isMAC: An Adaptive and Energy-Efficient MAC Protocol Based on Multi-Channel Communication for Wireless Body Area Networks

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Abstract

Recently, the use of wireless body area networks (WBAN) has been increasing rapidly in medical healthcare applications. WBANs consist of smart nodes that can be used to sense and transmit vital data such as heart rate, temperature and ECG from a human body to a medical centre. WBANs depend on limited resources such as energy and bandwidth. In order to utilise these resources efficiently, a very well organized medium access control (MAC) protocol must be considered. In this paper, a new, adaptive and energy-efficient MAC protocol, entitled isMAC, is proposed for WBANs. The proposed MAC is based on multi-channel communication and aims to prolong the network lifetime by effectively employing (*i*) a collision prevention mechanism, (*ii*) a coordinator node (WCN) selection algorithm and (*iii*) a transmission power adjustment approach. The isMAC protocol has been developed and modelled, by using OPNET Modeler simulation software. It is based on a networking scenario that requires especially high data rates such as ECG, for performance evaluation purposes. Packet delay, network throughput and energy consumption have been chosen as performance metrics. The comparison between the simulation results of isMAC and classical IEEE 802.15.4 (ZigBee) protocol shows that isMAC significantly outperforms IEEE 802.15.4 in terms of packet delay, throughput and energy consumption.

Keywords: Wireless Body Area Networks, Energy Efficiency, Medium Access Control, Multi-channel Communication.

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1. Introduction

Today, manufacturing small-sized and battery-powered smart wireless sensor nodes is possible as a result of the improvement in electronic and sensor technologies. More than one sensor node can be deployed on a human body, and connected to a wireless network coordinator node in a WBAN. These devices allow continuous and reliable health monitoring and real-time feedback to the user or to medical professionals. Moreover, the measurements and computations can be logged over an extended period of time to observe the patient's health progress [1-3]. Sensor nodes generally measure one or more physical or biological signals from the environment in which they are deployed. Other than sensing features, wireless sensor nodes have the ability to collect data from environment, (i.e. the human body in this study) process it and transfer it to a specified destination

WBANs have great potential in terms of medical technology and its applications. Numerous researchers, both from industry and academia, have been studying several issues associated with WBAN applications for many years. WBANs offer a wide range of uses in medical applications. For instance, sensors can provide remote health monitoring of elders or chronic disease patients without affecting their daily routines. WBANs require an efficient use of limited energy sources; especially those implanted in the human body have a limited amount of energy, and in need of saving power to maximize their lifetime. In general, a WBAN is designed as a single-hop network using star topology with a WCN, communicating with a number of smart nodes placed in the near vicinity (usually less than 1 m). The WCN should have adequate transmission power because it is responsible for the collection and transmission of gathered data from the sensor nodes to the Central Node (CN) located remotely from the WBAN [4]. Although a personal WBAN zone is around an individual, and is typically considered to have a diameter of 3 meters, body-worn wireless sensors are capable of communicating with each other up to a distance of 10 meters [5].

However, in daily life, two people and even more can easily be present in a smaller area than 3 meters-diameter, causing signal interference among the WBAN member nodes if the nodes are communicating on the same frequency. Such interference results in collisions and packet loss. Therefore, nodes need to send the same data repeatedly, despite causing an increase in network traffic and reducing network throughput. In order to prevent collisions due to the signal interference and prolong the network's life, we propose a new MAC protocol (isMAC), using channel hopping and a WCN rotation mechanism.

The isMAC scheme is a "many to one communication" approach, using two-tier star topology. It supports the periodic data-gathering applications even if sensor nodes have different time intervals. To provide the energy balance among the sensor nodes, it selects a WCN based on three metrics: current energy level, how many times the sensor node works as a Coordinator Node (N_{WCN}), and sensor node priority (S_{NP}). The key features and benefits of the isMAC are as follows:

- Multichannel TDMA approach to reduce collisions
- No need to queue message packets for member nodes
- Collision preventing mechanism
- Limited contention period
- Low End-to-End packet (EED) delay
- High throughput values.

The rest of the paper consists of four main sections. In Section 2, the related works are presented. In Section 3, the isMAC is explained in detail. An example of the networking scenario utilizing the proposed isMAC is presented in Section 4. The comparative performance evaluation of isMAC is illustrated in Section 5. Finally, the conclusions are presented in Section 6.

2. Related Work

The four main MAC techniques used in sensor networks are Code Division Multiple Access (CDMA), Frequency Division Multiple Access (FDMA), Carrier Sensed Multiple Access (CSMA) and Time Division Multiple Access (TDMA). Of these schemes, CDMA requires high computational resources whereas FDMA needs complicated hardware. CSMA does not support dense network traffic, and TDMA has synchronization obligations [6].

Because of the high demand for CDMA and FDMA protocols, the TDMA or CSMA approaches are more suitable for WBAN applications. TDMA-based MAC protocols, especially in medical applications, usually have better performance than CSMA-based protocols with the exception of dynamic network topology [7]. Hence, we prefer the CSMA-based contention period in the setup phase, and TDMA infrastructure for the communication phase, in order to minimize collisions, overhearing and idle listening.

Many studies can be found in the literature with regard to MAC protocols for WBANs [8-14]. Issues related to energy efficiency are also discussed comprehensively in some surveys [15-18]. Several studies are theoretical in nature, and some others are related to practical medical data-gathering applications [19-23]. Although many works are interested in energy efficiency, only a few works consider inter-user signal interference, user mobility and multi-channel solutions.

De Silva et al. [24] investigated the inter-user interference effect for WBANs when they are placed in the same vicinity. Their work particularly deals with trying to understand the impact and significance of this effect showing that in the presence of five or more highly-rate BSNs in the same environment, the Packet Delivery Ratio (PDR) can fall to as low as 65%; moreover, inter-user interference causes the PDR to reduce dramatically - by almost 35% in cases of eight or more BSNs.

Marinkovic et al. [25] presented a TDMA-based energy efficient MAC protocol especially designed for inter-BAN communication. The protocol exploited the fixed network structure of WBAN to implement an effective TDMA strategy that resulted to be quite efficient for crucial medical applications, as it minimizes collisions. On the other hand, due to the static network topology, we presume it may not respond well to a dynamic network topology.

