TRW-MAC: A thermal-aware receiver-driven wake-up radio enabled duty cycle MAC protocol for multi-hop implantable wireless body area networks in Internet of Things

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Abstract: Implantable Wireless Body Area Network (IWBAN), a network of implantable medical sensors, is one of the emerging network paradigms due to the rapid proliferation of wireless technologies and growing demand of sophisticated healthcare. The wireless sensors in IWBAN is capable of communicating with each other through radio frequency (RF) link. However, recurring wireless communication inside the human body induces heat causing severe thermal damage to the human tissue which, if not controlled, may appear as a threat to human life. Moreover, higher propagation loss inside the human body as well as low-power requirement of the sensor nodes necessitate multi-hop communication for IWBAN. A IWBAN also requires meeting certain Quality of Service demands in terms of energy, delay, reliability etc. These pressing concerns engender the design of TRW-MAC: A thermal-aware receiver-driven wake-up radio enabled duty cycle MAC protocol for multi-hop IWBANs in Internet of Things. TRW-MAC introduces a thermal-aware duty cycle adjustment mechanism to reduce temperature inside the body and adopts wake-up radio (WuR) scheme for attaining higher energy efficiency. The protocol devises a wake-up estimation scheme to facilitate staggered wake-up schedule for multi-hop transmission. A superframe structure is introduced that utilizes both contention-based and contention free medium access operations. The performance of TRW-MAC is evaluated through simulations that exhibit its superior performance in attaining lower thermal-rise as well as satisfying other QoS metrics in terms of energy-efficiency, delay and reliability

Keywords: wireless body area networks, wake-up radio enabled MAC, duty cycle, multi-hop

1. Introduction

Recently, an unprecedented growth has been observed in Micro-Electro-Mechanical Systems (MEMS) [1] as wireless communication technologies that have engendered a new family of networks interconnecting miniature devices called Internet of Things (IoT). IoT, being a vigorous communication paradigm, can connect objects from various domains including sensors, smart phones, vehicles, and home appliances exploiting the Internet architecture and enable an intelligent resource and information sharing [2]. IoT, thus appears to be one of the most potential architectures that promotes the proliferation of several "Smart" applications. Among those, IoT healthcare is regarded as one of the eminent ones, and its associated technologies gained significant research attention [3].

Implantable Wireless Body Area Networks (IWBANs), composed of tiny wireless sensor nodes implanted either subcutaneously or through invasive surgery into the patient's body, is one of the striking IoT healthcare technologies in recent years. The implanted sensors, upon sensing diverse physiological data from different body parts, disseminate to a central coordinator device known as Body Coordinator (BC), exploiting wireless channel for further processing [4] [5]. In one hand, IWBAN thus provides more accurate and automated body monitoring system due to less human intervention, and in another hand, it significantly reduces the healthcare expenditure yielding efficient healthcare resource utilization.

Yet, the "in-body" environment poses some significant communication challenges for IWBANs. The continual sensing and communication operations induce heat inside the body resulting in significant tissue damage [5] [6] [7]. Such damage may cause disastrous consequences even leads to death if thermal rise is not controlled and continue for a considerable period. Hence, thermal control is regarded as one of the pivotal factors in devising communication protocols for IWBANs. Moreover, human body has higher propagation loss [8] that often restricts the direct communication between the sensors and the BC. Since sensor nodes are battery-powered, energy efficiency is another striking requirement for the communication protocols of IWBANs. Direct communication also requires higher transmitting power thereby contradicts the energy efficiency demands. Thus, IWBANs require multi-hop communication where sensor nodes transmit the sensed data using low transmission power to a nearby node that relays the data to another node and eventually the data traverses through multiple hops until it reaches the BC.

An IWBAN consists of in-vivo sensors to estimate a broad-spectrum of physiological parameters, such as heart rate, body temperature, blood pressure, oxygen saturation level, electrocardiogram (ECG) etc. [9] . The miscellaneous data also require satisfying diverse Quality of Service (QoS) demands (i.e., delay, reliability etc.). For example, electroencephalogram (EEG), electrocardiogram (ECG) and Electromyography (EMG) etc. are delay constrained but respiration monitoring, pH level monitoring have concerns on achieving higher degree of reliability. Therefore, a communication protocol designed for IWBANs need to consider the meeting of QoS as well.

The medium access control (MAC) protocols designed for wireless body area networks primarily focused on energy efficiency [10] [11] [12]. These protocols exploit duty cycle mechanism in which a node is periodically put into sleep state to save energy to the maximum possible. The protocols mainly employ Time Division Multiple Access (TDMA) or Carrier Sense Multiple Access (CSMA) as medium access mechanism. However, duty cycling mechanisms still suffer from two main problems: idle listening and overhearing [12] [13]. Idle listening is the radio listening of the packets when no transmission is going on. Overhearing is the reception of a packet by a node which is not intended for it. To tackle the problems, a hardware-based solution termed "Wake-up Radio (WuR)" has been emerged that exploits two different radio: an Wake-up radio (WuR) and a main radio (MR). The MR is the usual radio for transmission and reception of data. The WuR aims to minimizes the energy consumption by switching the MR off when there is no data for transmission. Upon generating data, a node transmits a wake-up call (WuC) using WuR. The wake-up receiver can detect the wake-up call and generate interrupt to turn on the MR which then continues the communication activities. The WuR can be ceaselessly turned on or it can be duty cycled as well. It has been shown that an WuR consumes approximately 1000 times lower energy than that of MR [14] [15].

A handful of WuR enabled MAC protocols have been devised in the context of WBANs [16]. WuR based MAC protocols are classified as transmitter-initiated [17] [18] [19] [20] [21] or receiver-initiated [22] [23] [24]. In transmitted initiated protocols, the transmitter initiates the communication by sending a WuC to the potential receivers while in a receiver-initiated protocols, a receiver transmits WuC inviting the transmitter to initiate data transmission to that receiver. Along with the energy efficiency, the protocols also aimed to address the QoS provisioning issues. Considering the thermal-rise as an important concern for IWBANs, only one research attempt has been found that devised a thermal-aware duty cycle MAC protocol [25] . However, the protocol does not employ the WuR and mainly designed for single hop IWBANs. Therefore, to the best of our knowledge, a thermal-aware MAC solution that exploits wake-up radio along with considering the meeting of certain QoS for multi-hop IWBANs, still does not exist in the literature.

This paper proposes TRW-MAC-a thermal-aware receiver-driven wake-up radio enabled duty cycle MAC protocol for multi-hop IWBANs in IoT healthcare. Considering the communication challenges for IWBANs as mentioned above, we aim to present a full-blown MAC scheme that tackles the challenges in a single MAC protocol. As follows, we summarize our overall contributions:

• We propose a thermal-aware duty-cycle adjustment mechanism that intents to lower thermal-rise inside the body.

• We devise a wake-up estimation scheme considering the multi-hop transmission that establishes a staggered wake-up schedule to reduce end-to-end latency.

• We design a superframe structure that appoints separate transmission times utilizing contention-based and contention-free medium access for different traffic categories.

• We conduct experiments through simulations to assess the performance of TRW-MAC.

The rest of the paper is organized as follows: Section 2 compiles the related works. Section 3 discusses some preliminaries including system models and assumptions behind the protocol along with the traffic taxonomy. Section 4 presents the design of TRW-MAC in detail. Section 5 exhibits the protocol performance conducted through simulations and finally, Section 6 presents concludes the paper.

