Power Saving MAC Protocols for Wireless Body Area Networks (WBANs)

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Abstract

Two important criteria of Wireless Body Area Networks (WBANs) are low power consumption and delay. These criteria can be met by designing efficient Medium Access Control (MAC) protocols. In this paper, two TDMA-based MAC protocols are proposed. The first protocol, TM-MAC makes use of only a main radio. The second proposed protocol, TWM-MAC makes use of a WUR alongside the main radio. The two proposed protocols are compared with different categories of standard MAC protocols and it is shown that they outperform the standard ones by improving the power consumption and delay. The TWM-MAC consumes 55% less power consumption than the Scheduled Channel Polling MAC (SCP-MAC) protocol for a high traffic scenario on the high-rate platform while the TM-MAC consumes 85% less power consumption than the SCP-MAC. For a low traffic scenario, the TWM-MAC performs 53.5% better than the SCP-MAC protocol and 77.5% better than the Very Low Power MAC (VLPM) protocol on the high and low-rate platforms respectively. An improvement in delay was observed with the TWM-MAC protocol for high traffic situations. The TWM-MAC protocol surpasses the VLPM protocol by 81.1% in terms of latency for a high traffic scenario and 3.2% for a low traffic scenario.

Keywords: Power consumption, delay, MAC protocols, TDMA techniques, Wake-up radio, WBAN

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1. Introduction

Wireless body area network (WBAN) is the positioning of smart and small body nodes with sensing abilities in and on the human body for monitoring important signs about the body functioning in a convenient and non-disruptive manner [1], [2], [3], [4]. Biological data is acquired by the body nodes and forwarded to a Body Network Coordinator (BNC), which then relays the information to other tiers of the communication systems. WBAN is a promising communication technology for remote monitoring of important signs, remote control of medical procedures and premature detection of serious conditions [5], [6], [7]. However, the small sensor nodes deployed in a WBAN have limitations on their battery capacity and lifetime [8]. This poses a problem for long term monitoring of patients and thus there is a need for devising minimal power mechanisms on the energy-restricted body nodes. For attaining Quality of Service (QoS), the MAC layer acts as the principal layer of the communication protocol stack [8-9] The main synchronisation process between sensor nodes and the channel is performed at the MAC layer. A good and flexible MAC protocol must possess attributes to diminish power consumption due to packet collisions, overhearing of nodes, idle listening and overhead of control packet [9] [10]. By overcoming these energy wastes, MAC protocols can prolong the lifetime of the WBAN. Furthermore, exploiting radio technologies can significantly improve power consumption requirements of a WBAN [11], [12].

MAC protocols can be classified into contention based and contention free protocols as shown in Figure 1. Contention based MAC protocols that employ channel polling also known as Low Power Listening (LPL) techniques are Wise-MAC [13], B-MAC [14] and X-MAC [15]. Contention based MAC protocols employ Carrier Sense/ Collision Avoidance (CSMA/CA) mechanism and for transmission of data, nodes have to compete for channel access [16]. Prior to transmit data, the nodes in the network carry out Clear Channel Assessment (CCA) [17]. Contention based LPL MAC protocols have high-energy wastage due to the long preambles. In addition, the nodes need to wake up periodically by turning on their radio to check for channel activity. Thus, contention-based MAC protocols are not always reliable for a WBAN. Scheduled Contention MAC protocols are S-MAC [18] and T-MAC [19], the nodes follow a common schedule for communicating information [16].

Time Division Multiple Access (TDMA) is a technique, adopted by contention free MAC protocols in which the nodes have a particular time slot for transmission of data [17], [16]. TDMA based protocols allow low duty cycling techniques which is one of the major contributions of higher achievable energy efficiency. However, TDMA based MAC protocols consume extra energy during synchronisation after periodic intervals of time. Nevertheless, contention free MAC protocols can support traffic variations in a WBAN and resolve any Carrier Sense Assessment (CCA) drawbacks caused by contention-based MAC protocols [4].

Furthermore, MAC protocols can be categorised into unsynchronised and synchronised protocols. Unsynchronized MAC protocols such as B-MAC, SCP-MAC and X-MAC imply that nodes do not have to be time synchronized or wait for an active period to transmit data. To check for traffic, there is asynchronous polling of the channels by the nodes. Normally, unsynchronized MAC protocols employ Low Power Listening (LPL) mechanism. In synchronized MAC protocols such as T-MAC, the nodes transmit data only in the active periods. The nodes have a prior knowledge about the precise instants of active periods. Thus, the requirement for long preambles is avoided. In addition, there is transmission of SYNC frames from time to time to maintain synchronization with one or more nodes [20], [21].

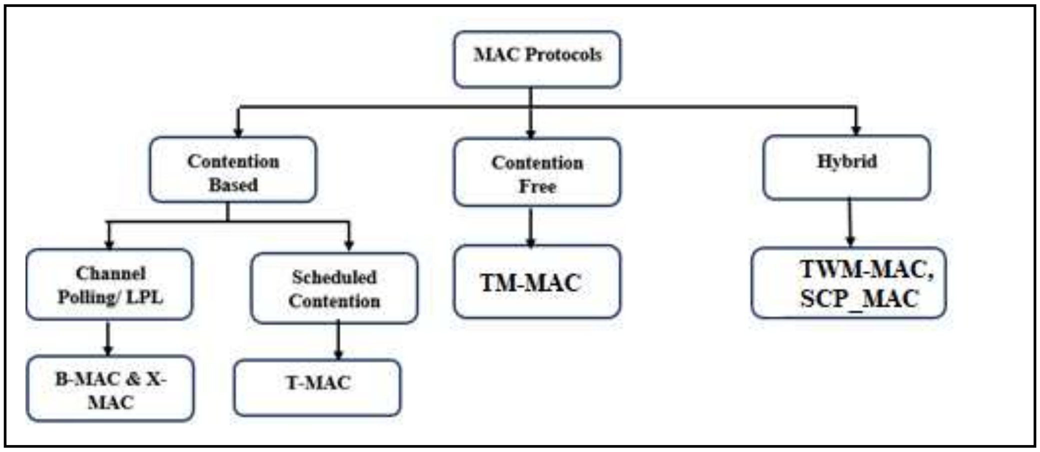
Energy efficiency is an important requirement in WBAN, and many recent research works focus on the design of energy efficient MAC protocols [22]. In [3], the problems of idle listening and overhearing was resolved by a MAC protocol, which adapts itself to varying traffic. This protocol keeps track of traffic information and the duty cycles of the nodes are modified in accordance with the acquired information. The authors in [23] presented a WUR, which has addressing abilities. This allowed non- intended nodes to switch in sleep state immediately after interpretation of the wake-up packet. In [24], the authors discuss the concept of WUR for wireless sensor networks. They mentioned the gap in literature for the use of a WUR in MAC protocols. A description on the WURs is given along with the hardware architectures. They conclude that using a WUR is a promising technique for an effective design of a MAC protocol. The work in [25] introduced a MAC protocol, which replenishes the battery of sensor nodes by energy harvesting techniques. In addition, it is adaptive to topology changes, and showed good performance in terms of throughput and energy trade-offs. In [26], the

authors presented a MAC protocol which takes advantage of the static nature of a WBAN. Effective TDMA MAC protocol with less power consumption was observed through the reduction of overhead of control packets and idle listening. The work in [27] introduces a technique to handle urgent and important transfer of information for body sensors operating in Medical Implant Communication Service (MICS) frequency band.
In [21], the authors made a normal/periodic traffic assumption, for which data communication takes place by the initiation of the BNC according to a pre-calculated schedule. The work has not considered the case where body nodes can send data at periodic intervals of time. The work in [28] presented the VLPM protocol employing a WUR. Traffic was categorised into the uplink and downlink mode. The WUR-based protocol had a good performance in terms of power consumption at low traffic rates, but it required optimisation for high traffic rate variations. The VLPM protocol showed a poor performance at high traffic rates due to the application of piggybacking for resource allocation. The delay that the VLPM protocol imposes on the network is not suitable for a WBAN since the network needs to deal with emergencies as well. From the literature review conducted, it is noted that devising energy efficient MAC protocols that can adapt to both high and low traffic rates of WBAN are required.

The main contributions of this paper are:

- Two TDMA based MAC protocols are proposed. The first proposed MAC protocol, TM-MAC adopts a pure TDMA MAC approach without the use of a WUR while the second proposed protocol, TWM-MAC employs a WUR with low power demands alongside the main radio.
- As opposed to previous research works, in the proposed protocols the body nodes initiate data communication instead of the BNC. The information is forwarded to the BNC at pre-defined intervals of time. The three main types of traffic that have been considered in this work include
    - Periodic or normal,
    - On-demand,
    - Emergency traffic
- Existing protocols from each category shown in Figure 1 are implemented to evaluate the WBAN behaviour in terms of power consumption and latency and to compare their performance with the proposed protocols.
- The two proposed protocols outperform the existing ones by improving the power consumption and delay. The TWM-MAC protocol consumes 55% less power consumption than the Scheduled Channel Polling MAC (SCP-MAC) protocol for a high traffic scenario on the high-rate platform while the TM-MAC consumes 85% less power consumption than the SCP-MAC. For a low traffic scenario, the TWM-MAC performs 53.5% better than the SCP-MAC protocol and 77.5% better than the Very Low Power MAC (VLPM) protocol on the high and low-rate platforms respectively. The improvement in delay was mostly observed with the TWM-MAC protocol for high traffic situations.
- The TWM-MAC surpasses the VLPM protocol by 81.1% in terms of latency for a high traffic scenario and 3.2% for a low traffic scenario.

The rest of the paper is structured as follows. Section 2 demonstrates the proposed model and describe the two proposed MAC protocols. Mathematical models of the standard and proposed MAC protocols are presented in section 3. The performance of the proposed MAC protocols is evaluated in section 4. Finally, the conclusion is



presented in section 5.

__Fig. 1:__ Classification of MAC protocols investigated in this work

2. Proposed Model and Methodology

This section discusses the proposed network topology in which periodic, on-demand and emergency traffic are considered. Communication occurs between the BNC and the body nodes, and the latter forwards data to the BNC for periodic and emergency traffic. The proposed protocols are modelled to be adaptable to the heterogeneous traffic of a WBAN and to have the minimal power consumption and delay. The selection of a good MAC protocol depends strictly on the application concerned [29]. Since WBAN deals with sensor nodes having varying data generation periods, the TM-MAC and TWM-MAC protocols are designed to be flexible to any network load.

2.1 Network Model

In the network topology shown in Figure 2, there are N sensor nodes deployed on the human body for monitoring purposes. Eight body nodes are placed on the human body along with one BNC.

