. Priority Mode

In the health care monitoring, there are four human vital signs that are usually monitored: body temperature, pulse rate, blood pressure, and respiratory rate. These parameters are important to measure and assess the health state of the human body. Because of its importance, we need to prioritize these vital nodes in such a way that it will achieve higher throughput.

In the proposed routing protocol, there are two kinds of operation mode: no-priority and priority mode. In the no-priority mode, all nodes in the network are treated with the same priority level. It means, no priority is given to vital nodes. On the other hand, in the priority mode, priority is given to vital nodes or pre-determined nodes.

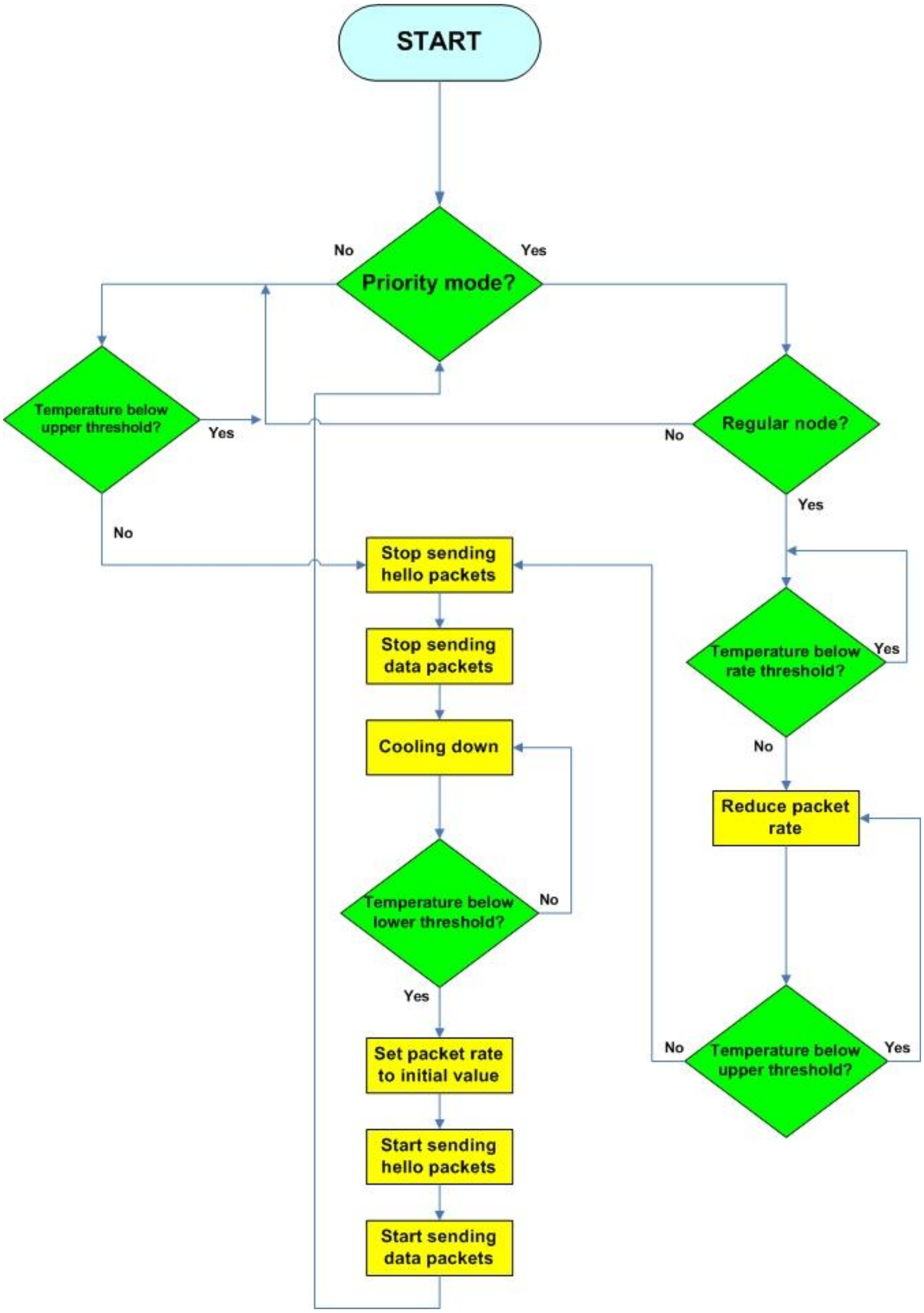


Figure 12. Flowchart of the priority mode.

