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THE (Temperature Heterogeneity Energy) Aware Routing Protocol for IoT Health Application

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ABSTRACT In this paper, we focus on an interesting E-Health monitoring system that efficiently utilizes the concept of the Internet of Things (IoT). Wireless body area network (WBAN) composed of a set of target-oriented sensors placed around the human body and transmit its collected data to a coordinator that carries it to some cloud system. WBAN standardized with the newly emerged IEEE802.15.6 with its specifications for Physical (PHY) and medium access control (MAC) layers only. Regrettably, the Network layer is not addressed by the standard where it plays an important role in the overall performance. In this paper, we design the temperature heterogeneity energy (THE) aware routing protocol for WBAN as a complement for the standard. "THE" aims to control the temperature raising caused by the on-body sensor and affects the skin comfortableness. In the meantime, "THE" maintains the network in high-performance conditions in terms of long node lifetime and high packet throughput. To fulfill these desired tradeoffs, the sensed data is classified into three data levels with variable transmission priority to each level, namely, emergency (abnormal) data priority 7 (highest priority), critical data priority 6, and normal data assigned priority 5. "THE" protocol is based on a utility function that chooses the WBAN's parent node (PN) that has the largest amount of remaining energy, the highest data rate, the minimum distance to the coordinator, and the minimum sensor's temperature. Hopping the data through the parent node (two-hops) is applicable for the data with normal priority while high priority data (critical and emergency) is transmitted to the coordinator in one-hop only. The proposed "THE" protocol's performance validation performed via Monte Carlo simulation analysis which proves that "THE" protocol achieved better performance against conventional protocols (SIMPLE and iM-SIMPLE) in terms of network lifetime, number of dead nodes, total remaining energy, and throughput.

INDEX TERMS Wireless body area network (WBAN), routing protocols, residual energy, Internet of Things (IoT), health application.

I. INTRODUCTION

Wireless sensor networks (WSNs) are a set of large number of sensor nodes that are deployed randomly to monitor various tasks. It has a lot of applications such as environment monitoring [1], green houses, forest monitoring, and smart home applications [2]–[6]. The integration between WSN and Internet of Things (IoT) [7], [8] in many health applications [9], [10] have attained the attention from vast research fields [11] to provide the services to the patients in remote areas with the cheapest cost [12].

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Wireless Body Area Network (WBAN) is the proper technology for constructing scalable and robust IoT healthcare systems.

A WBAN typically contains a number of nodes that are placed in and on the body of a patient to collect vital signs from critical parts of the body. Out of these nodes, one plays the role of Coordinator Node (CN) and the remaining are sensing nodes. The sensor nodes sense some metrics that are needed to be monitored, such as temperature, blood pressure, heart beats, etc. They continually transmit the data they sense wirelessly to the CN, which in turn transmits the data also wirelessly to a remote server. Each node has a battery that supplies its circuitry with energy. The problem with the battery is its replacement when it runs out of energy.

The replacement can cause to the patient significant inconvenience if the node is on the body, or severe pain if it is in the body (implanted). To alleviate this problem, it is a considerable target to extend the battery lifetime, the conventional works focus on reducing the node energy consumption while we concentrate on optimizing the network performance with consideration for the users' comfortability in general.

WBANs are not limited to the healthcare field only but can be used in the entertainment field as well. In order to regulate their use in both fields, the IEEE 802.15.6 standard 11 has been drafted. It specifies eight priority levels, $0, 1, \ldots, 7$ (7 is the highest), for node's data. In particular, the standard reserves the top three levels for medical applications and the rest for entertainment applications. When a node transmits data to the CN, it may do that in one-hop due to the physical proximity of the nodes. However, as a means of reducing transmission energy, multi-hops may be used. Basically, the source node uses one or more nodes as relays on the way towards the coordinator node. This gives rise to the need for routing protocols for WBANs. Unfortunately, networking layers above the MAC layer are not addressed by the IEEE802.15.6 standard. Therefore, designing a routing protocol for WBANs is of paramount importance, and it is indeed what the present paper proposes. Such a protocol should meet four criteria due to the special nature of WBANs. First, it should consume minimal energy. Second, it should be reliable, as a failure or over accepted error rate may lead to a fatality. Third, it shouldn't have high thermal heat that may harm the part of the body the node is adjacent to. A node may heat up seriously due to transmission and reception, so minimizing both in the protocol minimizes the heat buildup. Forth, it should not conflict with the IEEE802.15.6 standard, but complement it and integrate with it. The "THE" protocol proposed aims to fulfill the above four criteria. For example, it exploits the priority levels provided by IEEE802.15.6, thus complementing the standard. In particular, it assigns a different data rate for each priority level. The other three criteria are met as detailed in the sequel. The remainder of the paper is arranged as follows. In section II, related research is reviewed, while in section III, the proposed "THE" protocol is introduced. In section IV, the effect of node temperature to the skin is studied, also in section V, the operational steps of the "THE" protocol are discussed. Simulation setup and results are presented in section VI, and the conclusions are outlined in section VII.

II. RELATED WORK

There are many routing protocols proposed for WBANs that aim to tackle different problems. One may classify these protocols based on the number of hops. There are one-hop [14]–[16] protocols and multi-hop protocols [17]–[19]. One-hop protocols have the advantage of decreasing delay and ensuring end-to-end data delivery and increasing delivery reliability. However, one-hop protocols have the disadvantages of consuming much transmission energy, thus depleting the limited-energy batteries, by contrast, multi-hop protocols have the advantage of conserving the transmission energy, as they do not transmit to the far CN directly but to some relay nodes closer than the CN. Saving on transmission energy prolongs the battery lifetime. However, multi-hops also have some disadvantages. First, the node adjacent to the CN becomes a bottle-neck, suffering excessive load, as it receives packets needed to go to the CN from most of the nodes. Second, due to the hop by hop transmission, latency is introduced into the data. Some multi-hop protocols are cluster-based [20], [21], with each cluster having a Cluster Head (CH). If a node has traffic to transmit, it first transmits it to its CH, which in turn transmits it to the CN. That is, traffic goes from the source node to the coordinator node always in two-hops. However, clustering is not enough to avoid node heating [22], [23], a problem that may be harmful to the body.

A WBAN protocol that employs all three techniques above, one-hop, multi-hops and clustering is Stable Increased-throughput Multi-hop Protocol for Link Efficiency in Wireless Body Area Networks (SIMPLE) [24]. Exhibiting energy efficiency and high throughput, it uses a cost function to select a node, called Parent Node (PN), with high residual energy and minimum distance to the CN. Nodes far from the CN transmit their data to the PN while those near to CN transmit their data directly to it. That is, the transmission is always either one-hop or multi-hops. iM-SIMPLE: iMproved stable increased-throughput multi-hop link efficient routing protocol for Wireless Body Area Networks [25] is an extension to SIMPLE protocol, it uses the same cost function as SIMPLE protocol also it is very close in operation to it. The main difference between SIMPLE and iM-SIMPLE is that it derives the problems of increased throughput and energy consumption minimization as an Integer Linear Program. In addition to supporting mobility as the patient can move from one place to another. Thus the mobility concern seems to be very complicated. For simplicity, iM-SIMPLE take into account only arms movement. The arm moves in two different directions. When it moves in the same direction to the other hand, it becomes close to the sink. Therefore this mobile node creates a connection with sink or parent node. While, in reverse direction, as the human arm moves far from the sink, more energy is needed to transmit sensed data. As a result, it depletes its energy in a short time. The mobility of the node may cause decreased throughput as well as high path loss. So mathematical modeling is analyzed in order to minimize energy consumption and maximize throughput. However, both SIMPLE and iM-SIMPLE protocols do not consider at all the temperature rise of nodes, either implanted or on-body.