The following network and traffic assumptions are made:

1. The base station (sink) is deployed out of the sensing range. A static network is assumed after the nodes have been deployed meaning that the nodes are fixed in this model.
2. A BNC or gateway is used in the same network and is placed in the middle.
3. The sensor nodes have stringent battery capacity, and the batteries are not rechargeable.
4. The BNC has less energy constraints as compared to the sensor nodes and it is rechargeable.
5. Every single node in the network have the same processing and sensing capabilities with a distinctive Identity (ID) address.
6. In this model, there is heterogeneous traffic meaning that the sensor nodes transmit data at different data rates.
7. Both the body nodes and the BNC generate traffic. Periodic or normal traffic is started by the body nodes to forward data to the BNC at regular fixed interval of time. On-demand traffic is initiated by the BNC if the healthcare providers or the user himself wants to access information about the body functions. Sporadic situations are categorised under emergency traffic in which body nodes start a critical communication process.

The BNC is the master node which consumes less energy than the body sensor nodes. Two WBANs send information to a monitoring station for further processing and transmission to other tiers of the communication system as shown in Figure 2. The BNCs are used to coordinate the nodes' synchronisation process and transmission of data.

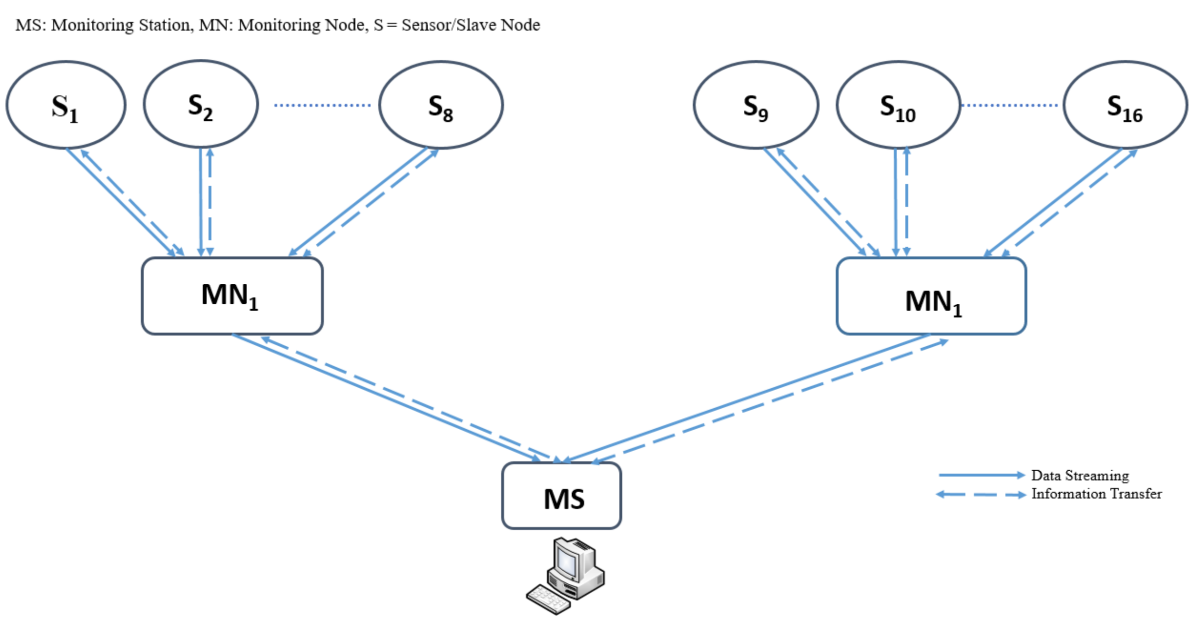


Fig. 2: *Two WBANs communicating to a Monitoring system*

2.2 Principle of Operation

2.2.1 Proposed Protocol 1: TM-MAC protocol

One of the proposed MAC protocols in this paper, TM-MAC employs a star network configuration of IEEE 802.15.4 Standard at 2.4 GHz. The ultimate goal is to be able to assess the power consumption of a pure TDMA-based approach to enable a power-efficient and reliable communication protocol to adapt to the heterogeneous traffic in WBAN. The BNC is informed of the ID addresses of every sensor node in the network prior to packet transmission. This permits reliable communication by making sure that the slave nodes are properly synchronized with the BNC.

The following state machine shown in Figure 3 was devised to demonstrate the working of the TM-MAC protocol for WBAN.

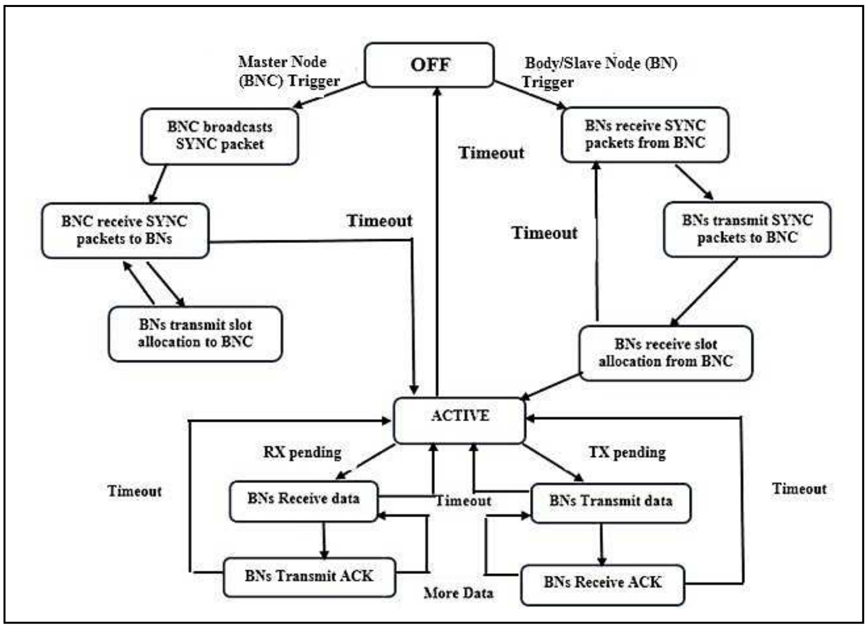


Fig 3: *TDMA based TM-MAC State Machine*

When the body node (slave node) is triggered, it switches on and changes the transceiver into the receive state. The transceiver waits for a SYNC packet from the BNC. The body node then synchronizes with the BNC by transmitting a SYNC packet back to the BNC. The SYNC message contains information about the slot allocation to the nodes. After synchronisation, the body node changes into active state after which it can transmit or receive data. After the node transmits data, the BNC sends an acknowledgment (ACK) to the node. In addition, if the node receives data from the BNC, an ACK is sent to the latter. The loop continues if there is more data transmission or reception or else it switches to an idle state.

2.2.2 Proposed Protocol 2: TWM-MAC Protocol

The design of the second proposed protocol, TWM-MAC which is a TDMA based MAC protocol with a WUR takes into consideration a collision free transmission, which shall result into a lower power consumption and delay. In addition, achieving the best performance at varying traffic rate with priority considerations is among the main aims of the TWM-MAC protocol. Having the WUR allows the main radio to stay in the sleep mode without waking up each time to listen for incoming signals.

For data communication in implanted nodes, this WUR scheme is highly recommended since fast response is required along with low power consumption and latency [30]. The use of a WUR simplifies the design and implementation of the radio hardware and the sleeping node is awakened at the right instant for communicating information. In addition, the WUR does not make use of internal power supply to generate wake up signals [7]. The TWM-MAC protocol follows a star topology whereby all the coordination in the network is performed by the BNC. The Industrial, Scientific and Medical (ISM) band at 2.4 GHz is employed for the WUR. For emergency traffic, a wake up packet is sent by the body node to the BNC. Upon receiving the packet, the latter forwards a beacon with resource allocations to the body node and data transmission takes place. The body nodes are updated in priori with traffic patterns of the network. As such if a body node has critical data to send, it is given priority. A timing diagram is given in Figure 4 for demonstrating the uplink and downlink traffic. In addition, the flowchart in Figure 5 shows the functioning at the BNC.

