

# Analysis of MAC Protocols for Real-Time Monitoring of Heart and Respiratory Signals

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**Abstract**—Wireless sensor networks have several appealing medical applications. The deployment of wireless technologies in the medical field imposes several considerations on the choice of communication methods, protocols, wireless technologies, and type of devices. One of the most challenging problems is the choice of the best medium access control protocol in order to resolve problems such as the correlation of traffic, heavy collisions, and free channel recognition. Real-Time monitoring of heart and respiratory signals has gained increasing attention in the last few decades, as there is more interest in continuous monitoring of heart activity which can significantly improve early detection of heart problems. This paper suggests a Multi Attribute Decision Making (MADM) methodology [1], [2] in order to study, analyze and recommend the most optimum protocol for the purpose of heart monitoring. The aim of this approach is to rank existing alternatives, according to several attributes that are often inconsistent.

**Index Terms**—eHealth, MAC protocol, Fuzzy AHP, Fuzzy MADM.

## I. INTRODUCTION

In order to prevent data collisions in different nodes, the medium access control layer is used to share fairly and efficiently the bandwidth resources among communicating nodes. Therefore, the MAC layer plays an important role in achieving high network performance. Therefore, the development of energy-efficient MAC protocols for the wireless networks has been a hot topic for many years. Significant research efforts have been devoted to examining and proposing several new MAC protocols that were used in medical applications. For instance, the IEEE 802.15.4 was adopted for wireless medical networks [3], which can support low data rate applications, however, it does not support applications with high data rates requirement. Other similar protocols that were proposed and used for medical applications include DTMA [4], PB-TDMA [5], BodyMAC [6], extension of IEEE 802.15.4 [7] and H-MAC protocol [8].

Monitoring heart and respiratory signals is one of the appealing applications of wireless protocols in the medical field. In order to use the best protocol for synchronizing heart and respiration signals, it is necessary to use a method that can identify the best protocol. The Multi Attribute Decision Making (MADM) is one of the commonly used decision-making methods in order to find the best protocol according to the characteristics of each of the protocols. The MADM method has been used frequently in several applications, such

as finding the best routing method, however, the method was not used in the selection of protocols in wireless networks with medical applications.

The analytic hierarchy process (AHP) is a very useful methodology for multiple criteria decision-making in fuzzy applications for selecting an optimum solution from existing strategies or prioritization of solutions based on set of requirements. The process of AHP reflects natural behavior and human thinking. This approach examines complex issues based on their interactions, transforms them in a simple way, and finally provides an optimum solution. The AHP process can be used when decision-making is faced with multiple competing alternatives with specific decision criterion.

This article presents a method for the selection of the most suitable medium access protocol for simultaneous monitoring of the heart and respiration signals, including IEEE 802.15.4, DTMA, PB-TDMA, BodyMAC and H-MAC. The protocols are investigated using several criterion, including energy efficiency, network lifetime, collision, high traffic load, overhead costs and synchronizations.

Energy efficiency and network lifetime are considered among the most important characteristics in wireless sensors. In addition, the two factors are related. for instance, increasing the energy efficiency will result in increasing network life time. On the other hand, collisions may significantly affect the network lifetime and energy efficiency. High traffic load reduces energy efficiency and network lifetime. Therefore, it is obvious that there are several correlations between these performance parameters. As a result, the selection of an optimum protocol using these design parameters is not straightforward. In this paper, we propose a method for the selection of the best protocol is to maximize network life and energy efficiency in sensor networks that are used for real-time monitoring of heart and respiratory signals.

