Traffic-Aware Medium Access Control Protocol for Wireless Body Area Networks

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***Abstract*—Wireless body area networks (WBANs) can significantly improve healthcare, diagnostic monitoring, and other medical services. However, existing standards, such as IEEE 802.11 and IEEE 802.15.4 cannot fulfill all the requirements of WBANs. Numerous medium access control (MAC) protocols have been studied, most of which are derived from the IEEE 802.15.4 superframe structure with some improvements. Nevertheless, the MAC protocols do support required quality of service (QoS) for various forms of traffic coexisting in a WBAN. This paper proposes a traffic-aware MAC (TA-MAC) protocol for WBANs that allocates time slots dynamically based on traffic priority. The performance study shows that the proposed TA-MAC outperforms IEEE 802.15.4 MAC and the conventional priority-based MAC in terms of throughput and energy efficiency.**

Keywords-Wireless body area network; medium access control; energy efficiency; quality of service; traffic priority; IEEE 802.15.4.

I. INTRODUCTION

A wireless body area network (WBAN) is a special-purpose sensor network that is designed to autonomously connect various medical sensors and appliances located inside and around the human body and is capable of long-term health monitoring remotely or within a hospital. The general organization of a WBAN is shown in Figure 1. A WBAN consists of biomedical sensor nodes used to monitor physiological signals, such as electromyography (EMG), electroencephalography (EEG), temperature, heart rate, and blood pressure [1]. Quality of service (QoS) is an important benchmark to achieve in WBANs. The key requirements in WBANs are small device size, low power consumption, negligible electromagnetic effects to the human body, short transmission delay, high reliability, and effective communication. WBANs have specific requirements and considerations that the IEEE 802.15.4 medium access control (MAC) protocol does not fully address [2].

MAC protocols play a vital role in prolonging the lifespan of a network by controlling the sources of energy waste such as packet collisions, overhearing, control packet overhead, and idle listening [3] [4]. The main approaches adopted for energy savings in MAC protocols for WBANs are lower-power listening (LPL), schedule contention, and time division multiple access (TDMA). In the LPL mechanism, nodes wake up for a short duration to check the activity in the channel without receiving data. Scheduled contention is a combination of scheduling process and

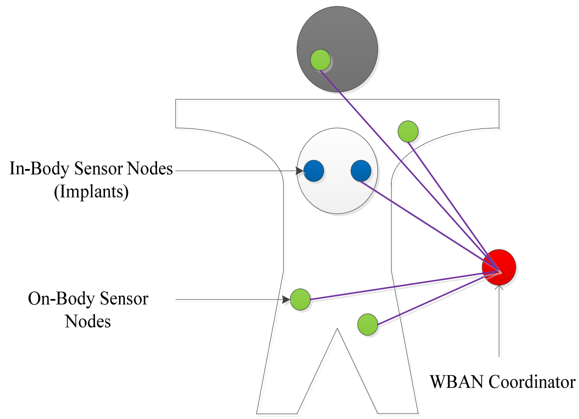

Figure 1. The general organization of a WBAN.

contention-based mechanism to avoid the problem of scalability and collision.

The IEEE 802.15.6 standard [5] defines new physical (PHY) and MAC layers to address both medical/healthcare applications and other nonmedical applications with diverse requirements. The MAC layer in the standard intends to define short-range wireless communication in and around the human body. The standard aims to support low complexity, low cost, ultra-low power, and highly reliable wireless communication for use in close proximity to or inside the human body (but not limited to the human body) to satisfy an evolutionary set of entertainment and healthcare products and services.

The design of MAC protocols has a significant impact on energy efficiency, interference, reliability, and QoS provision. One MAC protocol cannot satisfy the requirements of all applications because the protocols are hardware- and application-dependent [6]. The MAC protocol suitable for WBANs must handle specific challenges and issues associated with WBAN topology and node constraints. In [7], the different PHY and MAC layer design approaches to develop efficient mobile health (mHealth) applications for WBANs are surveyed and discussed. The key design features, MAC layer challenges, energy consumption, coexistence, and issues concerning channel modelling are analyzed and summarized in [8] [9].

