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A Power-Efficient MAC Protocol for WBAN

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요 약

Wireless Body Area Network (WBAN)을 위한 핵심과제 중 하나는 에너지 제약적 센서노드에 에너지 효율적이고 유연한 작업주기 기술을 적용하여 네트워크 수명을 극대화하는 것이다. 본 논문에서는 WBAN에 적합한 일반용, 응급용, 그리고 주문형(on-demand) 방식의 트래픽을 신뢰 있게 전달하는 방법의 효율적인 MAC 프로토콜을 제안한다. 본 프로토콜은 두 가지 방식의 웨이크 업(Wakeup) 메커니즘을 지원하며 첫 번째는 트래픽 기반의 웨이크 업 메커니즘으로 이는 노드의 트래픽 패턴을 이용하여 일반 트래픽을 수용한다. 또한, 두 번째 방식은 레디오 웨이크 업 통신 메커니즘이며 이는 웨이크 업 전송을 이용하여 응급 및 온 주문형 트래픽을 수용한다. 본 논문에서는 제안한 프로토콜이 WBAN 시스템의 수명기간을 향상 할 뿐만 아니라 불규칙적으로 발생하는 사건들을 처리 할 수 있는 신뢰적인 방법을 제공함을 알 수 있다. 시뮬레이션 통하여 제안된 프로토콜의 성능이 WiseMac을 전력 소모 및 지연 측면에서 우수한 성능향상을 보여준다.

Abstract

A key challenge for Wireless Body Area Network (WBAN) is to maximize the network lifetime with power-efficient and flexible duty cycling techniques on energy-constraint sensor nodes. In this paper, we propose a novel power-efficient MAC protocol for WBAN that accommodates normal, emergency, and on-demand traffic in a reliable manner. This protocol supports two wakeup mechanisms, a traffic-based wakeup mechanism, which accommodates normal traffic by exploiting the node's traffic patterns, and a wakeup radio mechanism, which accommodates emergency and on-demand traffic by using a wakeup radio. It can be seen that the proposed protocol not only improves the lifetime of WBAN but also provides a reliable method to handle sporadic events. Simulation results show that the proposed protocol outperforms WiseMAC in terms of low-power consumption and delay.

Key words: Power efficient, MAC, low-power, WBAN, BSN

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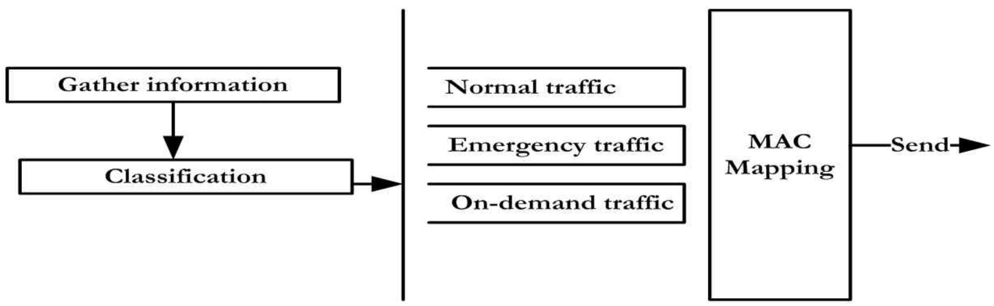
Ⅰ. Introduction

Wireless body area network (WBAN) is becoming increasingly important for sporting activities, unobtrusive healthcare systems, and members of emergency services as well as military services. It allows the integration of intelligent, miniaturized, low power, in-body and on-body sensor nodes to monitor the body function and the surrounding environment. Each intelligent node has enough capabilities to process and forward the physiological information to a base station for diagnosis and prescription. WBAN provides unobtrusive health monitoring for a long period of time with real-time updates to the physician. It can be used to develop a smart and an affordable health care system that includes diagnostic procedure, maintenance of chronic condition, and supervised recovery from a surgical procedure.

Current research work focuses on the development of biocompatible sensors and radio interfaces for in-body and on-body communication. One of the major concerns in WBAN is to extend the node's life time from months to years. The medium access control (MAC) protocol plays an important role in determining the energy consumption in wireless communications. Traditional MAC protocols mainly focus on improving bandwidth utilization, throughput, and latency; however, they lack energy conserving mechanisms. Generally, the main sources of energy wastage are collisions, idle listening, overhearing, and control packet overhead. Some contention-based protocols use low-power listening [1] and preamble sampling [2] in order to reduce the idle listening. Others, such as SMAC [3], TMAC [4], and DMAC[5], reduce idle listening by applying a synchronized schedule between nodes. However, these protocols incur significant synchronization overhead.

