Study of MAC Protocols for Mobile Wireless Body Sensor Networks

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Abstract

Wireless Body Area Networks (WBAN) also referred to as a body sensor network (BSN), is a wireless network of wearable computing devices. It has emerged as a key technology to provide real-time health monitoring of a patient and diagnose many life threatening diseases. WBAN operates in close vicinity to, on, or inside a human body and supports a variety of medical and non-medical applications. The design of a medium access control is a challenge due to the characteristics of wireless channel and the need to fulfill both requirements of mobility support and energy efficiency. This paper presents a comparative study of IEEE 802.15.6, IEEE 804.15.4 and T-MAC in order to analyze the performance of each standard in terms of delay, throughput and energy consumption.

Keywords: Biomedical, IEEE 802.15.6; T-MAC, IEEE 802.15.4, mobility, low-power communication, wireless body sensor networks, implantable sensors, healthcare applications, biosensors.

1. Introduction

Recently, Wireless Sensor Networks (WSNs) have emerged as a key enabling technology for provisioning of health care services. In particular, short range WSNs such as Body Area Networks (BANs) offer the potential for various medical applications to significantly improve patient care and reduce the cost associated with health care. BANs are equipped with in-body (i.e. implant) or on-body sensors that monitor vital life signs and report them to a central unit or gateway, known as a BAN coordinator, for processing the data or further transmission on to outside networks. Recently, researchers from academia and industry have focused their interest on the development of the IEEE 802.15.6 (Standard,Kyung *et al*. 2010) specification as the future standard for BANs for both medical and non-medical applications, with priority given to medical application data. IEEE 802.15.6 is a new standard for Body area networks (BeP.L.Lo *et al*. 2009). It is developed by IEEE 802.15 Group 6 and has various advantages to other wireless communication standards. IEEE 802.15 standards focus on short range, low complexity, low cost and very low power consumption infrastructures.

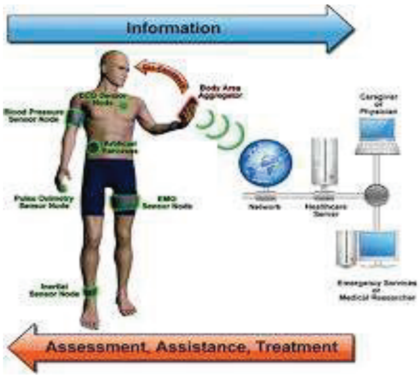


Figure 1. Wireless Body Sensor Networks

2. Related work

Several MAC protocols for WBANs have been introduced to minimize the energy consumption. These MAC protocols can be classified into two categories: Contention-based (CSMA) and Contention-free (TDMA). Packets transmissions are managed in the form of time frames and time slot. A time slot can be considered as a dedicated transmission resource used to carry data with minimum or no overhead. In a TDMA, the channels are divided into fixed/variable time slots which are assigned to a particular sensor node to transmit during its slot period. Slots are collision-free since they are pre-allocated to individual nodes at initialization. Contention-based MAC such as Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) protocols nodes competes for the channel to transmit data. Nodes have to perform Clear Channel Assessment (CCA) before transmission of data. If the channel is busy, the node defers its transmission until it becomes idle. Comparison of CSMA/CA and TDMA is given in Table 1.

Table 1. Comparison of CSMA/CA and TDMA

Feature	CSMA/CA	TDMA
Power Consumption	High	Low
Bandwidth utilization	Low	Maximum
Traffic level support	Low	High
Mobility (Dynamic)	Good	Poor
Synchronization	N/A	Necessary