In this paper, we propose a traffic-aware MAC (TA-MAC) protocol for WBANs that prioritizes the nodes by using a priority-guaranteed CSMA/CA procedure in the

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contention access period (CAP). For TA-MAC, we classify data traffic into four priorities and categorize the CAP into four sub-phases with dynamically changing length. This protocol is designed to support various QoS requirements for the data classified by priorities in WBANs. The proposed TA-MAC supports CAP and contention-free period (CFP). In the CAPs, the operation is based on a priority-guaranteed CSMA/CA procedure in which different WBAN nodes are assigned different priorities. The CFP is used to carry the large number of data packets to the coordinator.

This paper is organized as follows: In the following section, some related research is reviewed and discussed briefly. The proposed MAC protocol is presented in Section 3. In Section 4, the performance of the proposed TA-MAC is evaluated via computer simulation and compared with IEEE 802.15.4 MAC and the conventional priority-based MAC protocol. Section 5 concludes the paper.

II. Related Works

The IEEE 802.15.4 MAC protocol was designed for low-data-rate applications and is the most commonly used MAC protocol in wireless sensor networks to support low power and low data rate in cases where latency and bit rate are not critical [11]. The general characteristics of IEEE 802.15.4 MAC are low power consumption, support for low-latency devices, star or peer-to-peer operation, and dynamic device addressing. The superframe structure of IEEE 802.15.4 MAC consists of a CAP, a CFP, and an inactive period. The CFP contains up to seven guaranteed timeslots (GTS). The duration of the superframe is described by the values of macBeaconOrder (BO) and macSuperFrameOrder (SO). The BO describes the beacon interval at which the coordinator may transmit its beacon. IEEE 802.15.4 MAC does not have any mechanism for prioritizing among the different kinds of data traffic, and low-priority data can block the transmission of high-priority data.

There have been many significant developments of MAC protocols for WBANs. Most of the MAC protocols are already used for specific purposes, but they can be adopted with certain modifications to fulfill the requirements of WBANs. Most research has focused on the IEEE 802.15.4 standard for low-rate wireless personal area networks.

An IEEE 802.15.3-based MAC protocol was developed as part of a body area system for ubiquitous multimedia applications [12]. The main objective of a body MAC [13] is to achieve energy efficient and flexible operation in terms of bandwidth allocation and to support a sleep mode to fulfill the requirements of WBANs. The context-aware MAC protocol [14] was designed to guarantee the real-time transmission of life-critical and emergency data. In heartbeat-driven MAC (H-MAC) protocol [15], efficiency is achieved through the TDMA approach by reducing idle listening and avoiding collisions. In [16], support for multiple physical layers including ultra-wideband is taken into account. A multichannel management scheme for WBANs is introduced in [17]. In the traffic priority and load-adaptive MAC protocol presented in [18], the transmission schedules of packets are determined based on their priorities. The traffic-adaptive MAC (TaMAC) protocol [19] uses a traffic-based wakeup mechanism and a wakeup radio to accommodate normal, emergency, and on-demand traffic in a reliable manner. A traffic load-aware sensor MAC is reported in [20] for collaborative body area sensor networks. In [21], a traffic-aware dynamic MAC protocol (TAD-MAC) for both invasive and noninvasive WBANs is introduced. In [22], a novel priority-based channel access algorithm for contention-based MAC (NPCA-MAC) protocol is devised to solve the contention complexity problem. A hybrid and secure MAC (PMAC) protocol for WBANs [23] uses two CAPs for accommodating normal and critical data, whereas one CFP is used for accommodating the large amount of data packets. In low-delay traffic-adaptive MAC (LDTA- MAC) protocol [24], GTSs are allocated dynamically based on traffic load to improve some of the shortcomings of the IEEE 802.15.4 MAC.

Existing standards, such as IEEE 802.11 and IEEE 802.15.4 cannot fulfill all requirements of WBANs. Therefore, numerous MAC protocols have been studied. Most of them are derived from the IEEE 802.15.4 superframe structure with some improvements and adjustments. However, they do not support differentiated QoS for various kinds of traffic coexisting in a WBAN.