To identify the best medium access protocol for heart monitoring, the following protocols are analyzed: IEEE 802.15.4, BodyMAC, H-MAC, PB-TDMA, and DTDMA. Several performance characteristics are studied for these protocols, including energy efficiency, network life span, interference, high traffic load, overhead costs and synchronization. Therefore, considering these performance metrics, a proper analysis method can identify the most appropriate protocol that will help improving efficiency of health monitoring process by

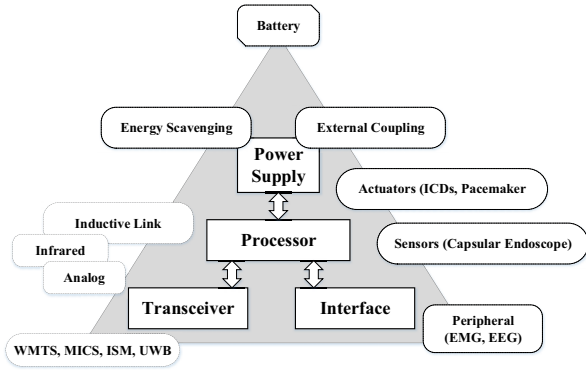


Fig. 1. Potential issues of a MAC protocol for WBAN.

utilizing information on heart rhythm and respiration.

There exist several studies on MAC protocols for health applications, therefore, this section is intended to summarize most relevant works in this direction. The work in [9] [10] proposed a protocols to synchronize nodes' clock very frequently in order to avoid performing time synchronization for sensor nodes. On the other hand, B-MAC [11] and X-MAC [12] are asynchronous protocols, where clock synchronization is not needed. B-MAC transmits a long preamble signal which lasts longer than RXs sleep period. While X-MAC improves B-MAC by having the TX transmitting the strobe preamble packets which can be cut off by RX's ACK signal for energy saving. Protocols that share similar design include [13] [14] [15] [16].

As an example, an energy-efficient hybrid system was proposed by Ghamari *et al.* [17] to minimize the required transmission energy consumption of such systems by utilizing energy harvesting techniques and low-power MAC protocols. In order to minimize power consumption, it is also important that the upper layer, i.e. the application layer, uses a better strategy of sampling and transmitting data that is more convenient for its application. Furthermore, authors in [18] believe that, in order to lower the power consumption, it is possible to reduce the sampling rate below the Nyquist rate while still achieving an acceptable quality reconstruction. Other related work can be found in [19] [20] [21] [22].

This rest of this paper is organized as follows: Section II presents MAC protocols. Section III discusses how heart and respiration signals are monitored. In Section IV the design of the MADM fuzzy model has been described. Section V concludes the paper with future directions.

## II. MEDIUM ACCESS PROTOCOLS WITH MEDICAL APPLICATIONS

When MAC protocols are used in existing medical applications, in particular wearables, they should be able to support a wide range of synchronous operations. For instance, devices such as Medical Implant Communication System (MICS), and band/frequency channels on the industrial, scientific, medical (ISM), and ultra-wide band (UWB) ones. Therefore, there

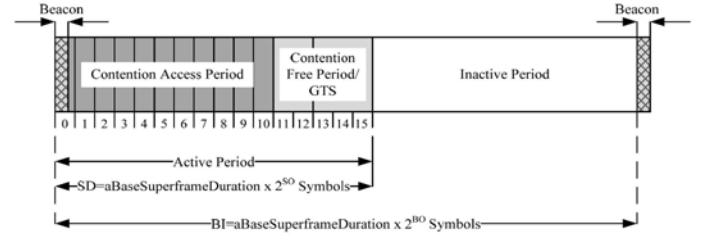


Fig. 2. IEEE 802.15.4 super frame structure.

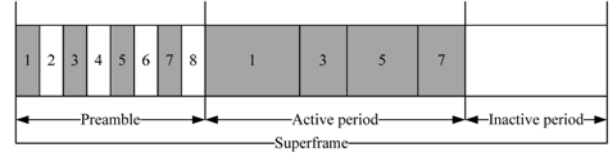


Fig. 3. PB-TDMA super frame structure.

should be a support for connections at multiple physical layers. In addition, the use of MAC protocols in medical monitoring applications have several critical factors including scalability and compatibility with network changes, latency, throughput, and bandwidth utilization. On the other hand, several medical devices are connected into mobile networks such as WPAN and WBSN, with dynamic topology. Such networks are affected by several factors, including human body position, node density, types of sensors, location of the person, etc. Therefore, such network paradigm should be managed continuously and successfully.