It should be noted that our proposed "THE" protocol is a modified version of the iM-SIMPLE protocol. The major difference is that "THE" uses two additional criteria to those of selecting the PN node, namely, the node's temperature and data rate.

WBAN routing protocols can also be classified based on their target goal, besides routing of course. One class is QoS aware protocols [26], [27], whose aim is preserving high performance metrics despite currently working conditions which may at times be unfavorable. In these QoS aware protocols, the protocol is divided into modules, each responsible for a specific metric, e.g. end-to-end delay module, a packet delivery ratio module and a power consumption module. However, these protocols care more about performance than thermal problems. That is, they have no module for keeping the temperature within a predefined safe limit.

Another class is thermal aware routing protocols [26]–[28]. These protocols targeted to reduce the temperature increase of implanted nodes to avoid burns to the adjacent tissues. In [31], a protocol is proposed whereby each node along the route chooses a successor based on its temperature. If it has more than one option, it chooses the one with the lowest temperature. If it finds that the temperature of all potential successors is above a predefined threshold, it saves the data temporarily and waits till the temperature of one of the hot nodes falls below the threshold. If the waiting exceeds some predefined time limit, without finding a successor, the node returns the packet to the node that sent it. The latter node retransmits the packet to the former, which repeats the above procedure. If the packet keeps going forwards and backwards more than a certain number of times, the packet is dropped altogether. Clearly, the potential multiple transmissions of the same packet cause bandwidth waste as well as temperature rise, defeating the awareness of the protocol.

In [32], another thermal aware protocol is proposed. The protocol uses source routing to find in one shot a route that results in minimum temperatures at the participating nodes. The protocol achieves this aim by letting nodes continually communicate to each other their temperatures. With the WBAN represented as a weighted graph, the temperatures being the weights, the source is able to construct a minimum-temperature route using the shortest path algorithm. Being source routing, the protocol also solves the problem of overflowing hops.

The trouble, however, with the thermal aware protocols mentioned above is that they solve the heating problem of only implanted nodes, ignoring on-body nodes whose heating can admittedly cause skin burns or discomfort at the least. One contribution of the present paper is addressing heating of on-body nodes.

III. MODEL AND PROPOSED PROTOCOL

Our proposed algorithm composed of multiple procedures. The system model of the WBAN composed of one CN and a set of N on-body nodes, as shown in Figure 1. The N nodes are placed *directly* on the skin of the patient whereas the CN is separated from the skin. The most commonly used material to fabricate casings of medical nodes is Nikel which has a high thermal conductivity for the heat resulted due to a prolonged burst of activities causing skin burn or at least discomfort.

Our proposed algorithm composed of multiple procedures.

1) Traffic classification: Out of the N nodes in the system, the two nodes (EEG and ECG) are classified as critical nodes and assigned the standard priority level 6, which is used for periodically transmitted vital critical data. On the other side, the remaining $(N - 2)$ nodes are classified as normal nodes and assigned priority level 5, which is used for aperiodically transmitted data that may tolerate delay.
2) Hopping optimization in our "THE" protocol, critical classified nodes transmit their data directly (in one-hop) to the CN to satisfy the latency minimization requirement. On contradictory, normal classified nodes, transmit their data to the PN node only if PN nodes is closer to it in order to deliver it to the CN (in two-hop fashion). However, in abnormal conditions (e.g. glucose level sours high abruptly) the priority of a normal node is raised to level 7, the emergency level, where we force all other normal nodes to suspend operation temporarily, thus sufficient resources are afforded to meet the emergency requirements.
3) PN selection: The selection of the PN node is a critical issue for our "THE" protocol because the failure of this node leads immediately to losing the data it had acquired and was about to transmit to the CN in addition to affecting the performance of far nodes. Therefore, the selection of the PN node is based on maximizing a novel utility function (as shown in Eq. 1).

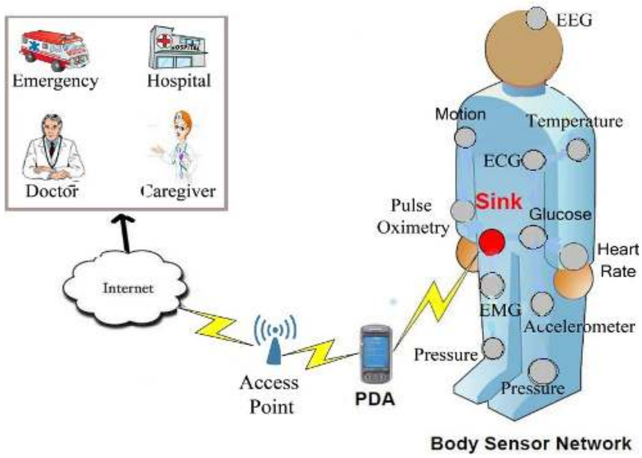


FIGURE 1. Example of sensor nodes in WBAN system.

The utility u_i of some node i, $i = 1, 2, \ldots, N$, is given by

$$u_i = \frac{R_i E_i}{T_i D_i} \quad (1)$$

where R_i is the ith node's data transmission rate (kbps), D_i is the distance from the node to CN (m), T_i is the node's temperature (° C), and E_i is the node's residual energy (Joule).

This utility function works through the selection of a node with the largest amount of remaining energy, the highest data rate, the minimum distance to the coordinator and the minimum sensor's temperature. Initially, we assume that all nodes have the same initial energy and the same temperature, so the utility function selects the closest nodes to CN and shortlists with the highest data rate. Gradually, changes in energy and temperature occurs due to the process of its own data and/or routing other nodes' data. This changes allow full functionality of the utility function to select the best PN node. The selection is based on the closest node to the CN with high transmission data rate which has large amount of remaining energy and lowest temperature. Selecting the PN based on remaining energy grantees the balance between all nodes' remaining energy and prolongs the network lifetime. While the short distance to CN reduces communication errors. When the PN node has a high transmission data rate, improvement in the network throughput could be achieved. Lastly, low temperature node could route the other nodes' traffic and avoid reaching the temperature threshold fast to grantee skin comfortability. The node with the largest u_i is selected to be the PN node for this round. Since the quantities on the right hand side of (1) change from round to round, so is the utility u_i. This rotation in the selection of the PN grantees the network stability.

Due to the continuous processing and transmission of data, a raise in the nodes' temperature occur that needs to be controlled via a threshold temperature (T_{SH}). In "THE" protocol, the temperature threshold is set to T_{THH} (High temperature threshold), keeping T_{Gb} as a guard band. If the temperature of a node reaches the threshold of T_{THH}. The node shall immediately transmit the data it has to the PN node (i.e. multi-hops), relinquishing the CN (i.e. one-hop) if it was being used. In order to prevent the temperature from reaching the skin harmful temperature of T_{SH}. That is, it is assumed that the last transmission after reaching the threshold of T_{THH} shall cause a temperature rise of no more than the guard band of T_{Gb}. Then the node shall sleep until its temperature cools down to T_{THL} (Low temperature threshold), at which value it wakes up again and resume work. This sleeping has an additional benefit, namely, conserving the node's energy [34].

IV. EFFECT OF NODE TEMPERATURE TO THE HUMAN SKIN

To calculate the effect of node temperature to the skin we shall use a straightforward heat flow method [35] based on Fourier's law [36] which represents the skin and a hot surface (node) as two semi-infinite slices of material. When the two slices come into touch, heat flows from the hotter slice (node) to the cooler slice (skin) until equilibrium is reached. The temperature of the interface between the two slices, called contact temperature and denoted by T_c. Fourier's law states that the rate of heat flow, and hence the time when equilibrium will be reached and also the contact temperature depends upon the properties of the two materials as follows.

$$T_c = \frac{b_s T_s + b_h T_h}{b_s + b_h} \ ^{\circ}\mathrm{C} \tag{2}$$

where Ts = Skin surface temperature, °C; T_h = Temperature of the hot surface, °C; b_s = Thermal penetration coefficient of the skin, $\mathrm{JS}^{-1/2}$ m^{-2} K^{-1}; b_h = Thermal penetration coefficient of the hot surface, JS $^{-1/2}$ m^{-2} K^{-1}. That is, given the thermal properties of skin and the material, contact temperature can be calculated.