Timmons et al. [26] proposed an adaptive energy-efficient MAC protocol (MedMAC) based on contention-free TDMA channels, which supports implantable and body-worn devices. The simulation results show that MedMAC outperforms IEEE 802.15.4 for low and medium data rate applications; however it is not efficient for high data rate medical applications.

Using a flexible bandwidth allocation method, Fang et al. [27] developed a TDMA-based MAC protocol (BodyMAC) for WBANs in order to improve energy efficiency. In this protocol, CSMA/CA is utilized in the uplink frame of the Contention Access Period (CAP), which is not a reliable scheme due to its unpredictable Clear Channel Assessment (CCA) and collision problems, resulting in restriction of the total throughput.

Lee et al. [28] suggested a multi-channel management protocol and a distributed, beacon-enabled algorithm to achieve aggregate throughput and channel efficiency by reserving the channel using one-to-one mapping between the beacon slot and the data channel. It was based on single MAC for two different physical layers, requiring a control channel.

However, it was not proposing any proper solution for the WBANs coexisting in the same vicinity.

Ullah and Kwak [29] recommend a Ta-MAC protocol utilizing traffic information to enable low-power communication. Even though delay in Ta-MAC is minimized compared to other MAC protocols, and it is reliable for normal and emergency traffic, a special out of band radio for each node is required to use this protocol in real world applications. In our protocol, for emergency traffic, a CN needs just a separate transceiver to listen to the 16th channel.

The Reservation Based Dynamic TDMA (DTDMA) [30] protocol uses slotted ALOHA in CAP field of a super frame to reduce collisions and enhance power efficiency. Through the adaptive allocation of slots in a DTDMA frame, WBAN's coordinator adjusts the duty cycle adapted to the traffic load. Compared to IEEE 802.15.4 MAC protocol, DTDMA is more dependable in terms of a lower packet drop rate and low energy consumption. It does not support emergency or on-demand traffic. However, the 16th channel is reserved for emergency traffic in our protocol.

Heinzelman et al. [31] introduced a clustering-based protocol (LEACH) that effectively uses randomized rotation of local cluster base stations. A cluster in a network consists of one cluster head and a number of ordinary nodes, and each ordinary node directly communicates with the cluster head. Also, there is a single base station that only communicates with cluster heads. Direct communication involving high transmission power is used to ensure that the cluster heads can reach the base station. Due to hardware and energy constraints of simple sensor nodes, the computation of complex algorithms is extremely difficult. Nevertheless WCN rotation algorithm is adapted to the isMAC protocol in order to distribute the energy usage among the member nodes of the WBAN.

Most of the WBAN studies mentioned above use a single channel communication technique that is not suitable for mobile and dense WBANs [8-12, 24-25, 29]. Taking into account multi-channel protocols usually require channel management, complex frequency calculations and special hardware [28], our study conversely aims to respond to the communication problems associated with portable and dense WBANs which are composed of commercially available mobile sensor nodes using limited resources in the most efficient way. In addition, isMAC has three main features: multi-channel architecture, WCN rotating, and collision preventing mechanisms.

3. isMAC, The Proposed Adaptive and Energy-Efficient MAC Protocol Based on Multi-Channel Communication

This section consists of three fundamental issues, each of which is explained briefly in the following subsections.

3.1 isMAC Communication Infrastructure

The principal reasons for wastage of energy can be expressed in terms of six notions - collisions, packet retransmission, overhearing, protocol overhead, idle listening and traffic fluctuation. From this point of view, a well-designed MAC protocol should avoid such waste of resources while sustaining maximum throughput, minimum latency and communication reliability.

Considering all these factors, we propose an effective solution to maximize energy efficiency. Our presented protocol has two primary goals: (*i*) to prolong the network lifetime by rotating the WCN role among WBAN member nodes and by using different transmission powers for the WCN and WBAN member nodes, (*ii*) to prevent packet collisions during intra-WBAN and inter-WBAN communication.

In a WBAN, collisions are the main cause of unnecessary energy consumption, and should be minimized. They occur when some of the WBANs using the same channel come close to each other, causing signal interference during data collection and transmitting process. Our approach offers a channel-hopping method that aims preventing such types of collisions, and ensuring sustainable communication on a free channel. The development of a new multi-channel communication protocol may reduce packet collisions and hence increase channel efficiency.

TDMA approach has been adopted because of its suitability for star topology by means of minimizing overhearing, reducing packet retransmission and idle listening. The central node (CN) in a cluster assigns a time slot for each WCN. To ensure the quality of service (QoS), the CN can allocate non-sequential multiple time slots for a WBAN according to its nodes' requirements. The development of a new multi-channel communication protocol may reduce this kind of inefficiency. It should support data transmission among the nodes should be supported so that their radios are active only at the right time in order to avoid collisions.

In WBANs, as wireless nodes are placed on, in or around human bodies, the Specific Absorption Rate (SAR) values should be considered carefully. isMAC protocol minimizes localized SAR into the body, by adjusting all nodes' transmission powers according to their destination [17].

3.1.1 Intra-WBAN and Inter-WBAN Communication

In **Fig. 1**, four people are represented as four distinct WBANs. Dashed circles indicate the communication territory of the WBAN member nodes for each person; and, large coloured circles around the dashed ones represent the communication region of each WCN. The intersection of the large coloured circles of each individual shows the probability of signal interference between WCNs. Nevertheless, our model prevents collisions because it selects a dedicated time slot for each WCN that leads to a very low probability of packet collisions. If there is a collision between different WBAN member nodes, their inter-BAN communication channel is changed by the WCNs according to a predefined collision prevention method.