In WBAN, most of the traffic is correlated, i.e., a patient suffering from a fever triggers temperature, blood pressure, and respiration sensors at the same time [6]. These changes may also affect the oxygen saturation level (SpO2) in the blood. These types of physiological parameters increase the traffic correlation. A single physiological fluctuation triggers many sensors at the same time. In this case, considering a contention-based protocol, such as CSMA/CA, encounters heavy collisions and extra energy consumption. Also, in CSMA/CA, nodes are required to sense the channel before transmission. The clear channel assessment (CCA) is not guaranteed in the MICS band since the path loss inside the human body due to tissue heating is much higher than in free space [7]. On the other hand, TDMA-based protocols provide good solutions to the traffic correlation and CCA problems. These protocols are energy conserving protocols because the duty cycle is reduced and there are no contention, idle listening, and overhearing problems. However, common TDMA needs extra energy for



<Fig. 1> WBAN traffic classification

periodic time synchronization. All sensors (with and without data) are required to receive the periodic packets in order to synchronize their clocks. In this paper, we propose a power-efficient MAC protocol, which improves energy efficiency by exploiting the traffic patterns of the nodes. This protocol is mainly based on the TDMA architecture since the CSMA/CA and other contention-based protocols incur severe medium access problems such as heavy collisions and unreliable CCA. In addition, we categorize the traffic into Normal, Emergency, and On-demand traffic. Normal traffic is data traffic in a normal condition such as routine health monitoring of a patient. Emergency traffic is initiated by nodes and requires quick access to the channel (less than one second). On-demand traffic is initiated by the coordinator/physician to acquire certain information, mostly for the purpose of diagnosis and prescription. Figure 1 illustrates the MAC mapping of the WBAN traffic.

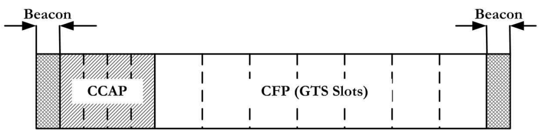
The following paper is divided into four sections. Section 2 presents related works. Section 3 presents our protocol description including wakeup mechanisms. In section 4, we present the simulation results. The final section concludes the paper.

Ⅱ. Related Work

The design and implementation of a low-power MAC protocol for WBAN has been a hot research topic for the last few years. A lot of research has been dedicated to the development of MAC strategies due to their strong influence on the energy consumption. A system architecture of WBAN is presented in [8], where the authors use an IEEE 802.15.4/Zigbee compliant radio. This architecture performs real time analysis of sensor's data, provides feedback to the user and forwards all the information to a telemedicine server. The body area system for ubiquitous multimedia applications (BASUMA) project uses a UWB front-end and an IEEE 802.15.3 based MAC protocol for low-power communication [9]. In [10], a real-time MAC protocol is presented, where the channel is divided into frames and each node transmits in one frame. Li et al. proposed a novel TDMA protocol that exploits the biosignal features to perform TDMA synchronization and improves energy efficiency [11]. Other protocols like WASP, CICADA, and BSN-MAC are proposed in [12 – 14]. Nicholas et al. investigated a non-beacon IEEE 802.15.4 for low upload/download rates [15]. The performance analysis of a non-beacon IEEE 802.15.4 and IEEE 802.11e is presented in [16], where the authors concluded that the non-beacon IEEE 802.15.4 is more energy efficient in controlled environments (without interference) but it results in poor QoS in some co-existence scenarios.

Ⅲ. Proposed Protocol Description

In our protocol, the channel is bounded by TDMA-based superframe structures as depict in figure 2. The superframe contains a beacon, a configurable contention access period (CCAP), and a contention free period (CFP). The beacon is used for synchronization and resource allocation. The CCAP period contains few minislots (3 or 4) of equal duration and is used for short data transmission. This period uses a slotted-ALOHA protocol instead of CSMA/CA. The CFP period contains a series of guaranteed time slots (GTS), which are used for data transmission.