IEEE 802.15.4 MAC protocol (K.Kwak *et al.* 2011) with GTS management scheme is the most popular TDMA based protocol. In (L.Huaming *et al.* 2010) ,the author proposed H-MAC protocol based on heart beat for synchronization , however this technique requires additional materiel to sense the heart beat which increase the cost of the network. S-MAC, B-MAC and T-MAC (W. Ye *et al*. 2002) are example of duty cycling protocols which have low power consumption since the duty cycle can be adjusted in order to avoid idle listening and overhearing. S-MAC protocol presents a fixed duty cycle which means useless radio wake-ups can take place consuming though sensor energy. As a solution for this problem, T-MAC protocol was presented to change dynamically the duty-cycle depending on traffic information and thus avoid useless wake-ups. In (C.Li *et al.* 2010), authors propose a modified medium access control (MAC) protocol, named Hybrid Unified-slot Access (HUA) protocol for WBANs based on the integrated superframe structure of IEEE 802.15.4. The slotted ALOHA is employed in the contention access period (CAP) to request the slot allocation. Mini-slot method is designed to enhance the efficiency of the contention. In (Ali, K.A 2010), a priority based MAC protocol based on the IEEE 802.15.4a (IEEE. IEEE 802.15.4a 2007) standard for WBANs called Urgency-based MAC (U-MAC) targeted for medical application is proposed. In U-MAC protocol, sensor nodes are grouped into critical and non-critical nodes. Critical nodes packet transmissions are prioritized over non-critical nodes packet transmissions through non-critical nodes packet retransmission cut-off. The U-MAC protocol has been evaluated mathematically. In (Zhou, G 2008), authors defined BodyQoS to design and implement the QoS system for body sensor networks using a hybrid access mechanism called Virtual MAC (VMAC) presenting a bunch of advantages for instance: the ability to support asymmetric architecture capable to adapt to variable factors such as heterogeneous traffic, reliable data communication, guaranteed bandwidth and adaptive resource scheduling.

3. Overview of MAC protocols

3.1 TMAC protocol

T-MAC lets wireless sensor nodes turn on their radio at synchronized times, and turn them off after a certain time-out| when no communication occurs during some time. Messages are transmitted in bursts. This scheme allows dynamic adaption of the radio-on time to changing message rates. The T-MAC protocol saves more energy than its predecessor S-MAC in a network where message rates vary. The S-MAC protocol lets nodes turn the radio on for a xed time. S-MAC requires tuning to the message rate, whereas T-MAC does not. The T-MAC protocol has a problem with asymmetric communication patterns, where nodes may go to sleep while their neighbors still have messages for them. This early sleeping problem reduces the maximum throughput dramatically (T.van Dam *et al*. 2003).

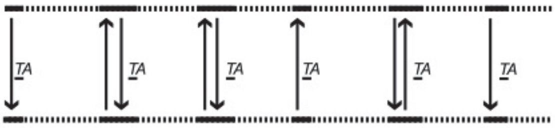


Figure.2. The basic T-MAC access scheme with adaptive active times

Figure 3 shows the basic operation and data exchange of T-MAC. To reduce potential collisions, each node waits for a random period of time within a fixed contention interval before the medium is accessed. For example, in Figure 3.(a), nodes A and C are trying to send data to node B, but node A wins the medium and transmits its data to node B. The minimum time a node remains active to listen for activity is expressed as TA and it must be long enough to hear a potential CTS from one of its neighbors. Once a node hears CTS, it knows that another node won the medium. This node then stays awake until the end of the transmission, which can be observed by overhearing the acknowledgment (ACK) sent by node B. This event initiates the beginning of the next contention interval and node C will have an opportunity to transmit its data if it wins the medium. Figure 3.(a) also shows a potential problem occurring in T-MAC. Assume that messages flow from top to bottom, that is, node A sends only to node B, node B sends to node C, etc. Every time node C wants to send a message to node D, it must contend for the medium and may lose to either node B (which may transmit an RTS before C does) or to node A(node C overhears a CTS transmitted by node B). While node C stays awake after overhearing node B's CTS message, its intended receiver (node D) is not aware of C's intention to transmit data and therefore returns to the sleep mode after TA has expired. This problem is referred to as the early sleeping problem, and one possible solution to this problem is shown in Figure 3.(b). In the future-request-to-send technique, a node with pending data can inform its intended receiver by transmitting a future-request-to-send (FRTS) packet immediately after overhearing a CTS message. Node D, upon receiving the FRTS message, knows that node C will attempt to send data to it and will therefore remain active. However, sending the FRTS message immediately after CTS could interfere with node B's reception of node A's data, therefore, node A first sends a dummy message called Data-Send (DS) to delay the transmission of the actual data. DS has the same size as FRTS and can collide with FRTS at node B, which is of no consequence since it does not contain any useful information. In summary, T-MAC's adaptive approach allows it to adjust a node's sleep and awake intervals based on the traffic load. In T-MAC, nodes send messages as bursts of variable length and sleep between such bursts to conserve energy. Both S-MAC and T-MAC con-centrate message exchanges to small periods of time, which results in inefficiencies under high traffic loads. Finally, intended receivers are kept awake using messages that indicate future transmissions, which can significantly increase the idle listening times (and therefore energy consumption) of nodes (Waltenegus Dargie *et al.* 2010).