TABLE 1. Thermal properties of materials and human skin [35].

Material	Thermal conductivity k	Density ρ	Specific heat c	Thermal penetration coefficient
Aluminium	204	2700	900	22265
Copper	382	8900	390	36413
Nikel	92	8910	440	18991
Iron and Steel	45	7800	450	12568
Silver	416	10500	230	31696
Glass	0.76	2600	840	1288
Concrete	0.8–1.4	2300	879	1271–1682
Pine wood	0.11–0.15	432–641	2803	365–519
Human Skin (vasoconstricted)	0.2–0.3	860	5021	929–1138
Human Skin (vasodilated)	0.4–0.9	860	5021	1314–1971

The thermal penetration coefficient $b = \sqrt{k.\rho.c}$ $\mathrm{JS}^{-1/2}$ m^{-2} K^{-1}(k = thermal conductivity $\mathrm{Wm}^{-1}\mathrm{K}^{-1}$, ρ = density Kg m^{-3}, c = specific heat capacity J $\mathrm{Kg}^{-1}\mathrm{K}^{-1}$. Table 1 Thermal properties of materials and human skin.

The contact temperature can then be compared with empirical data [33] to know if a burn is likely to occur.

Let's take an example [35], consider a short contact between human skin (assume b = 1000 JS $^{-1/2}$ m^{-2} K^{-1}) and aluminium.

(b = 22, 265 JS $^{-1/2}$ m^{-2} K^{-1}). Assume also a skin temperature of 33°C and surface temperature of 80°C.

Then from Eq. 2:

$$T_c = \frac{(100 * 33) + (22265 * 80)}{23,265} = 78.0^{\circ}\mathrm{C} \tag{3}$$

A contact temperature of 78.0°C is probable to make a fractional thickness burn.

A problem with the method presented above is that it is oversimplified. In practice, contact will not be ideal and skin condition shall be essential. This has led to the method being corrected.

Identical contact temperature (T_{ceq}) is the temperature between two semi-infinite slices of material in ideal touch, one slice of hot material and the other of human skin, that would give identical effect on human skin as the absolute contact between human skin and the hot surface.

Identical contact temperature (T_{ceq}) is given by

$$T_{ceq} = T_{\mathbf{c}} - (T_{\mathbf{c}} - T_{\mathbf{cc}})e^{-}(b_c/b_s)t \tag{4}$$

where $T_{\mathbf{c}}$ = Contact temperature from above using a best measure of skin condition (e.g. vasodilated, 36 or 33°C, vasoconstricted, 30°C), $T_{\mathbf{cc}}$ = Contact temperature if the solid surface were made absolutely of a coating on the skin (e.g. sweat, grease etc.) and corrected for level of contact with a weighting factor (minimum = 0.2, low = 0.4, medium = 0.6, high = 0.8, maximum = 1.0), b_c = Thermal penetration coefficient of the coating on the skin and corrected for the level of contact as for $T_{\mathbf{cc}}$, t = Contact time in seconds.

Let's take an empirical example that explain the contact temperature of skin in ideal touch [35].

Assume the skin of a machine operator contacts bare steel at 70°C for about 1 second. The skin is vasodilated and sweaty and contact is light.

1) From Table 1 and Eq. (2) $T_C = \frac{12568x70+1500x36}{12568+1500} = 66.4°C$
2) b for sweat (e.g. water at 60°C) is 1636 JS $^{-1/2}$m^{-2}K^{-1}
3) Weighting factor follow level of contact = 0.4 : $b_c = 0.4x1636 = 654$ JS $^{-1/2}$ m^{-2} K^{-1}
4) $T_{cc} = \frac{654.4x70+1500x36}{654.4+1500} = 46.3°C$
5) From Eq. (4) $\mathbf{T_{ceq}} = \mathbf{T_c} - (\mathbf{T_c} - \mathbf{T_{cc}})e^{-}(b_c/b_s)t$ $= 66.4 - (66.4 - 46.3)e{-}^{(654.4/1500).1} = 53.4°C$

A $\mathbf{T_{ceq}}$ value of 53.4°C is then compared with temperature values for skin damage.

V. "THE" OPERATIONAL STEPS

Now, we introduce the operational steps of the "THE" protocol. First, any node of Priority 5 (normal data) shall transmit its data to the PN node. If the quantity measured by such a node becomes at some point in time abnormal, e.g. an organ temperature exceeds 40°C whereas it should normally be 37°C, the node's priority will immediately change to Priority 7 and at the same time all other nodes are forced to stop. When a node is in Priority 7, it transmits directly to the CN (one-hop). This situation will remain until the abnormality disappears, at which time the node returns back to Priority 5 and the stopped nodes resume work. Second, any node of Priority 6 (critical node) shall transmit its data in one-hop to the CN node. As can be seen, the "THE" protocol uses a hybrid transmission methodology switching between one-hop and multi-hops. We calculated the node's consumed energy based on first order radio model [37].

$$E_{tx}(k,d) = E_{tx-elec}(k) + E_{tx-amp}(k,d) \tag{5}$$
$$E_{tx}(k,d) = E_{tx-elec} \times k + E_{amp} \times k \times d^2 \tag{6}$$
$$E_{Rx}(k) = E_{Rx-elec} \times k \tag{7}$$

where E_{tx} is the transmission consumed energy, E_{Rx} is the receiver consumed energy, $E_{tx-elec}$ and $E_{Rx-elec}$ are the energies needed to turn on the electronic circuit of transmitter and receiver, respectively. E_{amp} is the energy demanded for amplifier circuit, whereas k is the packet size. The communication medium in WBAN is the human body which attenuates the radio signal. So, we contribute path loss coefficient parameter pl in the radio model. Therefore the node energy consumption will be

$$E_{tx}(k,d) = E_{elec} \times k + E_{amp} \times pl \times k \times d^{pl} \tag{8}$$

There are two transceivers used frequently in WBAN technology. The Nordic nRF 2401A and Chipcon CC2420 [24]. We used The Nordic nRF 2401A transceiver as it is low power transceiver. The energy parameters for this transceiver are listed in Table 2.

In the following algorithm, it is assumed that the transmission of packets by nodes takes place in rounds and most of the packets were received successfully and there's no retransmission of failed packets. It is assumed that the WBAN shall work for L rounds before it goes to rest (maintenance, replacement, calibration, etc.). It is assumed that out of the N nodes, there are n critical nodes, meaning they have to be treated favorably (Priority 6 in the standard). It is assumed that the node can figure out its location and the node's distance can be considered constant. The algorithm takes as input the distance to CN, data rate, temperature, and energy for each node; the first two are properties of the nodes, i.e. remain fixed in all rounds, whereas the second two change during operation, i.e. can change from round to round. It is assumed that the transmission of a packet by a node increases the temperature of the node by a fixed amount ΔT and decreases its energy by a fixed amount ΔE. It is assumed that at the beginning all nodes are active. An active node i will be forced to sleep if its temperature $T[i]$ exceeds a user-defined threshold temperature T_{THH}. The temperature of a sleeping node shall decrease by a fixed amount δT in each round it remains sleeping. When the temperature of the sleeping node cools down to a user-defined T_{THL} where $37 < T_{HL} < T_{THH}$, the node is awakened.

TABLE 2. Radio parameters.

Parameters	nRF 2401A	Units
$E_{tx-elec}$	16.7	nJ/bit
$E_{Rx-elec}$	36.1	nJ/bit
E_{amp}	1.97e-9	j/b

TABLE 3. Simulation parameters.