As a result, the choice of the best MAC protocol is critical, as its performance will be affected by the types of sensors used and the type of data traffic. It is known that the rate of necessary data sensed and collected from sensors nodes in a WBSN may vary from body to body. In addition, the rate might be different for different types of sensors implanted on the same body, for instance, heart rate adjuster may requires several kbps, while a capsular endoscope can reach several Mbps. Figure 1 illustrates some potential issues of a MAC protocol for wireless networks with medical applications.

In wireless networks with medical applications, traffic dependence is very evident, for example, a particular disease may trigger simultaneously temperature sensors, blood pressure and respiration. These changes may also affect the level of oxygen saturation in  $SpO_2$  blood. These types of physiological parameters increase the correlation of traffic. In order to resolve the correlation of traffic, the behavior of the CSMA/CA protocol for wireless medical networks has been investigated and has led to the use of the CSMA/CA protocol due to high energy consumption and high collision in these networks.

TDMA-based protocols provide appropriate solutions for problems such as traffic correlation, heavy collision, and free channel detection. However, the TDMA requires additional energy for timing synchronization. All sensors need to receive periodic packages in order to synchronize their clock. Therefore, it is required to design and implement a TDMA protocol

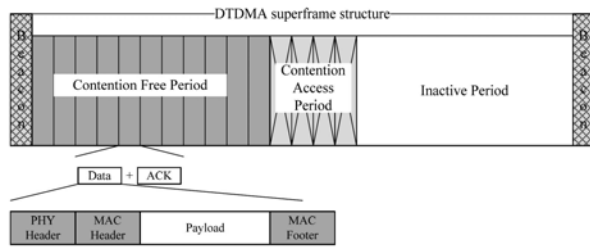


Fig. 4. DTDMA super frame structure.

that can accommodate heterogeneous traffic efficiently.

The development of the low-power MAC protocol for the wireless medical network has been a hot topic for the past few years. Significant research efforts have been devoted to examining and proposing new MAC protocols. Some researchers have included IEEE 802.15.4 for wireless medical networks that are used to support low data rate applications, but does not support enough applications with high data rates (data rates of more than 250 kilobits per second). Researchers are also studying, researching and improving protocols such as PB-TDMA, BodyMAC, DTDMA and H-MAC protocols.

The IEEE 802.15.4 protocol is a low power standard designed for use in cases where data rates are low. IEEE 802.15.4 has two operating modes: a beacon-enabled mode and another mode is non beacon-enabled. In beacon-enabled mode, the network is controlled by a coordinator that normally transfers beacons to synchronize the device and control the dependency of the vital signs parameters. As shown in Fig. 2, a channel with a very large frame structure is attached. The IEEE 802.15.4 protocol has been used thoroughly in the design and implementation of several wireless paradigms, in particular, for wireless medical networks,. This is due to its low power connectivity and support for low-data applications. Non beacon-enabled IEEE 802.15.4 protocol was proven to be efficient for medical sensors with low data rates and asymmetric human body traffic.

In this paper, data transfer is based on periodic interruptions, which does not fit well for wireless medical networks. Additionally, the data rate of nodes on the body varies a lot, as it can range from low rate of 10 Kbps up to 10 Mbps. This reduces the lifetime of sensor nodes significantly. While considering protocols such as CSMA/CA slot, can yield better performance in terms of delay than non-slot protocols, but it also has higher power consumption.

A Dynamic Reservation-Based TDMA (DTDMA) protocol is proposed for conventional wireless medical networks that provide time slots to nodes with buffered packets. However, this protocol does not support On-demand traffic. Although traffic-based slots are a good approach, the DTDMA protocol has some limitations when it is considered for the MICS band. The MICS band has ten sub-channels, each of which has a bandwidth of 300 kbps below. The DTDMA protocol has the ability to operate on a sub-channel, but does not have the ability to simultaneously operate on the ten sub-channels.

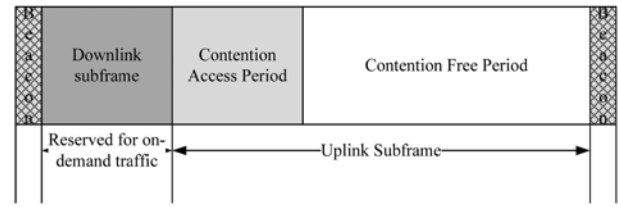


Fig. 5. BodyMAC super frame structure.

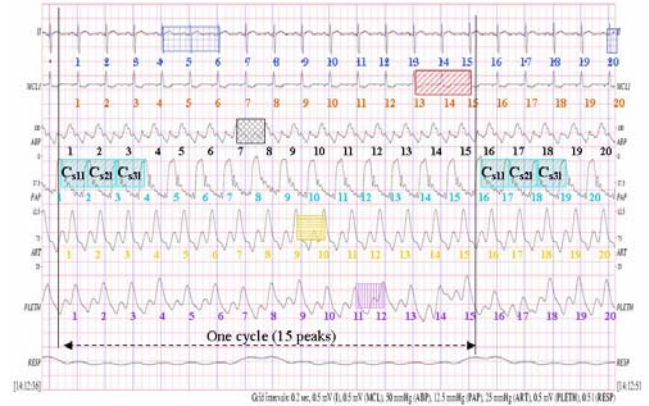


Fig. 6. An example of time slots in the H-MAC.

Figure3 shows the structure of the DTDMA frame. Another protocol used in the MAC layer for wireless medical networks is PB-TDMA. The PB-TDMA protocol is based on the TDMA mechanism. This protocol assigns designated slots for non-collision-free data transfer. These slots are replicated in five periods, a complete series of slots called a frame.

As shown in Fig. 4, in this protocol, each TDMA frame contains a pre-amplifier and a data transfer slot. The results of the simulations performed with NS-2 show that the protocol, like DTDMA, can only send ordinary traffic and its efficiency is lower than the S-MAC and IEEE 802.15.4 in terms of energy efficiency.

The BodyMAC protocol shown in Fig. 5 is also TDMA-based, which is not suited for essential traffic. The superiority of this method is to modify demand-side traffic using downlink frames. But because the protocol uses CSMA/CA to access the channel, it has low reliability for wireless medical networks.

One of the TDMA-based protocols for wireless heart rate rhythm is called the H-MAC protocol. As shown in Fig. 6, the H-MAC protocol, without distributing timed and beaconing information, achieves TDMA time synchronization and reduces energy costs.

In H-MAC, biometric sensors extraction of synchronized information from their biogeochemical sensors, these sensed signals are in the form of a distributed or palpable heart, or directly generated by heart palpitations. Therefore, the knowledge about the priority of sending data to the leads and creating synchronization at the time of sending, accessing, disseminating and receiving data plays an important role in raising the quality and accuracy of the signal. In other

words, this protocol uses an event-driven model for delivery of biological data, where the nodes can be off and their sensing portion remains off until an event is sensed.

The H-MAC protocol can improve energy efficiency in health sensor networks by utilizing information about heart rate rhythms. This protocol considers the scheduling of slots of time for single-file topology wireless networks. Peaks are used as synchronous beacons and the distance between the peaks as a slot for data transmission.

An external coordinator, such as smart phone, PDA or personal computer, has been used to calculate the length of the frame and allocated slots based on the number of biological sensors and their data rate requirements. Control packets are sent for synchronization when the first peak is detected. In addition, synchronous recovery mechanism is used due to the possibility of failure of the peak detection algorithm and the loss of heart rhythm information due to temporal unavailability of biological signals or noise.

One of the drawbacks of the protocol is the delay caused by the constant lack of biological signal strength. For instance, the length of the biological signal is not fixed when professional athletes are increasing physical movements. This is due to the dynamic signaling rate of the heart signal in the allocation slot and the increasing or decreasing number of signals sent within the time slot. On the other hand, the delay can be caused by the heart itself or collision due to the asynchronous sending of peaks in the allocated slots. Next, we intend to analyze existing protocols and select the most suitable one for heart and respiratory signals monitoring.