III. Traffic-aware MAC Protocol

In this section, the proposed TA-MAC is presented in detail. The priority level of different kinds of data traffic, dynamic timeslot allocation, and data transfer procedures are discussed in the following subsections.

A. Priority Level of Traffic

Among WBAN applications, medical and consumer electronics (CE) signals represent the majority of data traffic in the network. Emergency traffic, which is directly related to the life of a patient (e.g., emergency alarm signals) should be regarded as the most important service and must be in the first priority level. Continuous medical traffic with common vital signals (e.g., EEG, electromyography) ranks in the second priority level. Discontinuous medical traffic (e.g., temperature, blood pressure) ranks in the third priority level. CE traffic (e.g., audio/videos transmitted in an event-driven manner) is ranked in the fourth priority level. The priority levels for different kinds of traffic are shown in Table I.

TABLE I. Different Levels of Traffic Priority

Traffic	Priority level	Traffic	Example
Emergency traffic (ET)	1	P_1	Emergency alarm signal
On-demand traffic (OT)	2	P_2	Continuous medical signal (e.g., EEG, EMG)
Normal traffic (NT)	3	P_3	Discontinuous medical signal (e.g., temperature, blood pressure)
Nonmedical traffic (NMT)	4	P_4	Audio/video/data

B. Dynamic Timeslot Allocation

The IEEE 802.15.4 MAC protocol consists of CAPs and CFPs. In this paper, we focus on the channel access of CAP because the performance of a CAP significantly influences the collision probability and the final throughput. When numerous nodes are densely deployed in a narrow region, contention complexity is increased and leads to high energy consumption and high collision. Contention complexity is one of the requirements of WBANs that must be satisfied so that the necessary QoS and low power consumption can be best achieved. Here, we divide the CAP into sub-phases for each priority level of traffic; i.e., ET-CAP (Phase 1), ODT-CAP (Phase 2), NT-CAP (Phase 3), and NMT-CAP (Phase 4) as shown in Figure 2. Nodes that transmit P_1 traffic can access channels through all phases from 1 to 4. P_2 can access channels from Phases 2 to 4. Similarly, P_3 can access channels through Phases 3 and 4. The node that transmits P_4 can use only Phase 4 to access the channel. Phase 1 always occupies the first time slot of the CAP [25]. To avoid wasted timeslot utilization, the length of sub-phases L_2, L_3, and L_4 dynamically change and are calculated by the coordinator according to number of priority nodes on that sub-phase using (1), (2), and (3), respectively.

The length of Phase 1 in Figure 2 is fixed; it is one time slot long and always occupies the first time slot of the CAP. However, the lengths of the remaining phases are variable and represented as

$$L_2 = \frac{N_2(L-1)}{\sum_{i=2}^{4} N_i}, \quad (1)$$

$$L_3 = \frac{N_3(L-1)}{\sum_{i=2}^{4} N_i}, \quad (2)$$

and

$$L_4 = L - L_3 - L_2 - 1, \quad (3)$$

where N_i is the number of ith priority nodes and L is the length of CAP in the unit of timeslot.

C. Data Transfer Procedure

In the IEEE 802.15.4 MAC protocol, the CAP is suitable for the transfer of short data and command messages, and the CFP is designed for transferring continuous data. The coordinator continuously broadcasts beacons to all nodes, and active nodes receive the beacons. The nodes send a request to the coordinator for allocation of time slots in the CAP. According to the number of requests received, the coordinator also allocates TDMA slots in the CFP. To alleviate the collision of data traffic, a GTS scheduling criterion is defined. For P_1 and P_3, the data are transmitted immediately after successfully accessing the channel in the CAP. However, for P_2 and P_4, the nodes uniformly send GTS request command frames in the CAP to apply for GTS allocation. The data transfer procedures for different priorities of traffic are shown in Figures 3 and 4. In the CAP, TA-MAC employs the priority-based CSMA/CA procedure, which is based on the IEEE 802.15.6 standard. Each priority class has differentiated maximum/minimum contention windows and contention probability values to provide priority-based channel access to satisfy the QoS requirements of WBANs [5].