Parameter	Value
Number of simulation rounds, L	8000
Number of WBAN nodes, n	8
Initial node energy, $E_i, i \in [1..n]$	0.5 J
Initial node temperature, $T[1..n]$	37°C
High temperature threshold, T_{THH}	42°C
Low temperature threshold, T_{THL}	40.3°C, 39.5°C, 41.5°C
Distance from node to CN , $D[1..n]$	$\{17, 9, 12, 15, 13, 10, 14, 20\}$ cm
Node data rate, $R[1..n]$	$\{250, 196, 86, 98, 30, 25, 44, 50\}$ kbps
Node temperature increment per packet, ΔT	0.01 °C
Node temperature decrement per round slept, δT	0.02 °C
Packet size, K	4000
Path loss coefficient, pl	3.38
Node energy decrement per packet transmitted, δE	$6.68e{-}4{+}2.6e{-}4{*}(D^{3.38})$
Noise model	Additive white Gaussian noise (AWGN)

VI. SIMULATION SETUP AND RESULTS

To validate our protocol we simulated the system with the consideration in Table 3 using Matlab. In the simulation, the following parameters will be fixed to the shown valued.

Algorithm 1 "THE" Protocol

Input : N (number of BAN nodes), n (number of critical nodes), $D[1..N]$ (node distance to CN) ,$D_{PN}[1..N]$(node distance to PN), $T[1..N]$ (initial node temperature), $E[1..N]$ (initial node energy), $R[1..N]$ (node data rate), ΔT (increment of node temperature per packet transmitted), δT (decrement of node temperature per round slept), T_{THH} (high temperature threshold for a working node), T_{THL} (low temperature threshold for a sleeping node), δE (decrement of node energy per packet transmitted) as shown in table 3

Output: Transmission (action) of all node data to CN, in either one-hop or two-hops

```
for ( round=1 to L ) {
    // Declare and/or initialize some operational parameters and indicators
    max = −1, PN = −1, Having_Abnormal_Packet[1..N] = 0, Sleeping[1..N] = 0
    // Check sleeping nodes and either cool them down more or wake them up
    for ( i= 1 to N ) {
        if Sleeping[i] = 1 AND T[i] > T_THL then
            T[i] = T[i] − δT
        else
            Sleeping[i] = 0
    // For non-critical nodes, find the node with the maximum utility u[i] and make
       it PN
    for ( i=1 to N-2 ) {
        if Sleeping[i]=0 then
            u[i] = R[i]E[i] / (T[i]D[i])
            if u[i] > max then
                max = u[i];    PN=node i
    // First, transmit urgent packets, if any, to CN single-hop
    for ( i=1 to N ) {
        if Sleeping[i]=0 then
            // Transmit packets of critical nodes
            if i ≥ n then
                if node i has a packet then
                    Transmit packet to CN.
                    T[i] = T[i] + ΔT;    E[i] = E[i] − δE
            // Transmit abnormal packets of normal nodes
            else if node i has an abnormal packet then
                Having_Abnormal_Packet[i] = 1
                Transmit packet of node i to CN.
                T[i] = T[i] + ΔT;    E[i] = E[i] − δE
        if T[i] > T_THH then
            Sleeping[i]=1
    // Second, transmit non-urgent packets, if any, of normal nodes to CN
       multi-hop
    for ( i=1 to N-2 ) {
        if Sleeping[i] = 0 AND Having_Abnormal_Packet[i]=1 then
            if D[i] > D_PN[i] then
                Transmit packet of node i to PN.
                T[i] = T[i] + ΔT;    E[i] = E[i] − δE
                Transmit packet of PN (just received from node i) to CN
                T[PN] = T[PN] + ΔT;    E[PN] = E[PN] − δE
```

The 8 nodes of our WBAN have been added in their accurate place based on their function [38] as shown in Figure 2 are:

- Node 1, (temperature sensor), monitors body temperature.
- Node 2, (Insulin Pump), delivers insulin 24 hours a day.

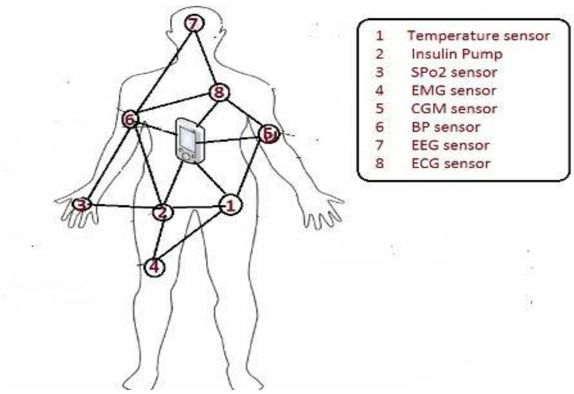
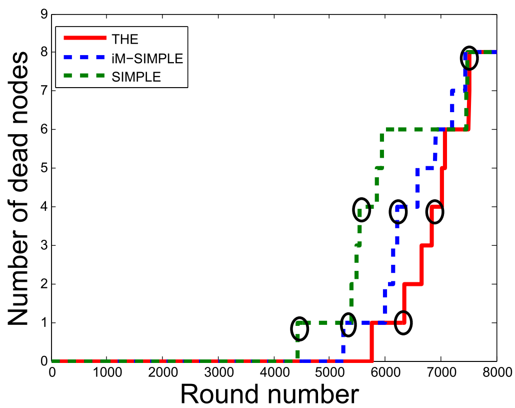


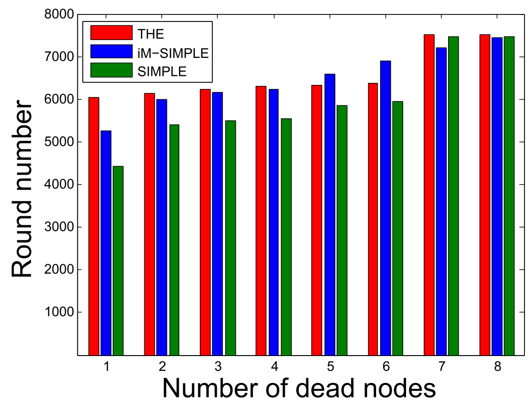
FIGURE 2. **Deployment for the 8 nodes of the WBAN under the "THE" protocol.**

- Node 3, SpO2 (peripheral capillary oxygen saturation), monitors the amount of oxygen in the blood.
- Node 4, EMG (Electromyography), monitors the electrical activity produced by skeletal muscles.
- Node 5, BP (Blood Presure) monitors blood pressure of the patient.
- Node 6, CGM (Continuous Glucose Monitoring), monitors glucose levels in real-time throughout the day and night to ensure the right amount of insulin is released at the right time.
- Node 7, EEG (Electroencephalography), monitors electrical activity of the brain.
- Node 8, ECG (Electrocardiogram), monitors the electrical activity of the heart over a period of time.