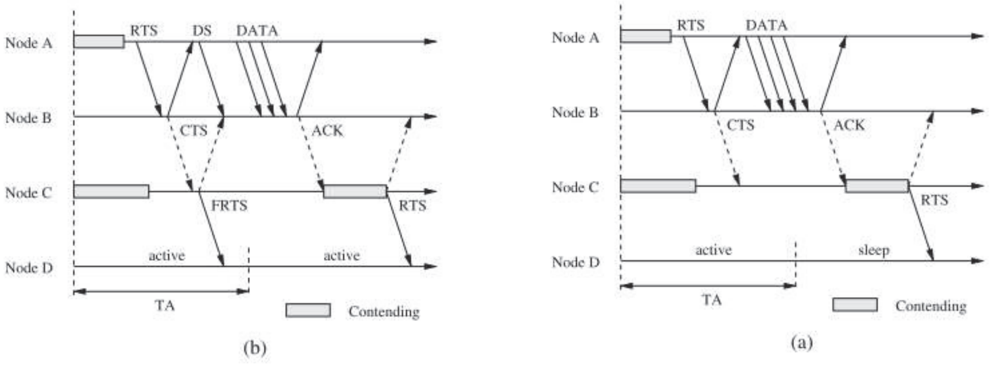


Figure 3. Data exchange in T-MAC, showing the early sleeping problem in (a) and the future-request-to-send technique in (b).

3.2 IEEE 802.15.4 protocol

The MAC sublayer provides two services: the MAC data service and the MAC management service interfacing to the MAC sublayer management entity (MLME) service access point (SAP) (MLME- SAP). The MAC data service enables the transmission and reception of MAC protocol data units (MPDU) across the PHY data service. The features of MAC sublayer are beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association and disassociation.

3.2.1 Superframe structure

LR-WPAN allows the optional use of a superframe structure. The format of the superframe is defined by the coordinator. The superframe is bounded by network beacons and is divided into 16 equally sized slots. The beacon frame is sent in the first slot of each superframe. If a coordinator does not want to use the superframe structure, it may turn off the beacon transmissions. The beacons are used to synchronize the attached devices, to identify the PAN and to describe the structure of superframes.

The superframe can have an active and an inactive portion. During the inactive portion, the coordinator shall not interact with its PAN and may enter a low-power mode. The active portion consists of contention access period (CAP) and contention free period (CFP). Any device wishing to communicate during the CAP shall compete with other devices using a slotted CSMA-CA mechanism. On the other hand, the CFP contains guaranteed time slots (GTSs). The GTSs always appear at the end of the active superframe starting at a slot boundary immediately following the CAP. The PAN coordinator may allocate up to seven of these GTSs and a GTS can occupy more than one slot period.

The duration of different portions of the superframe are described by the values of macBeaconOrder and macSuperFrameOrder. macBeaconOrder describes the interval at which the coordinator shall transmit its beacon frames. The beacon interval, BI, is related to the macBeaconOrder, BO, as follows: BI = aBaseSuperFrameDuration2 BO, $0 \leq BO \leq 14$. The superframe is ignored if BO = 15. The value of macSuperFrameOrder describes the length of the active portion of the superframe. The superframe duration, SD, is related to macSuperFrameOrder, SO, as follows:

SD =aBaseSuperFrameDuration2 SO, $0 \leq SO \leq 14$. If SO = 15, the superframe should not remain active after the beacon. The active portion of each superframe is divided into a aNumSuperFrameSlots equally spaced slots of duration 2 SO aBaseSlotDuration and is composed of three parts: a beacon, a CAP and CFP. The beacon is transmitted at the start of slot 0 without the use of CSMA. The CAP starts immediately after the beacon. The CAP shall be at least aMinCAPLength symbols unless additional space is needed to temporarily accommodate the increase in the beacon frame length to perform GTS maintenance. All frames except acknowledgement frames or any data frame that immediately follows the acknowledgement of a data request command that are transmitted in the CAP shall use slotted CSMA-CA to access the channel. A transmission in the CAP shall be complete one IFS period before the end of the CAP. If this is not possible, it defers its transmission until the CAP of the following superframe. An example superframe structure is shown in Figure 4. The CFP, if present, shall start on a slot boundary immediately following the CAP and extends to the end of the active portion of the superframe. The length of the CFP is determined by the total length of all of the combined GTSs. No transmissions within the CFP shall use a CSMA-CA mechanism. A device transmitting in the CFP shall ensure that its transmissions are complete one IFS period before the end of its GTS. IFS time is the amount of time necessary to process the received packet by the PHY. Transmitted frames shall be followed by an IFS period. The length of IFS depends on the size of the frame that has just been transmitted. Frames of up to aMaxSIFSFrameSize in length shall be followed by a SIFS whereas frames of greater length shall be followed by a LIFS. The PANs that do not wish to use the superframe in a nonbeacon-enabled shall set both macBeaconOrder and macSuperFrameOrder to 15. In this kind of network, a coordinator shall not transmit any beacons, all transmissions except the acknowledgement frame shall use unslotted CSMA-CA to access channel, GTSs shall not be permitted.

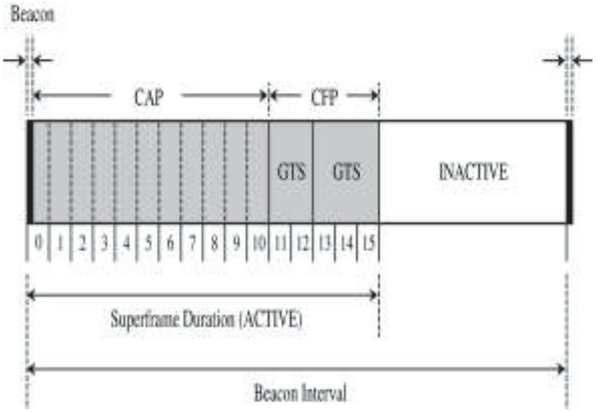


Figure .4. Superframe Structure

3.3 IEEE 802.15.6 protocol

IEEE 802.15.6 is a very new standard which aims to meet the society's various demands on modern health related field , mainly improve the performance in aspects like shorter range communication, higher transfer data rate, lower device complexity, ultra lower power constraint, lifetime, in-body environment, security, Qos, etc. Task group 6 (TG6) is set up to propose a new standard for Body Area Networks; we now called it IEEE 802.15.6. The first draft was released by the research group in May, 2010. And the latest draft of the new standard, which is the third version, released in April, 2011. IEEE 802.15.6 established to define the PHY and MAC for short range, low complexity, low cost, ultra-low power and high reliable wireless communication in, on, or around the human body. The IEEE 802.15.6 draft operates with one-hop star and two-hop restricted tree topologies. In the one-hop topology, frames are exchanged between nodes and hubs while in the two-hop restricted tree, a hub and a node may use a relay node to exchange frames. This analysis concentrates on the one-hop topology. The hubs are responsible for coordinating channel access by establishing one of the following three access modes:

- Beacon mode with beacon period superframe boundaries
- Non-beacon mode with superframe boundaries
- Non-beacon mode without superframe boundaries

The time base is divided into equal length beacon periods (also known as superframes) and each superframe is further divided into allocation slots. In the first two access periods the time base is common between hubs and nodes and it is dictated by the hub; i.e. the hub establishes superframe boundaries and defines the number of allocation slots in it. In the first access mode, the hub communicates the superframe structure via beacon frames or Timed frames (T-Poll). The second access mode does not transmit beacons and the superframe structure is enforced through the use of Timed frames (T-Poll). In the non-beacon mode without superframe boundaries each node establishes its own time base independently. The analysis in this paper concentrates on Beacon Mode with beacon period superframe boundaries. The superframe structure, shown in Figure 5, starts with a beacon followed by two consecutive periods each consisting of an Exclusive Access Phase (EAP), Random Access Phase (RAP), Type I/II access phases, and an optional B2 frame that precedes the Contention Access Phase (CAP). It must be noted that the length of these phases is variable and their length is given in numbers of allocation slots. By setting any of these lengths to zero the access phases can be eliminated. This superframe structure allows three types of access:

3.3.1 Random access (Contention based): CSMA/CA or Slotted ALOHA for the narrowband and ultra-wide band physical layers respectively.

3.3.2 Improvised and unscheduled access: Post (i.e. a hub instruction) or Poll (i.e. a data request from the hub).

3.3.3 Scheduled access (Contention free): 1-period or m-periodic.

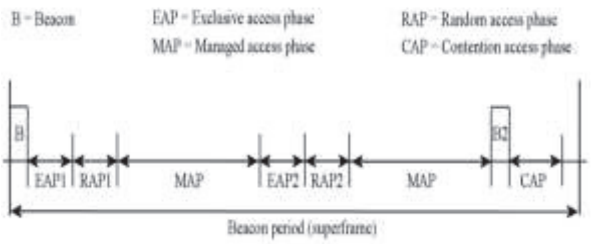


Figure5. IEEE 802.15.6 superframe structure

The EAP1, EAP2, RAP1, RAP2 and CAP are random access phases. The EAPs are reserved for high priority traffic while the RAPs are used for non-recurring transfers using contention. Type I/II access phases are set aside for scheduled transfers, unscheduled and improvised transfers. Devices that have type I/II scheduled allocations can start their transfer when the reserved allocation slot time has commenced, whereas devices with unscheduled and improvised access must be awake and wait for a poll or post frame from the hub, before they can transmit. Type I and Type II access cannot be mixed in each of the Type I/II phases in one superframe. Type I and type II phases differ in the units used to request reservations, with the device requesting allocation intervals in time (Type I) or in number of frames (Type II). Scheduled allocation can be either 1-periodic or m-periodic. In 1-periodic allocations devices exchange frames with the hub in every superframe while in m-periodic allocation devices and hubs exchange frames every m superframes allowing the device to sleep between transfers. The allocations can be uplink, downlink or bilink. In bilink, transfers occur in both directions and are initiated by the hub using post/poll frames. The draft defines four acknowledgement policies: 1) not acknowledged frames (N-Ack), 2) immediately acknowledged (I-Ack), 3) block acknowledged later (L-Ack) and 4) block acknowledged (B-Ack).

4. Mobility support model

A study has been conducted in (N.Bradai *et al.* 2013) in order to compare the specification and characteristics of medium access protocols for WBAN, however the authors did not take into account the effect of mobility criteria on MAC protocols. To highlight its impact on the previous mentioned MAC protocols, we used MoBAN which is a configurable mobility model for Wireless Body Area Networks (WBANs). A mobility model for mobile networks determines the node positions at any instance of simulation time and so influences the network topology and link properties. Consequently, the precision of the model has a major impact on the precision of the evaluated network performance. A proper mobility model for WBANs should be able to statistically model the right movement patterns of the individual nodes installed on the body as well as the whole body movement. At the same time, it should be adaptable for various application scenarios in which the movement patterns, the human activities, and the surrounding environment may differ. MoBAN model has been specifically designed so that it can be configured for being used for performance evaluation of a broad range of application scenarios including WBANs. Both global movement of the WBAN and the individual node mobility within the WBAN have been taken into consideration. The model can be used in simulating both intra- and extra-WBAN protocols. The Model is constructed based on the RPGM group mobility model. It implements various time and space correlations for selecting the posture of the body and the movement behavior (M.Nabi1 *et al.* 2011). The structural block diagram of the MoBAN implementation is shown in Figure 6.

5. Performance Analysis

We have performed our simulation in Castalia 3.2 designed for Wireless Sensor Networks (WSN), Body Area Networks (BAN), and generally networks of low-power embedded devices (*Castalia Simulator*). We proceeded to analyze the performance of three MAC protocols TMAC, ZigBeeMAC and IEEE 802.15.6 (BaselineMAC). For this purpose we adopted the following parameters: a star topology, BypassRouting for the routing layer (algorithm which does not perform any routing function), and the throughput test application for the application layer. For the physical radio parameters we assumed that the receiver (Rx) sensitivity is -87 dBm and the transmitter power equals -15 dBm. Three metrics has been considered to evaluate the effectiveness of the three MAC protocols under mobility constraint: packet received per node, energy consumption and latency. The latency equals to the arrived message time minus the message creation time and the throughput is defined as data quantity transmitted successfully from the source to the destination within a period. The calculation is based on the total number of packets received successfully. We run our simulation using 12 sensor nodes with predefined locations including the PDA (see Figure 7), we used 20 seed sets, and the rate varies from 10 to 30.

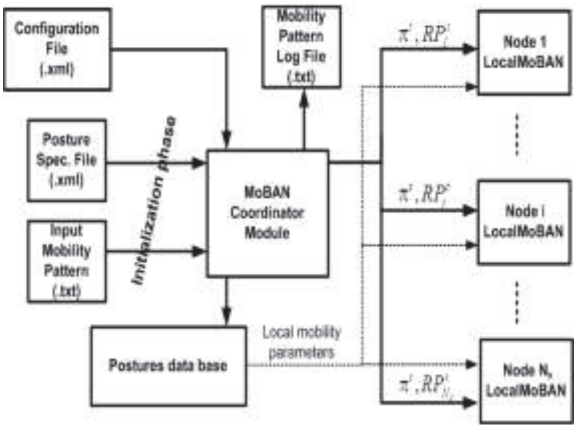


Figure 6. MoBAN implementation

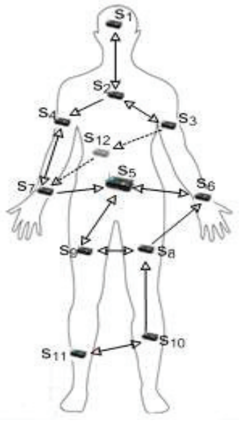


Figure 7. An illustration of sensors locations in WBSN

5.1 Packets received per node analysis

In this section, we have evaluated the throughput for GTSOFF and GTSON modes, simulation results are illustrated in Figure 9.The y axis is average packers received per node (only node 0 receives packets but it receives them from multiple nodes, this is what the “per node” means). The x axis is the sending rate for each node measured in packets/sec. Generally observing, IEEE 802.15.4 protocol outperforms both IEEE 802.15.6 and TMAC protocols under mobility constraint in terms of the percentage of packets received per node when GTS functionality is turned on in both General and non temporal, notice that when the rate is minimal (case of rate = 14), the GTSon noTemporal curve achieves the maximum, this is something to be expected since GTS reduces interference and make a more efficient use of the wireless medium, we also notice that the throughput is better when the channel has no temporal variation as temporal variation introduces channel fading breaking though the connectivity between the sender nodes and the base station, whereas with no temporal pathloss variation, the links are kept in a relatively good state . A moving person is expected to generate large link quality variations i.e. Running and Walking position model, meaning that most of packets are lost due to quickly appearing and disappearing link. A solution to enhance connectivity between sensors and the base station can be limited to changing dynamically the radio transmission power, however this solution increases the heating effects due to radiation absorption by the tissue i.e. SAR (Specification Absorption Rate) exceeds threshold value, hence the radio transmission has to be as low as possible while maintaining the connectivity. GTS advantage is observable when a body is in state position: SITTING and LYING DOWN position model, thus more packets are received while the connectivity condition is verified (S.K.S *et al.* 2003), but as soon as the body start moving quickly, GTS performance is degraded and packets are more likely to be dropped in correlation to rate.The access mechanism used in each period of IEEE 802.15.6 superframe and in IEEE 802.15.4 Contention Access Period is CSMA/CA .

