2TM-MAC : A Two-Tier Multi-channel Interference Mitigation MAC Protocol for Coexisting WBANs

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Abstract—**Wireless Body Area Networks (WBANs) have been developed rapidly with the increasing popularity of wireless network and wearable technologies. The inherent characteristics of convenience and efficiency for health monitoring facilitate the depth and width of WBAN applications. However, the inter-WBAN interference problem affects the network performance in intensive WBAN scenarios, degrading reliability and increasing latency of health data. In this paper, we propose a Two-Tier Multi-channel Medium Access Control (2TM-MAC) protocol with interference mitigation for reliable health monitoring. Specially, the 2TM-MAC establishes an inter-WBAN interference matrix for every WBAN to show the mutual interference among coexisting WBANs. We design a multi-channel selection algorithm at the first tier to select different numbers of channels for each WBAN to avoid inter-WBAN interference and collisions. At the second tier, the hub of each WBAN schedules the available channels assigned from the first tier to sensor nodes according to their traffic requirements, mitigating the intra-WBAN interference as well. 2TM-MAC protocol enhances the reliability of emergency data and service experience in healthcare applications. Simulation results show the 2TM-MAC protocol significantly improves the network throughput and decreases the average packet delay compared with IEEE 802.15.6 for densely deployed coexisting WBANs scenarios.**

I. INTRODUCTION

Wireless Body Area Network (WBAN) is a human-centered, highly reliable, short-range wireless communication network that consists of one hub and several connected sensor nodes attached to or implanted in human body [1]. WBAN is designed to monitor vital signs or other health-related data to provide 24/7 health monitoring with great convenience and comfortable experience. WBAN technology-driven applications have been explosively developed and widely popularized in e-healthcare to alleviate the constricts between limited medical resources and increasing need of aging population. The related applications that enable medical wellness, prevention, diagnosis, treatment and monitoring services are expected to create \$1.1-\$2.5 trillion in growth annually by the global economy by 2025, occupying about 41% of the projected market share in IoT applications [2].

In some densely-deployed WBAN scenarios, such as hospitals and nursing homes, the inter-WBAN interference in adjacent WBANs may result in incomplete or delayed of medical data transmissions [3]. Inter-WBAN interference becomes a challenge to high-reliability and low-latency data transmissions for disease diagnosis and health monitoring. WBANs adopt human body as communication medium, making it different from other networks in terms of wireless channel, network topology, and many other aspects [4]. The dynamic inter-WBAN interference generated by moving human body [5] was analyzed with a three dimension Markov Model. Sun et al. [6] presented a stochastic geometry analysis framework for inter-user interference in WBANs and considered the specific channel characteristics of WBANs near the human body. Wang et al. [7] analyzed the co-channel interference for non-overlapping WBANs by using the advanced Geometrical Probability approach.

Some interference mitigation mechanisms [8], [9] are proposed to improve network performance. A distributed TDMA-based beacon interval shifting scheme [8] was proposed to avoid the wake-up period of each WBAN coinciding with other WBANs by employing carrier sensing before a beacon transmission to reduce interference. But beacons from different WBANs may still collide since each WBAN does not know the shifting patterns of others. Chen et al. [9] proposed a Two-layer Medium Access Control protocol (2L-MAC) for WBANs interference mitigation. However, multiple WBANs in 2L-MAC contend to access the same channel, leading to high collision probability and low priority nodes starvation. Multi-channel protocols are proposed allowing multiple transmissions at the same time to reduce potential interference and enhance network performance [10]–[12]. An Adaptive Channel Estimation and Selection Scheme (ACESS) [11] maintained a history table and predicted the conditions of available channels based on two-state Markov chain with an exponentially controlled channel history for coexistence mitigation in WBANs. The Multi-channel MAC (MC-MAC) protocol [12] employed a novel channel mapping mechanism instead of keeping a channel list to save energy and reduce low priority nodes starvation. Sensor nodes contend for the idle channels according to the received list of idle channels in Beacon for intra-WBAN transmission.