One of the reasons of low throughput in wireless ad hoc networks is collision. Since the nodes in wireless networks are using the same air medium, the possibility of collision happens in the network is higher than that in wired network, especially when more number of packets are transmitted in the medium. The priority mode tries to mitigate this challenge by using cross-layer communication between routing and application layer. In priority mode, we define two kinds of nodes: priority node and regular node, and one additional threshold: temperature rate threshold. Priority node is the node which is given priority to increase its throughput. Regular nodes are the nodes other than priority nodes.

Temperature rate threshold is the threshold located between the lower and upper threshold. The rate threshold only affects regular nodes. As usual, starting from the lower threshold, when the temperature rises and reaches the temperature rate threshold, the routing layer will give a message to the application layer to reduce the packet rate. This packet rate will be maintained until it reaches the upper threshold where the node will stop sending packet and cool down. After the temperature reaches the lower threshold, the node will operate normally and the packet rate will be set to the initial value. Figure 11 and Figure 12 shows the temperature rate threshold and flowchart of the priority mode mechanism, respectively.

C. Performance Evaluation

To evaluate the performance of the proposed routing protocol, we simulate it using a simulator called Castalia [22]. Castalia is an OMNeT++-based simulator for Wireless Sensor Networks (WSNs), Body Area Networks (BANs) and generally networks of low-power embedded devices.

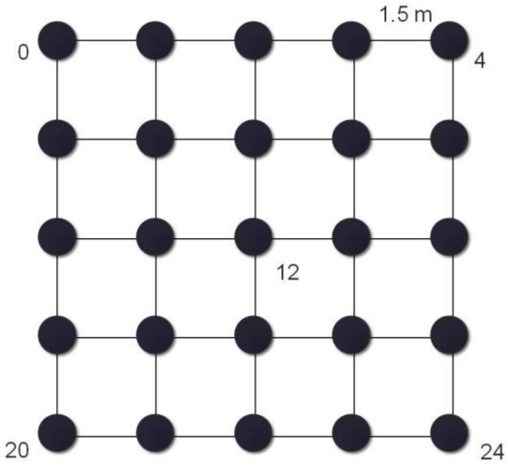


Figure 13. Network topology.

This simulator provides realistic wireless channel and radio models and also a realistic node behavior especially relating to access of the radio.

The proposed routing protocol is first compared to an existing WBANs routing protocol named TARA (Thermal-Aware Routing Algorithm). We compare our protocol with TARA because among the existing temperature-aware routing protocols, TARA is the only protocol that uses Pennes bioheat equation to calculate temperature rise. Some other protocols, such as LTR, ALTR, or LTRT, simply increases 1 unit of temperature for every packet a node receives. Therefore, TARA is more realistic in its way of calculating temperature rise. Our protocol also uses the same method to calculate temperature rise.

In the simulation, we use 25 nodes in a grid topology of 6 x 6 m^2 and they are labeled using number from 0 to 24 as shown in Figure 13. The grid topology was also commonly used by the existing temperature aware routing protocols [11]-[15]. Node 0 acts as the sink node to which all the data packets are sent. The other nodes other than node 0 act as source nodes and send data packets toward the sink node. The distance between nodes is 1.5 meters and the transmission range is around 2.2

Table 3. Simulation parameters.

Parameter	Value
Simulator	Castalia 3.2
Number of nodes	25
Topology	Grid topology
Network area	6 x 6 m^2
Distance between nodes	1.5 meters
Radio model	802.15.6 BAN radio
Tx power	-25 dBm
MAC protocol	Tunable MAC
Data payload	50 bytes
Packet rate	0.6 packet/second
Temperature upper threshold	37.01℃
Temperature rate threshold	37.005℃
Temperature lower threshold	37.00℃

meters. It means that each node is able to reach at most its one hop diagonal neighbor node. As provided by the Castalia simulator, we use the radio model of 802.15.6 BAN radio model with the Tx power of -25 dBm. The list of simulation parameters can be seen in Table 3.

This simulation is divided into two parts. In the first part, we compare the performance of the proposed routing protocol and TARA in terms of temperature rise. Figure 14 shows the average network temperature for both TARA and the proposed routing protocol over time. We can see that generally the TARA protocol produces higher temperature rise over time and from the logarithmic trend line the TARA protocol produces around 50% higher temperature rise than that of the proposed protocol one. Because we are plotting the average temperature of all nodes over time, the increasing slope in the graph means that all nodes are experiencing temperature rise while the decreasing slope means that there is at least one node in the network is in the cooling down state. Figure 15 shows the temperature over time for a node. Here, we take node 12 as our example.