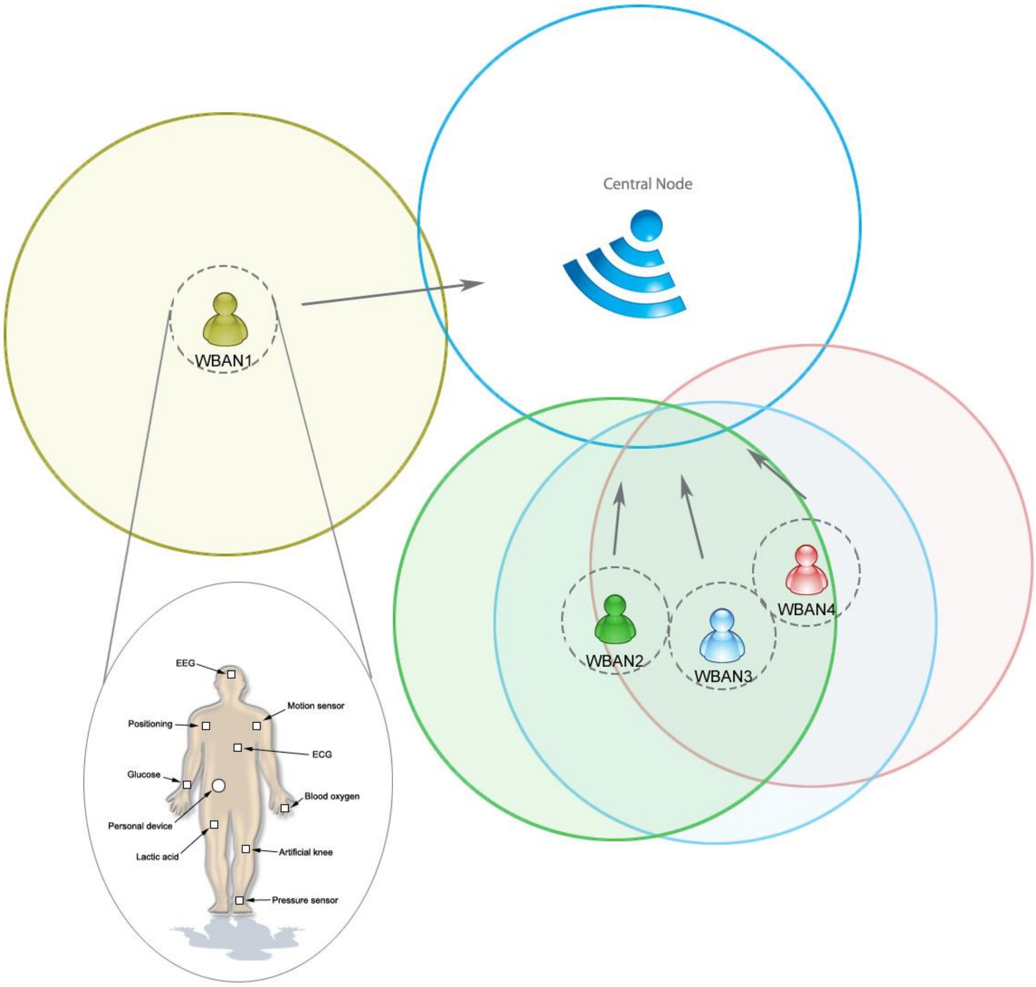

Fig. 1. Intra-WBAN and Inter-WBAN communication scheme

For intra-WBAN communications, WCNs gather data from sensor nodes right before transmitting them to the CN in order to send up-to-date data. For emergency situations, a CN just needs a separate transceiver to listen to channel 16; thus, taking immediate action is possible.

3.1.2. Frame Structure

Fig. 2 describes the communication infrastructure for the proposed MAC layer. At first, the CN broadcasts a beacon for all WCNs; then, the contention period begins. During this period, each WCN sends a participation request to the CN in order to become involved in the new communication frame.

The operation of the suggested MAC protocol is separated into two stages. Each stage starts with a setup phase, followed by a transmission phase. In the setup phase, a WCN is determined as follows:

Each node starts listening to the information channel (the 15th channel) after sensor nodes are awoken. Each node sends *"hello"* packets consisting of the sensor node's ID, WBAN ID and S_{NP}. If a node has the lowest priority level for its WBAN ID, it becomes the WCN and starts playing the "*WCN role*". Other nodes are informed about the WCN node by the coordinator node itself. Otherwise, it becomes a member node and continues listening to the WCN in order to attend the new contention period.

Then, the WCN begins listening to the CN during the contention period. Soon after the CN sends a beacon, all WCNs join the contention period and use their own time slots in order to send gathered data packets from member nodes to the CN. The CN collects all join requests then allocates a dedicated slot for each WBAN randomly. After this reservation process, all WCNs know their exact transmission order (time slot), their communication channels to the WBAN inter-communication channel, and send a beacon to their member nodes in order to collect data, just like the CN does, before time slot arrives.

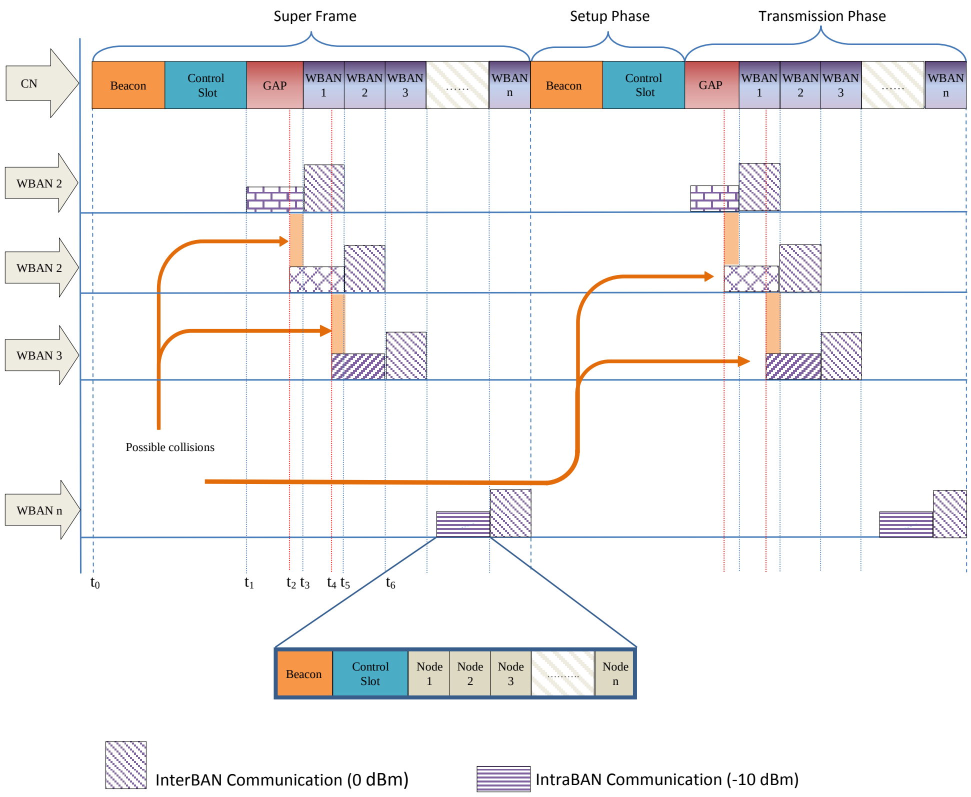

Fig. 2. The communication infrastructure for proposed MAC protocol

In **Fig. 2** t_n represents the start and stop times of packet transmission for BANs. In our scheme, for instance, the collision may occur between BAN_1 and BAN_2 only if the following conditions are fulfilled at the same time.