<Fig. 2> Superframe structure of the proposed MAC protocol

The protocol has two wakeup mechanisms, a

<Table 1> Proposed MAC solutions for Normal, Emergency, and On-demand traffic

	Normal Traffic	Emergency Traffic	On-demand Traffic
Nodes	Send data based on the traffic-based wake-up table	Send a wake-up radio signal to the coordinator in case of an emergency event.	Receives a wakeup radio signal from the coordinator and respond
Coordinator	Send beacon/receive data based on the traffic-based wake-up table	Receives a wake-up radio signal and respond	Sends a wake-up radio signal to the nodes

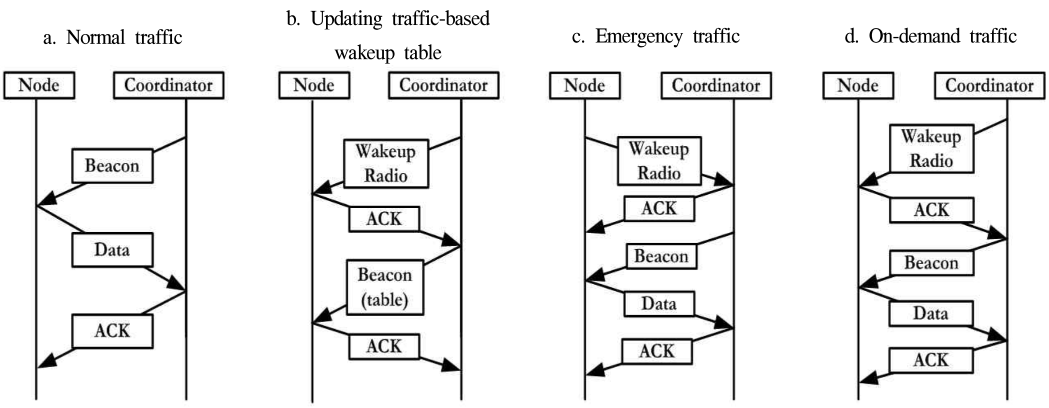
traffic-based wakeup mechanism, which is used for normal traffic only, and a wakeup radio mechanism, which is used for emergency and on-demand traffic only. In the traffic-based wakeup mechanism, the operation of each node is based on traffic patterns. The initial traffic pattern is defined by the manufacturer/ coordinator and can be modified later. These traffic patterns are repeated per BAN day, BAN hour, BAN minutes, BAN seconds, and BAN milliseconds. This categorization allows simple representation of the traffic levels. For example, a high traffic node sends data x times per BAN minute or BAN millisecond. The coordinator can change the traffic levels from low to high (vice-versa) by simply changing the traffic patterns. The traffic patterns of all nodes are organized into a table called traffic-based wakeup table as shown in Table 1.

The table is maintained and modified by the coordinator according to application requirements. Based on the node's traffic patterns, the coordinator can calculate its own traffic pattern (in case of low-traffic applications). This saves significant amount of energy at the coordinator. To access the channel, the node wakes up based on the traffic patterns and waits for a beacon from the coordinator. Since the coordinator knows the traffic patterns of each node (using the traffic-based wakeup table), it sends a beacon to the node. The node grabs the beacon that contains resource allocation information such as synchronization, priority levels, and channel/slot allocation information. The data transmission starts in the GTS slot and ends with an acknowledgement from the coordinator. Figure 3(a) shows the data transfer model for normal traffic. In addition, figure 3(b) shows the updating process of the traffic-based wakeup table.

In case of emergency and on-demand traffic, the protocol uses a wakeup radio mechanism. The operation is based on a wakeup radio where a coordinator/node sends a wakeup radio signal. To access the channel in case of an emergency event, the nodes send a wakeup radio signal to the coordinator as shown in figure 3(c). Unlike normal traffic, nodes are not required to wait for the beacon since this may exceed the delay requirement. The emergency nodes get the beacon (if required) and send the emergency data. To access the channel in case of an on-demand event, the coordinator/physician sends a wakeup radio signal (followed by a beacon frame) to the nodes as shown in figure 3(d).