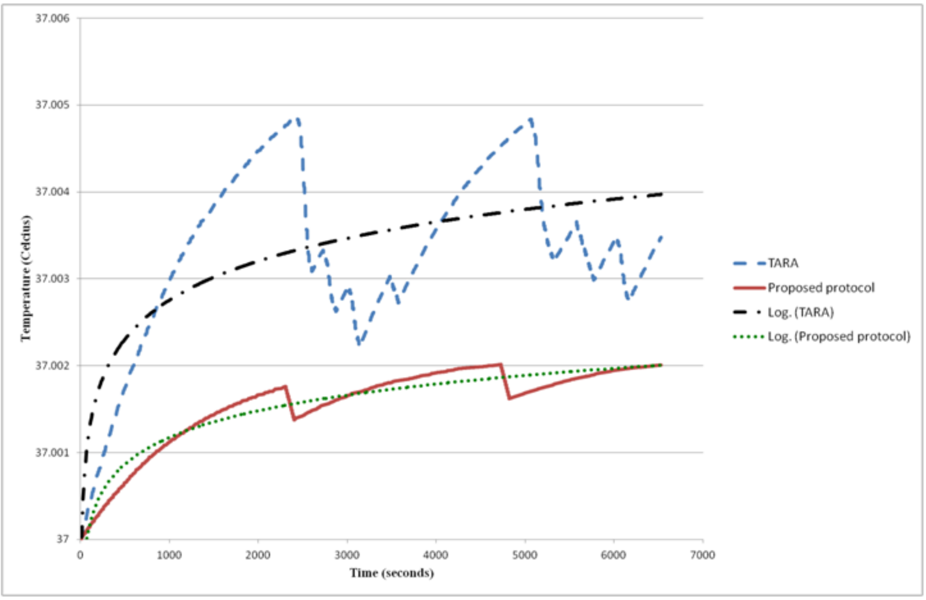


Figure 14. Average node temperature over time.

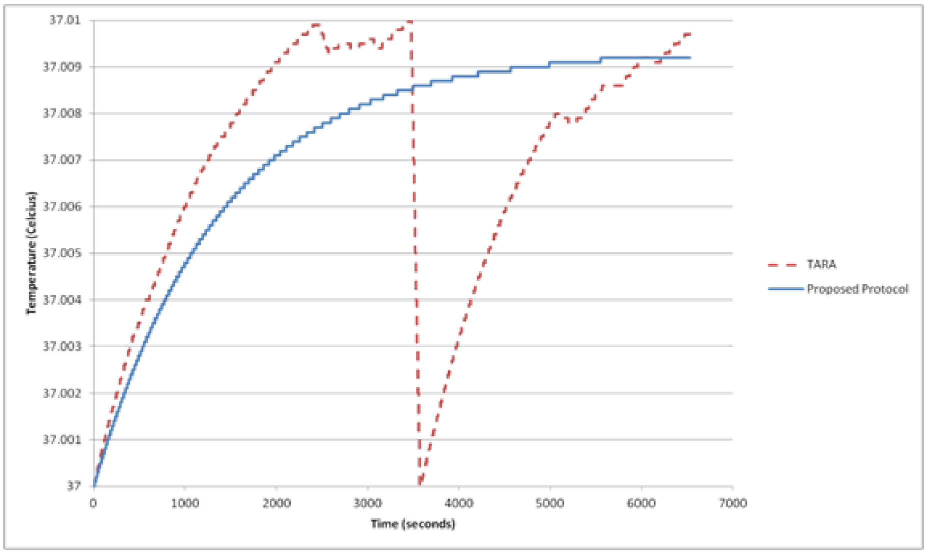


Figure 15. Temperature of node 12 over time.

We can see in the graph that the temperature rise rate of the proposed protocol is around 50% lower than that of the TARA protocol. After around 3000 seconds, the TARA protocol has reached the temperature upper threshold and has to cool down for a certain period. On the other hand, for the proposed protocol, even after 6000