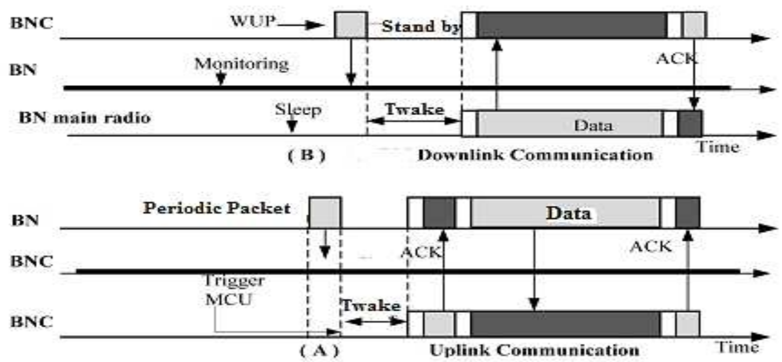


Fig. 4: *Timing diagram of the TWM-MAC protocol for uplink and downlink traffic*

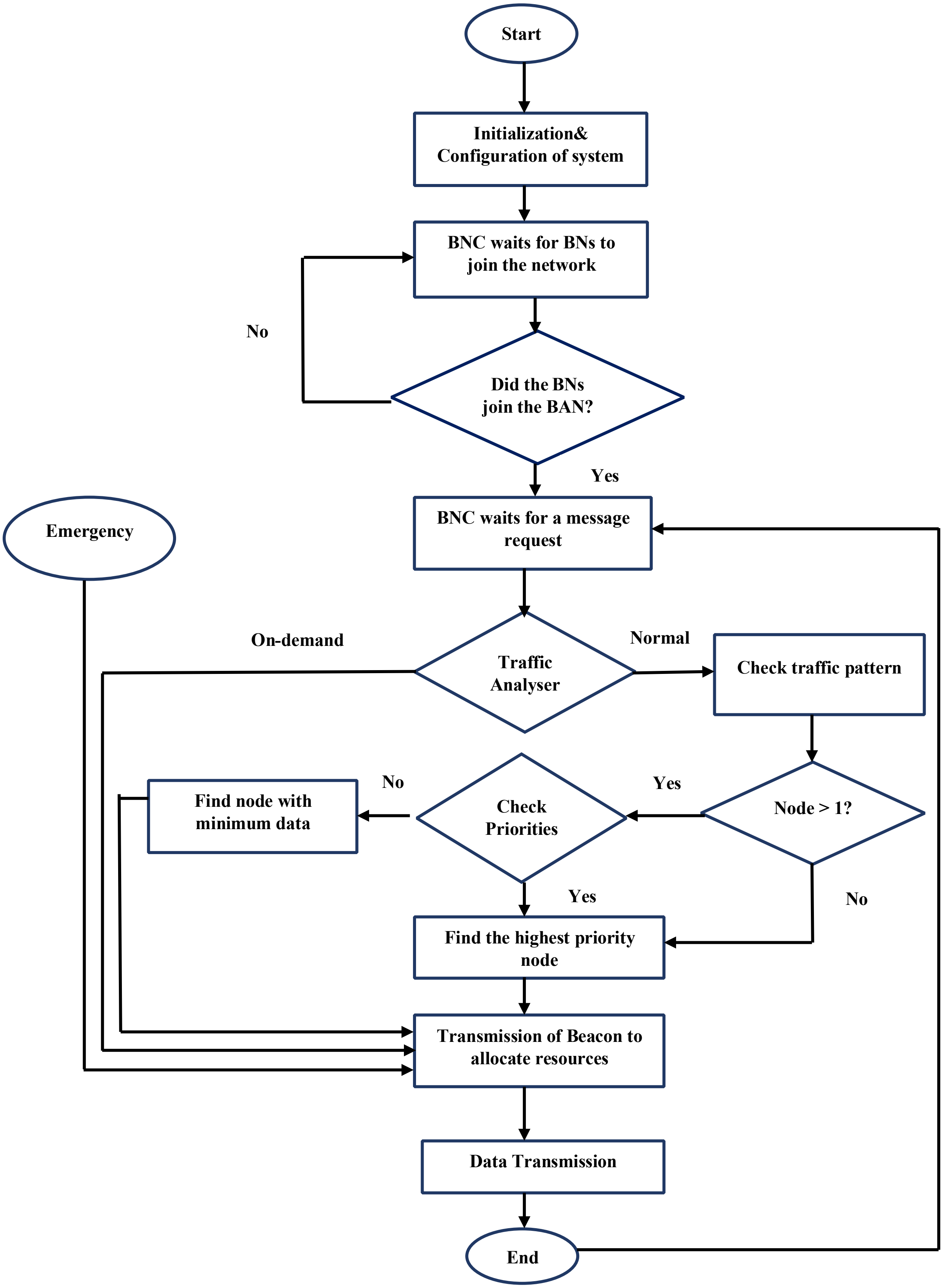


Fig. 5: *BNC Functionality*

3. Performance Evaluation

In this section, mathematical models for the two main important metrics of node power consumption and delay are obtained for the two proposed MAC protocols and the standard MAC protocols. Table 1 shows the parameters and their respective descriptions for analysis of power consumption and latency [21], [27].

Table 1: Parameters and their descriptions

Parameter	**Description**	**Value(HR)**	**Value(LR)**
ε	Crystal Tolerance	20 ppm	30 ppm
L_{ack}, L_{cts}, L_{rts}, L_p	Length of Frame X where X = {ack, cts, rts, preamble}	8 Bytes	8 Bytes
L_{beacon}, L_{data}. $L_{si(SCP\text{-}MAC)}$	Length of beacon and data frame	32 Bytes	32 Bytes
P_{tx}	Power consumed due to transmission	34.7 mW	29.9 mW
P_{rx}	Power consumed due to reception	60.2 mW	25.4 mW
P_{sl}	Power consumed in sleep state	37 µW	37 µW
R	Data Rate of Radio	1 Mbps	76.8 kbps
T_{sync}	Transmission time of SYNC frames	90 s	90 s
T_{cca}	Time to perform clear Channel assessment	128 µs	256 µs
T_{cw}	Length of contention window	2 ms	4 ms
T_{set}	Radio start-up transient time	195 µs	250 µs
T	Data generation time	Variable	Variable
T_{wup}	Duration of wake up packet	21.2 ms	21.2 ms
T_{wake}	Time taken to wake up radio	1.5 ms	1.5 ms
$T_{d\_ack(VLPM)}$	Time taken to acknowledge data	16.9 ms	16.9 ms
$T_{res\_ack(VLPM)}$	Time taken to acknowledge piggybacking WUP	1.04 ms	1.04 ms
$T_{res\_wup(VLPM)}$	Time taken for piggybacking WUP	1.25 ms	1.25 ms
T_{wbn}	Time taken to send low power wake up packet	2.56 ms	2.56 ms
T_{wack}	Time required to acknowledge low power wake up packet	2.56 ms	2.56 ms

3.1 Mathematical Models for Power Consumption Analysis

Models for the delay and power consumption of the MAC protocols are based on an analysis presented in [20]. Average power consumption of body nodes as a function of the time taken to transmit and receive data and duty cycles is formulated in equation (1).

$$P_{avg} = T_{tx}P_{tx} + T_{rx}P_{rx} + (1 - T_{tx} - T_{rx})P_{sl} \quad (1)$$

3.1.1 Ideal MAC protocol

To define an ideal MAC protocol, it was assumed that there are no energy wastages such as collisions of packets idle listening, overhearing and control overhead packets. Communication between the nodes do not require synchronization or any contention mechanism.

Prior to transmission and reception of data, there is a radio start-up transient T_{set}. According to [20], time taken to transmit, T_{tx} and receive, T_{rx} are given by equation (2) and (3) respectively.

$$T_{tx} = \left(T_{set} + \frac{L_{data}}{R}\right)\frac{1}{T} \quad (2)$$

$$T_{rx} = \left(T_{set} + \frac{L_{ack}}{R}\right)\frac{1}{T} \quad (3)$$

3.1.2 B-MAC protocol

B-MAC employs LPL mechanism and a long preamble. In this protocol, the aim of the long preamble in this protocol is to ensure that receiver nodes identify the preamble and hence stay active for reception of data. The schedule of each node differs as a function of their task. The nodes switch from the sleep state to the active state and performs channel polling at regular interval of time. As per [28], if a preamble is discovered during sampling of the medium, the nodes stay active otherwise they go in the sleep mode.

Before each transmission, there is a preamble, which is transmitted during the channel-polling interval, T_w. Therefore, T_{tx} for the body node is given by equation (4).

$$T_{tx} = \left(T_{set} + T_w + \frac{L_{data}}{R}\right)\frac{1}{T} \quad (4)$$

A total of N data frames are received from the nodes during the one data generation interval. An average of the polling interval is considered since B-MAC protocol employs random polling of the channel.

Therefore, T_{rx} for the body node is given by equation (5).

$$T_{rx} = \frac{T_{set} + T_{cca}}{T_w} + \left(\frac{Tw}{2} - Tcca + \frac{Ldata}{R}\right)\frac{N}{T} + \left(Tset + \frac{Lack}{R}\right)\frac{1}{T} \quad (5)$$

3.1.3 X-MAC protocol

X-MAC uses short preambles. Listening to the channel for a preamble is done by nodes that wake up periodically. There is transmission of continuous short interval preambles by the transmitter. Along with the preamble, data packets are forwarded by body nodes.

Prior to each data transmission, there is a preamble for synchronization of the transmission timing. According to [20], the polling time of the channel for receiving one preamble is equivalent to the sum of two preambles duration, T_p, and one Acknowledgment (ACK), T_{ack} as per equations (6) and (7) respectively.

$$T_p = T_{set} + \frac{L_p}{R} \tag{6}$$

$$T_{ack} = T_{set} + \frac{L_{ack}}{R} \tag{7}$$

The average number of preambles transmitted is given by equation (8).

$$NP = \frac{T_w}{2(T_p + T_{ack})} \tag{8}$$

Therefore, T_{tx} and T_{rx} are formulated in equations (9) and (10) respectively.

$$T_{tx} = \left(NP \times T_p + T_{set} + \frac{L_{data}}{R}\right)\frac{1}{T} \tag{9}$$

$$T_{rx} = \frac{2T_p + T_{ack}}{T_w} + (NP + 1)\frac{T_{ack}}{T} \tag{10}$$

3.1.4 SCP-MAC Protocol

In this protocol, the long preamble is substituted by a short duration wake-up tone. Piggybacking is employed for the synchronization process. There is the same channel polling method as B-MAC protocol [28]. But channel polling occurs only when neighbouring nodes are transmitting as this helps in obtaining a better energy efficiency.

The time duration of the wake-up tone taking into account clock drift, ε is presented in equation (11).

$$T_{tone} = \frac{4T\varepsilon}{N} + T_{cca} \tag{11}$$

Two contention windows with a back-off time of $T_{cw}/4$ are used by SCP-MAC [28] . The receiver node acquires half of the wake-up tone and the second contention window [20]. T_{tx} and T_{rx} of the body node are given by equations (12) and (13) respectively.

$$T_{tx} = (2T_{set} + T_{tone} + \frac{L_{si} + L_{data}}{R})\frac{1}{T} \tag{12}$$

$$\begin{aligned} T_{rx} = (T_{set} + T_{cca})\frac{1}{T_w} + \left(3T_{set} + 2T_{cca} + \frac{L_{ack}}{R}\right)\frac{1}{T} \\ + (3T_{set} + \frac{T_{tone}}{2} + \frac{T_{cw}}{4} + T_{cca} + \frac{L_{si} + L_{data}}{R}) \times \frac{N}{T} \end{aligned} \tag{13}$$

3.1.5 T-MAC Protocol

T-MAC protocol is derived from S-MAC protocol and has been improved by making the active period shorter if the channel is idle. After synchronization, the body nodes stay on for a short period to detect any channel activity [28].

There is transmission of synchronisation frames at T_{sync} periods permitted by a short latency within the contention window.

Thus, T_{tx} and T_{rx} for the body node are given by equations (14) and (15) respectively.

$$T_{tx} = \left(2T_{set} + \frac{L_{rts} + L_{data}}{R}\right)\frac{1}{T} + \left(T_{set} + \frac{L_{beacon}}{R}\right)\frac{1}{T_{sync}} \tag{14}$$

$$\begin{aligned} T_{rx} = (2T_{set} + T_{cw} + \frac{L_{rts}}{R})\frac{1}{T_w} + \left(2T_{set} + \frac{L_{cts} + L_{ack}}{R}\right)\frac{1}{T} \\ + \left(T_{set} + T_{cw} - \frac{L_{beacon}}{R}\right)\frac{1}{T_{sync}} \end{aligned} \tag{15}$$

3.1.6 Very Low Power MAC protocol (VLPM)

A WUR is used along with the main radio in this protocol. The nodes do not take part in polling of the channel. In order to save energy, the main radio stays in the sleep mode. If the WUR detects any request for data transmission, it sends a wake-up packet (WUP) to the main radio. After the wake-up packet has been decoded, the microcontroller (MCU) triggers the main radio. The main benefit of this protocol is that the nodes wake up only if there is data transmission, therefore helping in conserving energy. Furthermore, there is the use of piggybacking resource allocation, which is suitable for low traffic.

Considering the uplink traffic, T_{tx} and T_{rx} are given by equation (16) and (17) respectively.

$$T_{tx} = (T_{wup} + 2T_{set} + \frac{L_{data}}{R})\frac{1}{T} \tag{16}$$

$$T_{rx} = (T_{wake} + T_{set} + T_{res_{ack}} + T_{d_{ack}})\frac{1}{T} \tag{17}$$

Similarly, for downlink traffic, T_{tx} and T_{rx} are given by equation (18) and (19) respectively.

$$T_{tx} = \left(\frac{L_{data}}{R} + T_{set} + T_{wake}\right)\frac{1}{T} \tag{18}$$

$$T_{rx} = (T_{res_{wup}} + 2T_{set} + T_{dack})\frac{1}{T} \tag{19}$$

3.1.7 Proposed TM-MAC Protocol

Our proposed protocol is a synchronous MAC protocol. The channel access period is defined as per T-MAC protocol.