However, most of the existing interference mitigation mechanisms only rely on the hub in each WBAN to maintain and update the history information of inter-WBAN and intra-

WBAN resource allocation, increasing the storage and processing complexity of hub. Moreover, nodes with different user priorities contend to access the single or multiple channels. High-priority nodes occupy most of the slots and channel resources, leading to the starvation of low priority nodes. In the contention progress, only traffic user priorities are considered, neglecting the data variability and diverse Quality of Service (QoS) requirements of different traffic nodes. In coexisting WBANs scenario, different WBANs may provide different kinds of services for people at the same time. The service priorities should also be considered. Medical service related data even those with low user priority should also be transmitted in privilege than that of non-medical service.

To this end, we propose a Two Tier Multi-channel MAC Protocol (2TM-MAC) to mitigate intra- and inter-WBAN interference in this paper. At the first tier of 2TM-MAC, data center allocates interference-free channels for coexisting inter-WBANs. At the second tier, hub schedules the assigned channels from the first tier for intra-WBAN nodes to reduce intra-WBAN interference. The allocation design of two-tier multi-channel MAC protocol for inter-WBAN and intra-WBAN reduces the interference and packet delay and improves both the network throughput and channel utilization. Our main contributions are concluded as follows:

- Firstly, we establish an interference matrix at data center to record the inter-WBAN interference states of each W-BAN. Moreover, we design a channel selection algorithm for coexisting WBANs with considering both WBAN service priority and traffic user priority. Data center, instead of hub, performs the global allocation for all adjacent WBANs, reducing the configuration complexity and cost of hub in each WBAN.
- Secondly, we analyze the appropriate slots number for intra-WBAN nodes with diversified data arrival rates. Furthermore, we dynamically schedule the transmission channel and slots number for nodes according to their user priority and diversified traffic, reducing intra-WBAN interference and starvation of low priority nodes to satisfy diversity QoS requirements.
- Finally, we conduct extensive simulations to validate the advantages of 2TM-MAC on network throughput and average delay in multiple coexisting WBANs and nodes with diversity data arrival rates scenarios.

The remainder of the paper is organized as follows. Section II introduces the network model. Section III presents the proposed 2TM-MAC protocol. Section IV evaluates the network performance. Section V discusses and analyzes the simulation results. Finally, section VI concludes the paper.

II. Network Model

There are several coexisting WBANs and a data center in the monitoring scenario, as shown in Fig. 1. Each WBAN consists of a hub and several sensor nodes. The sensor nodes collect physiological data such as EEG, ECG, heartbeat, body temperature and so on. The collected health data are classified into different user priorities to satisfy the diversified QoS
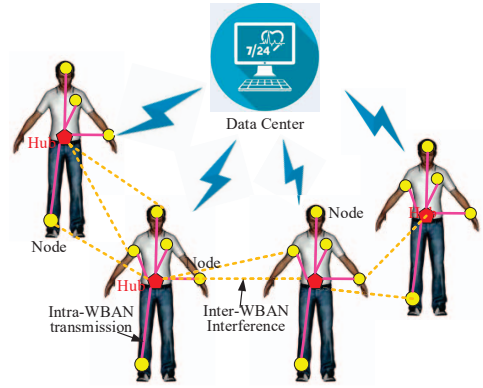

Fig. 1: Network model.

requirements. Eight user priorities ($UP_k, k = 0, 1, 2, ..., 7$) are predefined in IEEE 802.15.6. The higher user priority has more critical QoS requirements and will enjoy higher privilege to access the channel. Hub supports intra-WBAN data transmissions with nodes and data transactions with data center while nodes can only transmit data to hub. In densely-deployed WBAN environment, the communication range of WBAN overlaps. The intra-WBAN transmissions are easily interfered by adjacent WBANs, leading to collisions and unreliable data in high delay. Intra- and inter- WBAN interference exist among nodes and among hubs, respectively. If there are multiple available channels in the network, all of them can transmit data simultaneously in different channels, reducing interference and collision probability.