- Condition 1: Both BANs use the same channel for inter-BAN communication.
- Condition 2: t_1 must be less than t_3.
- Condition 3: t_2 must be more than t_3.

Otherwise, the probability of a collision between these two BANs equals zero because of the proposed multichannel TDMA approach.

3.1.3. The Operation Cycle of a Sensor Node in isMAC Protocol

Flowchart in Fig. 3 displays the operation cycle of a sensor node for the proposed protocol.

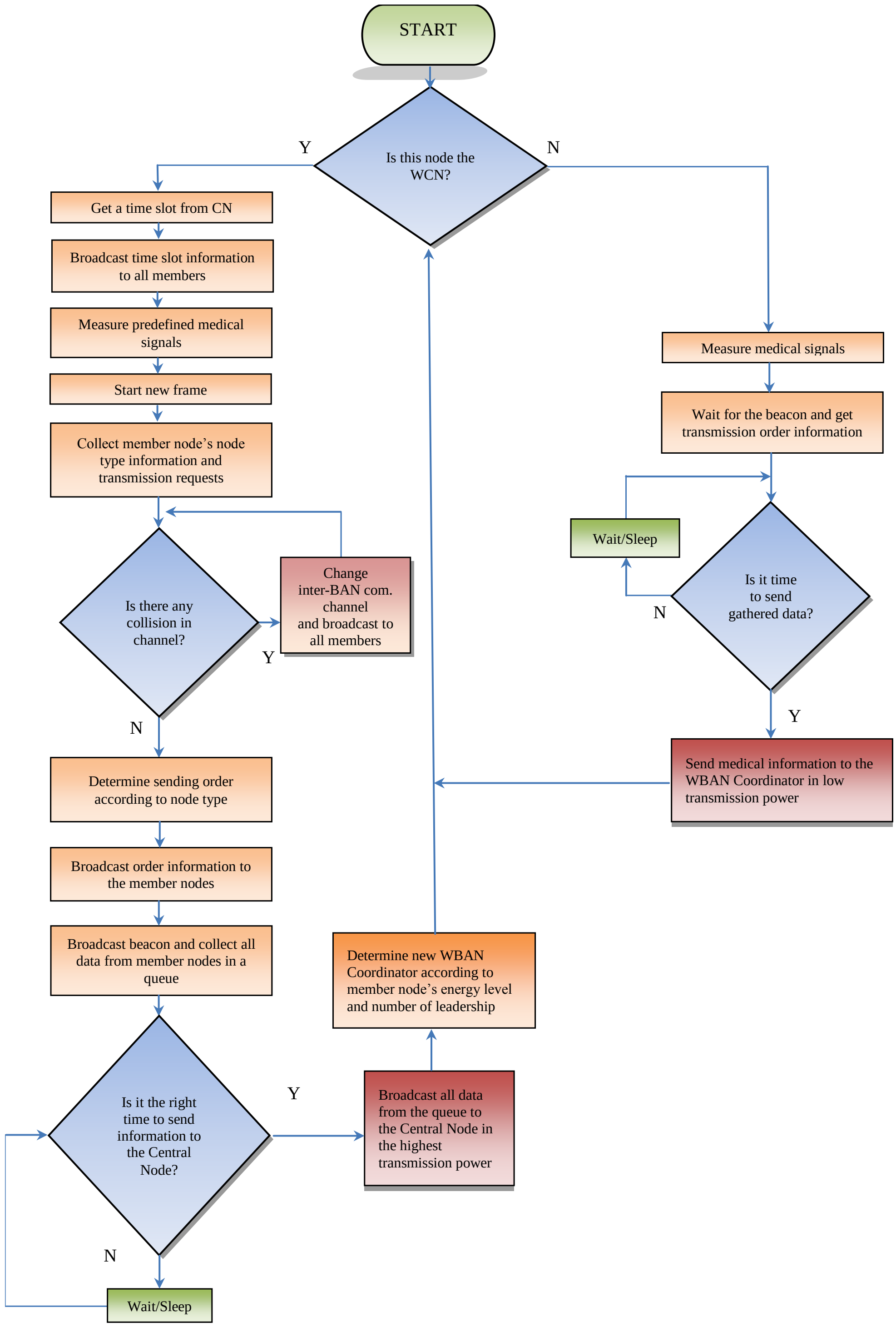

Fig. 3. The operation cycle of a sensor node in isMAC protocol

3.2 isMAC Channel Management

In isMAC model, the 16th channel is reserved for WCNs and the CN. The 15th channel is also reserved as an information channel through which only WCNs transmit information packets, which include Node ID, WBAN ID and WBAN's current communication channel.

Actually, using the 15th channel as an information channel is not compulsory. However, there should be a predetermined information channel that is never used for inter-BAN communication. For this reason, we prefer to use the 15th channel as the information channel in our model.

If a member node has data to send, and does not know its current WBAN communication channel, it begins listening to the 15th channel and keeps waiting for the information packet to be sent by its WCN. After receiving WCN information via this channel, it immediately joins the inter-BAN contention period.

Many multi-channel supported models have a central coordinator unit, which assigns idle channels for communication devices. However, free channel management is not necessary for isMAC protocol because, when a collision is detected by a WCN, it changes the inter-BAN communication channel to avoid repetition of the collision [28].

3.3 isMAC Collision Preventing Mechanism

One of the problems that directly affect the quality of communication is collision during packet transmission. The overlapped dashed circles in **Fig. 1**, show - that is, when the distance between the individuals involved is less than 3 meters - the possibility of collision and data loss. The moments of potential collision are also indicated in **Fig. 2**.

There are two ways to reduce collisions when using multi-channel supported TDMA-based protocols. The first way is to change the time slots, while the second way is to assign a different communication channel. In the first method, if there is a collision, the time slot of the WBANs whose packets are in collision can be changed by the CN. In our approach, the CN assigns time slots according to the complete sharing policy for each WBAN minimizing repetition of collisions. In the second method, if there is a collision, the WCN assigns a different communication channel for the related WBAN.