### III. HEART AND RESPIRATORY SIGNALS MONITORING

In the past decade, with the advent of semiconductor science and, consequently, the provision of affordable telecommunication devices, physicians and IT professionals have been able to monitor the state of physiology and health of professional athletes during training and competition through the use of emerging technologies. Considering that heart rhythm control is the most important pre-emptive factor in sudden illness and cardiac problems, in order to maximize the performance and quality of athlete exercises, the diagnosis and prevention of cardiac arrest and cardiac arrest when increasing physical movements require Continuous monitoring of average heart rate and regular heart rate control by controlling exercise. Generally, with increased physical movements, heart rate increases. Increasing and decreasing heart rate due to breaks and breathing disturbance leads to sinus arrhythmia, which means modulation of the distance between heartbeats. Increasing or reducing the distance between the heartbeats causes the need for heart and respiratory signal data to be sent continuously and in real time during a specific event.

In conventional methods, ECG is used to measure and monitor heart signals, consisting of a number of lead and ECG labels. These leads convert electrical signals from electrical charge changes into electrical current and transfer them to the recorder. These signals are printed on the device display or on the ECG chart after amplification after amplification. The

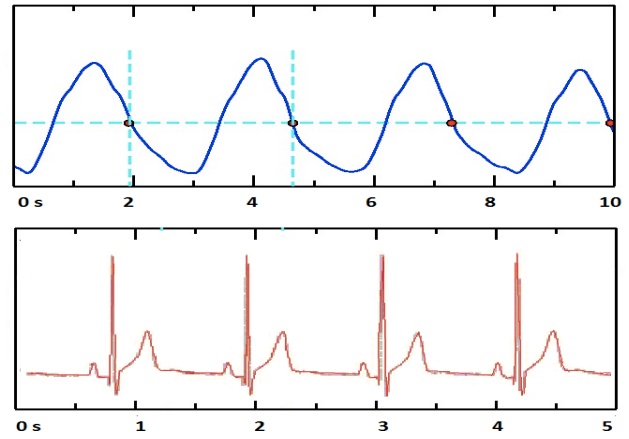


Fig. 7. An example of heart and respiration signals.

use of this device is not feasible for observing the athlete's heartbeat signals during professional training and competition due to the use of multiple leads and the wiring of these lenses from the ECG device to the body.

Therefore, the ability to measure athletic heart signals while running and exercise activities requires the implementation of a visible wireless electrocardiography device. Wireless electrocardiography means that all wires connected to the electrodes sticking to the body are eliminated. Regarding the removal of wires, each of the  $V_1$ , ..., and  $V_6$  tags should be sent as a stand-alone node to a wireless receiver (such as a smartphone, PDA, or personal computer) on a shared device.

The design of a wireless electrocardiography device will face challenges such as data synchronization, error control, data aggregation and routing.

Most network synchronization methods rely on data exchange between nodes. When one of the libraries generates a timestamp for synchronization to send a heart signal to the base station, the transmission of the timestamp packet until it reaches the recipient and decodes it may be subject to variable latency. This delays the base station from the precise comparison of the local clock of the two nodes and precisely synchronizes with the transmitter's line. Data synchronization in wireless electrocardiography involves challenges such as energy efficiency, accuracy, life span, wireless and dynamic medium, radio interference, asymmetric links, topology changes, congestion changes, overhead costs, and nodes starting at different times.

In addition to controlling the potential difference between the boards for receiving ECG signals, physical layer measures are taken into account to create electrical current and control the difference in the power of the ECG. Control of access to the common medium also results in equitable and efficient sharing of communication resources among the nodes in order to achieve an efficient network of In terms of energy consumption, transmission, delivery delays, collision avoidance and node synchronization.