2. Related Work

Over the past decades, a large multitude of research efforts have been made to devise MAC protocols for WBANs. IEEE 802.15.4 [26], a standard for low-power and low data rate applications, was initially considered as a base protocol for WBANs due to the low-power requirement for WBANs. The standard was mainly applied considering the single-hop star network configuration of WBANs. A significant adaptations [27] [28] [29] [30] were later made on IEEE 802.15.4 that addressed to improve the energy efficiency and some QoS metrics including delay, throughput, reliability etc.

In 2012, IEEE 802.15.6 [31] was emerged as a standard specific for WBAN. As medium access mechanism, IEEE 802.15.6 exploits both contention-based CSMA/CA and contention-free TDMA. The standard defines a number of periods namely Exclusive Access Phases (EAP1 and EAP2), Random Access Phases (RAP1 and RAP2), Managed Access Phase (MAP) and Contention Access Phase (CAP) in one superframe. It also defines diverse priority for diverse traffic types. In the superframe, higher priority traffic are transmitted during EAPs, the RAPs are utilized for non-periodic traffic and TDMA is used during MAP to transmit traffic required contention-free access. However, the standard also considered single hop star topology and did not address the thermal-rise challenges of IWBANs.

A plethora of research attempts were observed based on IEEE 802.15.6. In [32], the authors proposed an adaptive MAC protocol based on IEEE 802.15.6. In this research, the length of contention access and non-contention access phase are adjusted considering ratio of the nodes generating priority data. A context-aware MAC protocol was introduced in [33] aiming to meet dynamic demands of WBAN with respect to channel status and traffic type. Focusing on improving network reliability along with energy efficiency, S. Rezvani and S. AliGhorashi proposed HE-MAC [34]. S.Ullah and K.S. Kwak introduced an adaptive MAC protocol [35] exploiting TDMA that defined synchronization scheme to avoid collision. Exploiting the heartbeat vibration from physiological signal to synchronize sensors, a heartbeat driven MAC protocol (H-MAC) was introduced for WBANs [36].

Exploiting WuR, a number of protocols were introduced for WBANs [16]. Miller et. al. proposed Miller-MAC [37] aiming to reduce energy consumption using WuR. In [38], the authors proposed RTWAC-MAC- a radio triggered wake-up with addressing capabilities MAC to reduce idle listening and avoid unnecessary radio wake-ups. A power-efficient MAC [39] was proposed exploiting TDMA with WuR to save energy compared to CSMA/CA and achieving low delay. ULPA-MAC [40] is an ultra low power asynchronous MAC that considered both energy efficiency and throughput improvement. In [41], On-Demand MAC was proposed considering both lowering energy consumption and delay. It employs a contention free protocol and uses wake-up schedule for transmitting normal traffic. A load adaptive energy efficient MAC protocol was introduced in [42] that handles load variations through adaptive duty cycle. Guntupalli et. al. presented RI-CPT-WuR MAC [23] that allows consecutive packet transmission for the wining node to reduce the packet access competition for achieving higher energy efficiency. In [24], the authors proposed another receiver initiated WuR

MAC, RI-LD-MAC that aimed to reduce contention by classifying the nodes equally and assign distinct time slot for each group in each cycle of communication. Sub Carrier Modulation WuR (SCM-WuR) [43] was proposed that dynamically configures radio settings for transmitting WuC and data. An SCM-WuR may operate as either wake-up receiver or wake-up transmitter and has better latency and energy efficiency compared to the non-WuR-enabled duty cycle protocol [44].

The aforementioned protocols designed in the context of WBANs or generic WSNs, however, did not address the unique challenges of IWBANs, in particular, the thermal-rise issue. Recently, Monowar et al. proposed ThMAC [25] that considers thermal-rise in choosing wake-up schedule of a node. Nonetheless, the proposed scheme is applicable to single hop IWBANs. Moreover, it does not exploit the WuR for higher energy efficiency which already proved its supremacy with respect to the non-WuR duty cycle approaches. Therefore, this paper aims to propose a novel MAC solution considering the multi-hop requirements, thermal-rise, energy efficiency along with the QoS in terms of delay and reliability.

3. Preliminaries

3.1 System Models and Assumptions

Figure 1 illustrates our network model, where a number of WBAN nodes are implanted inside the human body (i.e., in-vivo nodes) and the BC is externally tied to the human body. The WBAN nodes are connected to each other as well as with the BC through wireless communication links as depicted in Figure 1(a). WBAN nodes are resource constrained in terms of energy (battery powered), memory and processing power, and hence are used to perform mostly sensing and data transmission operations with limited processing. On the other hand, we consider BC having external power supply along with higher processing capabilities. Upon sensing, WBAN nodes transmits the data to the BC which then process it and sends to another Base Station (BS) or server through a network architecture and this communication architecture is beyond our scope.

The deployment scenario as mentioned above can be represented as a connectivity graph, $\mathbf{G} = (N, E)$, where $N = n_1, n_2, \dots, n_n\}$ denotes the set of vertices depicting the nodes in the network, and E is the set of edges representing all possible communication links as portrayed in Figure 1(b). We assume each node n_i has fixed transmission power to communicate with the neighbors. We define the neighbor set of n_i, denoted as $NBR(n_i)$ are the nodes having communication links with n_i. We consider all communication links are symmetric, in particular, if $n_i \in NBR(n_j)$, then $n_j \in NBR(n_i)$. Due to being energy constrained, WBAN nodes have very limited transmission range, and hence can communicate to BC through multiple hops. We assume that a subtree **ST** from **G** has been already been built by any existing routing algorithm, rooted at the sink as illustrated in Figure 1(c). In this tree, only parent and child nodes communicate with each other. We express the parent and child of n_i are p_{n_i} and c_{n_i} respectively. In this routing path, some nodes only sources data,, some only forward other node's data or some might act both as source and forwarder.

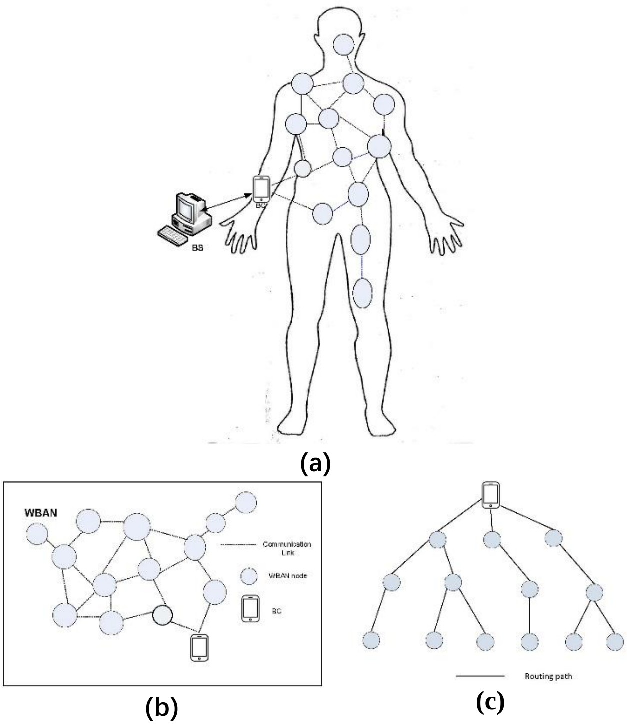


Figure 1. Network Model

3.2 Traffic Taxonomy

A WBAN typically includes wireless nodes to sense and transmit diverse traffic types. The diverse in-vivo nodes also may have different QOS requirements. This paper categorizes traffic types as follows:

• ***DS-Delay Sensitive***: This category of traffic requires fast delivery to the BC, and sometimes possesses certain deadlines. However, this type tolerates packet loss to certain extent. Some medical applications, such as, electroencephalogram (EEG), electrocardiogram (ECG) and Electromyography (EMG) belong to this type.