However, if the number of communication channels is less than the number of WBANs that are in close proximity to one another, a channel switching mechanism is required. The proposed channel switching mechanism is so simple and effective that it can be easily realized using (1).

In isMAC protocol, if the WCN detects a collision during data gathering process or gets a packet which contains different WBAN ID, it distinguishes that there is another WBAN in the communication area. Thus, a new set of inter-WBAN channels is calculated according to (1). After sending the collected data to the CN, WCN informs its member nodes about the newly determined channel. Then, all the WBAN members switch to the new channel.

The parameters and the equation used to compute the new communication channel are as follows:

NoC: Number of communication channels
Ch_{new}: New Communication Channel
WCN_{id}: WBAN Leader Node ID
W_{id}: WBAN ID

$$Ch_{new} = (WCN_{id} + W_{id}) \; Mod \; (NoC\text{-}1) \qquad (1)$$

Traditional multi-channel MAC protocols need to employ a channel manager device, and a channel allocation mechanism which is generally managed by a central coordinator node. To prevent collisions among different WBANs, a dedicated control channel should be used. Otherwise, all neighbour nodes should know their neighbours' communication channels to avoid using the same channels. Hence, they should continuously send each other information packets, containing their communication channel information.

All methods mentioned above cause the network load to increase unnecessarily. Contrarily, isMAC protocol does not need a channel coordinator or a dedicated control channel.

3.4 The isMAC WCN Rotation Mechanism

Basically, WCN rotation mechanism is used to share the energy consumption evenly among all member nodes, and to extend the lifetime of the whole network. In a WBAN, WCN has some special properties: (*i*) it needs more transmission power to reach the CN, (*ii*) its radio is on much longer than any other member node. Therefore, if all nodes have the same battery power, WCN's battery is consumed much faster than the other members'. When the battery is flat, WCN cannot send or receive data packets. This situation causes all WBAN members to lose the communication capability over the network. We designed a WCN selection and rotation mechanism in order to minimize this type of battery problem, and to utilize the battery recovery effect [32].

In our protocol, depending on the S_{NP} parameter, WBANs normally know beforehand which node will be the next WCN. However, according to the network conditions such as unexpected battery depletion or malfunction, it may be necessary to select a new WCN by taking into account the three major parameters. These parameters are used to select the most appropriate WCN and can be listed according to their priority of usage in terms of residual energy level (E_{RES}), number of WCN (N_{WCN}), and S_{NP} levels. The residual energy level (E_{RES}) is utilized in such a way that the node that has the highest E_{RES} value is chosen as the WCN.

The second parameter is the N_{WCN}, which represents the number of times a node has previously worked as a WCN. If two or more nodes have the same maximum residual energy levels, the node whose N_{WCN} is smallest will be chosen as the new WCN.

The last parameter S_{NP} is utilized when the E_{RES} and N_{WCN} values of two or more nodes are equal. The sensor node with the smallest S_{NP} is chosen as the new WCN. S_{NP} parameter is determined according to the importance and the type of the data to be sensed. For example, ECG data is more crucial than body temperature data; thus, the sensor node that measures heart signals has a higher S_{NP} value than the sensor node measuring body temperature.

A WCN should be changed after a predefined N_{WCN} threshold value, according to the criteria mentioned above. In our case, the N_{WCN} threshold value is specified as 20.

According to our MAC scheme, as all WBANs use star topology, WCN or WBAN membership is the role that all WBAN sensor nodes need to be responsible for and, therefore WCN is changed periodically. The scheme aims to reduce idle listening as well as the probability of collisions in order to gain serious power savings.

3.5 The Simulation Model of isMAC

A simulation model has been developed to demonstrate isMAC protocol performance using OPNET Modeler software. **Fig. 4** demonstrates the hierarchical scheme for this simulation model.

In our WBAN model, five different WBAN nodes are employed in order to collect the data, each of them sending the gathered data to the CN in predetermined periods.

In OPNET, a networking scenario is composed of a number of sub-models. From top down, it can be described as (*i*) network model, (*ii*) node model, and (*iii*) process model. The network model specifies the topology to be used. The node model describes the specialities of the nodes in the network model using modules. Lastly, the process model is executed utilizing proto-C codes embedded in the modules. Seven modules and interconnecting transmission lines are shown in the node model of a WBAN. In this model, the "*source module*" is used for producing the data packets that come from the upper layer to the MAC layer, while the "*statistics module*" is employed for calculating the data packets sent by other nodes and for keeping statistics. "*Rx*" and "*Tx*" modules are deployed for both inter-BAN and intra-BAN communication while the "*MAC module*" is used for defining the wireless medium access protocol.