Therefore, in order to synchronize, to avoid collision and to

correlate traffic in sending biomedical signals, it is necessary to have access control schedule access to timed-out medium such as TDMA, because the timing-based method, in contrast to the competition-based method, such as CSMA/CA, has advantages such as Collision-free, Low-overhearing, Low-duty-cycle operations, and definitive transfer. One of the factors that causes asphyxiation and collision in the transmission of heart signals is the difference in the distance between the leads sticking to the body and the base station. This causes the need for a scheduling-based access control protocol to synchronize heart rate signals from different libraries. To overcome this problem, an event-centered model with biological beaconing can be used to synchronize heart signals, which can be shown that the breathing signal can be modulated, but also the ability to synchronize with the heart signal, for example, a The respiratory cycle corresponds to about three heartbeats, as shown in Fig. 7.

A person has the ability to significantly prevent temporary respiration, and the irregularity of the rhythm of respiration is optional. This causes insomnia between the rhythm of breathing and heart rate. To overcome this problem, you can use the previous timings in which the breathing signal is extrapolated to estimate it and generate the beaconing signal virtual. Using this solution, you can use breathing as a beacon to correct the H-MAC protocol.

The ratio of the heart-to-breath signal at the beginning of the synchronization can be detected using  $HRR = \left| \frac{Heart}{Resp} \right|$ . However, several signals might not be detected when increasing physical movements by athletes. In order to extract the peak information from the biomarker database, the complex QRS identification algorithm in the ECG and the automatic beat detection algorithm used in the H-MAC protocol can be used. The results show that using these algorithms, sensitivity (SE) and positive predictivity (PP) can be up to 99%. In the ECG complex identification algorithm, the accelerometer sensor is used to monitor biological signals due to the speed of physical movement of the body. As the speed increases, the size of the discovery intervals decreases, which reduces the signal-to-noise ratio, and so it is necessary to select the leads with higher signal-to-noise ratio.

In order to increase the reliability and increase the compatibility of the detection algorithms for the heart signal, breathing signal peaks are used. Such algorithm is commonly used to synchronize heart signals in the HR-MAC protocol. Since a breathing cycle contains three heart signals, there are three large frames that are used to transmit three consecutive heart signals, usually framed between two beacons. In addition, the number of peaks can be counted from the speed of the athlete. The number of H-MAC protocol retrievals can be reduced by estimating the the information of the signals mathematically. This, however, increases the delay in sending signals and decreases the reliability of the signal.

TABLE I  
DEGREE OF IMPORTANCE OF THE ALTERNATIVES RELATIVE TO EACH OTHERS USING LIKERT SCALE

| The importance degree  | Membership functions |
|------------------------|----------------------|
| Absolutely unimportant | (0, 0, 1/6)          |
| Unimportant            | (0, 1/6, 1/3)        |
| Less important         | (1/6, 1/3, 1/2)      |
| Important              | (1/3, 1/2, 2/3)      |
| More important         | (1/2, 2/3, 5/6)      |
| Strongly important     | (2/3, 5/6, 1)        |
| Absolutely important   | (5/6, 1, 1)          |

#### IV. PERFORMANCE ANALYSIS OF MAC PROTOCOLS USING MADM

The multi-attribute decision-making model is one of the models that belong to a larger family of models called multi-criteria decision-making. Decisions in this family are based on several different and sometimes conflicting criteria.

In deciding several criteria, which is the approach used in this paper, the benchmark for decision is indicators. The purpose of this approach is to select an alternative from existing alternatives or to rank existing alternatives with respect to several indicators usually incompatible. In MADM models, there is human judgment in scoring alternatives or doing paired comparisons, and so judgments may be uncertain. This uncertainty is usually due to the existence of qualitative information, incomplete information, inaccurate information, or partial ignorance. Uncertainties Judgments can be divided into general categories, uncertainty in the amount of judgments, and uncertainty about the veracity of judgments performed. In MADM models, two probability theory and fuzzy theory approaches have been used to consider uncertainty in judgments. Among these two approaches, fuzzy theory has become widespread in its application due to its similarity to human perception and expression, as well as computational convenience. Fuzzy MADM is modeled as follows:

$$MADM = \begin{cases} \text{Select} & A_1, A_2, \dots, A_m \\ \text{s.t. :} & C_1, C_2, \dots, C_n \end{cases} \quad (1)$$

Where  $m$  specifies the number of alternatives and  $n$  specifies the number of indices. In general, in the various MADM issues, the following features are common. In this model, methods such as ELECTRE, TOPSIS, Linear Assignment and AHP are used. In the following, AHP fuzzy method is explained. Therefore, considering the leading issue of using the fuzzy AHP method, which is one of the methods of the fuzzy MADM model, is very suitable.