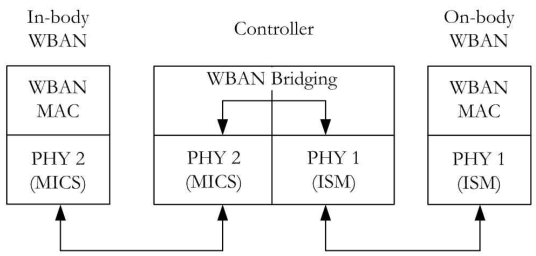
Since in-body and on-body nodes operate on different frequency bands and have correspondingly different physical layers (PHYs), the simultaneous operation on more than one frequency band becomes important. In order to accommodate multiple PHYs (radio interfaces)/multiple channels, we introduce a function called bridging that virtually connects different nodes working on different PHYs. Bridging function enables one MAC to support multiple PHYs. One MAC means a common hybrid MAC framework.

The bridging function is an enhanced MAC function that establishes logical relationships between different PHY nodes as illustrated in figure 4. However, the node running the bridging function must have two or more different PHY interfaces in order to work on two



<Fig. 3> Data transfer models for normal, emergency, and on-demand traffic

or more different channels at the same time. All necessary information, i.e., network info, channel ID (band/PHY), node's ID, connection ID and connection type (MAC layer), source and destination node's ID is recorded in a specific table. According to the records in the table, a channel mapping is implemented in the intermediate node that supports at least two bands/PHYs. The bridging function is also regarded as a link-layer MAC protocol data unit (MPDU) relay. The intermediate node receives and stores data from one channel, and then forwards it on another channel towards the destination. The process is transparent to upper layers and accommodates different PHY techniques.



<Fig. 4> Bridging protocol stack

Generally, in-body nodes cannot establish direct communication with on-body nodes due to power limitations, high path loss, and different PHYs. Therefore, they exploit the bridging function and forward all data frames to the on-body nodes via bridge. Moreover, the in-body nodes do not support peer-to-peer transmission in same network, and thus, data transmission between in-body nodes are relayed by the bridge.

Ⅳ. Simulation Results

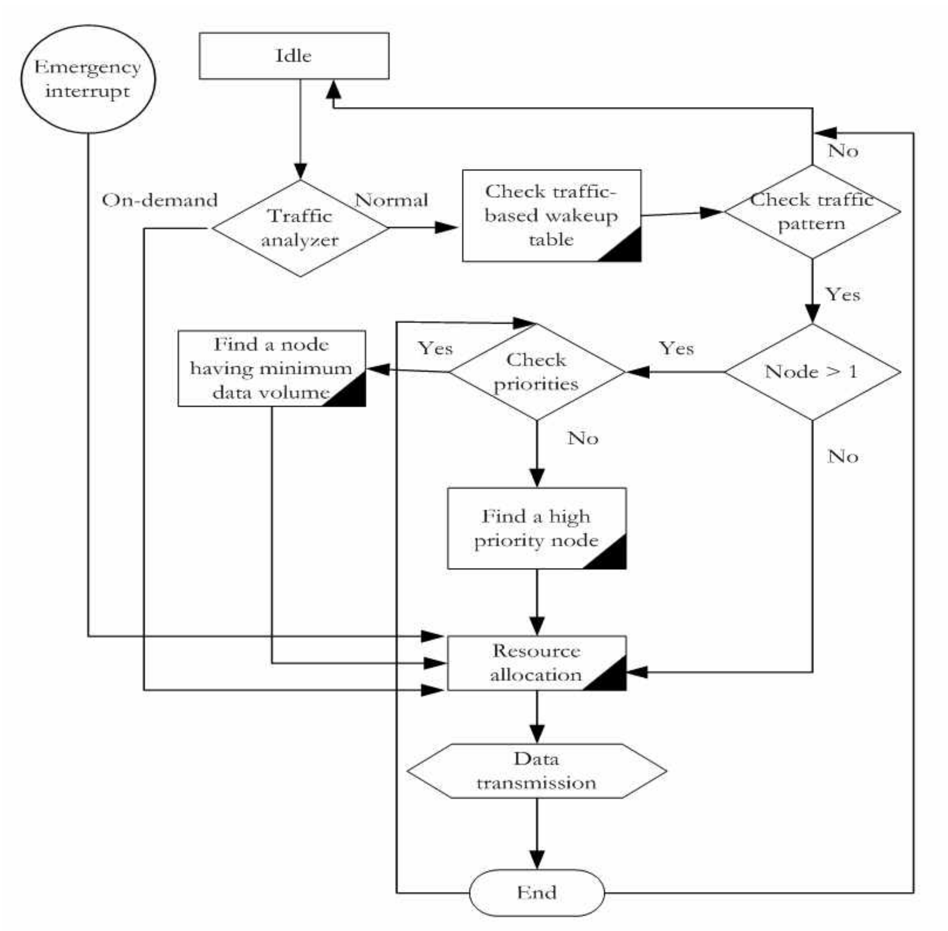
In this section, the performance of the proposed MAC protocol is analyzed and compared with WiseMAC protocol [17]. We use MATLAB for extensive simulations. The simulation flow diagram at the coordinator is given in figure 5. For normal traffic, the coordinator uses the traffic-based wakeup table to determine if a node intends to transmit. If more than one node has the same traffic pattern, resources are allocated to a high priority node. However, if more than one node has the same traffic pattern (same wakeup time) as well as priority, then resources are allocated to a node having minimum data volume. The remaining nodes wait until the high priority node(s) finish its/their transmission. In addition, the remaining nodes are subsequently served based on their priorities. For on-demand traffic, the coordinator directly sends