Nodes keep on synchronising themselves with surrounding nodes at the start of the active period. Synchronisation frames are sent at T_{sync} intervals of time. At the start of active periods, the nodes maintain synchronisation by exchanging SYNC frames. There is transmission of beacons during the polling interval and hence the normalised polling time combines the start-up time, T_{set}, beacon transmission time, T_{beacon} and the crystal tolerance, ε. Based on the proposed principle of operation of the pure TDMA-based MAC protocol, equations (20) and (21) are derived for the body node.

T_{tx} and T_{rx} for the body node are

$$T_{tx} = \left(2T_{set} + \frac{L_{data}}{R}\right)\frac{1}{T} + \left(T_{set} + \frac{L_{beacon}}{R}\right)\frac{1}{T_{sync}} \tag{20}$$

$$\begin{aligned} T_{rx} = {} & (T_{set} + 2T_{w}\varepsilon + \frac{L_{beacon}}{R})\frac{1}{T_{w}} \\ & + \left(T_{set} + T_{wake} + \frac{L_{ack}}{R}\right) \times \frac{1}{T} \end{aligned} \tag{21}$$

3.1.8 Proposed TWM-MAC Protocol

In our second proposed MAC protocol, the use of the piggybacking concept for resource allocation has not been considered as opposed to protocols such as the VLPM protocol. The reason behind this design was to provide a good performance at varying traffic rates and this is an important objective for WBAN. At the start of each frame, the body nodes send a wake-up packet to the BNC to initiate data transmission. Afterwards, the BNC acknowledges the wake-up packet and sends a beacon that contains all information about synchronization and resource allocations. In this proposed protocol, data transmission is initiated by body nodes instead of the BNC for normal/periodic traffic unlike the MAC protocol in [21] . Both high and low traffic are considered as opposed to the work presented in [28] . Based on the proposed principle of operations of the proposed TDMA MAC protocol with WUR, equations (22) to (25) are derived.

T_{tx} and T_{rx} of the body node for uplink traffic are

$$T_{tx} = \left(2T_{set} + \frac{L_{data}}{R} + T_{wbn}\right)\frac{1}{T} \tag{22}$$

$$T_{rx} = \left(T_{set} + T_{wack} + T_{wake} + \frac{L_{beacon} + L_{ack}}{R}\right)\frac{1}{T} \tag{23}$$

T_{tx} and T_{rx} for the downlink traffic are

$$T_{tx} = \left(2T_{set} + T_{wake} + T_{wack} + \frac{L_{data}}{R}\right)\frac{1}{T} \tag{24}$$

$$T_{rx} = \left(T_{set} + T_{wbn} + \frac{L_{beacon}}{R} + \frac{L_{ack}}{R}\right) \times \frac{1}{T} \tag{25}$$

3.2 Delay Formulation

Latency is an important metric in this area as WBAN deals with critical data of patients. Delay analysis was performed for each MAC protocol.

The total delay of the different protocols that are simulated in the paper are given by equations (26) to (32). Note that the equations of the two proposed protocols are given by equations (31) and (32).

$$D_{BMAC} = T_w + T_{ack} + \frac{L_{data}}{R} + T_{set} + T_{cca} \tag{26}$$

$$D_{xmac} = 2T_p + 2T_{ack} + \frac{T_w}{2} + \frac{L_{data}}{R} + 2T_{set} \tag{27}$$

$$D_{scpmac} = \frac{T_w}{2} + T_{ack} + \frac{L_{data}}{R} + 4\varepsilon\, T_{sync} + T_{cca} \tag{28}$$

$$D_{tmac} = T_w + T_{ack} + \frac{L_{data}}{R} + T_{set} + T_{cca} \tag{29}$$

$$D_{vlpm} = T_{wup} + 3T_{set} + \frac{L_{data}}{R} + T_{wake} + T_{Res_{ack}} + T_{d_{ack}} \tag{30}$$

$$D_{TM-MAC} = 3T_{set} + \frac{L_{data}}{R} + T_{ack} + T_w + T_{beacon} \tag{31}$$

$$D_{TWM-MAC} = 3T_{set} + \frac{L_{data}}{R} + T_{wbn} + T_{wack} + T_{wake} + T_{ack} + T_{beacon} \tag{32}$$

4. Results and Analysis

The parameter values used in this paper and listed in Table 1 are obtained from [21], [28] .The CC1000 transceiver parameters are used to model the low rate platform and the transceiver nRF2401A is used to model that of a high rate platform [20], [31]. The ideal MAC protocol is used as a benchmark to evaluate the power consumption of all the implemented MAC protocols. The MAC protocol performing closest to the ideal MAC consumes less power. A downlink traffic analysis is made for the VLPM protocol and the proposed TWM-MAC protocol. Delay analysis is performed for the low-rate platform with the CC1000 transceiver.

4.1 Uplink Power Consumption analysis of MAC protocols on a high-rate platform

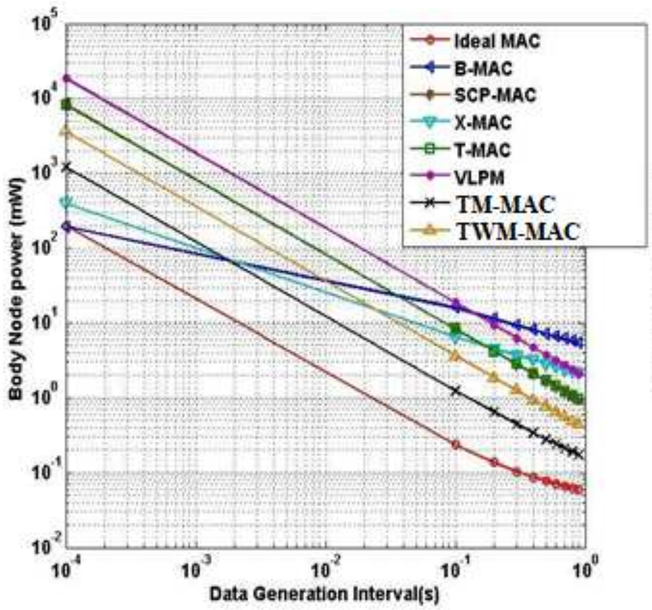
For the high traffic case as shown in Figure 6(a), the proposed TM-MAC protocol performs closest to the ideal MAC protocol. As data generation time increases from 10^{-4} seconds to 1 second, power consumption of the ideal MAC protocol decreases from 200.9 mW to 0.05708 mW. The VLPM protocol has a decreasing power consumption of 1.868×10^{4} mW to 1.905 mW for the same data generation time. This accounts for the VLPM power consumption to be in the range of 93 to 33 times higher than the ideal MAC protocol. This poor performance of the VLPM protocol was mentioned in [28]. Power consumption for SCP-MAC protocol decreases from 8189 mW to 0.8587 mW for a data generation interval from 10^{-4} seconds to 1 second. This results in the power consumption for the same data interval time to be 40.8 to 15 times higher as compared to the ideal MAC protocol. With a decrease in power consumption from 3618 mW to 0.3988 mW for the same data generation time being analysed, the proposed TWM-MAC protocol results in 18 to 7.0 times higher power consumptions than the ideal MAC protocol. The proposed TM-MAC protocol has a power consumption of 1205 mW to 0.16 mW, which accounts to a 6.0 to 2.8 times higher power consumption than the ideal MAC protocol.

As compared to the other MAC protocols investigated in this paper, the two proposed TDMA based MAC protocols with and without the use of a WUR performs better in terms of power consumption for the high traffic WBAN simulation model. This improvement can be explained by the contention-free characteristics of the proposed MAC protocols in which traffic variations in WBAN are considered and any CCA issues are resolved as compared to the contention-based MAC protocols.

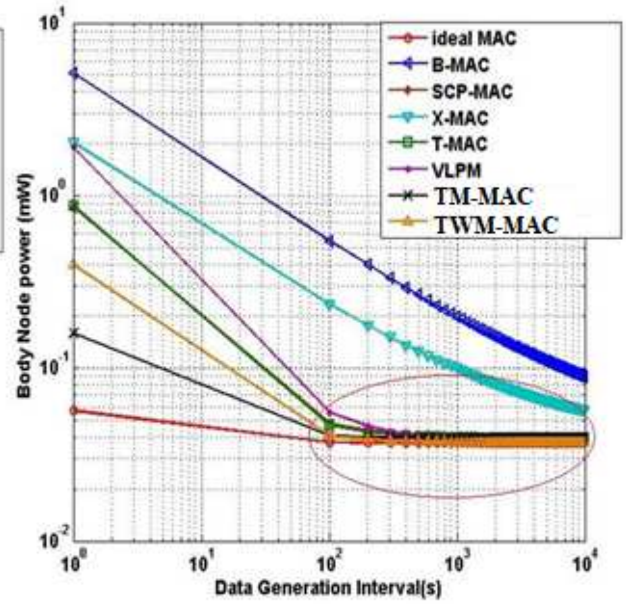
For the low traffic, it is observed in Figure 6(b) that synchronised MAC protocols outperform the unsynchronised MAC protocols. B-MAC protocol, which is an unsynchronised MAC protocol, consumes the highest power as compared to others. As data generation time increases from 1 s to 10^{4} s, the power consumption of the ideal MAC protocol decreases from 57.1 µW to 37 µW. The power consumed by the VLPM protocol decreases from 1905 µW to 37.2 µW, which accounts to be 33.4 to 1.0 times higher than the ideal MAC protocol for the same data generation interval. SCP-MAC has a power consumption of 858 µW to 39.8 µW for the range of data interval time 1 s to 10^{4} s resulting in 15 to 1 times higher power consumption as compared to the ideal MAC protocol. The proposed TWM-MAC has a power consumption of 398.8 µW to 37.04 µW, which is 7.0 to 1.0 times higher than the ideal MAC protocol for a data generation interval of 1 s to 10^{4} s. The proposed TM-MAC protocol without a WUR has a decreasing power consumption from 160 µW to 39.5 µW, accounting for 2.8 to 1.0 times higher power consumption than the ideal MAC protocol for the same time interval. It can be observed as traffic rate decreases after a data generation time of 10^{2} s, the TM-MAC protocol has the lowest power consumption of all.

Figure 6(c) is a zoomed in view of the circled part of Figure 6(b). For very low traffic rates as shown in Figure 6(c), MAC protocols with the WUR outperform the other MAC protocols. For the range of data generation time 10^{2} s to 10^{4} s, VLPM protocol consumes 1.5 to 1.0 times more power than the ideal MAC protocol.