We study the effect of node's temperature of ''THE'' protocol on network lifetime, total remaining energy and throughput comparing results with SIMPLE and iM-SIMPLE protocols. Figure 3 shows the number of dead nodes versus time (expressed as rounds). This number reflects the lifetime degradation of the WBAN, with the stability defined [24] as the time interval from the start of network operation till the first node dies (its energy fully depletes). While the network lifetime is defined as the time interval from the start of network operation till the last node dies (its energy fully depletes). As can be seen, in our protocol the first dead node occurred at the 5760 round, the last node dies occurred at last round 7520. While in SIMPLE protocol [24] the first dead node occurred at the 4436 round, the last node dies occurred at round 6000 and in iM-SIMPLE [25] the first dead node occurred at the 5236 round, the last node dies occurred at round 7243. The ''THE'' protocol for selecting the PN node

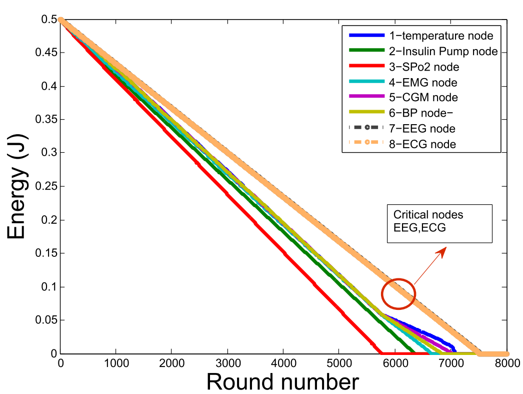


(a) WBAN lifetime

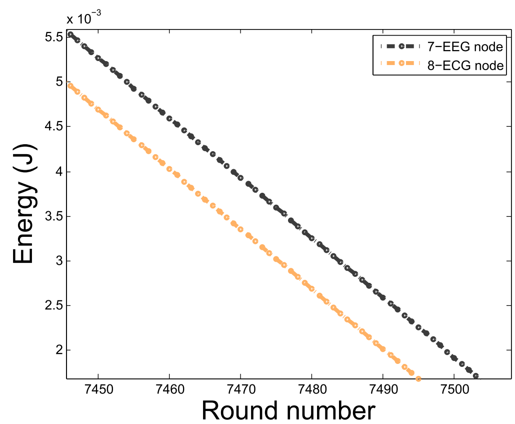


(b) Number of dead nodes

FIGURE 3. **Number of dead nodes.**

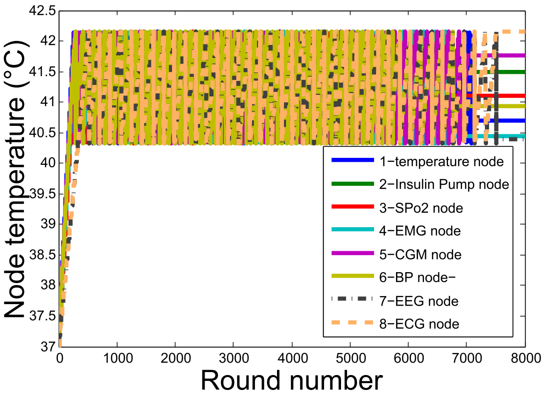


(a) stability of WBAN nodes

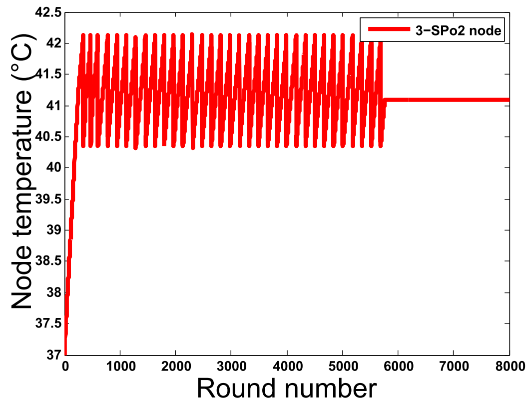


(b) stability of critical nodes

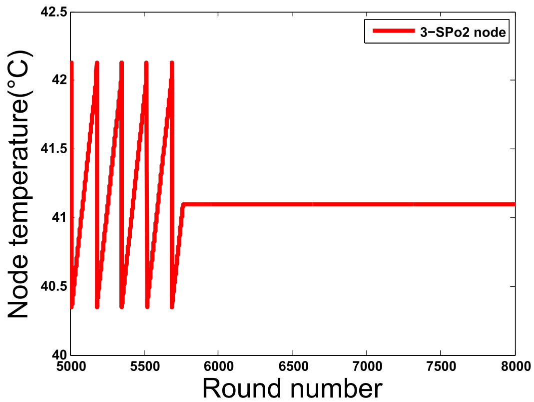
FIGURE 4. **Stability for the 8 nodes of the WBAN under the "THE" protocol.**



(a) Temperature for the 8 nodes atT_{THL}=40.3



(b) Temperature for node3(SPo2 node) atT_{THL}=40.3.



(c) Temperature for node3 start from round 5000 and T_{THL}

FIGURE 5. Temperature for the 8 nodes of the WBAN under the "THE" protocol at T_{THL} = 40.3.

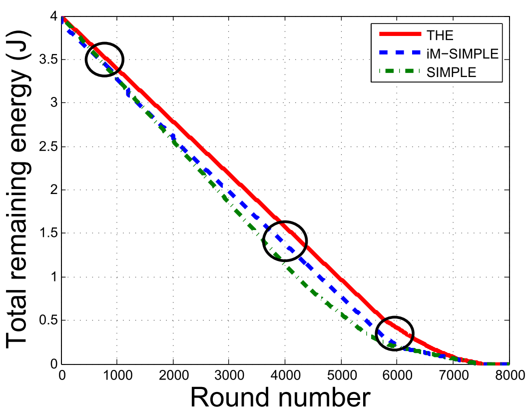


FIGURE 6. Total remaining energy.

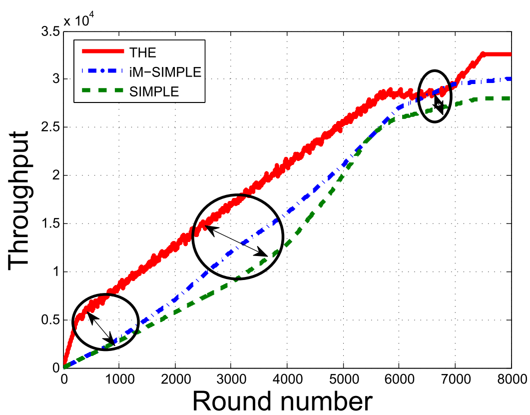
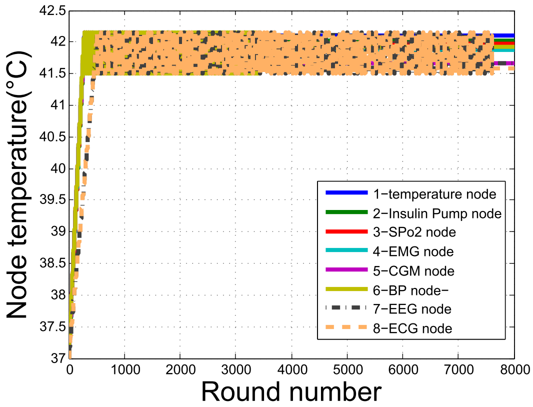
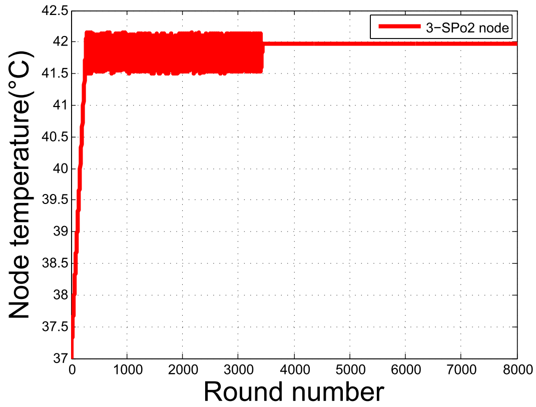


FIGURE 7. Throughput.