• ***RS-Reliability Sensitive***: This traffic type possesses some reliability demands, yet it is delay insensitive such as respiration monitoring, pH-level monitoring etc. Since RS traffic does not require online processing, so they are non-delay constrained, yet loss of packet may cause adverse effects.

• ***NR-Normal***: This type of traffic is neither delay sensitive nor reliability sensitive. Applications requiring periodic measurement of patient's bodily parameters including temperature, pulse rate, SPO2 etc. belong to this class of traffic.

4. TRW-MAC Design

The primary design goal of TRW-MAC is to maintain invulnerable temperature inside the body by regulating thermal rise that causes for the continuous wireless communication of the implants. Additionally, TRW-MAC aims to satisfy the diverse QoS demands and enhance the energy efficiency of the in-vivo nodes. TRW-MAC opts to meet these goals in a multi-hop network environment.

4.1 Estimating Thermal Rise

TRW-MAC adopts the mechanism for thermal-rise estimation as introduced in [5] [7]. This estimation model assumes that the WBAN or its components are inner to the cross section of a tissue which are further arranged into grids. Each implant is expected to be placed in a grid of fixed width and length. A node takes an initial temperature that changes periodically due to the communication operation of the nodes.

Thermal rise mainly causes because of the radiation emanating from the antenna. To measure the radiation level that is consumed by tissue, the parameter, Specific absorption rate (SAR) is used. The space encompassing the antenna is divided into near and far field. Equation 1 and 2 exhibits how SAR in the near and far field can be estimated [7]:

$$SAR_{NF} = \frac{\sigma\mu\omega}{\rho\sqrt{\sigma^2+\epsilon^2\omega^2}}\left(\frac{I\mathrm{dl}sin\theta e^{-aR}}{4\pi}\left(\frac{1}{R^2}+\frac{\gamma}{R}\right)\right)^2 \quad (1)$$

$$SAR_{FF} = \frac{\sigma}{\rho}\left(\frac{\overline{a}^2+\overline{b}^2}{\sqrt{\sigma^2+\omega^2\epsilon^2}}\frac{I\mathrm{dl}}{4\pi}\right)^2 \frac{sin^2\theta e^{-2\alpha R}}{R^2} \quad (2)$$

where, R is the distance between the source and the observation point, γ is the propagation constant, dl is the conducting wire length for a short dipole antenna, σ is the medium conductivity, I is the amount of current, ϵ is the relative permittivity, μ is the permeability, ρ is the mass density and $sin\theta = 1$.

Along with the radiation level, power dissipation of the sensor node circuitry also contributes to the thermal increase [7]. This is referred to as power dissipation density, P_c and is estimated as:

$$P_c = \frac{P_{circuit}}{V_s} \quad (3)$$

where $P_{circuit}$ denotes the power dissipation of sensor circuitry and V_s is the sensor volume.

Taking into account the factors for thermal-rise, the temperature of a node at a grid point (m,n) at time t, denoted as $T^t(m,n)$, can be measured exploiting FDTD [45] [7].

$$T^t(m,n) = \left(1 - \frac{\Delta_t b}{\rho C_p} - \frac{4\Delta_t K}{\rho C_p \Delta^2}\right) T^{t-1}(m,n) + \frac{\Delta_t}{C_p} SAR + \frac{\Delta_t b}{\rho C_p} T_b + \frac{\Delta}{\rho C_p} P_c + \frac{\Delta_t K}{\rho C_p \Delta^2} (T^{t-1}(m+1,n) + T^{t-1}(m,n+1) + T^{t-1}(m-1,n) + T^{t-1}(m,n-1)) \quad (4)$$

Here, Δ_t and Δ are the discretized time step and space step respectively, b denotes the blood pressure perfusion constant, C_p refers the specific heat of the tissue, T_b stands for the fixed blood temperature and K is the thermal conductivity of the tissue.

From equation 4, we can determine the temperature of a node at grid point (m,n) at time t which is a function of the temperature at (m,n) at time $t-1$, and the function of the temperature of surrounding nodes at grid points ((m+1,n), (m,n+1), (m-1,n), and (m,n-1)). As the implant nodes are surgically implanted, hence our assumption for fixed node positions is valid . By knowing the tissue properties, the properties of blood flow, and the heat absorbed by the tissue, the temperature at a given time can be easily estimated.

4.2 Superframe Structure

Due to adopting duty cycling, nodes in TRW-MAC alternates between Active and Sleep state. The superframe structure of TRW-MAC is depicted in Figure 2. A superframe interval is denoted as T_{super}. Each superframe initiates with a Beacon period where a node broadcast a beacon packet to its children. The beacon packet usually includes management information such as the clock synchronization with the child nodes, superframe duration, duration of Active and Sleep period etc. The Active period is followed by beacon period which is divided into a Reception period (Rx) and a Transmission Period (Tx). In the reception period, a node receives packets from its child nodes and attempts for transmission of the received packets along with its originated packets in the transmission period.

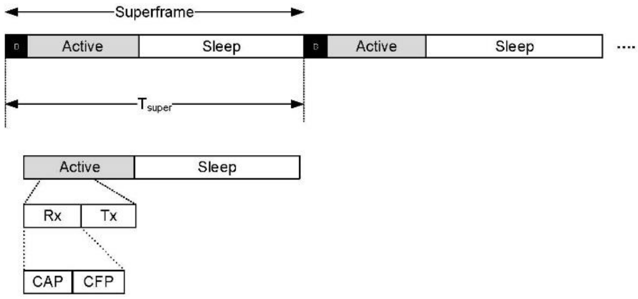


Figure 2. Basic Superframe structure of TRW-MAC

The reception period further includes a Contention Access Period (CAP) and a Contention Free Period (CFP). During CAP, a node transmits *DS* and *NR* packets, also the slot reservation request (SR) packet for *RS* packets exploiting random access mechanism such as CSMA/CA. However, due to the lower delay requirement *DS* packets are prioritized over the other packets as to be discussed later in section 4.5. CFP is exclusively used for *RS* packets that includes guaranteed transmission slots to ascertain contention free reliable transmission. A node notifies the reserved slots to its child nodes through the Acknowledgment packet during CAP. Provisioning diverse period for diverse traffic types reduces the contention which also contributes in achieving lower delay and higher packet delivery ratio.

TRW-MAC employs long sleep period where a node turns both their MR and WuR off to save energy as well as preventing thermal-rise.

4.3 Thermal-aware duty cycle adjustment

This section introduces a thermal-aware duty cycle adjustment mechanism that intents to reduce temperature increase inside the body.

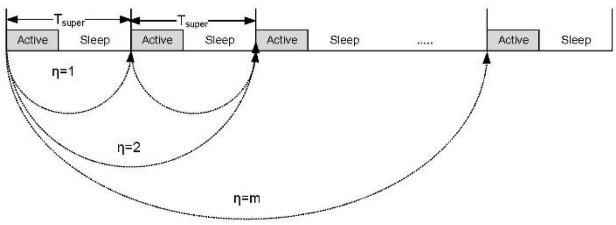


Figure 3. Wake-up Interval

Thermal rise inside the body mainly occurs for the radiation emanating from the node antenna which depends on the level of communication operation. Specifically, the more a node engages itself with the communication activities, the more the temperature surrounding the tissue increases which may result in tissue damage. To avoid such situation, we define hotspot threshold, H_{th} as the temperature threshold beyond which a node is regarded as hotspot and its status is set as $H_{n_i} = 1$. Contrarily, reducing the communication operation allows a node to be cooled down. Thus, through regulating the communication activity, the temperature surrounding a node can be controlled.