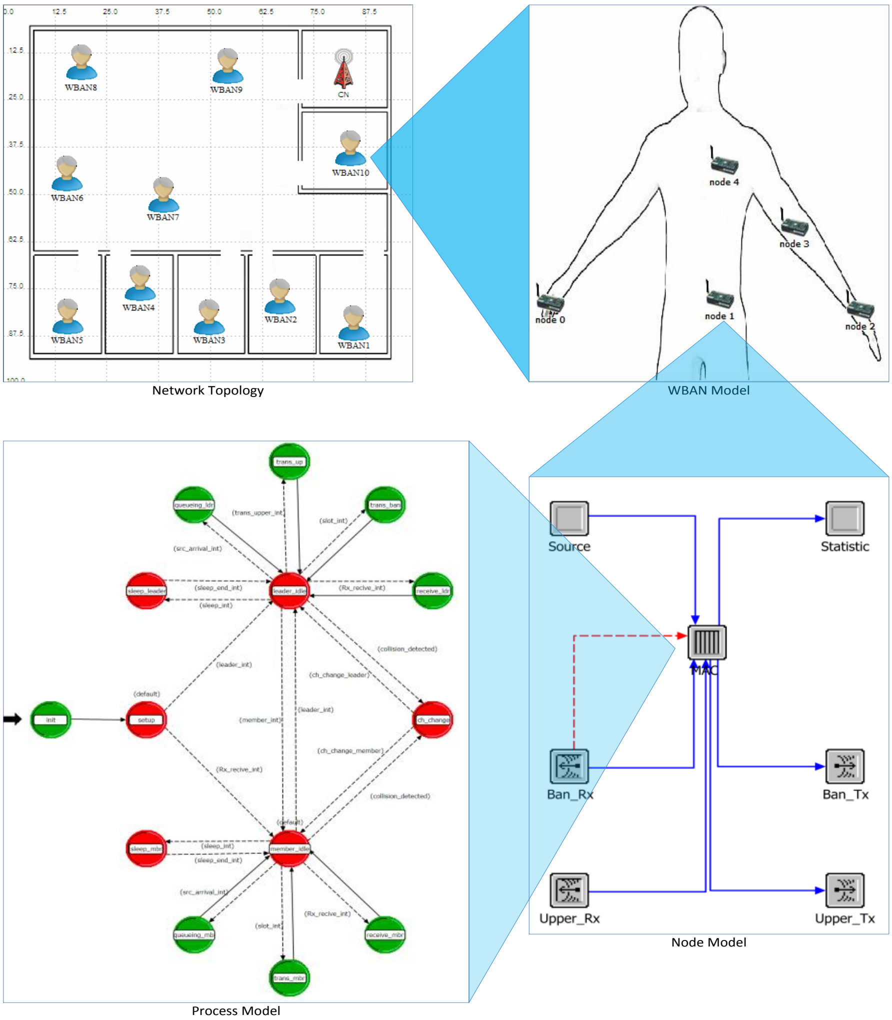

Fig. 4. Hierarchical scheme for the developed simulation model

The OPNET Modeler software does not have a specific statistical feature to indicate the energy consumption values. Therefore, the following parameters and equations (2-8) are used to calculate them.

P_L: Packet Length
T_d: Data Rate
P_{Rx}: Receive Power
P_{Tx}: Transmission Power
P_{idle}: Idle Power
P_{Sleep}: Sleep Power
NoS: Number of Total Slots (total time/slot size)
NoT: Number of Transmission Slots
NoR: Number of Receive Slots
T_I: Total Idle Time

$$E_{Rx} = \frac{P_L}{T_d} P_{Rx} \tag{2}$$

$$E_{Tx} = \frac{P_L}{T_d} P_{Tx} \tag{3}$$

$$\sum E_{idle} = T_I P_{idle} \tag{4}$$

$$\sum ER_x = E_{Rx} NoR \tag{5}$$

$$\sum ET_x = E_{Tx} NoT \tag{6}$$

$$\sum E_{sleep} = (NoS - (NoR + NoT)) P_{Sleep} \tag{7}$$

$$E_{total} = \sum ET_x + \sum ER_x + \sum E_{idle} + \sum E_{Sleep} \tag{8}$$

4. The Application of isMAC in an Example Networking Scenario

In a sample networking scenario, the parameters of the MICAz sensor nodes are utilized for comparison purposes assuming that identical nodes are used in each WBAN. Also, different sensor types are also used to measure different physical signals. Each node, placed on a person measures distinct physical data according to the sensor type, and each has a different priority value.

This example supposes that two or more nodes are placed in a WBAN, and these WBAN nodes can communicate with the WCN in a WBAN area by using the lowest possible transmission power. However, the highest transmission power should be used only to obtain the maximum communication distance between the WCN and the CN. Our WBAN nodes, which use 16 non-overlapping frequency channels in a half-duplex mode, are capable of changing transmission power between -10dBm and 0dBm. If a node is chosen as a WCN, it changes the transmission power to the maximum level (0dBm). On the other hand, if it is a member node, it sets the transmission power to the minimum possible level (-10dBm). This approach reduces unnecessary energy consumption during data transmission [33].

Fig. 5 demonstrates a map of randomly moving individuals, who are located within a certain area (100m x 100m), possessing WBANs. The dashed circles represent the effective communication zone for each WBAN member node. A computer wired to the CN gathers all data packets from WBANs and transmits them to a server on the internet. Thus, all medical information can be obtained by a third person (doctors/medical consultants/caregivers, etc.) via any internet-connected remote device.

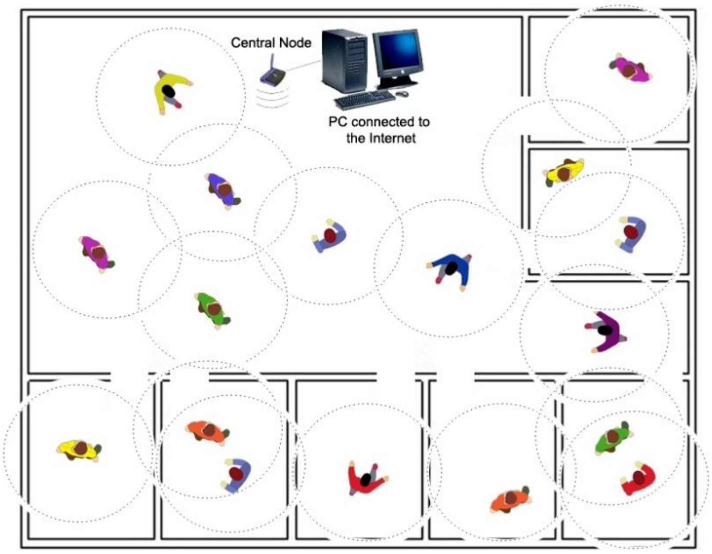

Fig. 5. Intra-WBAN interactions in proposed scheme

In our scenario, simulation is carried out using all parameters given in **Table 1** according to the following model assumptions:

Table 1. Simulation parameters

Number of WBAN	5-40
Number of Sensor Node in A WBAN	5
Simulation time	3600 sec
Slot Length (Intra WBAN)	5 msec
Slot Length (Inter WBAN)	15 msec-25 msec
Frequency Band	2400 MHz to 2483.5MHz
Data Rate	250 Kbps
P_{Tx}	33mW (-10dBm) 42mW (-5dBm) 52.2mW (0dBm)
P_{Rx}	59.1mW
P_{idle}	60 μW
P_{sleep}	3μW
Number of Channel	16
Channel model	Free space propagation model (LoS)

Model Assumptions

- In a WBAN, each node has a different type of sensor and priority value according to the sensed data. Critical data has higher priority than non-critical data.
- All nodes in a WBAN are identical and energy-constrained.
- Each sensor node has a unique node and WBAN ID
- Each WBAN has only one WCN at the one time.
- The CN is stationary and placed at a distance from the WBAN area.
- All WBANs are mobile and move randomly.