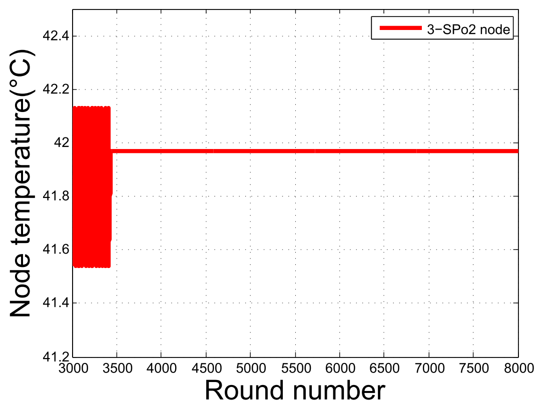
and the enforcement of the overheated nodes to sleep conserved the energy of those nodes as shown in Figure 3 and increases their lifetime. By comparing the lifetime between our "THE" protocol and both SIMPLE and iM-SIMPLE protocols in 3 points mainly at node1, node 6 and node 8 as shown in Figure 3. We take the average between them, so we can conclude that the "THE" protocol is more energy aware and prolongs the network's lifetime approximately by 11 % over SIMPLE protocol and by 6% over iM-SIMPLE protocol. Next, we shall measure the stability of each node which means the number of rounds till the node dies, as shown in Figure 4 the periodic nodes which are classified as critical nodes, namely, EEG and ECG achieve better stability than other nodes. Because those nodes shall not be a PN node and they are located near to the CN. On the other hand, other nodes died at different intervals because of the heterogeneity of those nodes in data rate and selecting the PN node every round from one of those nodes. Figure 5 shows the temperatures for the 8 nodes as the number of rounds increases. Initially, for each node, the temperature increases linearly with



(a) Temperature for the 8 nodes atT_{THL}=41.5



(b) Temperature for node3(SPo2 node) atT_{THL}=41.5



(c) Temperature for node3 start from round 5000 and T_{THL}

FIGURE 8. Temperature for the 8 nodes of the WBAN under the "THE" protocol at T_{THL} = 41.5.

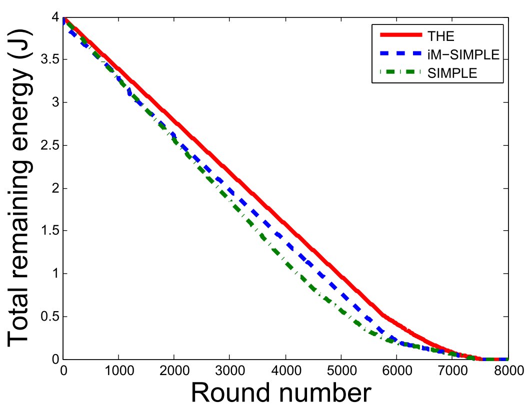


FIGURE 9. Total remaining energy at T_{THL} = 41.5 °C.

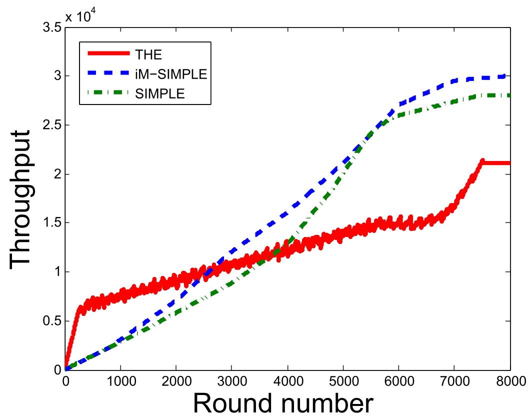
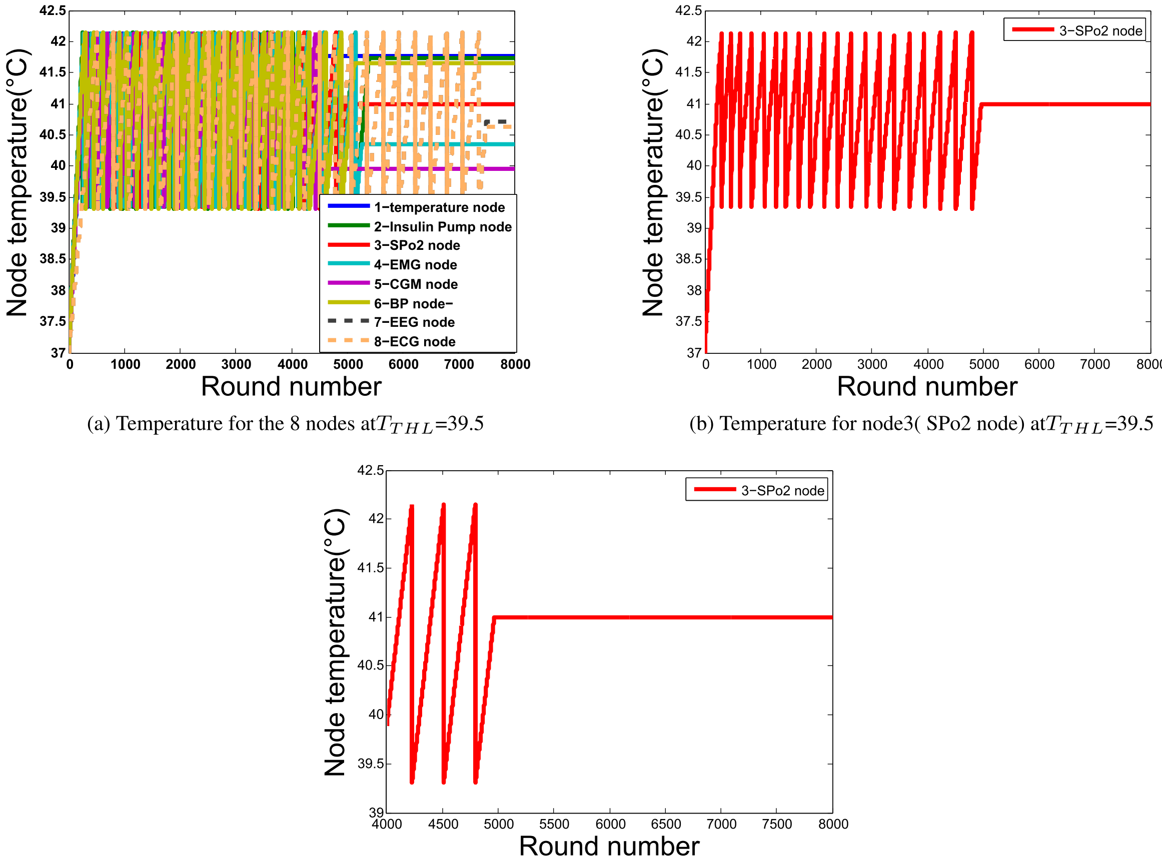


FIGURE 10. Throughput at T_{THL} = 41.5 °C.

the round number. This linearity stops when the temperature reaches the threshold value, where the temperature begins to oscillate in a sawtooth-like pattern. Let us take node 3 for example. The temperature started to rise, due to the continual transmission of packets, linearly as of round 1. At round 2500 (approximately) the temperature hit the threshold of 42 °C, where the protocol interferes and asks the node to sleep till the temperature becomes 40.3 °C. The node, however, shall not start sleeping before the data it currently has is transmitted. Transmitting this amount raises the temperature above the threshold, 43°C approximately, thanks to the guard band the temperature still below the skin harmful value of 44 °C. We used the guard band to keep the node's temperature always below the skin harmful value. When the node sleeps and cools down to 40.3°, it shall awake and resume work again. This type of temperature oscillation keeps on repeating till the node goes dead at round 6000 (approximately), roughly 300 rounds after iM-SIMPLE protocol [24] as shown in Figure 3, which indicates the feasibility of our



(a) Temperature for the 8 nodes at T_{THL}=39.5

(b) Temperature for node3(SPo2 node) at T_{THL}=39.5

(c) Temperature for node3 start from round 5000 and T_{THL}

FIGURE 11. Temperature for the 8 nodes of the WBAN under the "THE" protocol at T_{THL} = 39.5.