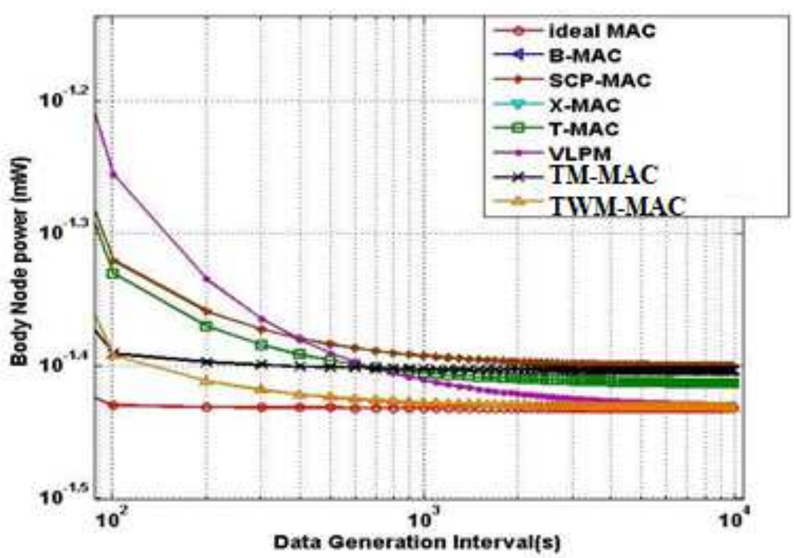
Our proposed protocol employing the use of a WUR has a power consumption close to that of the ideal MAC protocol. This positive performance can be explained by the use of the WUR which allows the main radio to stay in the sleep mode and be awake just when communication is about to take place.



(a)



(b)



(c)

Fig. 6: *Results based on a high rate platform: (a) High Traffic (b) Low Traffic (c) Zoomed in view of circled portion of Figure 6(b)*

4.2 Uplink Power Consumption analysis of MAC protocols for the low-rate platform

For the low-rate platform, the performance of the MAC protocols is analysed for the high traffic rate and low traffic rate scenarios.

For the high traffic rate, the plot of power consumption against data generation time is shown in Figure 7(a). The ideal MAC protocol has a reduction in power consumption from 289 mW to 0.06589 mW for a data generation interval from 10^{-4} seconds to 1 second. The VLPM protocol has 39.2 to 17.8 times higher power consumption than the ideal MAC protocol for the same data generation time. The power consumption for SCP-MAC, X-MAC, B-MAC and T-MAC protocols are 23.7 to 11, 1.4 to 20.6, 3.3 to 50 and 23.2 to 10.8 times higher than the ideal MAC protocols respectively. The proposed TWM-MAC protocol results in a decrease in power consumption from 2264 mW to 0.2633 mW. This causes the power consumption to be higher than that of the ideal MAC protocol by 7.8 to 4.0 times. The proposed TM-MAC protocol gives a power consumption of 786.3 mW to 0.1169 mW, which is 2.7 to 1.8 times higher than the power consumption of the ideal MAC protocol for a data interval time of 10^{-4} seconds to 1 second. This implies that the TDMA MAC protocols without any usage of WUR perform best at high traffic rate for a WBAN.

The results for the low traffic rate are given in figure 7(b). Figure 7(c) is a zoomed in view of the circled portion of Figure 7(b). The ideal MAC protocol has a decrease in power consumption from 0.06589 mW to 0.037 mW as data generation time increases from 1 second to 10^4 seconds. The VLPM protocol shows a drop in power consumption from 1.17 mW to 0.03711 for the same data generation interval. This results in 17.8 to 1.0 times higher power consumption as compared to the ideal MAC protocol. B-MAC, X-MAC, SCP-MAC and T-MAC have a power consumption that is higher than the ideal MAC protocol by 50 to 1.8, 21 to 1.4, 11 to 1.0 and 10.8 to 1.0 times respectively. Furthermore, for the proposed TWM-MAC protocol, body nodes consume 0.2633 mW to 0.03702 mW of power for a data generation interval of 1 s to 10^4 s. This results in a power consumption of 4 to 1 times higher than the ideal MAC for the same data generation interval. The proposed TM-MAC protocol has a power consumption of 0.1169 mW to 0.03824 mW, resulting in 1.8 to 1.0 times higher than that of the ideal MAC protocol for the same data generation time. It is observed for very low traffic rate that the TWM-MAC protocol has the lowest power consumption as compared with other implemented MAC protocols.

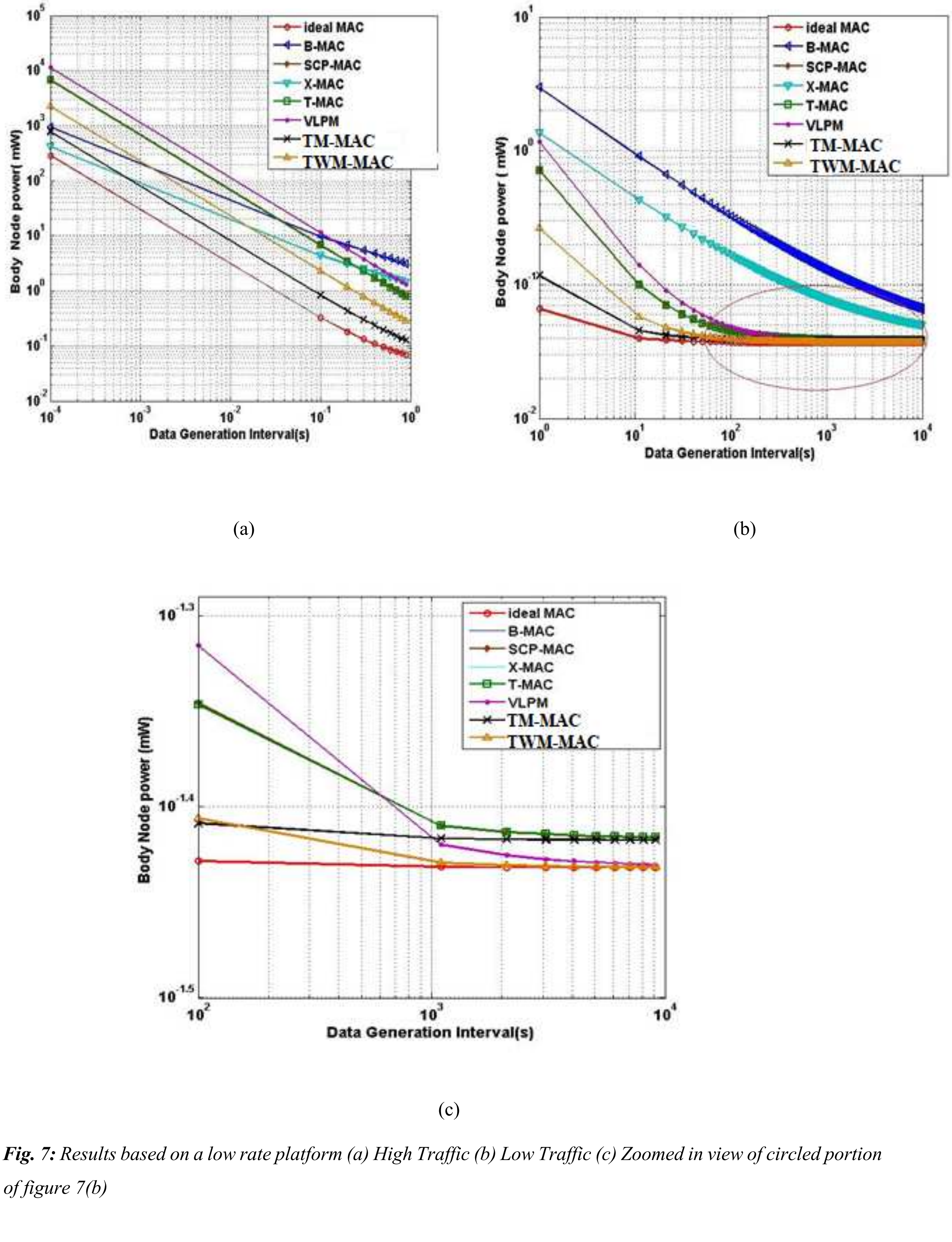


Fig. 7: *Results based on a low rate platform (a) High Traffic (b) Low Traffic (c) Zoomed in view of circled portion of figure 7(b)*

4.3 Downlink Analysis of Power Consumption for the low-rate platform

The downlink traffic of the proposed TWM-MAC protocol and the VLPM protocol is compared in Figure 8. It is deduced that the TWM-MAC protocol performs better than the VLPM protocol by consuming less power. At data generation interval of 1 second, VLPM protocol consumes 32.2 mW of power whereas the proposed TWM-MAC protocol consumes only 0.279 mW of power. Even at low traffic, the proposed TWM-MAC protocol performs better. For example, at a data generation time of 10^3 s, the proposed TWM-MAC protocol consumes 46.2% less power than the VLPM protocol for the downlink mode.

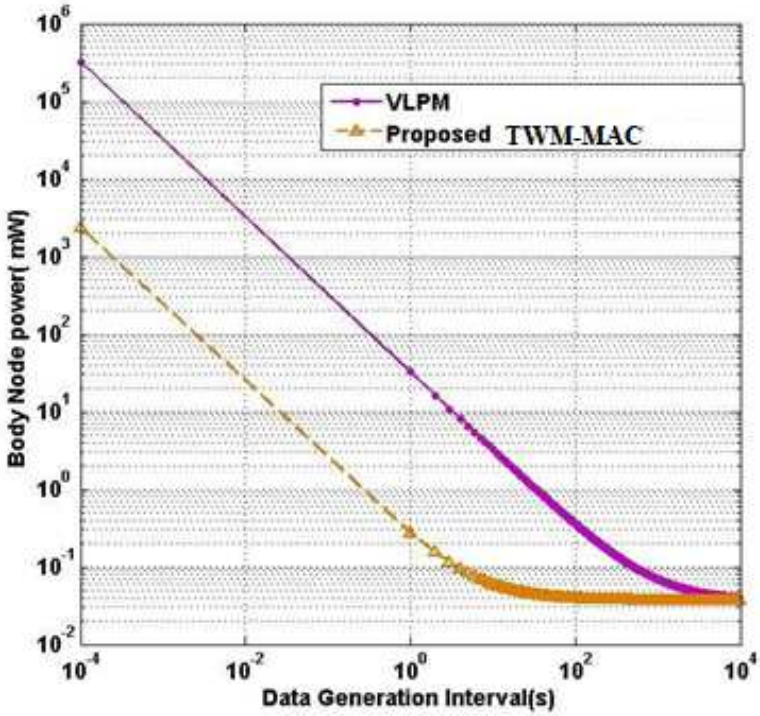
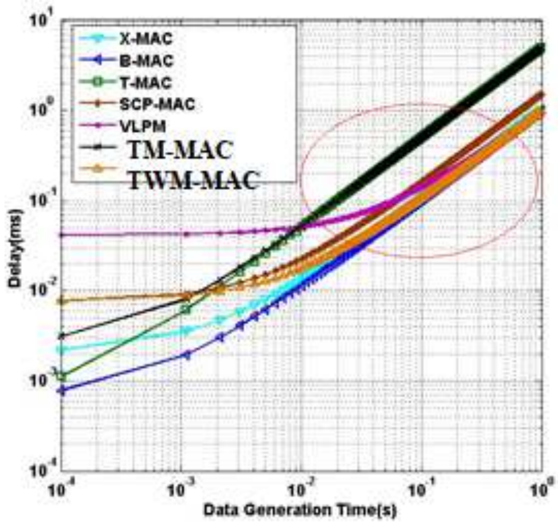