III. The Proposed 2TM-MAC protocol

We propose the 2TM-MAC protocol for coexisting WBANs to mitigate interference and guarantee the high reliability and low latency of data transmissions for health monitoring. 2TM-MAC protocol first selects different numbers of available interference-free channels for each WBAN at the first tier. Then, hub allocates the channels to every node according to their diversified traffic arrival rates at the second tier. 2TM-MAC not only reduces inter-WBAN interference and data packet delay, but also significantly improves channel utilization and network throughput.

A. WBAN service priority

In this paper, we newly define the WBAN service priority (SP) for coexisting WBANs. Different WBANs are probably providing different kinds of services for people at the same time. The service related data are transmitted in different QoS requirements. The priority of medical service should always be higher than non-medical service no matter what kind of data traffic. The WBAN having emergency health data for medical diagnosis and operation can obtain more channel resources to guarantee the high reliability and low latency data transmission.

The defined WBAN service priority considers both the traffic varieties and physiology data variable conditions. If the data traffic has the same user priority, we extra use the Acute Physiology and Chronic Health Evaluation (APACHE) clinical
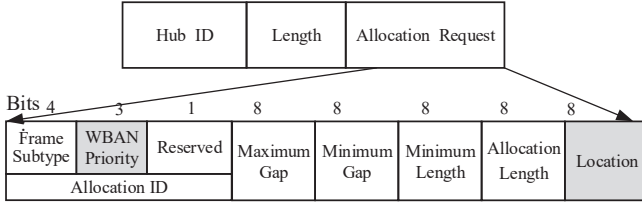
Fig. 2: The Data request frame format of hub.

scoring systems [13] to evaluate the data severity guaranteeing the access privilege. The APACHE scoring system has been widely used in clinical practice as decision-making tool and hospital efficacy measure. The Acute Physiology Score (APS), Age Score (AS) and Chronic Physiology Score (CPS) variables for calculating the overall APACHE scores make accurate health evaluation and prediction for patients. The APS includes 12 attributes and the values of each attribute vary from 0 to 4. AS values vary from 0-6 while CPS values vary from 2 to 5. The higher value of APACHE score is, the more severe predicted mortality risk of patients. WBANs in high service priority are more competitive in channel selection among densely-deployed coexisting WBANs.

B. The first tier: inter-WBAN multi-channel selection

At the first tier of 2TM-MAC, the data center establishes an interference matrix I_m,

$$I_m = \begin{bmatrix} I_{11} & \cdots & I_{1m} \\ \vdots & \ddots & \vdots \\ I_{m1} & \cdots & I_{mm} \end{bmatrix}$$

where m is the coexisting number of WBANs at the designated area. I_m is a composition of 0 and 1 to record the relation with its neighbor WBANs. The value 1 indicates there is inter-WBAN interference that the two WBANs had better not choose the same channel to reduce collision. The value 0 means the two WBANs are interference-free, and they can reuse the same channel simultaneously.

The interference matrix is maintained and updated by data center instead of the hub in each WBAN, saving energy consumption and reducing system complexity of WBAN. The data center collects the location and SP information of every WBAN, through which judges whether the adjacent WBANs exist inter-WBAN interference. The SP and location information of the current WBAN is attached to the data request frame sent by Hub, as shown in Fig. 2. We set the interference distance threshold of two WBANs as D. When the distance d_{ij} between $WBAN_i$ and $WBAN_j$ satisfies $d_{ij} \leq D$, it is considered that the two WBANs generate mutual interference. The values I_{ij} and I_{ji} in interference matrix are both marked as 1. If there is no interference, $I_{ij} = I_{ji} = 0$.

An undirected graph is shown in Fig. 3 to illustrate the progress of establishing the interference matrix I_m. The vertices represent WBANs while the connected links represent there exists inter-WBAN interference between two WBANs.
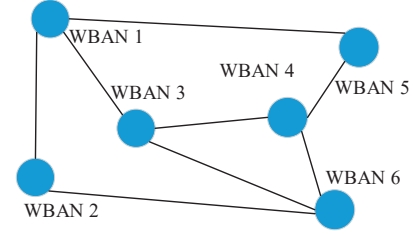

Fig. 3: Undirected graph.

According to the undirected graph, we can get the interference matrix I_6 shown as

$$I_6 = \left[\begin{array}{ccc|ccc} 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 \\ \hline 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 \end{array} \right]$$

A multi-channel allocation algorithm is designed to allocate different numbers of available interference-free channels for the coexisting WBANs, as shown in Algorithm 1. Algorithm 1 is performed in two steps based on the WBAN service priority and interference matrix. Assume there are n channels in the network. At first, all coexisting WBANs are numbered in a descending order $W_1, W_2, ..., W_m$ according to their WBAN service priority in data center. WBAN W_1 is the highest priority and data center allocates one channel to WBAN W_1 in privilege. For the next WBAN W_2, if they have inter-WBAN interference, data center allocates another channel to WBAN W_2. Otherwise, they can share the same channel. Data center operates the progress until every WBAN selects one channel to guarantee data transmission. Meanwhile, data center records the current occupied channel of each WBAN in interference matrix. Then, data center checks the available channels those are not occupied by adjacent interference WBANs and allocates a new channel for W_1. Data center repeatedly performs the progress until all WBANs select the available channels.

Algorithm 1 allocates channels according to the WBAN service priority, which could minimize the possibility of high priority WBAN switching channels. High priority WBANs choosing the channel in priority guarantee the quality of service. Data center allocates multiple interference-free channels to WBANs improving the network throughput. For a random WBAN W_i, the number of selected channels is determined by the number of interference WBANs N_i.

Data center operates 2TM-MAC to guarantee every WBAN obtains at least one inter-WBAN interference-free channel at the first tier. Hub checks the Channel Number field in the assignment frame to get the allocated channels information. Then hub allocates the available channels to intra-WBAN sensor nodes at the second tier for data transmission.

C. The second tier: intra-WBAN channel allocation

The sensing health data are classified into different data or user priorities to satisfy the diversified performance require-

Algorithm 1 Multi-channel Selection Algorithm

Require: The interference Matrix of coexisting WBANs I_m

Ensure: Multiple available interference-free or low-interference channels for every WBAN

1: n is the total number of network channels, O_k is the number of occupied channels around $WBAN_k$;

2: Sort all coexisting m WBANs in descending WBAN priority order $W_1, W_2, ..., W_m$;

3: **for** $k = 1 : m$ **do**

4:     **repeat**

5:         allocate an unoccupied channel to W_i;

6:         **for** $i = 2 : m$ **do**

7:             **for** $j = 1 : i$ **do**

8:                 **if** $I_{ij}==I_{ji}==0$ **then**

9:                     data center checks the channel of $WBAN_j$ and marks as C_j;

10:                     **if** C_j is not occupied by any interference WBANs of $WBAN_i$ **then**

11:                         the two WBANs W_i and W_j share the same channel C_j;

12:                     **end if**

13:                 **else**

14:                     allocate an available channel to W_i;

15:                 **end if**

16:             **end for**

17:         **end for**

18:         Recount O_k

19:     **until** $O_k == n$

20: **end for**

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ments. High user priority has privilege to access the channel. The user priorities of medical data generally range from 5 to 7, guaranteeing the severer traffic in high priority to be transmitted timely.

After acquiring the channel resource from the first tier, the hub schedules the channel resources to each sensor node. Different nodes have different data arrival rates, demanding different numbers of slots to transmit data. Nodes send data request frame which includes the priority and length of traffic to hub to reserve slots. In this paper, we only consider the periodic data. The hub allocates the appropriate number of slots to nodes according to their diversified data arrival rates and packet length.

For a random node UP_i with data arrival rate λ_i, the hub calculates the time duration needed T_d to transmit all related packets in a superframe in Eq. 1. T_d includes the transmission time of the Physical Layer Protocol Data Unit (PPDU) t_p, ACK time t_{ACK}, short interframe spacing time $pSIFS$, and guard time GT.

$$T_d = num * (t_p + t_{ACK}) + pSIFS + GT \qquad (1)$$

where t_p is a successful integrity packet duration. According to IEEE 802.15.6, t_p can be calculated as

$$t_p = \frac{L_{preamble} + L_{header} \times S_{header} + \frac{L_{total} \times S_{PSDU}}{\log_2 M}}{R_s} \qquad (2)$$

where R_s is the symbol rate. $L_{preamble}$ and L_{header} are the length of Physical Layer Convergence Protocol (PLCP) preamble and header, respectively. S_{header} denotes the spreading factor header and S_{PSDU} is the spreading factor for the transmission mode. M is the modulation constellation size. The length of total bits L_{total} is

$$L_{total} = L_{PSDU} + L_{CW} \times (n - k) + L_{pad} \qquad (3)$$

where L_{PSDU} is the length of physical service data unit and formed by the MAC header $L_{Mheader}$, the MAC payload L_{Mload} and Frame Check Sequence (FCS) L_{FCS}. L_{CW} denotes the number of BCH codewords and L_{pad} is the number of pad bits. They can be acquired from Eq. (4)-(6).

$$L_{PSDU} = 8 \times (L_{Mheader} + L_{Mload} + L_{FCS}) \qquad (4)$$

$$L_{CW} = \left\lceil \frac{L_{PSDU}}{k} \right\rceil \qquad (5)$$

$$L_{pad} = \log_2(M) \times \left\lceil \frac{L_{PSDU} + L_{CW} \times (n - k)}{\log_2(M)} \right\rceil - \qquad (6)$$
$$[L_{PSDU} + L_{CW} \times (n - k)]$$

where n and k are selected by BCH code.

num denotes the fragment number of packets. Given the length of superframe T_s, num can be obtained from

$$num = \left\lceil \frac{\lambda_i \times T_s}{L_{Mload}} \right\rceil \qquad (7)$$

Guard Time GT provides fit intervals to guarantee no overlaps between adjacent allocation intervals.

$$GT = pSIFS + pExtraIFS + mClockResolution \qquad (8)$$

where $pExtraIFS$ is the synchronization error tolerance and $mClockResolution$ is the timing uncertainty.

We define the allocation slot length as T_{slot}, then the hub can calculate the number of allocation slots N_{is} for a UP_i node in Eq. 9.

$$N_{is} = \left\lceil \frac{T_d}{T_{slot}} \right\rceil \qquad (9)$$

To improve channel utilization, the hub checks the allocated slots in each channel and chooses the channel with minimum allocated slots number at present as the first assignment option. The hub stores the scheduling information in beacon frames and broadcasts beacon to every node at the begin of superframe. After receiving the beacon frame, each node switches to their target channel and begins data transactions with the hub. In multi-channel mode, nodes transmit data over multiple channels simultaneously, improving network throughput and reducing packet delay.

IV. PERFORMANCE EVALUATION

In this section, network performance of the proposed 2TM-MAC is evaluated by Castalia based on OMNET++ with comparison of IEEE 802.15.6 MAC protocol in different conditions. There are 8 nodes in a WBAN and each node in the network only produces one user priority traffic. We
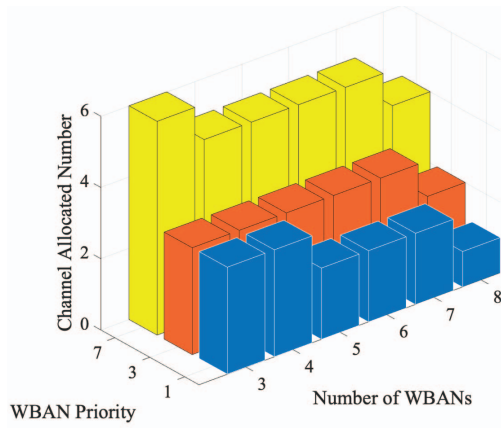
Fig. 4: Channel number of different priority vs No. of WBAN.