"THE" protocol. For another example, let us take node 6 (CGM), which is chosen to be the initial PN due to the protocol criterion of being closest to the CN. Since a PN relays packets from other nodes to the CN, in addition to transmit its own packets, its temperature reaches the threshold before the temperature of any other node does. Like node 3, and all other nodes for this matter, the temperature never reaches the skin harmful value. We tested our "THE" protocol under different values of T_{THL} and proved that setting T_{THL} to 40.3 °C achieves good results as shown in Figure 6 and Figure 7. Figure 6 shows the total remaining energy of all 8 nodes of the WBAN versus time, for the "THE" protocol at T_{THL} = 40.3 °C and both the SIMPLE [24] and iM-SIMPLE [25] protocols. It can be seen that the former protocol is more energy aware, especially in the middle rounds this energy savings is attributed to the sleeping times to 40.3 °C the nodes are forced to undergo, where the energy consumption ceases.

By comparisons with SIMPLE and iM-SIMPLE protocols in 3 points at the first rounds approximately at round 500, at the middle rounds approximately at round 4500, and at the last rounds approximately at round 6000 as shown in Figure 6 and takes the average between them, we can conclude that the "THE" protocol increases the total remaining energy by 7% than SIMPLE protocol and by 4% than iM-SIMPLE protocol. Considering the network's performance side, throughput is an efficient indicator which defined as the average number of packets transmitted successfully from the nodes to the CN as shown in Figure 7 the advantage of the "THE" protocol over both SIMPLE and iM-SIMPLE protocols in terms of throughput. By taking the average comparison of throughput between 3 points mainly at rounds 1000, 4000 and 6800, we can deduce that the "THE" protocol improves the throughput by 14% than SIMPLE protocol and by 10% than iM-SIMPLE protocol. This improvement is due to the proposed selection of the new round's PN node based on the value of computed utility function and setting T_{THL} to 40.3 °C. Sleeping to 40.3 °C conserves node's energy as well as improves throughput. The selection of the PN node with high data rate has a significant improvement for the spectrum utilization via increasing the number of packets transmitted to the CN each time unit. In the meantime, selecting the PN node with the shorter distance to the CN decreases the probability of packet loss that may be caused due to the channel noise or the path loss for the longer paths.

The choice of the threshold temperature is very sensitive. In order to emphasize this selectivity, we shall test our protocol against the change of the threshold within the neighborhood of 42 °C and study its effect on network performance in terms of throughput and total remaining energy by comparison with SIMPLE and iM-SIMPLE protocols.

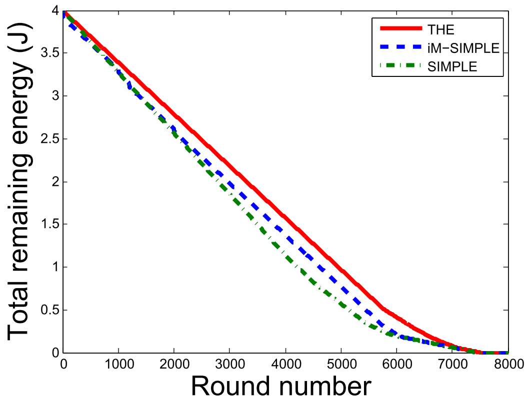


FIGURE 12. Total remaining energy at $T_{THL} = 39.5$ °C.

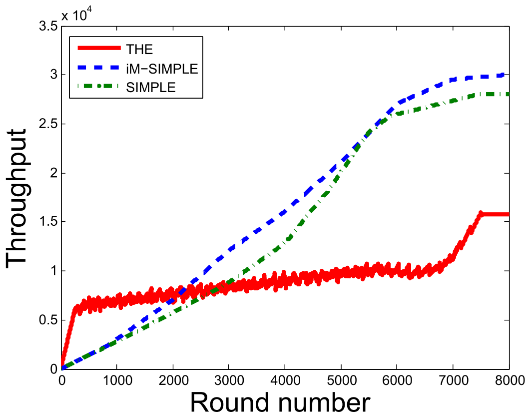


FIGURE 13. Throughput at $T_{THL} = 39.5$ °C.

Let us set T_{THL} to 41.5 °C for example, as shown in Figure 8. This shortens the sleeping time of the nodes thus the nodes reach the threshold of 42 °C much faster,as a result, the nodes change their state from awake to sleep many times in short times this gives rise to consume the node energy very fast as shown in Figure 9. Consuming node energy is the reason for the failure of almost nodes at earlier rounds that can lead to a decrease in the throughput after these rounds as shown in Figure 10. For another example let us set T_{THL} to 39.5 °C as shown in Figure 11. The figure depicted that there is an extending in the sleeping time that shows a decrease in the throughput as shown in Figure 13. In the meantime, the trade-off between conserving the node's energy and achieving a considerable throughput is clearly shown in Figure 12 where the threshold temperature of 42 °C reached much slower that enabled the node to has longer rounds of working and hence consuming more energy.

VII. CONCLUSION

In this paper, we proposed a routing protocol for WBAN IoT health application that tackles the network layer shortage and represents a complement for the IEEE802.15.6 std. The main goal of the developed routing protocol is to control the harmful effect to the human skin caused by temperature raising in the on-body nodes. The result depicted that the developed protocol maintains high network performance in terms of long node lifetime and high packet throughput. We adopted the protocol between one-hop and multi-hops transmission based on node's priority supported with a novel optimization utility function to select the round's parent node. The result depicted that "THE" protocol improves the network lifetime with an average of 11% and 6% over SIMPLE and iM-SIMPLE protocols respectively while maintaining the nodes' temperature comfortable. Additionally, "THE" granted throughput enhancement with 14% and 10% while decreasing the energy consumption by an average of 7% and 4% in comparison with SIMPLE and iM-SIMPLE protocols respectively. The results showed the sensitivity in selecting the node's maximum allowed temperature which triggers the node's sleeping procedure.

REFERENCES

[1] B. M. M. El-Basioni, A. I. Moustafa, S. M. A. El-Kader, and H. A. Konber, "Timing structure mechanism of wireless sensor network MAC layer for monitoring applications," *Int. J. Distrib. Syst. Technol.*, vol. 7, no. 3, pp. 1–20, Jul. 2016. doi: 10.4018/IJDST.2016070101.

[2] A. Ali, Y. Ming, S. Chakraborty, and S. Iram, "A comprehensive survey on real-time applications of WSN," *Future Internet*, vol. 9, no. vol. 4, p. 77, Nov. 2017. doi: 10.3390/fi9040077.

[3] B. M. M. El-Basioni, S. M. A. El-Kader, and M. Abdelmonim, "Smart home design using wireless sensor network and biometric technologies," *Int. J. Appl. Innov. Eng. Manage.*, vol. 2, no. 3, pp. 413–429, Apr. 2013.

[4] B. M. M. El-Basioni, S. M. A. El-Kader, and H. S. Eissa, "Independent living for persons with disabilities and elderly people using smart home technology," *Int. J. Appl. Innov. Eng. Manage.*, vol. 3, no. 4, pp. 11–28, Apr. 2014.

[5] G. Pau and V. M. Salerno, "Wireless sensor networks for smart homes: A fuzzy-based solution for an energy-effective duty cycle," *Electronics*, vol. 8, no. 2, p. 131, 2019.

[6] K. V. Nikam and S. P. Mohani, "IoT based greenhouse monitoring system implementation using data compressive sensing protocol in WSN," *Int. J. Adv. Res. Elect., Electron. Instrum. Eng.*, vol. 7, no. 6, pp. 3001–3008, Jun. 2018.

[7] T. M. Sale, S. Abdel-Mageid, S. M. Abd El-kader, and M. Zaki, "A quality of service distributed optimizer for cognitive radio sensor networks," *Pervasive Mobile Comput.*, vol. 22, pp. 71–89, Sep. 2015.

[8] M. A. Salem, I. F. Tarrad, M. I. Youssef, and S. M. Abd El-Kader, "QoS categories activeness-aware adaptive EDCA algorithm for dense IoT networks," *Int. J. Comput. Netw. Commun.*, vol. 11, no. 3, pp. 67–83, May 2019.