TRW-MAC controls the duty cycle of a node through a parameter, *wake-up interval* denoted as η. The wake-up interval of a node n_i is defined as the number of superframe interval at which the node wakes up and starts its communication activities. In particular, if $\eta = 1$, a node wakes up at each superframe interval. For $\eta = 2$, a node wakes up at every second superframe (at $2 \times T_{super}$ interval). Thus for $\eta = m$, a nodes wakes up at an interval $m \times T_{super}$ to continues its communication operation following the superframe structure as discussed earlier, and a node is allowed to be in the sleeping state between m superframes. Figure 3 illustrates the concept.

Algorithm 1 illustrates the thermal-aware duty cycle adjustment procedure of TRW-MAC. Here, we define three constant parameters: η_{min}, η_{max} and α. η_{min}, η_{max} denote the minimum and maximum wake-up interval value of a node respectively. α is the increasing factor of η, and we opt to observe the effect of thermal rise by gradually increasing its value, hence $\alpha = 1$. Moreover, as a default operation, TRW-MAC aims to communicate in every superframe period, hence, $\eta_{min} = 1$. For the maximum value of η, we empirically set the parameters as $\eta_{max} = 4$.

Algorithm 1: Thermal aware duty cycle adjustment at every node $\boldsymbol{n_i}$

INPUT: Hotspot status of n_i, H_{n_i}; Hotspot status of the parent, $H_{p_{n_i}}$; Data Generation interval of n_i, $T^{data}_{n_i}$; Wake-up interval of the child nodes, $\eta_{c_{n_i}}$; Wake-up interval of the parent node, $\eta_{p_{n_i}}$

1: **While** (TRUE)
2: *Case 0:*
3: **if** $H_{n_i} = 0$ AND $H_{p_{n_i}} = 0$ **then**
4: $\eta_{n_i} = \max(\min(\min_{\forall c_{n_i}}(\eta_{c_{n_i}}), \lceil \frac{T^{data}_{n_i}}{T_{super}} \rceil), \eta_{min})$
5: **end if**
6: *Case 1:*
7: **if** $H_{n_i} = 0$ AND $H_{p_{n_i}} = 1$ **then**
8: $\eta_{n_i} = \max(\eta_{n_i}, \eta_{min}, \eta_{p_{n_i}})$
9: **end if**
10: *Case 2:*
11: **if** $H_{n_i} = 1$ AND $H_{p_{n_i}} = 0$ **then**
12: $\eta_{n_i} = \min((\eta_{n_i} + \alpha), \eta_{max})$
13: **end if**
14: *Case 3:*
15: **if** $H_{n_i} = 1$ AND $H_{p_{n_i}} = 1$ **then**
16: $\eta_{n_i} = \eta_{n_i} + \alpha$
17: $\eta_{n_i} = \min(\max(\eta_{n_i}, \eta_{p_{n_i}}), \eta_{max})$
18: **end if**
19: **end while**

The algorithm regulates the wake-up interval of a node n_i based on the hostspot status of the node and its parent. There are four cases as shown in Table 1. In the first case, both node and its parent are in non hotspot condition. In this case, a node chooses its wake-up interval as per line 4 of the algorithm. It ensures that during non-heated situation, a node always chooses its wake-up interval as per the minimum value of two factors: (1) minimum wake-up interval of its child nodes, and (2) $\frac{T^{data}_{n_j}}{T_{super}}$. However, it will never be less than the minimum wake-up interval of a node. In the second case, a node is in non-hotspot condition while its parent is in hotspot. Here, a node may determine its wake-up interval as per the wake-up interval of its parent if the parent's wake-up interval is higher than the node's wake-up interval as shown in line 8. The third case occurs when a node itself is in hotspot situation but the parent is not. At this time, the node increases its wake-up interval additively with factor α but it never exceeds η_{max}. The longer wake-up interval keeps the node into sleep state so that its temperature gradually goes down as depicted in line 12 of the algorithm. In the last case, both the node and its parent are in hotspot condition. In this case, a node first increases its wake-up interval (line 16). Then it determines its wake-up interval to the wake-up interval of its parent if the parent's wake-up interval is higher than the node's current wake-up interval (line 17).

Case	Hotspot Status: Node	Hootspot Status: Parent
0	0	0
1	0	1
2	1	0
3	1	1

Table 1: Different cases of hotspot status

Notably, the algorithm requires the exchange of hotspot status and wake-up interval between parent and child nodes. The hotspot status requires 1 bit and the wake-up interval needs only 3 bits. A node embeds this information in the beacon, data and ack packet.

4.4 Wake-up time estimation for staggered multi-hop transmission

TRW-MAC aims to maintain staggered multi-hop transmission to reduce the end-to-end delay of the packet. In particular, a node in the routing tree attempts to transmit the packets as soon as it receives from its child nodes. The thermal-aware duty cycle adjustment mechanism ensures that the wake-up interval of a node will always be greater or equal to its parent's wake-up interval. Furthermore, TRW-MAC also requires clock synchronization between parent and its immediate child nodes. For a staggered transmission, a node n_i, being a non-leaf node, determines its wake-up time after receiving beacon from its parent as follows:

$$t^w_{n_i} = t^b + \eta_{n_i} \times T_{super} - T^{Rx}_{n_i} - T^{BP} - t^g \quad (5)$$

where, t^b is the time at which n_i receives its beacon from its parent, $T^{Rx}_{n_i}$ and $T^{BP}_{n_i}$ are the length of reception period and beacon period of n_i respectively and t^g is the guard time for clock drift.

If n_i is a leaf node, it determines the wake-up time as follows:

$$t_{n_i}^{w} = t^{b} + \eta_{n_i} \times T_{super} - t^{g} \tag{6}$$

Figure 4 illustrates the staggered multi-hop transmission of TRW-MAC. The concept has been illustrated using a small topology as shown in the right side of the figure. Here, node N4 and N5 are the leaf nodes. N2 and N3 are the immediate parents of N4 and N5 respectively. Here, as per algorithm 1, N5 and N3 maintains wake-up interval, $\eta = 1$, and for N2 and N4, $\eta = 2$. Since, N4 and N5 are leaf nodes, they determine their wake-up time according to equation 6 and wakes up just right before its parent to receive the beacon. Since, the leaf nodes have no children, hence, they just maintain transmission period in the corresponding superframe. However, being a non-leaf node, N2 and N3 wakes up as per equation 5 and finishes its own beacon period and reception period before receiving the beacon from their parent N1. After receiving the beacon from N1, both N2 and N3 transmits their received data as well as their originated data in the subsequent transmission period. Here, N1 determines its wake-up interval, $\eta = 1$. Thus, N1 is able to receive packets from both N2 and N3. N1 eventually transmits the received packets from N2 and N3 to the sink node in its own transmission period. Hence, the nodes maintain staggered transmission along the way to the sink with the aim of reducing end-to-end delay of the packets.