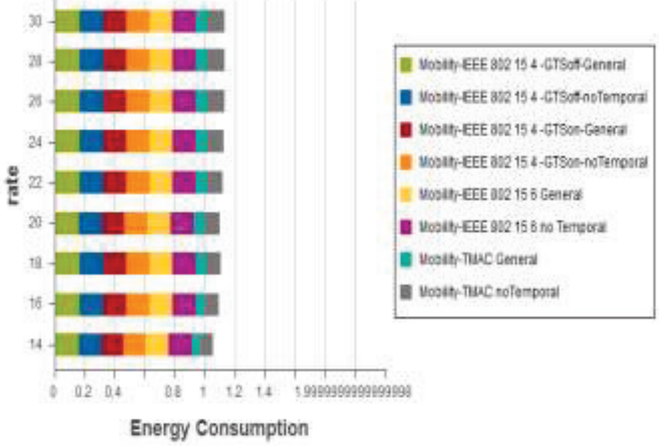


Figure 8. Throughput of WBSN

In IEEE 802.15.6 EAP and RAP periods, nodes contend for the resource allocation using CSMA/CA access procedure, thus frame collision probability is more likely to take place within nodes having the same priority at the beginning of an EAP/RAP period,because the back off counter is unlocked at approximately the same time leading to a collision of data frame,besides, most of the packets are lost since nodes have no longer access to the channel due to link breakage, this explains the IEEE 802.15.6 throughput in relation to rate and mobility model while TMAC protocol shows the worst performance compared to IEEE 802.15.6 and IEEE 802.15.4 in both temporal and no temporal channel variations , RTS packets are collided at the receiving node ,moreover when there is a high mobility,CTS might not be overheard by others nodes contending for the channel due to the absence of connection leading to increasing number of RTS collision at the receiving node, DATA and ACK packets are also lost when the connectivity is interrupted which explains the low throughput of TMAC packets as mentioned above in Figure 8.

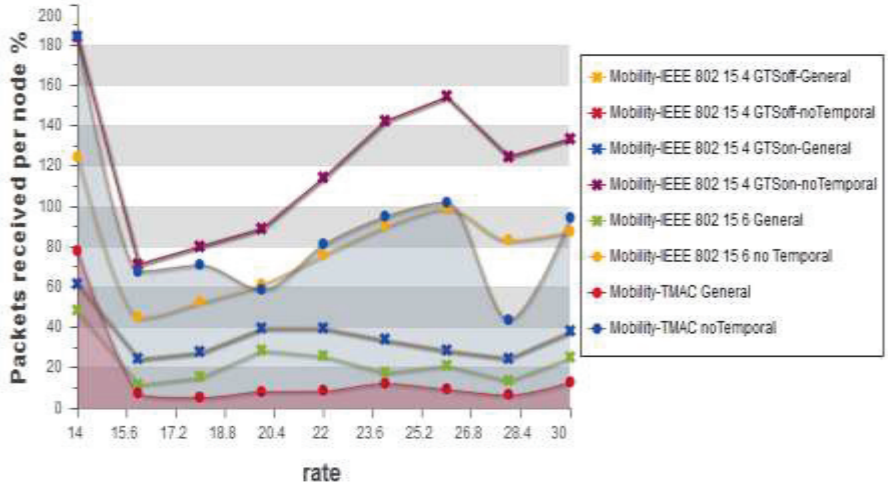
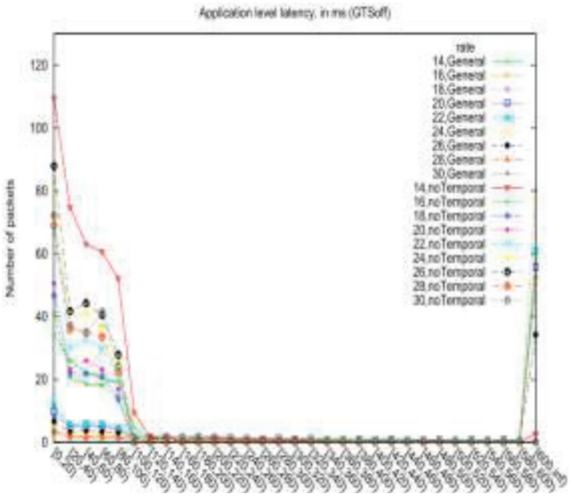


Figure 9. Energy Consumption vs Rate

As can be shown in Figure 9, the energy consumption consumed by IEEE 804.15.4 has an average value equals to 0.11 J compared with 0.16 J for IEEE 802.15.6. The results demonstrate that the energy consumption of our model is not directly dependent on transmissions; it depends however on the states of the radio. The IEEE 804.15.4 has an advantage over IEEE 802.15.6 with the inactive period in the superframe, during this period, all sensors radios are turned off which conserves an important amount of energy compared with IEEE 802.15.6, the more the radio is in TX or RX mode, the more it consumes energy similar to packet collision which leads to packets retransmission thus enhancing sensors being in the active mode.