Fig. 8: *Downlink Traffic Analysis*

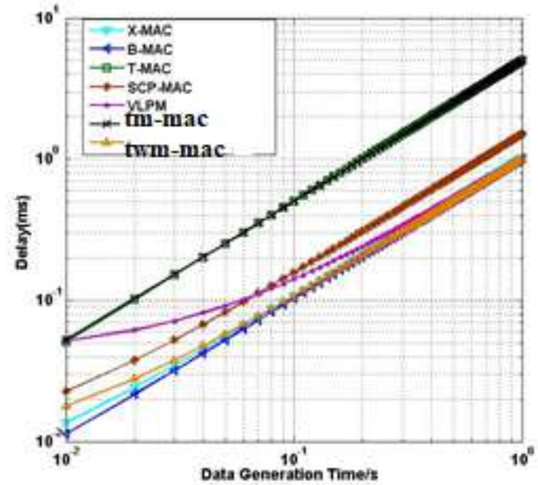
4.4 Delay Analysis of MAC protocols for the low-rate platform

For high traffic as shown in Figure 9(a) and 9(b), which is a zoomed in view of the circled portion of Figure 9(a), the contention-based MAC protocols have the lowest delay. For a data generation interval from 10^{-4} s to 1s, the latencies of X-MAC, B-MAC and T-MAC increase from 2.173 µs to 1018 µs, 0.779 µs to 1007 µs and 1.11 µs to 5001 µs respectively. The VLPM protocol has a delay increasing from 41.5 µs to 1041 µs for a data generation interval from 10^{-4} to 1 second. For high traffic, it can be deduced that the VLPM protocol has a poor latency performance. Thus, VLPM protocol cannot be used for high traffic applications. The TM-MAC protocol has an increase in delay from 3.1 µs to 5003 µs. The TM-MAC protocol has a slightly longer delay than the contention-based MAC protocols since at the start of communication process; synchronisation takes place, which imposes a certain delay prior to transmission. The TWM-MAC protocol has a latency increasing from 7.84 µs to 1008 µs for a data generation interval from 10^{-4} to 1 s. The protocol performs better than the TM-MAC and the VLPM protocol.

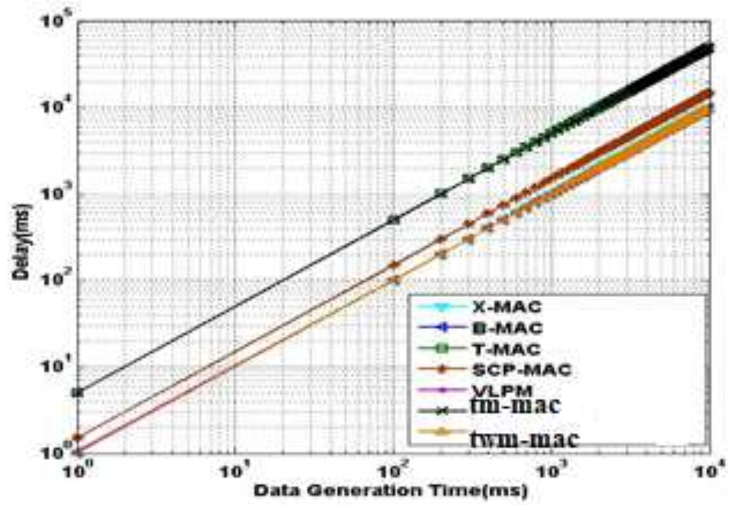
For low traffic as observed in Figure 9(c), SCP-MAC, T-MAC and the TM-MAC protocol have the highest latencies. The other protocols do not differ by much in terms of latency. The improvement in delay was mostly observed with the TWM-MAC for high traffic situations. Moreover, as compared to the VLPM protocol, both proposed MAC protocols have lower delays.



(a)



(b)



(c)

Fig. 9: *Delay Analysis (a) High Traffic (b) Zoomed in view of circled portion of figure 9(a) (c) Low Traffic*

5. Conclusion

Existing MAC protocols have high power consumption, which makes them unsuitable for WBANs. Moreover, they do not adapt themselves to the heterogeneous traffic in low energy WBANs. These shortcomings have prompted the design of two TDMA based MAC protocols which are TM-MAC and a TDMA MAC with a WUR, TWM-MAC protocol. The two proposed protocols showed better performance in terms of power consumption by body nodes for both high and low traffic situations in a WBAN.

Transceivers with both high and low data rates were used to evaluate the performance of the two proposed MAC protocols. Better performance for both protocols was observed on the low-rate platform. This is justified by the fact that the lower data rate (76.8 kbps) transceiver employs Frequency Shift Keying (FSK) whereas the high data rate (1 Mbps) transceiver uses Gaussian Frequency Shift Keying (GFSK) which is more bandwidth intensive [32]. The power consumption will vary depending on the requirements of the sensor nodes. Thus, if a sensor node has a shorter lifetime, a low data rate transceiver needs to be chosen.

With the low data rate transceiver, the proposed TWM-MAC protocol consumed 7.8 times more power than the ideal MAC protocol for a data generation interval of 10^{-4} seconds to 10^{4} seconds. The proposed TM-MAC protocol consumed 2.8 times more power that the ideal MAC protocol for the same data generation interval. Our analysis showed that the proposed protocols are more power efficient as compared to other standard MAC protocols, such as B-MAC, X-MAC, T-MAC, SCP-MAC and the VLPM protocols.