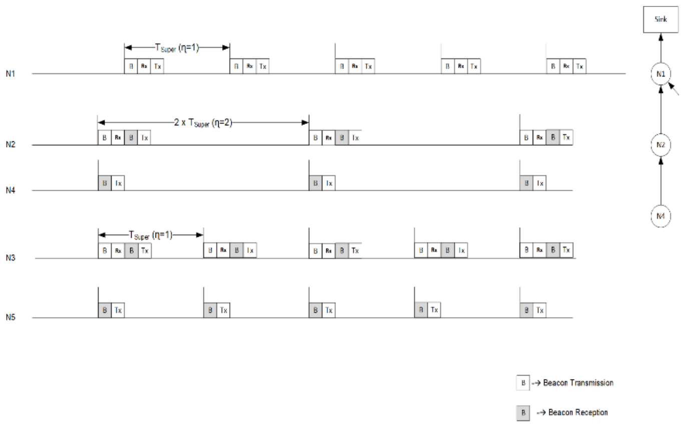


Figure 4. Staggered multi-hop transmission

4.5 MAC Operations

This section discusses the MAC operations of TRW-MAC during a superframe. Being wake-up radio enabled, TRW-MAC maintains two radios: MR and WuR. TRW-MAC adopts duty-cycled WuR, in particular, the wake-up radio will be periodically turned on to send (or receive) wake-up signal to (or from) the channel. Since, TRW-MAC is a receiver driven MAC, both the receiver and the sender WuR attempts to find a rendezvous time for data exchange as discussed in section 4.4. However, the MR is usually turned off and will be on when communication actually needs to take place. In this situation, a WuC is generated by the WuR to the MCU of a node.

As stated earlier, a superframe starts with a beacon period. At the appointed wake-up time, a node's WuR is turned on and it broadcast WuC to its immediate child nodes. The WuC includes the address of the node. Since the child nodes wake-up earlier than the parent and their WuR is already turned on, they receive the WuC and decode the address. Upon verifying the address, the child nodes turn on their MR and wait to receive the Beacon. The WuR of the parent, meanwhile, sends interrupt to the MC to switch on the MR. After waiting for short-inter-frame-space (SIFS) period followed by clear channel assessment (CCA) to avoid any ongoing transmission, the parent broadcast a beacon packet. The child nodes, then are synchronized with their corresponding parent, notified the relevant parameters i.e., wake-up interval of parent, superframe period, active period duration etc. Upon transmitting the beacon, a node waits to receive packets from its child nodes in the reception period. The node goes to sleep state if it does not receive any packet after waiting for a time-out period. Figure 5 depicts the communication during beacon period.

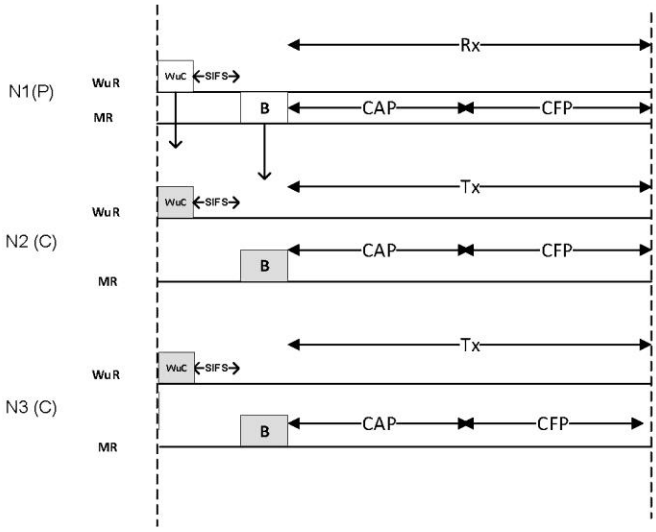


Figure 5. Communication during Beacon Period

The reception period starts with CAP where nodes contend for the channel access. CAP is utilized for transmitting *DS* and *NR* packets along with the slot reservation request of *RS* packets. Yet, due to the delay sensitivity, *DS* packets are prioritized during transmission over other types of packets, and hence, adopt different contention parameters as shown in Table 2.

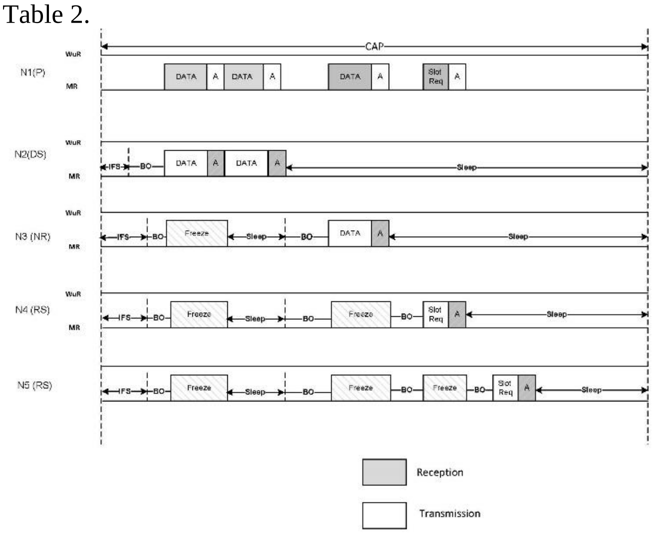


Figure 6. Communication during CAP

A node attempts for transmission if it has sufficient number of packets in its queue, determined by transmission threshold, Tr^{th}. A node also may have diverse packets in its queue. In that case, *DS* will be prioritized for transmission, and *NR* and *RS* packets will be of equal priority. The tie breaking can be done based on the number of packets in the queue. Notably, TRW-MAC does not transmit the data packet of RS type during CAP, rather it transmits its slot reservation request. In the slot reservation request, a node request its parent to reserve slots for certain number of RS packets in the queue, and the child nodes are notified about their allocated slot in the respective ACK packet by the parent. TRW-MAC adopts consecutive packet transmission as in [23] to reduce idle listening as well as collision probability. In particular, after winning the channel contention and transmitting the first data packet, a node informs its parent about the number of consecutive packets it will transmit. This information is piggybacked in the data packet. The parent also includes this value in the corresponding ACK packet. All other nodes immediately goes to sleep and wakes up again after transmission of the winning node ends, and continue the contention procedure.

Table 2: Contention parameters during CAP

DS	NR/RS
IFS: 2 slots	IFS: 4 slots
$CW_{min}: 2slots$	CW_{min}: 8 slots
$CW_{max}: 8slots$	CW_{max}: 16 slots

Figure 6 portrays the communication operations during CAP. Here, Node N1 is the parent and N2, N3, N4 and N5 are the child nodes. In this example, N2 and N3 are holding DS and NR packets respectively, and both N4 and N5 are carrying RS packets in their respective queue. Due to higher priority N2 chooses lower IFS and back-off period and wins the contention. Upon overhearing the value of consecutive packets of N2, N3, N4 and N5 go to sleep and wake up again after N2 finishes its transmission. Because of adopting same contention parameters, N3, N4 and N5 competes with each other. N3 wins the contention and finishes the data transfer. Afterwards, N4 and N5 get the channel access after waiting their respective contention parameters and transmit their corresponding slot reservation request to N1. N1 informs the designated slot information to N4 and N5 in the corresponding ACK packets. It is worth mentioning that, each node goes to sleep after finishing their transmission during CAP, and the data transmission during CAP continues until the period ends.