<Table 2> Input parameters

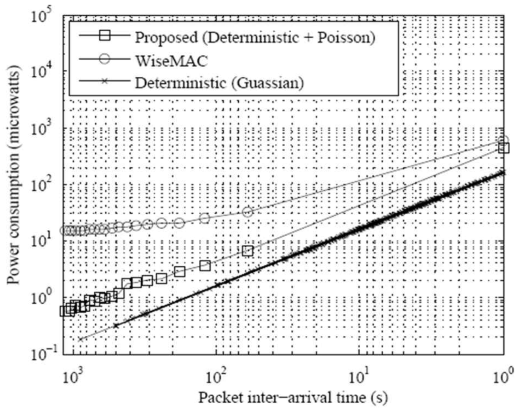
Parameters	Value
Packet size (Normal traffic)	152 bytes
Packet size (Emergency traffic)	50 bytes
Packet size (On-demand traffic)	120 bytes
Sleep power	5μW
Transmit power	27mW
Receive power	1.8mW
Setup time	0.8ms
Turn-around time	0.4ms
Beacon size	10 bytes
Ack size	10 bytes
Number of nodes	10

resource allocation information (a wakeup radio signal followed by a beacon) to a node as indicated in the flow diagram. Emergency traffic is generally considered as an interrupt to the normal operation of the coordinator. The entire process stops when an emergency interrupt/event (a wakeup radio signal) from a node is received. If required, resources can be allocated to an emergency node.

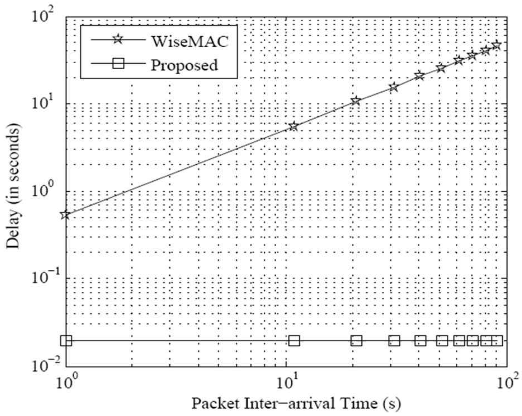
Generally, the traffic arrival rate of normal traffic is periodic (according to the traffic patterns) compared with emergency and on-demand traffic which is aperiodic. Therefore, we consider a Poisson generator to generate emergency and on-demand traffic, and a Deterministic/Gaussian generator to generate normal



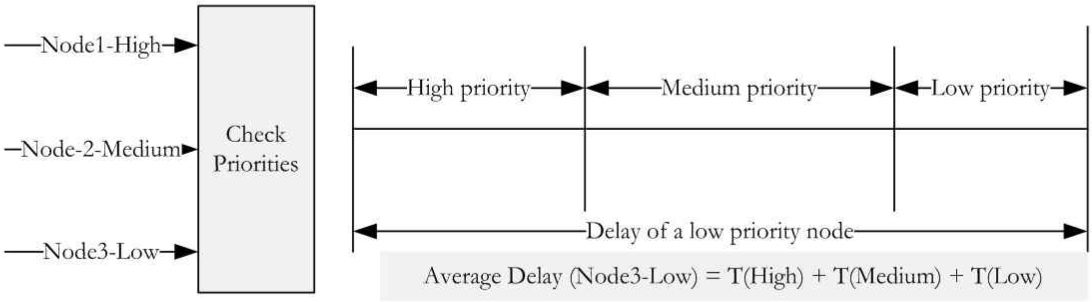
<Fig. 5> Flow diagram at the coordinator