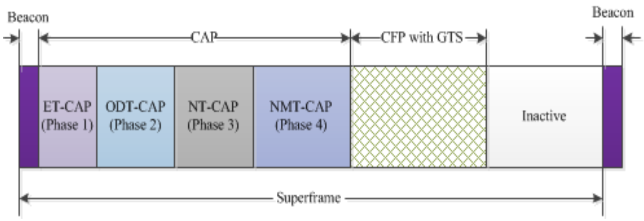

Figure 2. Superframe structure of the proposed MAC.

IV. PERFORMANCE EVALUATION

In this section, the performance of the proposed TA-MAC is evaluated via computer simulation and then compared to the existing IEEE 802.15.4 MAC and NPCA-MAC protocols.

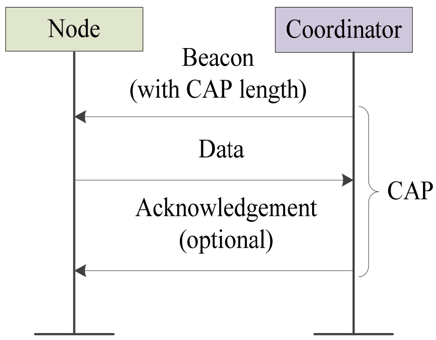

Figure 3. Data transfer for P_1 and P_3.

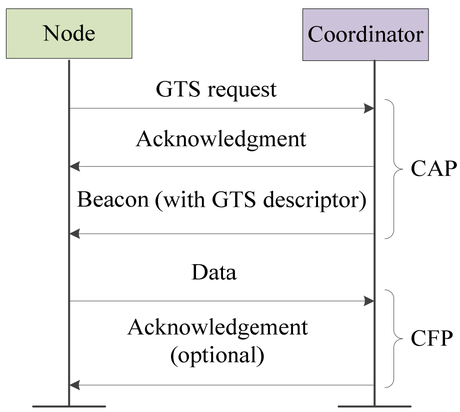

Figure 4. Data transfer for P_2 and P_4.

A. Performance Metrics

The performance metrics used in our simulation are throughput and energy efficiency. In this subsection, the metrics are summarized in brief. In addition, the effects of different priority levels are evaluated and discussed in terms of average transmission time.

Throughput in data communications refers to the actual level of traffic put through the network across a path between a transmitting device and one or more receiving devices, from end to end. It is defined as the average rate of successful packet delivery over a communication channel. Energy efficiency is one of the key requirements for WBAN MAC protocol designs.

Energy consumption depends on the behavior of the nodes on the network. A network with heavy traffic has higher energy consumption than one with low traffic activity. In order to comprehensively compare the MAC protocols, we calculated average energy consumption per bit to evaluate energy efficiency. The energy consumption per bit is defined as the total energy consumption over the total number of bits delivered during a simulation run [26].

B. Simulation Environment

Our performance simulation was carried out using the ns-2 network simulator version 2.35. In our simulation, it is assumed that several biomedical sensors are attached to or implanted into the human body. The sensors collect the sensed data and transmit them to the central coordinator, resulting in a star topology. All sensor nodes are randomly deployed within a 5 m radius around the central coordinator, and data are transmitted using one-hop communication [22]. The network parameters used for simulation are summarized in Table II as in [27].

TABLE II. SIMULATION PARAMETERS

Parameter	Value
Channel rate	250 kbps
Frequency band	2.4 GHz
Symbol times	16 µs
Superframe duration	122.88 ms
Transition time	194 µs
aUnitBackoffPriod	20 symbols
macBeaconOrder (BO)	3
macMaxCSMABackoffs	5
macMinBE	3
macMaxBE	5
Idle power	712 µW
Transmission power	36.5 mW
Reception power	41.4 mW

C. Simulation Results and Discussion

The overall throughput of the proposed TA-MAC, IEEE 802.15.4 MAC and NPCA-MAC is shown in Figure 5. The throughput is the total amount of data packets received by the coordinator in a specific time interval. Here, we can see that the throughput of all three protocols increases with the increase in the number of sensor nodes. When the network has low traffic load (i.e., less than 15 sensor nodes), all the three protocols perform similarly. With the increased number of sensor nodes, TA-MAC shows improved throughput over NPCA-MAC and IEEE 802.15.4 MAC. As a matter of fact, the classification of continuous and discontinuous data transfers and allocation of GTSs for continuous data makes TA-MAC outperform NPCA-MAC and IEEE 802.15.4 MAC.