[9] A. Gondalia, D. Dixit, S. Parashar, V. Raghava, A. Sengupta, and V. R. Sarobin, "IoT-based healthcare monitoring system for war soldiers using machine learning," *Procedia Comput. Sci.*, vol. 133, pp. 1005–1013, Sep. 2015. doi: 10.1016/j.procs.2018.07.075.

[10] P. A. Catherwood, D. Steele, M. Little, S. Mccomb, and J. Mclaughlin, "A community-based IoT personalized wireless healthcare solution trial," *IEEE J. Transl. Eng. Health Med.*, vol. 6, 2018, Art. no. 2800313. doi: 10.1109/JTEHM.2018.2822302.

[11] T. Wu, F. Wu, J.-M. Redouté, and M. R. Yuce, "An autonomous wireless body area network implementation towards IoT Connected healthcare applications," *IEEE Access*, vol. 36, pp. 11413–11422, 2017.

[12] M. R. Shabana and S. Prabakaran, "WBAN based modern medical care monitoring by IoT approach," *Int. J. Eng. Techn.*, vol. 4, no. 2, pp. 1–8, 2018.

[13] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.6: Wireless Body Area Networks*, IEEE Standards 802.15.6-2012, IEEE Standards Association, 2012.

[14] A. Kochhar, P. Kaur, P. Singh, and S. Sharma, "Protocols for wireless sensor networks: A survey," *J. Telecommun. Inf. Technol.*, vol. 1, no. 1, pp. 77–87, Apr. 2018. doi: 10.26636/jtit.2018.117417.

[15] M. Z. Hasan, F. Al-Turjman, and H. Al-Rizzo, "Analysis of cross-layer design of quality-of-service forward geographic wireless sensor network routing strategies in green Internet of Things," *IEEE Access*, vol. 6, pp. 20371–20389, 2018. doi: 10.1109/ACCESS.2018.2822551.

[16] M. Fatehy and R. Kohno, "A novel contention probability dynamism for IEEE 802.15.6 standard," *EURASIP J. Wireless Commun. Netw.*, vol. 2014, no. 1, pp. 1–10, 2014.

[17] M. Anwar, A. H. Abdullah, A. Altameem, K. N. Qureshi, F. Masud, M. Faheem, Y. Cao, and R. Kharel, "Green communication for wireless body area networks: Energy aware link efficient routing approach," *Sensors*, vol. 18, no. 10, p. 3237, Sep. 2018. doi: 10.3390/s18103237.

[18] Z. Haider and K. Memon, "Adaptive routing protocol for wireless body area networks with heterogeneous nodes," *J. Netw. Commun. Emerg. Technol.*, vol. 8, no. 1, pp. 6–12, Jan. 2018.

[19] C. Anastasiades, J. Weber, and T. Braun, "Dynamic unicast: Information-centric multi-hop routing for mobile ad-hoc networks," *Comput. Netw.*, vol. 107, no. 2, pp. 208–219, Oct. 2016. doi: 10.1016/j.comnet.2016.03.009.

[20] D. Yi and H. Yang, "HEER—A delay-aware and energy-efficient routing protocol for wireless sensor networks," *Comput. Netw.*, vol. 104, pp. 155–173, Jul. 2016. doi: 10.1016/j.comnet.2016.04.022.

[21] A. Abdel-Hady, H. M. A. Fahmy, S. M. A. El-Kader, H. S. Eissa, and A. Salem, "Multilevel minimised delay clustering protocol for wireless sensor networks," *Int. J. Commun. Netw. Distrib. Syst.*, vol. 13, no. 2, pp. 187–220, 2014.

[22] K. M. Awan, A. Ali, F. Aadil, and K. N. Qureshi, "Energy efficient cluster based routing algorithm for wireless sensors networks," in *Proc. Int. Conf. Advancements Comput. Sci. (ICACS)*, Lahore, Pakistan, 2018, pp. 1–7.

[23] R. Pachlor and D. Shrimankar, "LAR-CH: A cluster-head rotation approach for sensor networks," *IEEE Sensors J.*, vol. 18, no. 23, pp. 9821–9828, Dec. 2018.

[24] Q. Nadeem, N. Javaid, S. N. Mohammad, M. Y. Khan, S. Sarfraz, and M. Gull, "SIMPLE: Stable increased-throughput multi-hop protocol for link efficiency in wireless body area networks," in *Proc. 8th Int. Conf. Broadband Wireless Comput., Commun. Appl.*, Compiegne, France, 2013, pp. 221–226.

[25] N. Javaid, A. Ahmad, Q. Nadeem, M. Imran, and N. Haider, "iM-SIMPLE: iMproved stable increased-throughput multi-hop link efficient routing protocol for wireless body area networks," *Comput. Hum. Behav.*, vol. 51, pp. 1003–1011, Oct. 2015.

[26] Z. A. Khan, S. Sivakumar, W. Phillips, and B. Robertson, "A QoS-aware routing protocol for reliability sensitive data in hospital body area networks," *Procedia Comput. Sci.*, vol. 19, pp. 171–179, Jun. 2013.

[27] Z. Khan, N. Aslam, S. Sivakumar, and W. Phillips, "Energy-aware peering routing protocol for indoor hospital body area network communication," *Procedia Comput. Sci.*, vol. 10, no. 26, pp. 188–196, Oct. 2012.

[28] A. Bag and M. A. Bassiouni, "Energy efficient thermal aware routing algorithms for embedded biomedical sensor networks," in *Proc. IEEE Int. Conf. Mobile Ad Hoc Sensor Syst.*, Vancouver, BC, Canada, Oct. 2006, pp. 604–609.

[29] N. Javaid, Z. Abbas, M. S. Fareed, Z. A. Khan, and N. Alrajeh, "M-ATTEMPT: A new energy-efficient routing protocol for wireless body area sensor networks," *Procedia Comput. Sci.*, vol. 19, pp. 224–231, Jan. 2013.

[30] A. Bag and M. A. Bassiouni, "Hotspot preventing routing algorithm for delay-sensitive applications of *in vivo* biomedical sensor networks," *Inf. Fusion*, vol. 9, no. 3, pp. 389–398, Jul. 2008.

[31] Q. Tang, N. Tummala, and S. K. Schwiebert, "TARA: Thermal-aware routing algorithm for implanted sensor networks," in *Proc. Int. Conf. Distrib. Comput. Sensor Syst.*, 2005, pp. 206–217.

[32] D. Takahashi, Y. Hu, and F. Xiao, "LTRT: Least total-route temperature routing for embedded biomedical sensor networks," in *Proc. IEEE GLOBECOM*, Nov. 2007, pp. 641–645.

[33] F. C. Henriques and A. R. Moritz, "Studies of thermal injury: I. The conduction of heat to and through skin and the temperatures attained therein. A theoretical and an experimental investigation," *Amer. J. Pathol.*, vol. 23, pp. 530–549, Jul. 1947.

[34] A. A. Hady, S. M. El-Kader, and H. S. Eissa, "Intelligent sleeping mechanism for wireless sensor networks," *Egyptian Inform. J.*, vol. 14, no. 2, pp. 109–115, Jul. 2013.

[35] K. Parsons, "Contact between human skin and hot surfaces equivalent contact temperature," in *Proc. 5th Int. Conf. Environ. Ergonom.*, Nov. 1992, pp. 144–147.

[36] R. D. Ray, "The theory and practice of safe handling temperatures," *Appl. Ergonom.*, vol. 15, no. 1, pp. 55–59, Mar. 1984.

[37] Heinzelman, R.Wendi, C.Anantha, and B.Hari, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, Maui, HI, USA, Jan. 2000, p. 10.

[38] J. Elias, A. Jarray, J. Salazar, A. Karmouch, and A. Mehaoua, "A reliable design of wireless body area networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Atlanta, GA, USA, Dec. 2013, pp. 2742–2748.

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