- Each node senses the environment at different time intervals and always has a data packet to send to the CN.
- All member nodes should use minimum transmission power (-10 dBm), and only WCNs can use the maximum transmission power (0 dBm).
- Packet structure
  - Source Node ID= 1 Byte,
  - Destination Node ID= 1 Byte,
  - WBAN ID= 1 Byte,
  - Node Priority= 1 Byte,
  - Data= 20 Byte,
  - CRC= 1 Byte.

Table 2 presents the medical applications used in the example scenario and their requirements, such as data rate, bandwidth and accuracy.

Table 2. Medical sensor types and data rates [15]

Application	Data Rate	Band Width	Accuracy
ECG (6 probes)	71 Kbps	100-500 Hz	12 bit
Oxygen Saturation (SPO2)	16 bps	0-1 Hz	8 bit
Glucose	1600 bps	0-50 Hz	16 bit
Temperature	120 bps	0-1 Hz	8 bit
Movement sensor	35 Kbps	0-500 Hz	12 bit

5. Performance Evaluation and Numerical Results

The average EED, which is based on the number of WBANs in the example scenario, can be seen in **Fig. 6**. In both protocol models, the number of WBANs has been increased from 5 to 40, and the EED values have been obtained. According to Federal Communication Commission (FCC) rules, a device should join the network within 1 second in an emergency situation [17]. This is the main reason for limiting the maximum number of WBANs to 40. The simulation results obtained by using five BANs show that the EED value is about 8 milliseconds for the ZigBee model [34] and it is under 4 milliseconds for the isMAC model. If the number of WBANs is increased up to 40, the EED value rises to 18 milliseconds for the ZigBee model, but remains the same for the isMAC model. For the proposed MAC model, EED value obtained covers the period of all data collecting operations, including transmission to the CN; whereas, it represents only the period of data gathering from the WBAN member nodes to the WCN in the ZigBee model due to model limitations. In this case, it can be evaluated as isMAC protocol has better EED values compared to a model using the ZigBee protocol. For an ideal MAC protocol, having low and stable EED values is highly desirable.

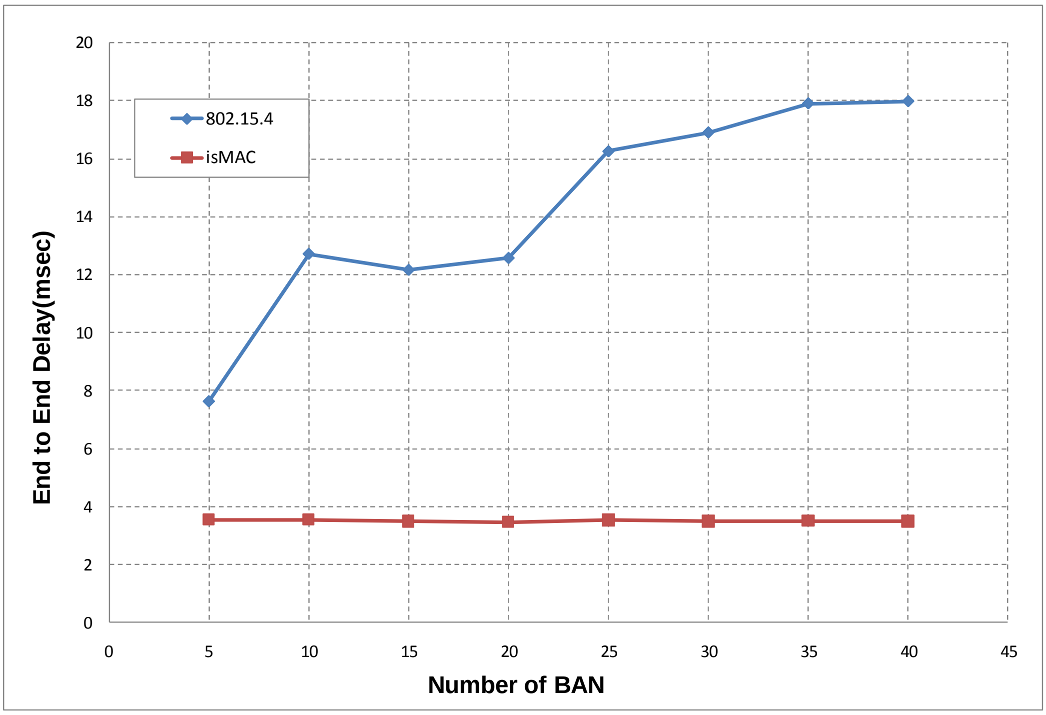

Fig. 6. The average end-to-end delay versus the number of BANs

Fig. 7 indicates the energy consumption of the WCNs for both MAC protocols, based on the number of WBANs. The energy consumption of each model is calculated using (8). The main reason for the decrease in energy consumption in the ZigBee model is the reduction in the number of packets transmitted. If five different WBANs exist in a network, the energy consumption of each WCN equals 6.75 joule, and when the number of WBANs is increased to 40, the energy consumption declines to 3.78 joule per WCN. In the isMAC model, the energy consumption each node is approximately equal, and is about 2 joule in each case. As seen in the graph it should be stressed that the energy consumption of a member node in a network using the isMAC protocol is much lower than that of the network utilizing the ZigBee protocol; since ZigBee does not have a time-based structure, and it always uses the same node as a WCN.