The fuzzy AHP was presented as an extension for AHP in solving fuzzy hierarchical problems. In other words, Fuzzy AHP was developed to avoid the functional hazards in solving ambiguous hierarchical issues. The fuzzy AHP selection method adopted in this work is based on paired comparisons, where a tree of the decision hierarchy is constructed. The comparisons represent the weight of each of the factors related to the rest of alternatives evaluated in the decision process. The

TABLE II  
DEGREE OF IMPORTANCE OF THE CRITERIA RELATIVE TO EACH OTHERS  
USING LIKERT SCALE

| The importance degree | Membership functions |
|-----------------------|----------------------|
| Lowest                | (0, 0, 1/6)          |
| Very low              | (0, 1/6, 1/3)        |
| Low                   | (1/6, 1/3, 1/2)      |
| Medium                | (1/3, 1/2, 2/3)      |
| High                  | (1/2, 2/3, 5/6)      |
| Very high             | (2/3, 5/6, 1)        |
| Highest               | (5/6, 1, 1)          |

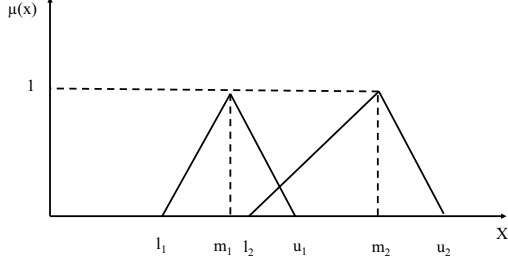


Fig. 8. Functions of membership of fuzzy triangular numbers  $M_1$  and  $M_2$ .

optimal selection is performed by the analysis of the matrices of paired comparisons.

Making calculations with fuzzy numbers is very time consuming and complex due to their specific structure. A special method of calculation is used to facilitate and apply fuzzy numbers. These special numbers are triangular, trapezoidal, triangular L-R and trapezoidal L-R numbers. A triangular fuzzy number (Fig. 8) can be represented by an ordered triplex  $(l, m, u)$  such that  $l$  is the lower, limit,  $u$  is the upper limit, and  $m$  is the mean.

The Likert Scale table [23] is used in order to determine the degree of importance of the alternatives and performance metrics relative to each others. Tables I and II shows these relations. For example, the significance of the energy efficiency index is important in relation to overhead costs, for this purpose the fuzzy number  $(3, 1/2, 2/3)$  has been used. Tables 2, 3, 4, 5, and 6 (matrix of paired comparisons) are also weighted using Table 2. On the other hand, for two triangular fuzzy numbers  $(u_1, m_1, l_1)$  and  $(u_2, m_2, l_2)$  whose member functions are shown in Fig. 8, the mathematical operators are defined as 2 to 4.

$$M_1 + M_2 = (u_2 + u_1, m_2 + m_1, l_2 + l_1) \quad (2)$$

$$M_1 \times M_2 = (u_2 \times u_1, m_2 \times m_1, l_2 \times l_1) \quad (3)$$

$$\frac{1}{M_1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right), \frac{1}{M_2} = \left(\frac{1}{u_2}, \frac{1}{m_2}, \frac{1}{l_2}\right) \quad (4)$$

In order to compare the magnitude of triangular fuzzy numbers, if  $M_1$  and  $M_2$  are two triangular fuzzy numbers, the degree of  $M_1$  to  $M_2$  is defined as follows.

$$V(M_1 \geq M_2) = \begin{cases} 1 & m_1 \geq m_2 \\ 0 & l_2 \geq 1 \\ \frac{u_1 - l_2}{(u_1 - l_2) + (m_2 - m_1)} & \text{otherwise} \end{cases} \quad (5)$$