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Figures

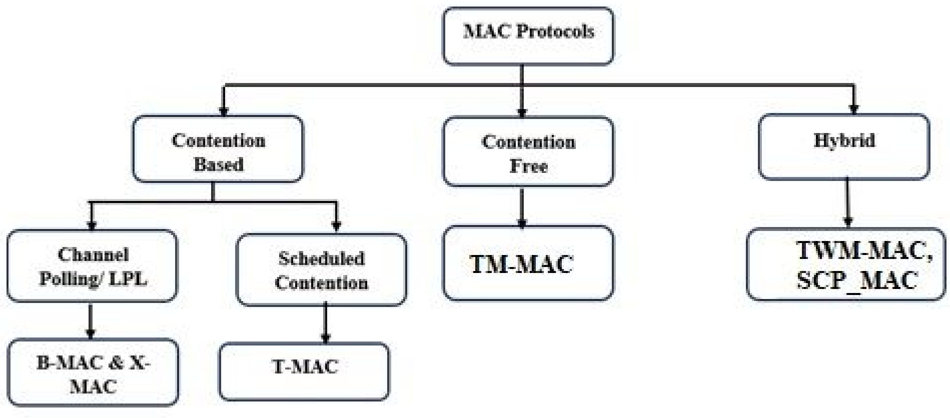

Figure 1

Classification of MAC protocols investigated in this work

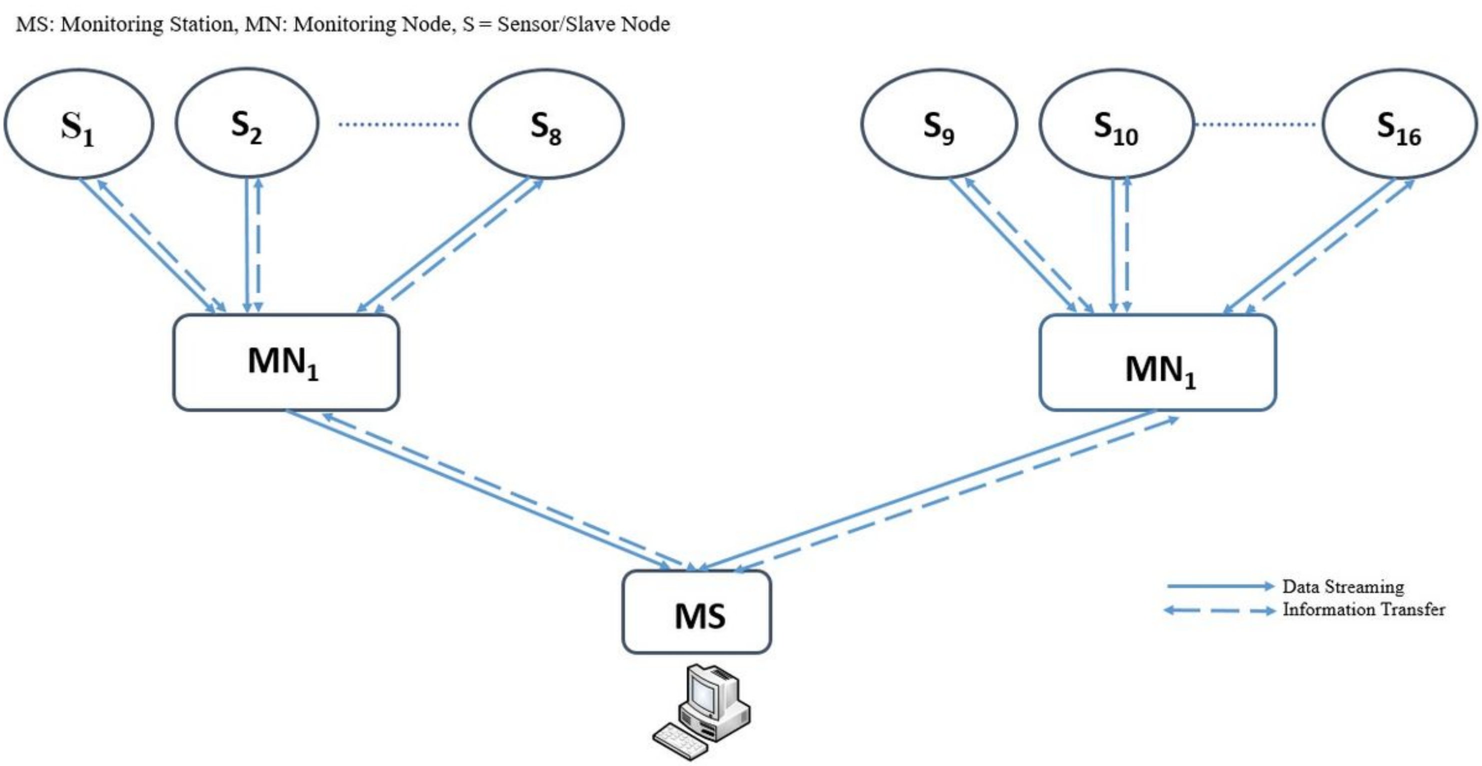

Figure 2

Two WBANs communicating to a Monitoring system

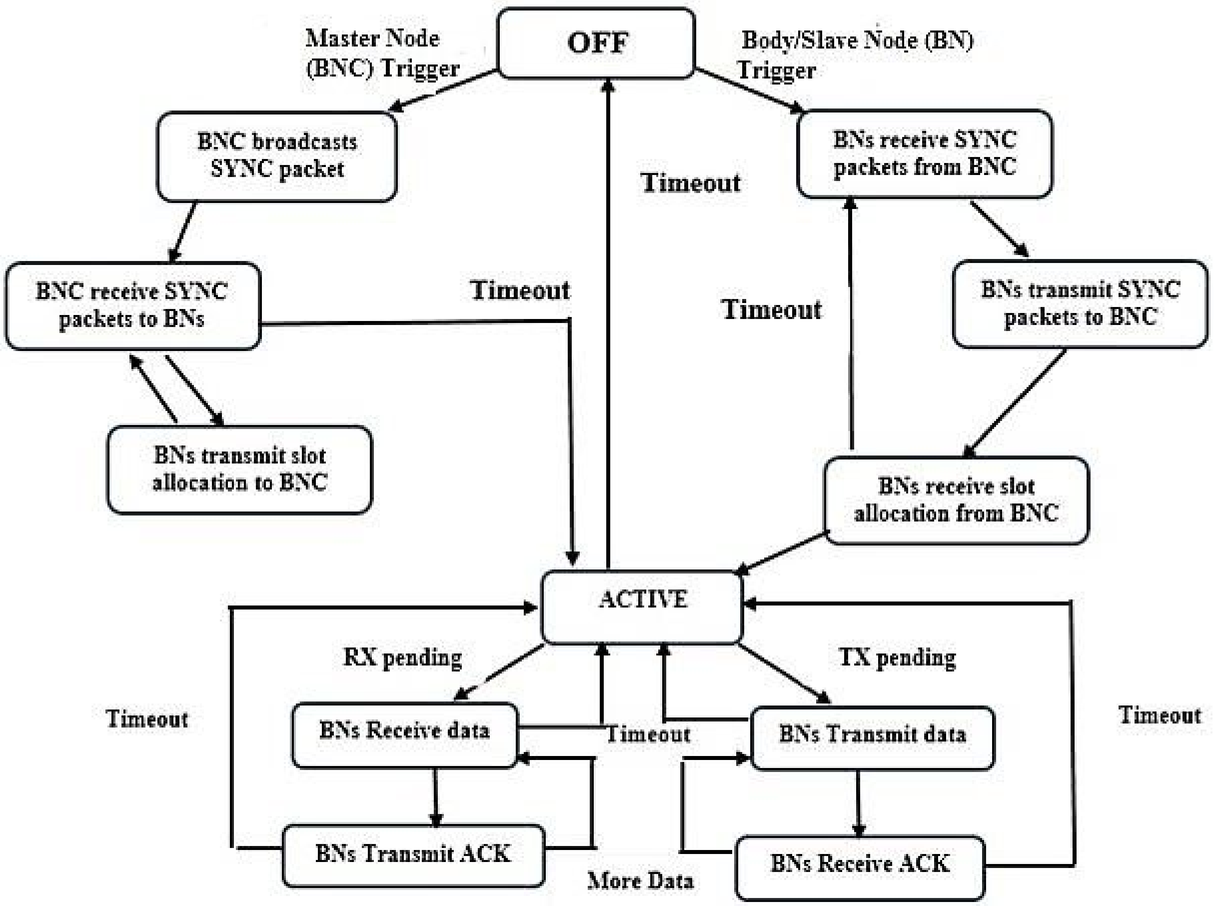

Figure 3

TDMA based TM-MAC State Machine

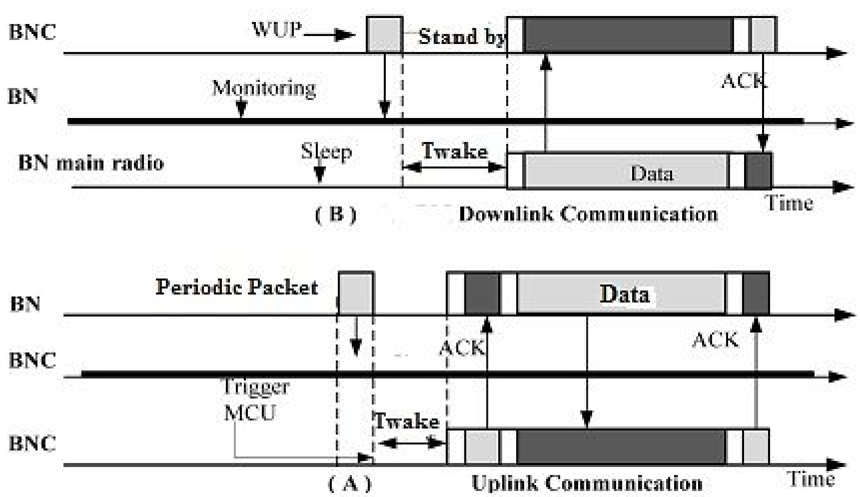

Figure 4

Timing diagram of the TWM-MAC protocol for uplink and downlink traffic

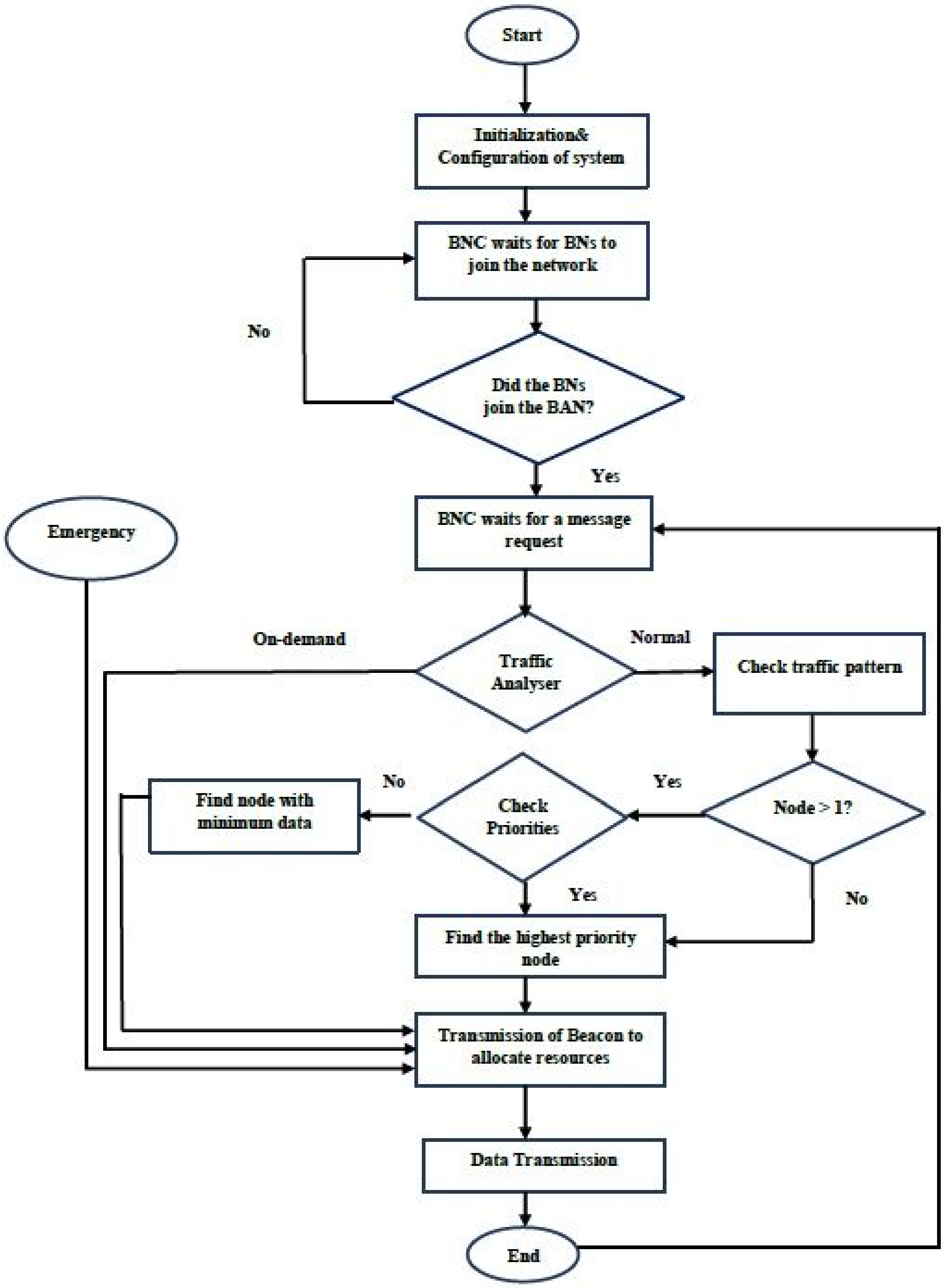

Figure 5

BNC Functionality

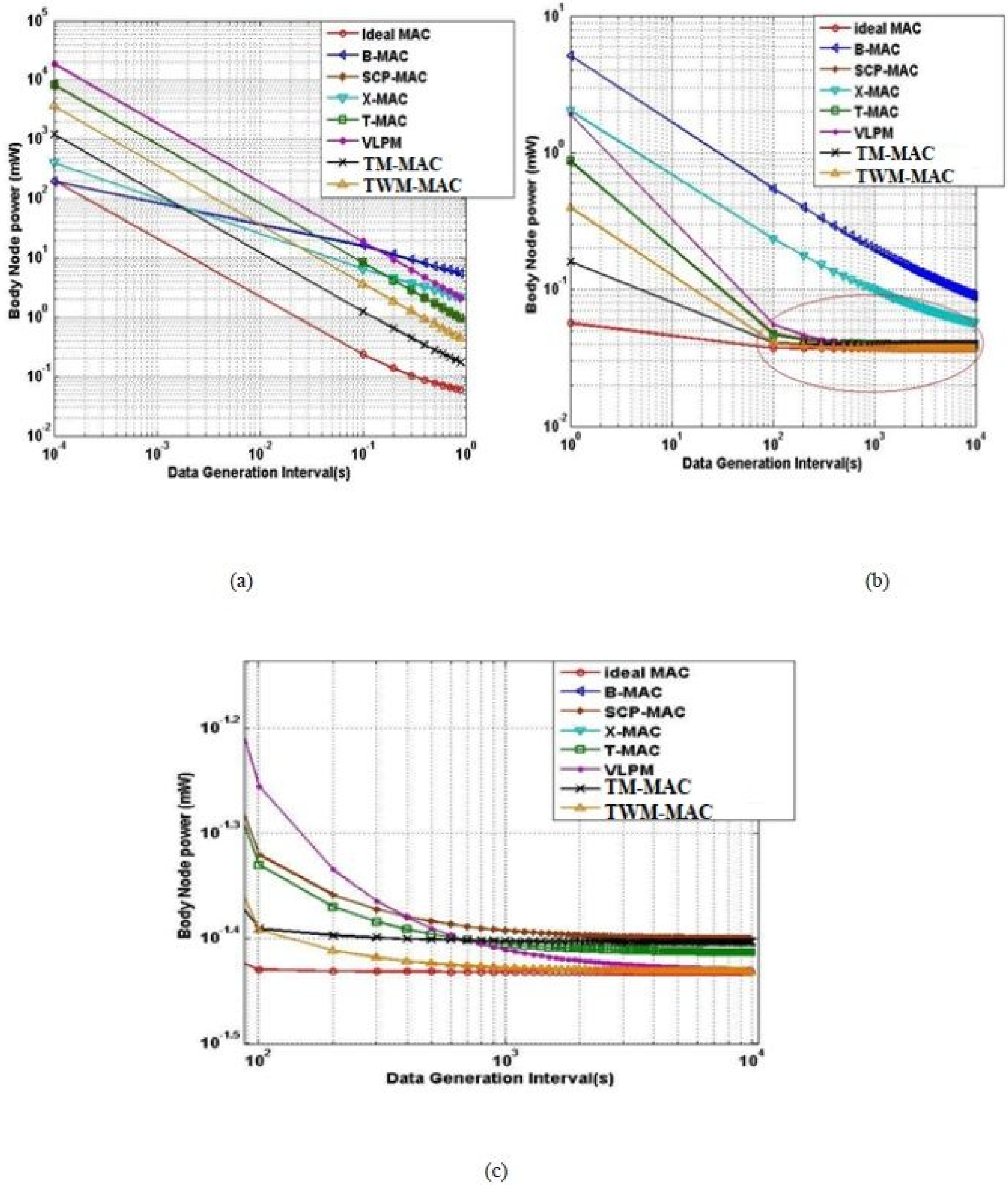

Figure 6

Results based on a high rate platform: (a) High Traffic (b) Low Traffic (c) Zoomed in view of circled portion of Figure 6(b)