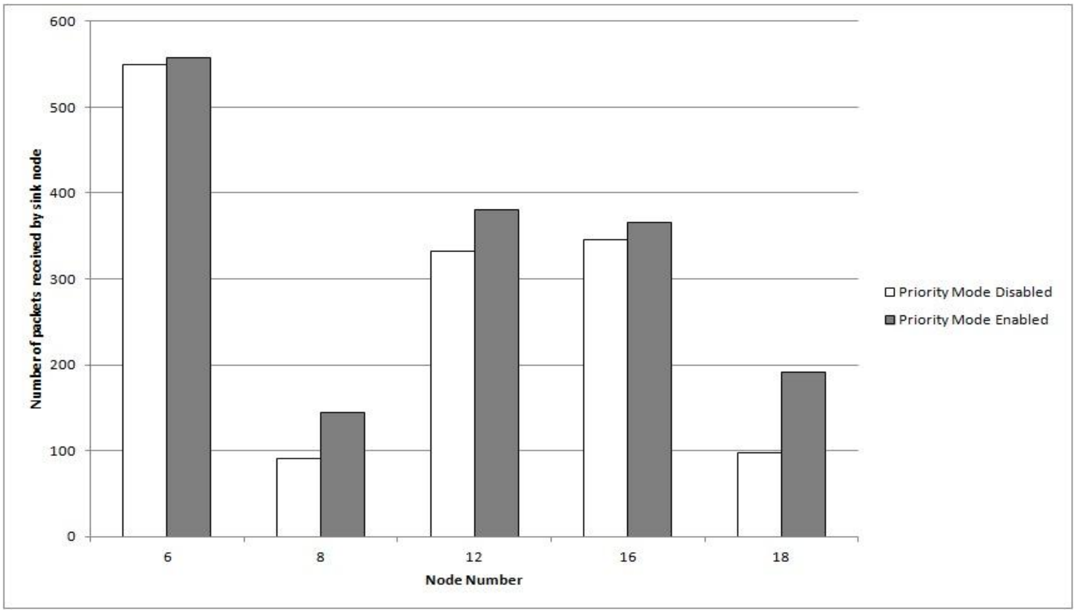


Figure 16. Number of packets received by sink node.

seconds it still has not reached the temperature upper threshold. It means that using the proposed protocol, a node can have a longer operational time before it reaches the temperature upper threshold because the temperature rise rate is lower.

In the second part, in order to increase the throughput of priority nodes, we compare the proposed routing protocol before and after the priority mode is enabled in the network. The throughput here is defined as the number of packets received by the sink node from the source node. We choose several nodes as priority nodes: node 6, 8, 12, 16, and 18 and then we compare their throughput before and after priority mode is enabled. Figure 16 shows the throughput of these nodes. We can see that the throughput of these nodes is higher after the priority mode is enabled. This is as the result of priority mode in which the regular nodes will reduce its packet rate after the temperature rate threshold is reached. This way, the load of the network will decrease and the sink node is able to receive more packets from priority nodes within the same period of time. In average, the throughput is higher by 35%.

V. CONCLUSIONS AND FUTURE WORKS

In this thesis, we presented a routing protocol for WBANs that have these characteristics. First, the proposed routing protocol is based on reactive routing protocol approach. The existing temperature-aware routing protocols for WBANs are using proactive approach and based on the comparison work that we conducted, we got the result that reactive routing protocol achieves 27.87% lower maximum temperature rise and 43.75% lower average temperature rise compared to that of proactive routing protocol. Second, the proposed routing protocol is temperature-aware. It has capability to calculate its temperature rise and to act based on its current temperature and pre-defined temperature threshold. Last, it has priority mode capability to prioritize vital nodes in the network. Priority mode uses cross-layer communication between routing and application layer to control the node's packet rate.

The proposed routing protocol is first evaluated and compared with TARA protocol and it achieves around 50% lower temperature rise rate. Then, to increase the throughput of vital nodes, the priority mode is enabled. In average, after the priority mode is enabled, the vital nodes achieve 35% higher throughput compared to that before the priority mode is enabled.

As the future works, we plan to add additional optimization such as incorporating uni-directional links into assumption. This is done to make the routing protocol to work in a more realistic environment since the nodes in WBANs are more likely to be heterogeneous. Additionally, to evenly reduce and distribute the temperature rise of the nodes in the network, a load balancing mechanism is also worth noting to be implemented in the routing protocol. By distributing the routing path, the energy consumption will also be distributed more evenly among the nodes, and thus reducing the maximum temperature rise of the network. Therefore, we plan to study and identify the problems and solutions related to uni-directional links and load balancing mechanism in mobile ad hoc networks routing protocols in general and to apply them into WBANs environment.

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ACKNOWLEDGMENTS

This thesis would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

First and foremost, my utmost gratitude to my supervisor Prof. Sangman Moh whose excellent guidance, caring, and patience I will never forget. His sincerity and encouragement to pursue my Master’s degree at mobile computing lab has been my inspiration as I hurdle all obstacles in the completion of this research work.

I would also like to show appreciation to members of my supervising committee Professor Illyong Chung and Kang Moonsoo for their valuable advice and insight throughout my research. I would like to thank the department of Computer Engineering for providing me the atmosphere to augment my knowledge.

I am particularly indebted to my parents, brother, and sister for their continuous love and support so that I can concentrate on my study. Without them, I would not have been able to complete this thesis.

In my daily work, I am fully grateful for everyone around me. My fellow lab members who have always been supportive and open to discuss research ideas. My compatriots who have been good and cheerful friends to me, making my life in Korea more exciting. A special thanks I would like to express to Ivan Christian, my roommate for this past two years. He has been a good friend and brother, who always encourage and support me in both academic and non academic aspects.

Part of this research was supported by the grant from MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency).