Performance comparison of IEEE 802.15.4 and IEEE 802.15.4e based MAC algorithm in wireless body sensor networks

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Abstract. One of the potential applications of Wireless Sensor Network for improving the lifestyle of human beings is Wireless Body Sensor Network (WBSN). A dedicated health monitoring system is referred to as the Ubiquitous Health Monitoring (UHM) system consisting of the Internet of Things (IoT) based access points which are made available in a cloud-based server. So, ZigBee based IEEE 802.15.4 technology is extensively used in the implementation of Medium Access Control (MAC) and Physical (PHY) layers. Hence, a comparison is provided in terms of the features of the modified IEEE 802.15.4e standard. An algorithmic approach for the MAC layer helped in regulated power consumption of the sensor node by controlling the transmission power for the packets. This is initiated in the algorithm by categorizing the packets as Delay sensitive and Delay insensitive. By regulating the channel access strategy using Medium Access Control (MAC) layer, the energy consumption of the transceiver reduces, thus improving the energy consumption of the communication system and lifetime of the sensor network. For better throughput using IEEE 802.15.4e, the performance of Deterministic and Synchronous Multi-channel Extension (DSME) is found to be trustworthy than Time Slotted Channel Hopping (TSCH).

Keywords: MAC, PHY, Energy efficiency, throughput, DSME and TSCH.

1. Introduction
Wireless Body Sensor Network (WBSN) is formed by tiny body sensor nodes placed on specific locations on the human body which forward the precious physiological data into an access point called Body Area Network (BAN) coordinator. While performing the sensing, processing and communication operation, each node spends certain amount of energy [1]. Ubiquitous Health Monitoring (UHM) system consists of one or more WBSN system with body sensor nodes placed at specific areas on the body, measuring distinct parameters, forwarding the information to an access point. This system has an emerging technology with recent advancements in ICT which enables increased energy efficiency in the medical healthcare system as well as accuracy in the availability of data at multiple points. Figure 1
shows the block diagram of UHM System. There are WBSN systems in each room with an IoT based access point. Each access point links to a cloud based system where vital data is stored. Thus, the global needs of healthcare system are satisfied with the state-of-the-art technology such as ‘IoT’ based access points and ‘cloud storage’ services [2].

![Fig 1. WBSN system as UHM system](image)

The information can be downloaded to a medical record system, mobile phone or computer of a medical practitioner [3]. This procedure facilitates the necessary immediate action to be initiated by any of the people attached to these systems as each room might have a minimum of one patient attached with the Body sensor nodes. As the sensor nodes are small in size, there must be minimum power consumption during those operations so as to conserve the energy for longer period. The protocols of Network, Medium Access Control (MAC) and Physical (PHY) layers set up the rules and tasks in order to manage the operation of the WBSN system. The amplitude of the voltage or current pulses representing the (data bits) signal, are subjected to the power consumption of the communication unit of the PHY layer. The radio (transceiver) of the body sensor takes up the responsibility of data transmission and reception.

When the sensed data in the form of bits (PHY layer) are to be transmitted through Radio Frequency (RF) link to the destination node, initially channel access mechanism needs to be functional. The algorithm of MAC layer senses the channel and determines the channel status to be ‘busy’ or ‘available’. Only if the channel status is ‘available’, the transmission will begin [18]. The radio of the PHY layer follows the instructions of MAC layer and switches the radio. If more than one-hop communication is required, then the decision of the network layer algorithm is needed as well. Hence, energy efficiency enhancement is contributed by the lower layers. The energy consumption of the radio chip must be well under the control of MAC and routing algorithm for increasing the life span of the sensor [4]. Depending on the regulation of power, the body sensor will have increased lifespan from months to year [5]. By solving few of the issues of the network management through algorithms for Medium Access Control (MAC) layer, energy efficiency improvement feature will be attended. An algorithmic approach for MAC layer proposed an increase in the life span of the Body sensor, and hence, network lifetime.

2. IEEE 802.15.4 based MAC algorithm

The Medium Access Control layer algorithms control the functions this layer. The physical layer performance is well managed by these algorithms and as such intended to provide high energy efficiency. The following standards of Wireless networks are more widely used in WBSN applications.

2.1. IEEE 802.15.4 standard

In this standard, the MAC and PHY layers are defined so as to meet the requirement such as high data rate, low power consumption, low latency, and high throughput. For Wireless Body Sensor Network, it
uses the popular multiple access protocol of Wireless networks known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [6, 7].

The following are some of the features of CSMA/CA used in WBAN.

a. Representation of data in super frame
b. Sophisticated data transfer model
c. Enhanced successful data delivery rate
d. Low power consumption leading to improvement in network lifetime
e. Security aspects in the protocols

The following sections describe a superframe structure of CSMA frame. A superframe has beacon period and control message fields as shown in Figure 2. Beacon is a short duration pulse used for marking the beginning of the frame. It is used for synchronization of the frame. During the Contention Access Period (CAP), body sensors contend for channel access. This is referred to as channel access using CSMA/CA protocol.

Fig 2. Superframe structure

In Contention Free Period (CFP), superframe structure has a dedicated time slot called Guaranteed Time Slot (GTS) for the transmission of data using TDMA protocol. In most of the emergency situations, this access mechanism is used for the transfer of data within low delay profile. In Inactive Period, the devices enter into low power (sleep) mode as energy saving strategy. Battery powered devices are operated using duty cycling to reduce power consumption. Each device periodically listens to the channel to check whether the message is pending or not. During this period, the sensor enters into “sleep” state whereas the radio is turned to standby mode.

The signal from PHY layer will be transmitted as bit through wireless channel. During the propagation, there will be fading of the signal which is estimated with fade depth distribution [8]. Latency is a prime parameter that decides the QoS of a WBSN system. The details of application packets received and the reason for failure of packets are provided. Greater the transmitting power, larger will be the signal to noise ratio and the range of transmission of the information. But this will lead to an increase in the power consumption of the node, reducing the efficiency and also life span of the body sensor node. Hence, a stipulated amount of transmitting power for the given BAN scenario should be estimated.

2.2 IEEE 802.15.4e Standard

In order to gratify the modern needs of industrial and healthcare sectors, IEEE 802.15.4 standard is added with an amendment to MAC layer and resulted as IEEE 802.15.4e standard. The new paradigm of IEEE 802.15.4e standard provides MAC extensions to different features. Few of them include, slotted access shared with dedicated slots, multi-channel communication, energy efficiency and frequency hopping. Most of the features are planned for supporting industrial sensor networks requiring internetworking services. There are two prime MAC behavioral modes utilising CSMA/CA or TDMA schemes. They are known as Time Slotted Channel Hopping (TSCH) and Deterministic and Synchronous Multi-channel Extension (DSME) respectively. A brief discussion of TSCH and DSME is given below [9, 19, 20].
(a) TSCH: This MAC scheme is applicable for process automation scheme with a demand of focus on the equipment. It has time slotted access feature which is enhanced from the IEEE 802.15.4 providing a higher throughput and low latency. With a multichannel feature, larger communication with more sensor nodes is possible. This adds improvement to communication reliability and results in increased network capability. It also has channel hopping scheme with a benefit of interference mitigation. It is most suitable for multi-hop networks allowing star, mesh, multi-hop or tree topologies.

(b) DSME: It supports industrial and healthcare applications requiring low latency and high flexibility. One of the key features of DSME is that it enables the MAC to operate in fully scheduled mode utilizing guaranteed time slots (GTS), termed as DSME-GTSs, for communications. The specialty of IEEE 802.15.4e superframe is the multi superframe structure with 3 or 4 superframes in it. Every one contains an Enhanced Beacon (EB), Contention Access Period (CAP) and Contention Free Period CFP. The CFP consists of slots that can be availed using GTS and contention based slots are available in CAP. Similar to IEEE 802.15.4 standard, EB will be transmitted at the beginning of slot -0 of the superframe. There are other features such as CAP reduction, group acknowledgement, distributed beacon scheduling and channel diversity modes.

Table 1 shows the comparison of MAC protocols of IEEE 802.15.4 and IEEE 802.15.4e standards. Under IEEE 802.15.4, as far as power consumption of radio is concerned, TDMA scheme provides better results than CSMA/CA at medium traffic levels. But, synchronization needs to be adjusted for every round of packet transmission. However, larger the distance between the sending and receiving nodes, larger will be the power consumption by the body sensor node.

| Performance parameters | IEEE 802.15.4 | IEEE 802.15.4e |
|------------------------|----------------|----------------|
|                       | CSMA/CA        | TDMA           | TSCH           | DSME           |
| Contentsions           | CAP or CFP     | CFP            | Fixed TDMA     | CAP and Multiple CFP |
| Power Consumption      | High           | Low            | Low            | Depends on the number of nodes |
| Scalability            | Medium         | Poor           | High           | High          |
| Traffic level          | Low            | Medium         | Medium         | High          |
| Synchronisation        | Not essential  | Essential      | Essential      | Beacon enabled |
| Latency                | Low            | Medium         | Bounded        | Deterministic  |

Under IEEE 802.15.4e, as DSME provides multiple CFP slots, CAP reduction scheme, group acknowledgement and deterministic facility; it is preferred in WBSN applications over TSCH.

3. WBAN Specific Protocols
IEEE 802.15.4 using low rate WPAN standard protocol provides low energy consumption but low data rate. It used Slotted CSMA/CA- contention free MAC protocol. Node power consumption per packet increases at medium data packet arrival rate. But it introduces hidden node problem. Multi-hop topology or use of relays could be more suitable in such cases. Instead of transmitting the data packets from source to destination through direct transmission, it can be forwarded through neighbouring nodes so as to reach the destination node. This is referred to as Minimum Transmission Energy (MTE) routing scheme. However, the results have shown that the energy consumed by the MTE scheme is more than the direct communication method [10]. Instead, the formation of a small local network with the BAN head as
access point will be considered [11]. It is essential to note that, the management (control) packets that are helping to transmit the data packets are to be exchanged initially. This is an essential phase of the network operation as the body sensor nodes must aware of the resources, transmission and reception schedules, information on availability of channel and other relevant information. However, the control packet causes protocol overheads which enhance the duty cycle of the body sensor nodes. MAC operation must be adaptive to control packet management, access and link establishments to meet the requirements of duty cycle in body sensor devices operating in a particular band of frequency. For MICS band, a 36 seconds access to the channel in an hour is set [12].

It is required to provide an algorithmic approach to MAC layer that utilises the network topology based on the condition of the body parameters. It is essential to improve overall energy efficiency factor of WBSN system during the normal conditions as it is the most common case. The initial transmission of control packets must contribute to an improvised energy efficiency factor in this case. A design of MAC protocol for WBSN resulting in favour of energy efficiency for normal condition of the patient is desired. Initially, the algorithm is able to categorise the data into delay sensitive and delay insensitive packets. Delay insensitive packets are to be sent with lesser number of handshake signals from the buffer based on the priority of the packets. This transmits the normal and prioritised packets with lesser amount of energy spent by the transceiver. Finally, the algorithm is analysed with DSME scheme under IEEE 802.15.4e standard. The methods of energy calculation, algorithmic approach and performances of MAC schemes are discussed in the next sections.

4. Energy Efficient Algorithmic Approach for MAC Layer

Low-Energy Adaptive Clustering Hierarchy (LEACH) algorithm is a protocol under hierarchical routing category. It makes use of several energy reduction concepts that are necessary for energy conservation of WBAN system. A LEACH protocol utilizes TDMA schedule based MAC algorithm for communication between the nodes inside the cluster tree [13]. Also it considers minimised overhead, and hence, contributes for low power consumption. It involves communication with cluster heads and thus avoiding over emitting problem [14].

4.1. Cluster Topology

The solutions such as routing scheme, clustering, novel Cluster Head (CH) selection and data aggregation bring down the energy consumption of the sensor nodes. Figure 3 illustrates the WBSN, comprising CH and Cluster Member (CM). The CH collects the data from all CM and transmits to the sink. The clustering approach provides a solution for monitoring the large Region of Interest (RoI). The monitoring of small areas can be achieved by Layered architecture.

![WBSN architecture](image)

CM – Cluster Member  
CH - Cluster Head

Fig 3. WBSN architecture

The monitoring application classifies data packets into Delay Sensitive (DS) and Delay Insensitive (DIS). The so called DS applications are not always delay sensitive in nature. In this case, the number
of bits of handshake signal can be reduced when the network is monitoring DIS packets. This can limit the energy consumed by the network. Figure 4 illustrates the classification of packets in the event monitoring system.

4.2. ALGORITHM

Input
State \{DS, DIS\}

Begin
While:
If state = = DIS
    Store data till the buffer limit;
    If (buffer limit = = full)
    {
        Reduce the no. of bits of handshake signal;
        Start transmission;
        If buffer contains priority packet
            Prioritize;
        else
            fifo;
        else state = = DS;
        Follow routing;
    }

The above algorithm is simulated using IEEE 802.15.4 standard and later with IEEE 802.15.4e standard. The observations are presented in the next section.

![Fig 4. Classification of packets in event monitoring](image)

The transition between DS and DIS monitoring is achieved through Markov model. Markov is a memoryless model in which the transition totally depends on the present state and not on the previous state [15].

5. Results
The proposed method is simulated in MATLAB with 9 nodes. The proposed algorithm is validated with LEACH protocol for DS packet transmission. For Delay insensitive packets, IEEE 802.15.4 and 15.4e standards are used. The handshake bits are varied with fixed buffer capacity and the difference of energy consumed is monitored. Table 2 illustrates the simulation prelims considered in evaluating the approach.
Table 2: Simulation prelims

| Parameter          | Value                        |
|--------------------|------------------------------|
| Network size       | $500 \times 500$ m           |
| Number of nodes    | 9                            |
| Initial energy of sink | 2 J                      |
| Propagation model  | Two ray ground               |
| Packet size        | 4000 bits                    |
| Transmission energy| $8.281 \times 10^{-5}$ J/bit |
| Receiving energy   | $3.5\times10^{-5}$ J/bit     |
| Packet generation rate | 0.02–0.2 kbps              |

**Figure 5.** Network lifetime

Figure 5 illustrates the lifetime comparison with respect to handshake signal size. The proposed model provides high lifetime with low handshake signals. The data arrival rate is assumed to be following Poisson’s distribution. As the number of bits of handshake signal is reduced, the proposed model provides good network lifetime.

**Figure 6.** Network throughput

Figure 6 illustrates the network throughput of the proposed algorithm. From the Figure 6, it is clear that the proposed MAC layer approach transmits large number of packets with smaller handshake bits. IEEE 802.15.4e based DSME MAC provides extensive features for the applications of WBSN requiring internetworked access point and hence, suitable for related applications in future. Hence, the algorithm is tested analytically using the probabilistic models of [16] and [17]. The throughput is analysed for increased number of sensor nodes as given in Table 3.
Table 3: Comparison of Throughput for IEEE 802.15.4 and 802.15.4e standards

| No. of sensor nodes | Normalised Throughput |
|---------------------|-----------------------|
|                     | IEEE 802.15.4 | IEEE 802.15.4e |
| 6                   | 0.303         | 0.44          |
| 8                   | 0.342         | 0.52          |
| 10                  | 0.358         | 0.553         |

Table 3 compares the throughput of the proposed algorithm using IEEE 802.15.4 and IEEE 802.15.4e standards with the number of sensor nodes. It is clear from the comparison that, in IEEE 802.15.4e based DSME MAC mode, a higher throughput is achieved than with IEEE 802.15.4 standard.

Table 4: Comparison of Energy consumption for IEEE 802.15.4 and 802.15.4e standards

| No. of sensor nodes | Energy consumption |
|---------------------|--------------------|
|                     | IEEE 802.15.4(J)   | IEEE 802.15.4e(J) |
| 6                   | 1.427 x 10^{-4}   | 9.44 x 10^{-5}   |
| 8                   | 1.450 x 10^{-4}   | 9.47 x 10^{-5}   |
| 10                  | 1.469 x 10^{-4}   | 9.52 x 10^{-4}   |

Table 4 compares the Energy consumption of the proposed algorithm using IEEE 802.15.4 and IEEE 802.15.4e standards with the number of sensor nodes. It is clear from the comparison that, the transceiver of sensor node consumes lower power with IEEE 802.15.4e based DSME MAC mode, than with IEEE 802.15.4 MAC standard. Hence, IEEE 802.15.4e standard provides enhanced energy efficiency factor than its earlier version. Hence, the algorithm provides an enhanced throughput for IEEE 802.15.4e standard than its earlier version.

6. Conclusion

Wireless Body Area Network is formed by establishing a duplex RF link between the Body sensor nodes and a BAN coordinator or access point. From the literature survey, it is studied that an amendment made on the existing IEEE 802.15.4 standard gives rise to IEEE 802.15.4e standard. Comparison of the two MAC modes namely TSCH and DSME shows DSME as the most preferable mode for WBSN. Features of DSME such as enhanced energy conservation strategies with improved reliability and latency attracts the MAC designers of WBSN. In the MAC layer’s algorithmic approach, the data packets are categorized into DS and DIS types. The DIS packets are transmitted with reduced number of bits based on the priority of data. By reducing the overhead bits or handshaking signal bits, the energy consumption of the radio has been reduced by 0.1 percent per cycle of data transfer. For DS type of packets, the cluster tree based algorithm with slotted TDMA scheme is incorporated. Hence, the proposed algorithm provides energy efficiency improvement based on the delay sensitive or delay insensitive category of packets. For WBSN, it is practically easier to implement the MAC modes available of IEEE 802.15.4e rather than with IEEE 802.15.4 standard. In future, a Ubiquitous healthcare system will be constructed with the sensor nodes desiring to get connected to internet based devices using IEEE 802.15.4e based MAC layer algorithm. Thus, the performance of DSME form of MAC algorithm in IEEE 802.15.4e proves to be the suitable technology in terms of throughput and life time enhancement of the WBSN system in place of IEEE 802.15.4 based MAC algorithm.

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