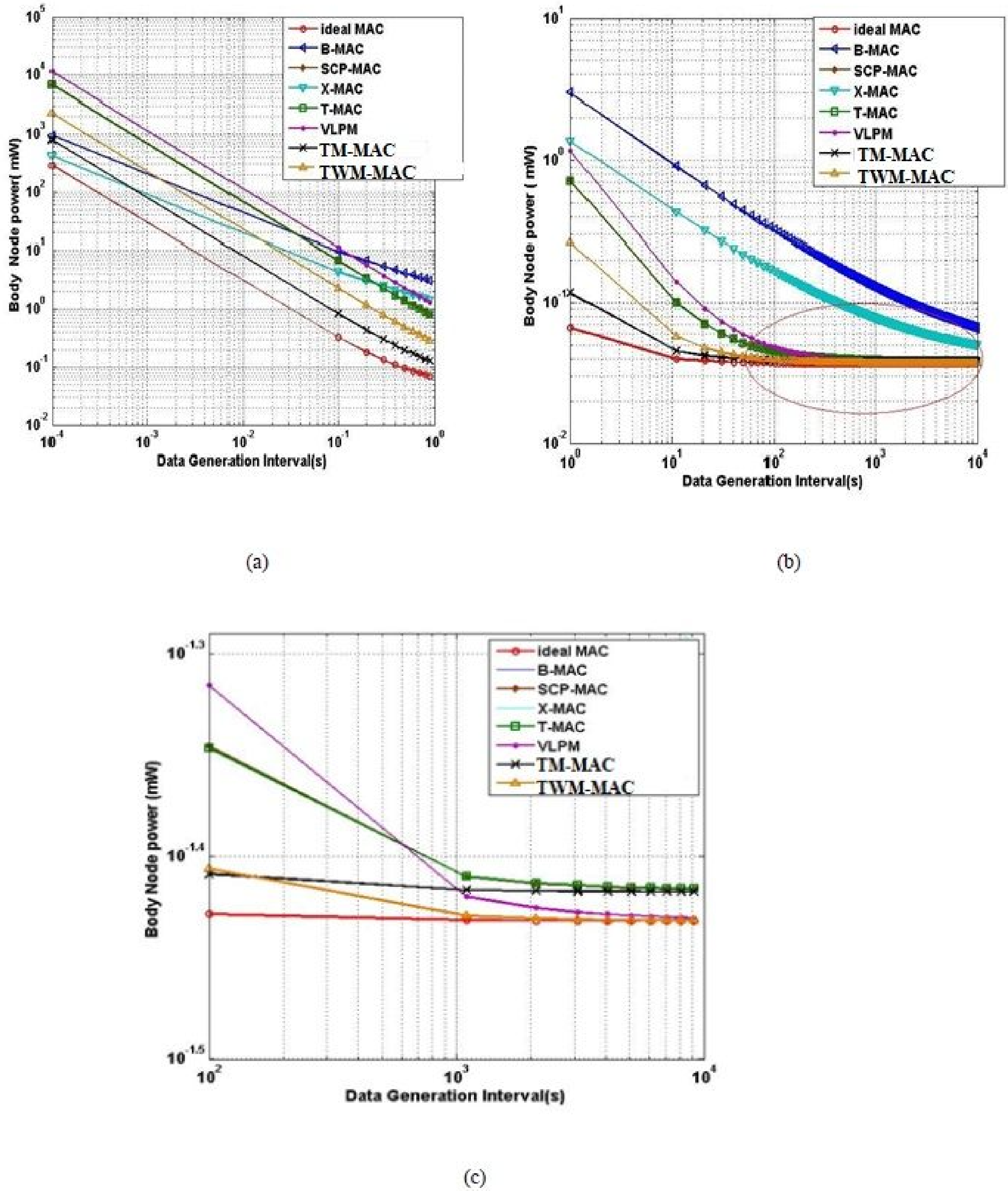

Figure 7

Results based on a low rate platform (a) High Traffic (b) Low Traffic (c) Zoomed in view of circled portion of figure 7(b)

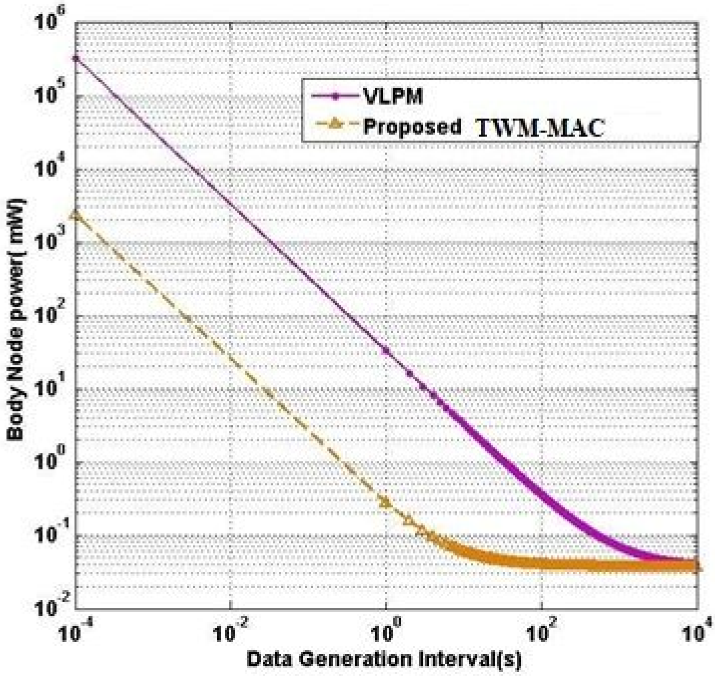

Figure 8

Downlink Traffic Analysis

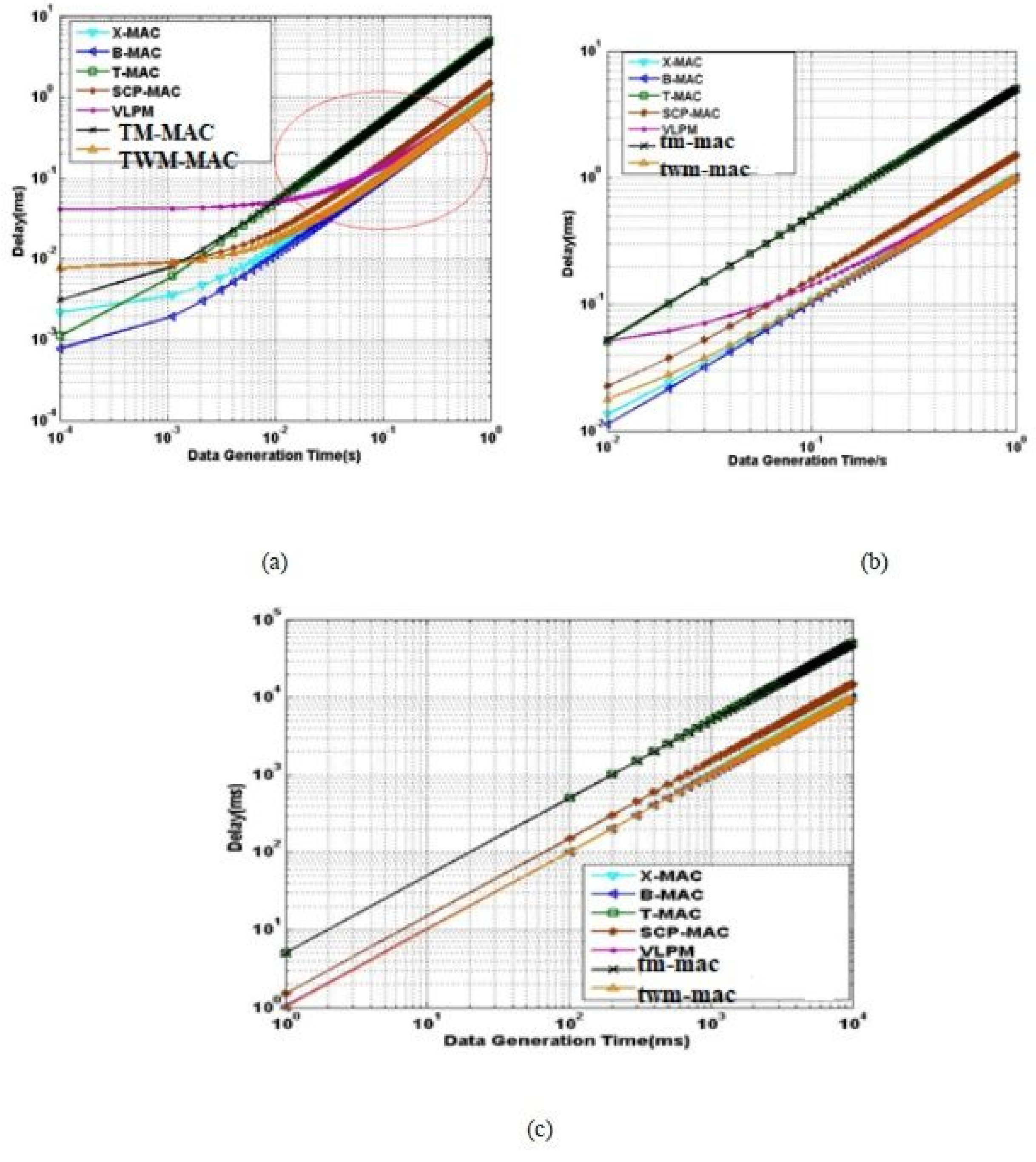

Figure 9

Delay Analysis (a) High Traffic (b) Zoomed in view of circled portion of figure 9(a) (c) Low Traffic