The average energy consumption per bit as a function of the number of nodes is illustrated in Figure 6. The proposed TA-MAC and NPCA-MAC show better performance than IEEE 802.15.4 MAC in all network scenarios. However, TA-MAC shows slightly better performance than NPCA-MAC when the number of nodes is greater than 15. In general, packet collision and retransmission result in more energy consumption. As the number of nodes is increased, the energy consumption of IEEE 802.15.4 MAC is increased sharply because of high contention complexity. However, in the proposed TA-MAC, prioritized channel access with differentiated contention window, classification of data transfer, and backoff exponential values reduce the contention complexity, number of collisions, and packet retransmissions thus contributing to reduced energy consumption.

For comparing the performance of the sensor nodes according to their priority level, scenarios with the different number of sensor nodes per priority level are taken into evaluation. Figure 7 shows the effect of four different priority levels in terms of average transmission time for the different number of sensor nodes. In this paper, transmission

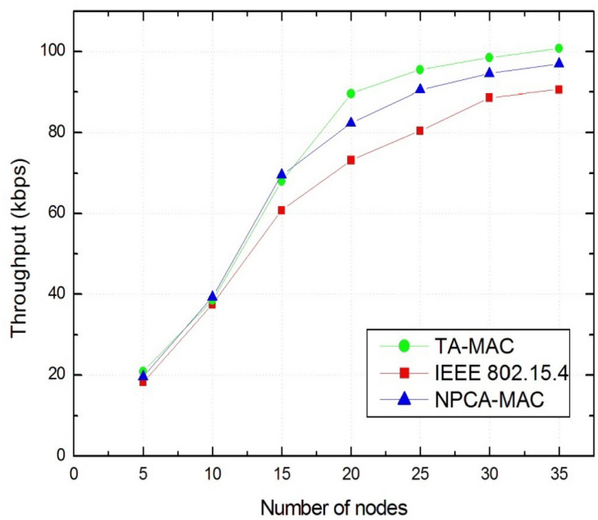

Figure 5. Network throughput.

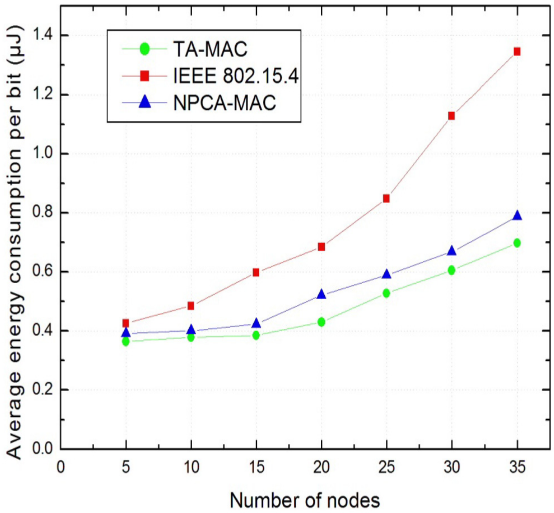

Figure 6. Average energy consumption per bit.