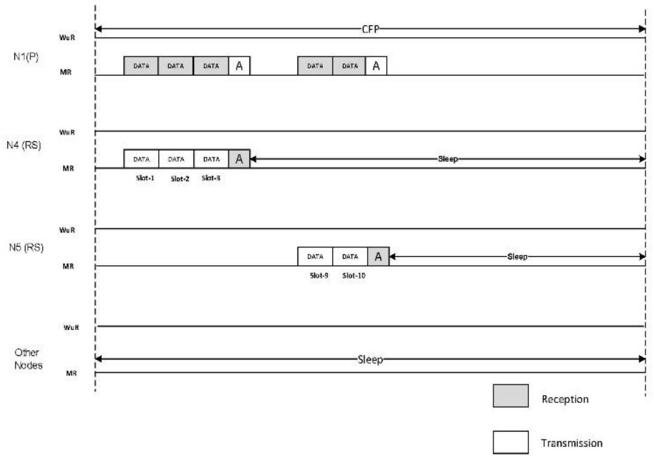


Figure 7. Communication during CFP

CFP is exclusively used to transmit RS packets as it requires higher reliability. The reservation of the slot ensures contention free transmission with guaranteed delivery. The nodes carrying RS packets in the queue wake up at their respective assigned slot and transmit packets through MR. Figure 7 illustrates the procedure. Here, node N4 is assigned slot no 1, 2 and 3, and N5 is assigned slot 9 and 10 depending on their number of RS packets as mentioned in the slot reservation request. Both N4 and N5 wake up at their corresponding slot time and finish data transmission reliably which is acknowledged by a cumulative ACK packet to each node. The nodes immediately go to sleep upon receiving the ACK. All the remaining nodes having other packet types are also in the sleeping state during CFP to conserve energy as well reducing thermal-increase.

5. PERFORMANCE EVALUATION

This section discusses the performance evaluation of TRW-MAC. The performance evaluation is done through experiments with simulations.

5.1 Simulation Environment

A network area of $10m \times 10m$ having 13 nodes with random uniform distribution is considered in our simulation. We consider the topology as depicted in Figure 1(c) in which we use static routing paths [1]. In this topology each node may act as a source as well forwarder. Each node generates traffic of certain type. In our experiment, we vary the number of sources. In each case, we set the distribution of the traffic type as shown in Table 4. We compare TRW-MAC with the receiver-initiated version of SCM-WuR and multi-hop implementation of 802.15.6 [46]. SCM-WuR is one of the dominant WuR enabled MAC protocols designed for generic WSNs but can be applied in the context of WBAN as well. For the receiver initiated SCM-WuR, we set the WuC transmission interval sent by the receiver as 1 second. 802.15.6 is the standard designed for WBAN and we consider the multi-hop and CSMA/CA implementation of the standard. The initial data generation time is randomly generated so that nodes do not generate data at the same time. In each result, packets refer to only data packets. The simulation has been conducted for 1000 seconds and we average the results over 10 random runs with different random seeds. Table 3 illustrates the simulation parameters we considered. We include 95% confidence interval in the plots. The simulation program has been developed in C++.

5.2 Performance Metrics

The following metrics are used to evaluate the performance of TRW-MAC.

Average Temperature Rise. The average temperature rise of the nodes implies the average increase in temperature of the nodes with respect to the opening temperature.

Energy Consumption. The energy consumption refers to the average energy consumption of the nodes. The

Table 3: Parameters and their values used in the simulation

Type	Parameter	Value	Unit
Physical Layer	Data Rate	250	kbps
	Battery Capacity	1500	mAh

[1] In an implanted WBAN, nodes are usually static, and we opt to measure the protocol performance irrespective of any routing protocol

	Tx Power:MR	52.2	mW
	Rx Power:MR	56.4	mW
	Listening Power:MR	56.4	mW
	Sleep Power:MR	0.3	μW
	Tx Power:WuR	5.25	mW
	Rx Power:WuR	0.024	mW
	Listening Power:WuR	0.024	mW
	Sleep Power:WuR	0.0035	mW
	PHY Header	6	bytes
MAC Layer	WuC	12.2	ms
	BP	10	ms
	CAP	30	ms
	CFP	20	ms
	GTS Slot time	500	μs
	SIFS	5	ms
	T_{super}	1	s
	Payload length	100	bytes
	Beacon length	10	bytes
	ACK length	10	bytes
	Max Retry Limit	3	
	Queue Size	10	packets
	Tr^{th}	2	packets
	Contention Parameters	As per Table 2	
Temperature	Relative Permittivity at 2 MHz, ϵ	826	
	Conductivity at 2 MHz, σ	0.5476	$[\frac{S}{m}]$
	P_c	0.002	
	C_p	3600	$[\frac{J}{kg^\circ C}]$
	Blood perfusion constant, b	2700	$[\frac{J}{m^3 s^\circ C}]$
	Discretized Time step, Δ_t	1	s
	Initial Temperature	37	$^\circ C$
	Current provided to sensor antenna, I	0.1	A
	Mass density, ρ	1040	$\frac{kg}{m^3}$
	K	0.498	$[\frac{J}{ms^\circ C}]$
	Discretized Space Step, Δ	0.2	m
	Hotspot threshold, H_{th}	$37.4^\circ C$	

power consumption values as shown in table 2 are used in estimating energy consumption.

End-to-End Latency. End-to-End latency of a packet is measured as the time between the packet originates at the source and the time it is received by the BC. In this experiment, End-to-End latency is measured at the BC which takes the average on the perceived end-to-end latency of distinct data packets.

Packet delivery ratio (PDR). PDR is the ratio of the total number of unique packets collected by BC to the total number of packets sourced by the nodes.

Table 4: Traffic Distribution

Traffic Type	Percentage of Node as Originator
DS	30%
RS	30%
NR	40%

5.3 Simulation Results

5.3.1 Effect of η_{max}

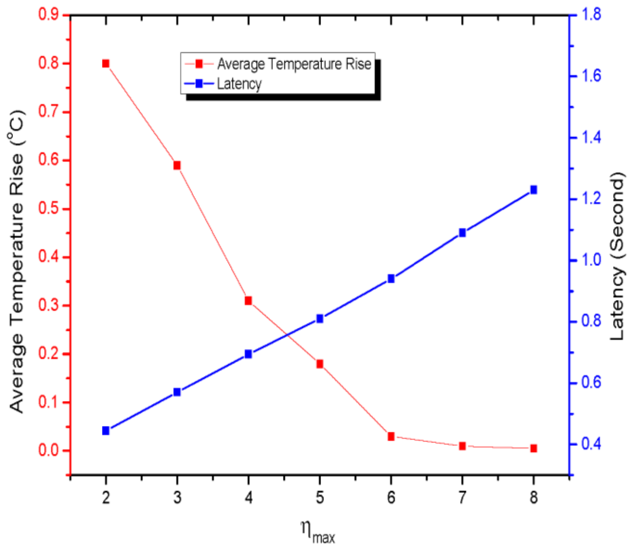


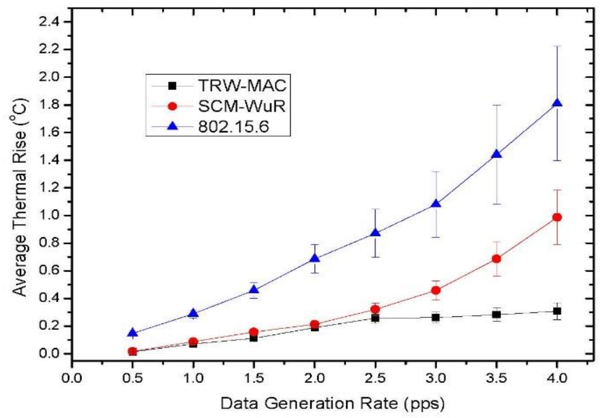
Figure 8. Effect of η_{max} on thermal-rise and latency

Figure 8 depicts the impact of η_{max} on thermal-rise and latency. In this experiment, we consider 8 sources with the traffic distribution as in Table 4. All sources generate traffic at 4 packets per second (pps). The bit error rate (BER) varies randomly between 10^{-6} to 10^{-2}.