In addition, the magnitude of the triangular fuzzy number of  $M_1$ , relative to the triangular fuzzy numbers of  $M_2, M_3, \dots, M_k$  is obtained using the following equation.

$$V(M_1 \geq M_2, \dots, M_k) = \min(V(M_1 \geq M_2), \dots, V(M_1 \geq M_k)) \quad (6)$$

After formulating a hierarchical structure for the decision problem, a decision matrix for paired comparisons between the criterion and paired comparisons is obtained. Then, for each of the rows of the paired comparison matrix,  $S_k$  value, which is a triangular fuzzy number, is calculated as follows.

$$S_k = \sum_{j=1}^n M_{kj} \times \left[ \sum_{i=1}^n x_i \sum_{n=1}^j M_{ij} \right]^{-1} \quad (7)$$

Where  $k$  represents the row number of the matrix, and  $i$  and  $j$  represent respectively the number of alternatives and criteria.

Next the paired comparison of all alternatives,  $S_k$ , are calculated. Then the degree of magnitude of each  $S_k$ , relative to the other values, is obtained using Equation (8). In the matrix of paired comparisons, we used six criterion,  $j$  ( $j = 1, 2, \dots, 6$ ), for the alternatives being evaluated:  $A_1 = \text{Body-MAC}$ ,  $A_2 = H - \text{MAC}$ ,  $A_3 = \text{IEEE 802.15.4}$ ,  $A_4 = \text{PB-TDMA}$ ,  $A_5 = \text{DTDMA}$ , which are denoted as  $S_1^j, S_2^j, \dots, S_5^j$ . As a result Consequently, we obtain the following values based on equation (6).

$$\begin{cases} V(S_1^j \geq S_2^j, \dots, S_5^j) = \min(V(S_1^j \geq S_2^j), \dots, V(S_1^j \geq S_5^j)) \\ V(S_2^j \geq S_1^j, \dots, S_5^j) = \min(V(S_2^j \geq S_1^j), \dots, V(S_2^j \geq S_5^j)) \\ V(S_3^j \geq S_1^j, \dots, S_5^j) = \min(V(S_3^j \geq S_1^j), \dots, V(S_3^j \geq S_5^j)) \\ V(S_4^j \geq S_1^j, \dots, S_5^j) = \min(V(S_4^j \geq S_1^j), \dots, V(S_4^j \geq S_5^j)) \\ V(S_5^j \geq S_1^j, \dots, S_4^j) = \min(V(S_5^j \geq S_1^j), \dots, V(S_5^j \geq S_4^j)) \end{cases} \quad (8)$$

Then, using the above values, we obtain the vector of relative importance, which indicates the relative value and relative importance of the five alternatives of the problem in terms of criterion  $j$ .

In the next step, we will normalize the obtained vector  $W_j$  by dividing each component by the sum of the components using six different criterion that have been introduced. Corresponding to the matrix of paired comparisons, the six vectors of relative importance associated with alternatives can be achieved, which are parented as column vectors in the matrix  $W$ .

$$W_A = [W_1^N, W_2^N, W_3^N, W_4^N, W_5^N, W_6^N] \quad (9)$$

Where  $W_j^N$  is normalized to  $W_j$ .

In the last step, we obtain the multiplication of the matrix  $W_A$  and the vector  $W_C^N$  (normalized to  $W_C$ ), then we rank the

options based on the values obtained from this multiplication. This method helps in identifying the best protocol according to the metrics used.

## V. CONCLUSION AND FUTURE WORKS

This paper used the fuzzy AHP method in order to conduct performance analysis for medium access protocols that are used for synchronization of heart and respiratory signals. Several performance metrics were analyzed for a number of commonly used protocols. As a result, the most appropriate protocol can be selected based on the metrics used. In the future, we intend to conduct more analysis on the protocols, and then use the modified one to find the best structure for cardiac and respiratory signaling. We also intend to propose a new protocol, called Heartbeat-Respiration Medium Access Control (HR-MAC), that can simplify synchronization, adapt the traffic dependency of physiological parameters, and make use of the information obtained for the diagnosis of cardiopulmonary function of professional athletes.

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