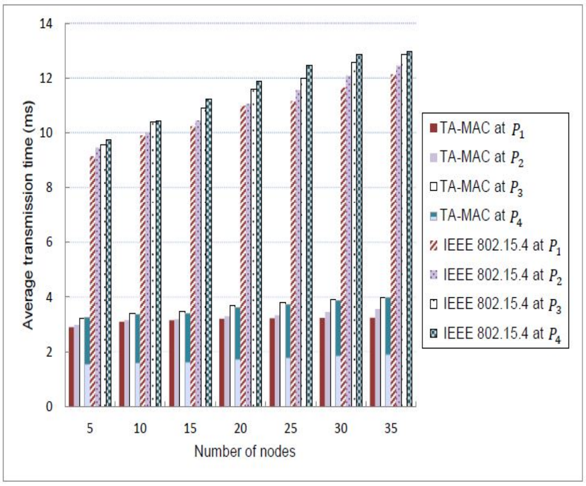

Figure 7. Effects of different priority level.

time is defined as the end-to-end delay from a sensor node to the coordinator. In Figure 7, the average transmission time of individual priority traffic is depicted for the proposed TA-MAC and IEEE 802.15.4 MAC, but the average transmission time of NPCA-MAC is not shown because it is almost the same as that of TA-MAC. This is primarily because NPCA-MAC also divides the CAP into four sub-phases according to the different priority levels of traffic as in TA-MAC. In NPCA-MAC, however, the continuous and discontinuous data transfer procedures and the use of GTSs were not considered. In addition, the number of sensor nodes per priority level is varied from 5 to 35 in Figure 7, and the impact on the average transmission time for the sensor nodes of each priority level is observed. As shown in Figure 7, the average transmission time tends to increase with the increase of priority level in both protocols. The difference is more noticeable in IEEE.15.4 in comparison to TA-MAC. It is obviously shown that TA-MAC shows better performance than IEEE 802.15.4 MAC.

V. CONCLUSIONS

In this paper, we have proposed a traffic-aware MAC protocol called TA-MAC for WBANs to support various QoS requirements. The proposed TA-MAC differentiates the access phase of the CAP and classifies the transfer procedure of priority-based traffic in WBANs. TA-MAC uses CFPs for continuous and large amounts of data. According to the simulation results, TA-MAC showed substantial improvements in terms of throughput and energy efficiency compared to IEEE 802.15.4 MAC and the conventional NPCA-MAC. A possible future work is to apply cognitive radio and multichannel access to the design of a MAC protocol for WBANs in order to mitigate the coexisting interference and improve network performance including QoS.

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REFERENCES

[1] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour,"Wireless body area network: A survey," IEEE Communications Surveys and Tutorials, vol. 16, no. 3, pp. 1658-1686, 2014.

[2] IEEE Std. 802.15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low data rate wireless personal area networks (WPAN), IEEE, Piscataway, NJ, USA, 2006.

[3] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient mac protocol for wireless sensor networks," Proc. of 21st Annual Joint Conference of the IEEE Computer and Communications Societies, vol. 16, pp. 1567-1576, June 2002.

[4] A. El-Hoiydi and J.-D. Decotignie, "WiseMAC: An ultra-low power mac protocol for the downlink of infrastructure wireless sensor networks," Proc. of 9th IEEE Symposium on Computers and Communication (ISCC'04), pp. 244-251, June- July 2004.

[5] S. Ullah, M. Chen, and K. Kwak, "Throughput and delay analysis of IEEE 802.15.6 based CSMA/CA protocol," Journal of Medical Systems, vol. 36, no. 6, pp. 3875-3891, 2012.

[6] S. Bhandari and S. Moh, "A survey of MAC Protocols for cognitive radio body area networks," Sensors, vol. 15, pp. 9189-9209, 2015.

[7] E. Kartsakli, A. Lalos, A. Antonopoulos, S. Tennina, M. Renzo, L. Alonso, and C. Verikoukis, "A survey on M2M systems for mHealth: A wireless communications perspective," Sensors, vol. 14, pp. 18009-18052, 2014.

[8] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, and R. Verdone, "A survey on wireless body area networks:

Technologies and design challenges," IEEE Communications Surveys & Tutorials, vol. 16, pp. 1635-1657, 2014.

[9] T. Le and S. Moh, "Interference mitigation schemes for wireless body area sensor networks: A comparative survey," Sensors, vol. 15, pp. 13805-18838, 2015.

[10] S. Mangold, S. Choi, G. R. Hiertz, O. Klein, and B. Walke, "Analysis of IEEE 802.11e for QoS support in wireless LANs," IEEE Wireless Communications, vol. 10, No. 3, pp. 40-50, 2003.