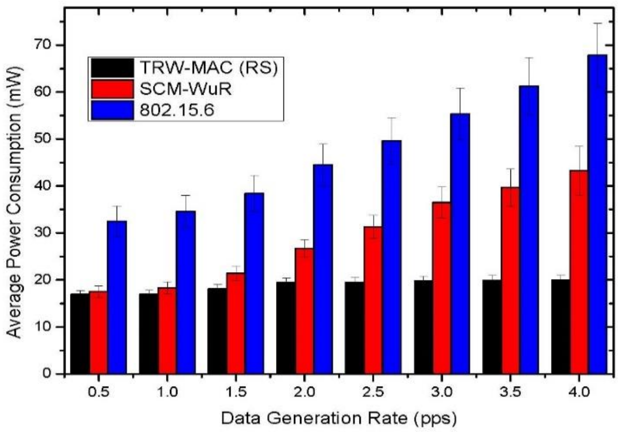
As the figure shows, the average temperature drastically reduces with increasing η_{max}. This is obvious since with higher η_{max}, the wake-up interval of the nodes increases, allowing nodes being in the sleeping state for a longer period of time, especially during higher traffic load at 4 pps. The decreased communication activities reduces the temperature of the nodes. However, the higher value of η_{max} increases the average end-to-end latency of the packets. Hence, there is always a trade-off between the average thermal rise and end-to-end latency with respect to η_{max}. We observe a moderate temperature rise ($\approx 0.2^oC$) and acceptable latency ($\approx$ 0.7ms) for delay sensitive packets at $\eta_{max} = 4$. Hence, we set this value for this parameter for TRW-MAC.

5.3.2 Effect of Data Generation Rate

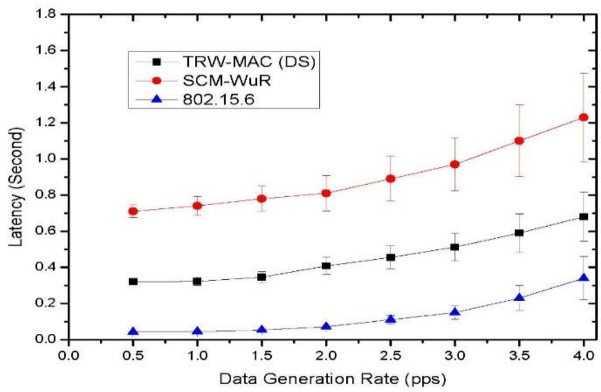
In order to quantify the effect of data generation rate in the performance of TRW-MAC with other protocols, we choose 8 sources with the mentioned traffic distribution in Table 4. The BER ranges from 10^{-6} to 10^{-2}. We vary the data generation rate from low traffic load (0.5 pps) to high traffic load (4 pps).



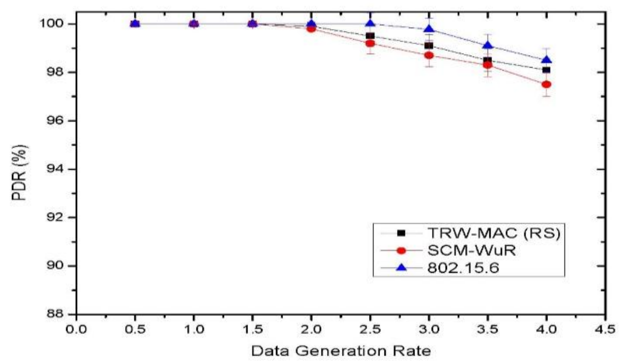
(a)



(b)



(c)



(d)

Figure 9. Effect of the Data Generation Rate on (a) Average Thermal Rise, (b) Average Power Consumption, (c) Average End-to-End Latency and (d) PDR

Figure 9 illustrates the effect of data generation rate on different performance metrics. None of the protocols except TRW-MAC maintains a tolerable thermal rise with the increasing traffic load as shown in Figure 9(a). The thermal-aware duty cycle adjustment mechanism of TRW-MAC governs the communication activities in a controlled way resulting in bearable average thermal rise ($\approx 0.2^{o}C$). On the contrary, SCM-WuR, yet an wake-up radio enabled protocol, fail to maintain a decent thermal rise, especially as the traffic load increases, as it adopts a fixed duty cycle approach. Among the protocols, 802.15.6 shows the worst performance in temperature control due to its long active period and no duty cycle adjustment procedure.

The mean power profile of the protocols is depicted in Figure 9(b). TRW-MAC clearly outperforms the other protocols in keeping lower energy consumption irrespective of the traffic loads. This is due to being WuR enabled protocol as well as the thermal-aware duty cycle adjustment procedure which prolongs the sleeping period of the nodes as the temperature goes high at higher traffic loads that in turn contributes in achieving lower energy consumption. SCM-WuR, however, shows similar performance at lower data generation rate but due to adopting fixed duty cycling, the average power consumption increases when the traffic load exceeds 2 pps. 802.15.6 exhibits the highest energy consumption among all due to employing its main radio into active state most of the time which also causes idle listening and overhearing.

The longer active state along with no excess delay for WuC management help in obtaining the lowest average end-to-end latency for IEEE 802.15.6 among all the protocols as shown in Figure 9(c). But it occurs sacrificing the power consumption and thermal-rise which are crucial metrics for an implanted WBAN. The increased contention and retransmission causes higher latency at high traffic loads for all the protocols. For TRW-MAC, we incline to measure the delay performance of *DS* traffic only. Compared to SCM-WuR, TRW-MAC shows better delay performance in all the traffic loads. This is due to employing staggered wake-up schedule in multi-hop transmission. TRW-MAC also segregates diverse period for diverse traffic type. Moreover, the prioritized contention parameters contributes in achieving lower end-to-end latency as compared to SCM-WuR. For SCM-WuR, after receiving data from the immediate child nodes, a node has to wait until it receives a WuC from its parent resulting in delay in each hop transmission.

Figure 9(d) illustrates the PDR performance of different protocols. At lower traffic loads, all the protocols achieve good PDR values close to 100% due to lower contention and congestion. However, as the traffic load goes higher, the PDR drops in every case. We evaluate the PDR of *RS* traffic for TRW-MAC. As the figure shows, TRW-MAC exhibits better PDR compared to SCM-WuR due to employing contention free period for reliability sensitive packets. At higher traffic loads, the longer inactive period causes increase in queue size which in turn increases the contention and congestion when a node wakes up. The drop in PDR for TRW-MAC at higher traffic load is due to the failure in reserving slot during CAP. IEEE 802.15.6, contrastively, shows better PDR performance through adopting longer active period.

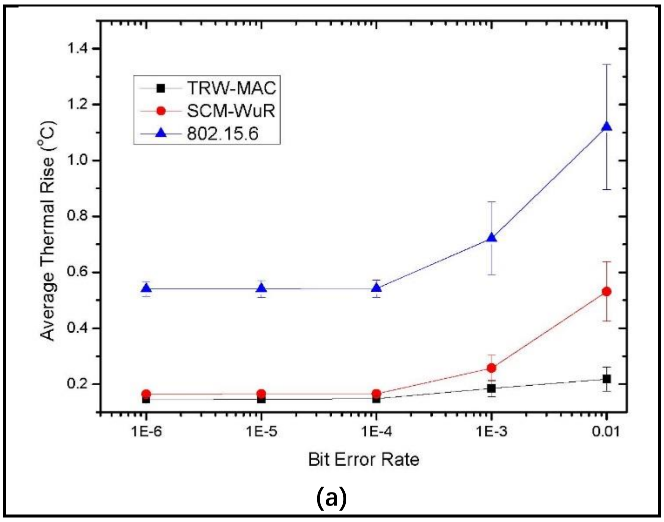
5.3.3 Effect of the Bit Error Rate

To evaluate the performance of TRW-MAC with other protocols under diverse channel condition, we model our experiment with 8 sources with the mentioned traffic distribution in Table 4. The effect of bit error rate ranging from 10^{-6} to 10^{-2} has been observed for different performance metrics. In each experiment, we set the data generate rate as 2 pps.

The thermal performance of the protocols for diverse bit error rate is illustrated in Figure 10(a). Under good channel condition (10^{-6} to 10^{-4}) BER, both TRW-MAC and SCM-WuR MAC exhibit lower thermal rise due to duty cycling with wake-up radio. However, as the BER increases beyond 10^{-3}, SCM-WuR shows a sharp increase in temperature. TRW-MAC, on the other hand, still able to maintain acceptable temperature even in extremely poor condition at 10^{-2} as it adapts the duty cycle in a highly conservative manner. Contrastively, being a non-wake-up-radio enabled protocol with longer active period, a significant performance gap has been observed for 802.15.6 in terms of thermal rise in every channel condition.

The same phenomena is noticed regarding average power consumption as depicted in Figure 10(b). TRW-MAC clearly outperforms other protocols due to its duty cycle adjustment procedure. At poor channel condition, in spite of increased retransmission and higher contention situation, TRW-MAC reduces its wake-up interval as the temperature goes high, resulting in lower energy consumption.

The duty cycle adjustment procedure of TRW-MAC, however, inhibits in achieving lower latency when the BER is at higher level (10^{-2}) as shown in Figure 10(c). In this situation, the staggered transmission of TRW-MAC does not work properly due to higher packet error probability that causes nodes to wait till the next wake-up interval of the parent, yielding higher latency. 802.15.6, however, exhibits the best performance in this condition for maintaining longer active periods. But it comes with a cost of higher power consumption and thermal rise. The average latency of SCM-WuR is the highest among all the protocols at good channel condition as it maintains a fixed wake-up interval and no staggered transmission is exercised. Yet, as compared to TRW-MAC, it shows better latency performance at poor channel condition since the wake-up interval of the nodes does not decrease.



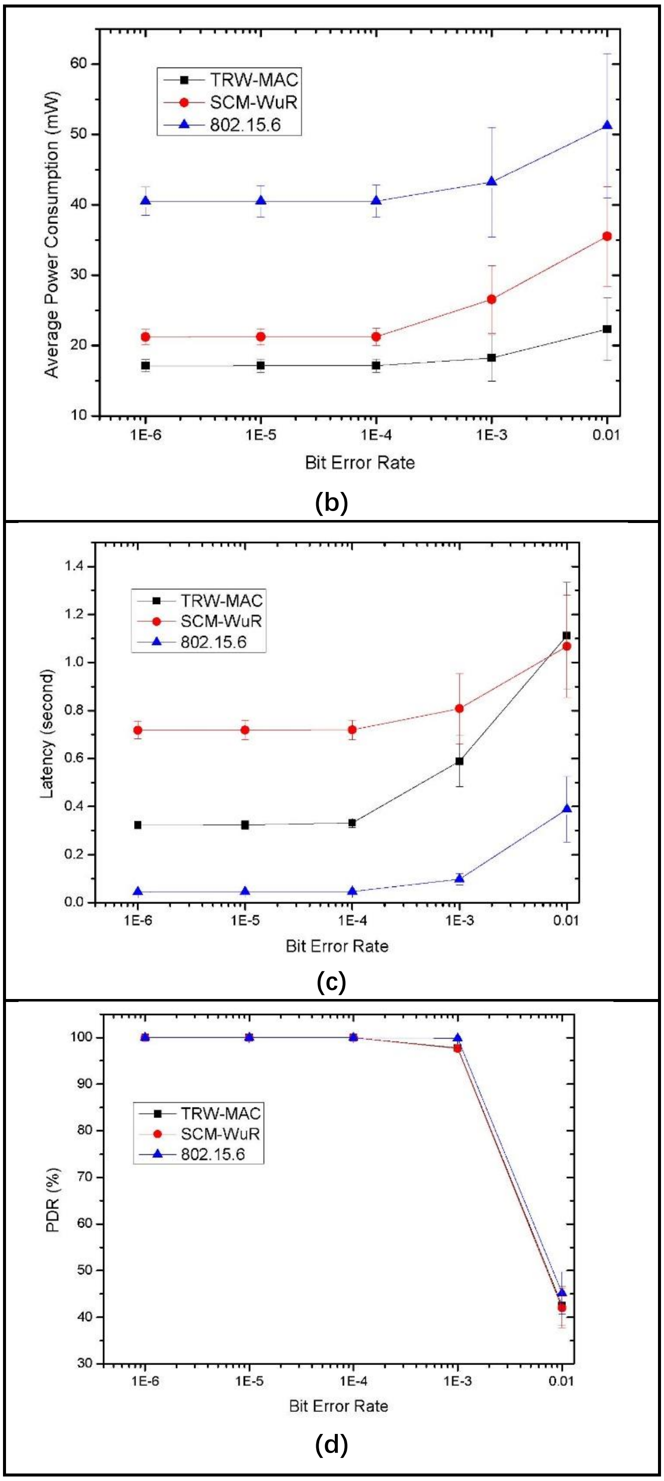


Figure 10. Effect of the Bit Error Rate on (a) Average Thermal Rise, (b) Average Power Consumption, (c) Average End-to-End Latency and (d) PDR

Figure 10(d) shows that all the protocols achieve close to 100% PDR in a good channel condition. However, the PDR drastically drops when the BER is 10^{-2} in each case. Even with the packet retransmission, the PDR is below 50% for all the protocols. 802.15.6 shows slightly better performance compared to SCM-WuR and TRW-MAC at this condition due to its increased communication activities.

6. Conclusion

A novel thermal-aware, receiver-driven, wake-up radio enabled duty-cycle MAC protocol, named TRW-MAC, has been presented for multi-hop IWBANs. Considering thermal-rise as one of the striking requirements for IWBAN, the proposed protocol presents a thermal-aware duty-cycle adjustment scheme. The protocol adopts a state-of-the-art wake-up radio scheme to obtain higher energy efficiency. A wake-up estimation scheme has been introduced to support staggered wake-up schedule in a multi-hop network architecture to attain lower end-to-end delay. Experimental results based on simulations demonstrate the effectiveness of TRW-MAC. It has been shown that TRW-MAC attains significantly lower thermal rise and energy consumption, compared to SCM-WuR and IEEE 802.15.6 in different traffic loads as well as channel conditions. TRW-MAC also exhibits an acceptable end-to-end latency and packet delivery ratio performance in diverse traffic loads and channel conditions.

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