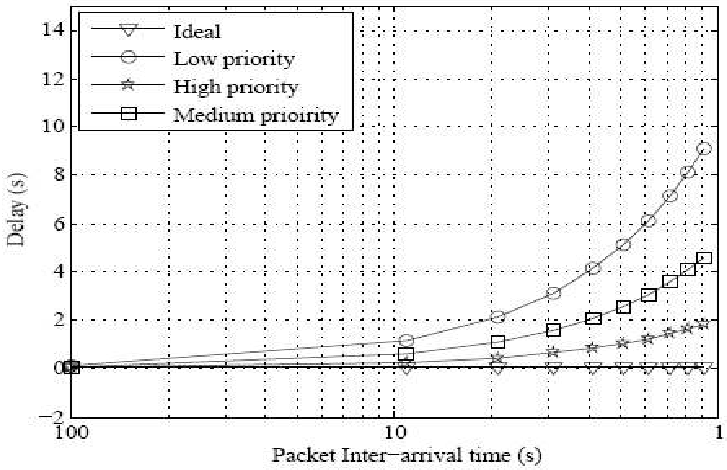
<Fig. 6> Average power consumption of the proposed protocol



<Fig. 7> Average delay of the proposed protocol



<Fig. 8> Priorities in the proposed protocol



<Fig. 9> Average delay for high, medium, and low priority nodes

traffic. The input parameters are given in table 2. We calculate the average power consumption and average delay as a function of the traffic. The average power consumption is calculated from the total power consumed in each state, i.e., sleep, transmit, and receive states, when transmitting one packet (152 bytes for normal traffic) every T seconds.

Figure 6 shows the average power consumption of the proposed protocol and compares it with the WiseMAC protocol. It can be seen that the average power consumption of the proposed protocol outperforms WiseMAC protocol since the nodes are required to wake up whenever they have data to send/receive. The extra power consumption used for preamble sampling in the WiseMAC protocol is avoided. Since we use two generators (Deterministic & Poisson), the arrival of Poisson traffic affects the average power consumption of the protocol as indicated by a slight curve change in the figure. For normal traffic only (with no emergency and on-demand events), the proposed protocol provides relatively low-power consumption as shown in the figure.

In the WiseMAC protocol, if a node has a packet to send/receive, it waits until the medium is sampled. This increases the delay of the WiseMAC protocol if the medium is busy or if the sampling period is high. However, in the proposed protocol, a node wakes up whenever it has a packet to send/receive. It does not have to wait for resource allocation information/beacon since the traffic patterns are pre-defined and known to the coordinator. This results in a reasonable delay as shown in figure 7 (For WiseMAC, the horizontal axis represents the inter-arrival time between the wakeup periods while for the proposed MAC it represents the inter-arrival time between wakeup periods as well as packets. Note that, according to the proposed protocol, the inter-arrival time between the wakeup periods and packets is equal). However, if more than one node has the same traffic pattern and priority, the average delay of the system is increased. Figure 8 shows an example of three nodes with high, medium, and low priorities. It can been seen that the average delay of a low priority node depends on the medium and high priority nodes, i.e., a low priority node has to wait until the medium and high priority nodes finish their transmission (see figure 5). The average delay of low, medium, and high priority nodes is shown in figure 9. This figure only shows the relative trend for a fixed size packet, i.e., 152 bytes. However, the delay of a low priority node may increase if the traffic volume of the medium and high priority nodes increases, in other words, if the packet size including the control packet overhead is increased.

Ⅴ. Conclusions

In this paper, a novel power-efficient MAC protocol for WBAN is presented. Two wakeup mechanisms are proposed, i.e., a traffic-based wakeup mechanism which is used for normal traffic, and a wakeup radio mechanism which is used for emergency and on-demand traffic. The proposed protocol is supported by a bridging function that allows communication between in-body and on-body nodes. The protocol is simulated and compared with WiseMAC protocol. It is shown that the proposed protocol outperforms WiseMAC protocol in terms of low-power consumption and delay.

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