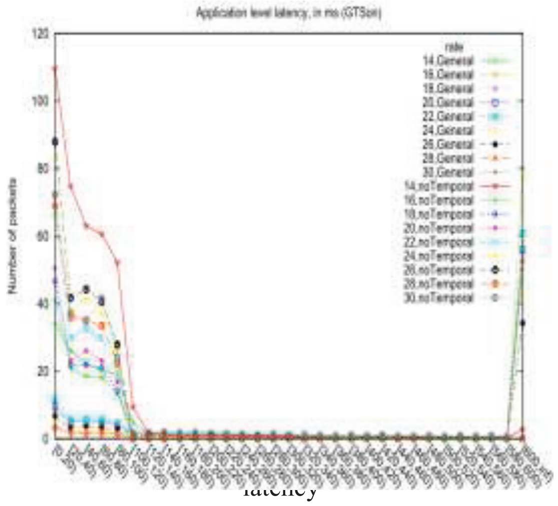
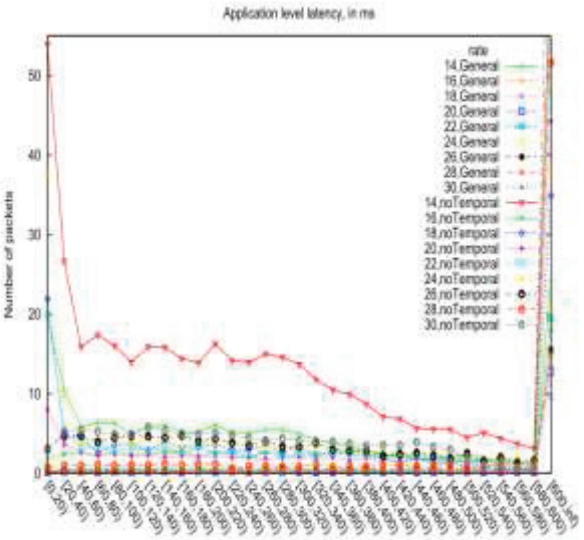


Figure 9. IEEE 802.15.4 GTSon application latency



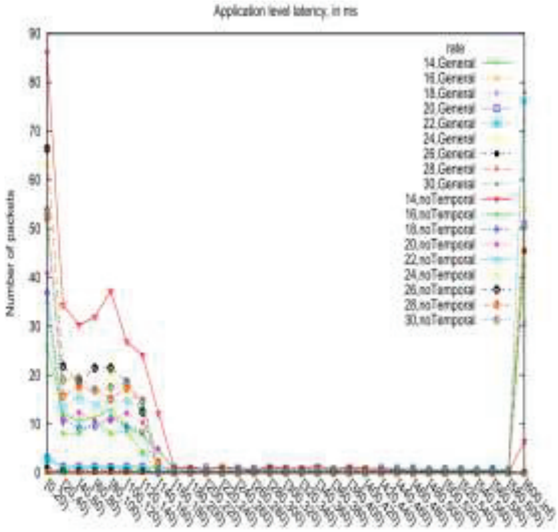


Figure 11. TMAC application latency

As can be shown in Figure 9 and 10 (GTSoff,GTSon) , most of the packets are received with under 120 msecs latency, which means that they are transmitted in the first MAC frame after their creation . We also noticed that no temporal is performing better as expected. The non-negligible portion of packets at the [600..inf) bucket is a sign of oncoming saturation for the temporal case (General). In case of IEEE 802.15.6 (see Figure 12) we can observe that the majority of the packets are received within the first frame of creation and we also see a big portion of packets with large delay. This indicates a potential saturation in this case, with overflown buffers, Figure 11 shows that TMAC presents a high latency compared to IEEE 802.15.4 and IEEE 802.15.6,most of the packets are received under 500 msecs , we also notice that temporal and no temporal channel effect is approximately similar in terms of latency performance, this indicates that TMAC protocol experience as well a potential saturation with overflown buffers explaining though the low performance points in the “packets received per node” graph.

6. Conclusion

WBAN provide promising applications in medical monitoring systems to measure specified physiological data and also provide location-based information .In this paper ,we presented an overview of the existing MAC protocols namely IEEE 802.15.4,IEEE 802.15.6 and TMAC to highlight prerequisites of WBAN ,we also studied the performance of IEEE 802.15.4 MAC,IEEE 802.15.6 MAC and TMAC under mobility constraint in terms of energy ,throughput and latency using OMNET++ with Castalia as simulating tools. The analysis shows that IEEE 802.15.4 outperforms IEEE 802.15.6 and TMAC with GTS ON and temporal variation.

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