[11] N. F. Timmons and W. G. Scanlon, "Analysis of the performance of IEEE 802.15.4 for medical sensor body area networking," Proc. of 1st Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (IEEE SECON '04), pp. 16-24, Oct. 2004.

[12] T. Falck, J. Espina, J. P. Ebert, and D. Dietterle, "BASUMA – The sixth sense for chronically ill patients," Proc. of International Workshop on Wearable and Implantable Body Sensor Networks, Apr. 2006.

[13] G. Fang and E. Dutkiewicz, "BodyMAC: Energy efficient TDMA-based MAC protocol for Wireless Body Area Network," Proc. of 9th International Symposium on Communications and Information Technology, pp. 1455-1459, Sep. 2009.

[14] Z. Yan and B. Liu, "A context aware MAC protocol for medical wireless body area network," Proc. of 7th Int. Wireless Communication and Mobile Computing Conf. (IWCMC 2011), pp. 2133-2138, July 2011.

[15] L. Huaming and T. Jindong, "Heartbeat-driven medium-access control for body sensor networks," IEEE Transactions on Information Technology in Biomedicine, vol. 14, no. 1, pp. 44-51, 2010.

[16] C. Li, L. Wang, J. Li, B. Zhen, H.-B. Li, and R. Kohno, "Scalable and robust medium access control protocol in wireless body area networks," Proc. of IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, pp. 2127-2131, Sept. 2009.

[17] W. Lee, S. H. Rhee, Y. Kim, and H. Lee, "An efficient multi-channel management protocol for wireless body area networks," Proc. of International Conference on Information Networking (ICOIN), pp.1-5, Jan. 2009.

[18] I. Anjum, N. Alam, M. A. Razzaque, M. Mehedi Hassan, and A. Alamri, "Traffic priority and load adaptive mac protocol for qos provisioning in body sensor networks," International Journal of Distributed Sensor Networks, vol. 2013, pp. 1-9, 2013.

[19] K. S. Kwak and S. Ullah, "A traffic-adaptive MAC protocol for WBAN," Proc. of IEEE GLOBECOM Workshops, pp. 1286-1289, Dec. 2010.

[20] O. Md. Rahman, C. S. Hong, S. Lee, and Y.-C. Bang, "ATLAS: A traffic load aware sensor MAC design for collaborative body area sensor networks," Sensors, vol. 11, no.12, pp. 11560-11580, 2011.

[21] M. M. Alam, O. Berder, D. Menard, and O. Sentieys, "TAD-MAC: traffic-aware dynamic mac protocol for wireless body area sensor networks," IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 2, no.1, pp. 109-119, 2012.

[22] B. Kim and J. Cho, "A novel priority-based channel access algorithm for contention-based MAC protocol in WBANs," Proc. of the 6th International Conference on Ubiquitous Information Management and Communication (ICUIMC 2012), pp. 1-5, Feb. 2012.

[23] S. Ullah, M. Imran, and M. Alnuem, "A hybrid and secure priority-guaranteed MAC protocol for wireless body area network," International Journal of Distributed Sensor Networks, vol. 2014, pp. 1-7, 2014.

[24] C. Li, B. Hao, K. Zhang, Y. Liu, and J. Li, "A novel medium access control protocol with low delay and traffic adaptivity for wireless body area networks," Journal of Medical Systems, pp. 1265-1275, 2011.

[25] S. Jin, Z. Weixia, and Z. Zheng, "Priority-based adaptive timeslot allocation scheme for wireless body area network," in Proc. of 13th International Symposium on Communications and Information Technologies (ISCIT), pp. 609-614, Sept. 2013.

[26] Y. Zhang and G. Dolmans, "Priority-guaranteed MAC protocol for emerging wireless body area networks," Annals of Telecommunications, vol. 66, pp. 229-241, 2010.

[27] X. Liang and I. Balasingham, "Performance analysis of the IEEE 802.15.4 based ECG monitoring network," Proc. of the 7th IASTED International Conferences on Wireless and Optical Communications, pp. 99-104, May-June 2007.