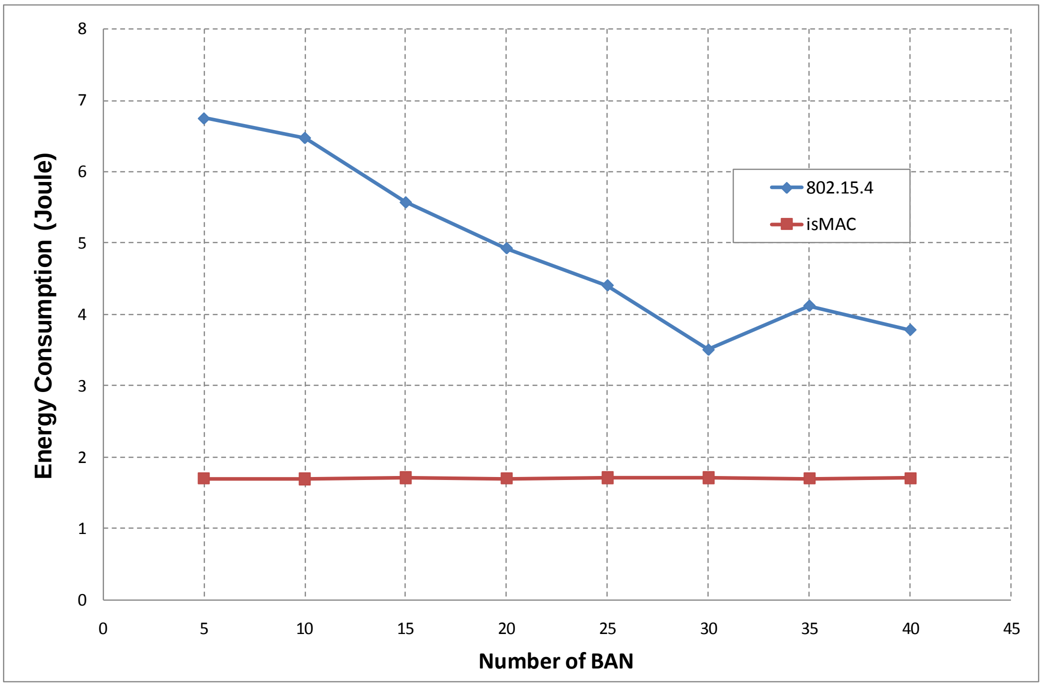

Fig. 7. The node energy consumption versus the number of WBANs

Fig. 8 presents the total throughput value of the network versus the number of WBANs. In isMAC, it is assumed that a packet is sent at the beginning of each time slot whereas in the model using the ZigBee protocol, the packet inter-arrival time is equal to the time slot length of isMAC. In that model, when five WBANs exist in a network, the total throughput value is about 0.5. If the number of WBANs is increased to 40, then the total throughput value drops to 0.3. Likewise, in isMAC, the throughput value almost equals 1, due to the re-installation operation of the WBAN structure. The ZigBee protocol contains a contention-based time interval. For this reason, it never exceeds the throughput value of 0.5 during the simulation. The results obtained prove that the isMAC has higher throughput values, and these are valid and stable for any numbers of WBANs. Therefore, isMAC can meet the WBAN requirements as all network resources are used efficiently.

In isMAC model, the TDMA approach and the free space propagation model are used together to keep packet loss to a minimum. The main reason why the remaining EEDs are constant is that all member nodes collect medical data just before sending packets to their WCN. Continuous change of WCN enables the energy consumption to be evenly balanced among all nodes, and extends the lifetime of the whole network. Although small fluctuations can be observed, almost all results are satisfactory. Obtaining high-throughput values and low collision rates is possible by using a well-designed multichannel TDMA approach, which has a very limited contention period and low probability of collision, since each node has its own time slot in which to transmit and receive data packets.

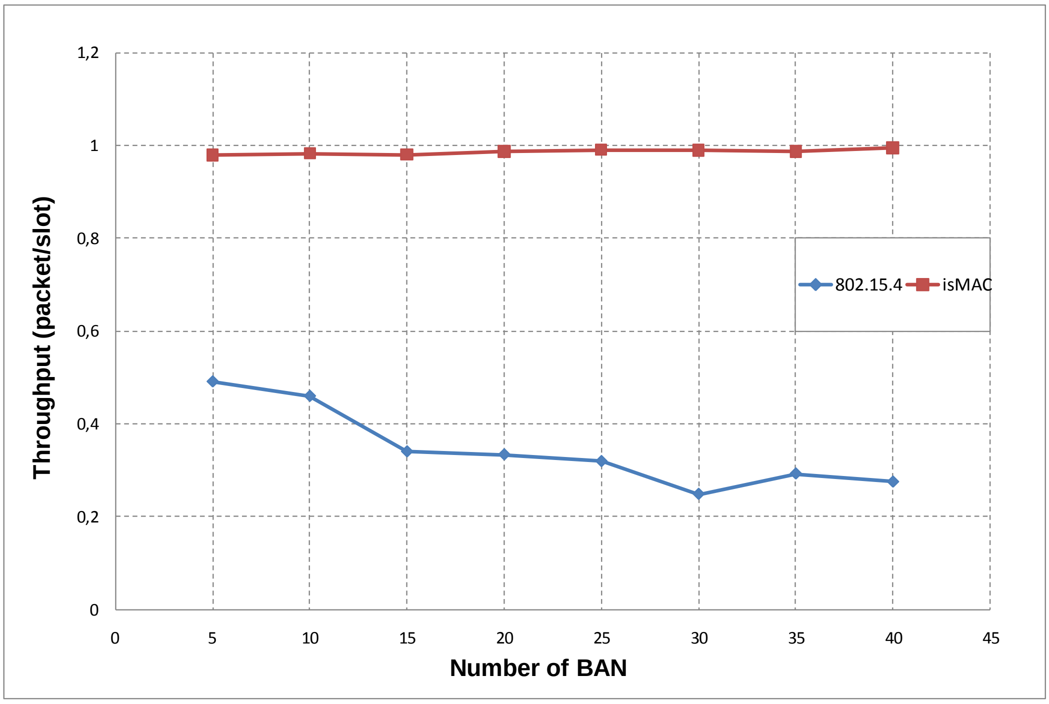

Fig. 8. The total throughput versus the number of BANs

6. Conclusion

WBANs are one of the recent growth areas with regards to sensor network applications in healthcare. Energy efficiency has great importance for battery-powered WBANs because of the limited energy source. For this reason, the efficient usage of energy directly affects the lifetime of the network. Hence, the MAC layer is the most effective place to ensure energy efficiency.

With this work, we have proposed a new, adaptive and energy-efficient MAC protocol based on multi-channel communication for WBAN. Our MAC protocol aims extending the network's lifetime by employing a collision prevention mechanism, a coordinator node (WCN) rotation mechanism and a transmission power adjustment method. We have developed, modelled, and simulated the proposed MAC protocol by using OPNET Modeler simulation software. Also, we utilized isMAC in an example scenario within the simulation presenting the results and comparing it with the classical IEEE 802.15.4 (ZigBee) protocol. In conclusion, the results obtained from the simulation demonstrate that isMAC outperforms IEEE 802.15.4 in terms of packet delay, throughput and energy consumption.

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