Fig. 5: Delay vs number of WBANs.

Fig. 6: Delay vs data arrival rates.

consider the relatively static health monitoring scenario, and human movement is out of consideration. Specific parameters used in the simulation are shown in Table I.

Figure 4 shows the number of channels variation with the changing number of coexisting WBANs in different WBAN priorities. Coexisting WBANs with different service priorities could obtain different numbers of channels to reduce inter-WBAN interference. WBAN in high priority could have more channels for intra-WBAN data transmission to satisfy emergency data QoS requirements. As the number of coexisting WBANs increases, the number of channels allocated to each WBAN decreases due to the limited channel capacity. When the number of WBANs is larger than the number of available channels, multiple WBANs may share one channel, leading to inter-WBAN interference.

In this paper, delay is divided into queuing delay t_q, transmission delay t_p, and I-ACK reception delay t_{ACK}, the expression of which is expressed as

$$Delay_i = t_{qi} + t_{pi} + t_{ACK} \qquad (10)$$

where t_{pi} is calculated by Eq. (2).

In Figure 5, delay changes obviously with the increasing number of coexisting WBANs. The delay of IEEE 802.15.6 increases rapidly when there are more than 4 WBANs in the monitoring scenario. The reason is that there are too many nodes in one channel waiting to transmit data, leading to high delay. In 2TM-MAC protocol, the traffic is allocated to multiple channels to reduce the average packet delay. With

TABLE I: System parameters

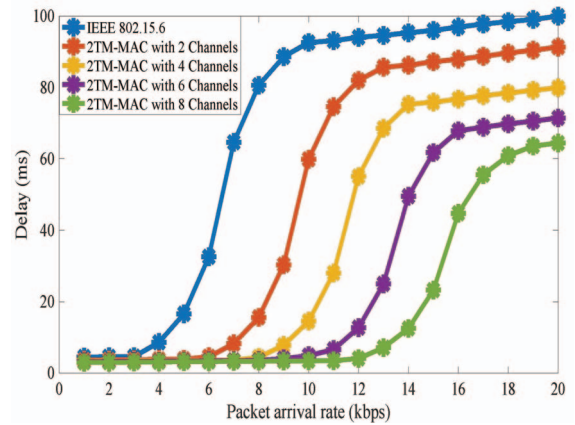| Parameters	Value
Superframe length	1 s
Slot length	5 ms
FCS	2 bytes
Beacon	15 bytes
ACK	9 bytes
PLCP preamble	90 bits
PLCP header	31 bits
MAC header	7 bytes
Symbol rate	600 ksps
Code rate (k/n)	51/63
pSIFS	75 μs
Simulation time	30 s
Frequency band	2400-2438.5 MHz
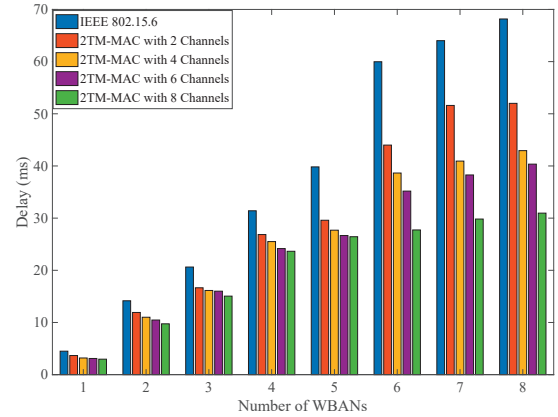
the number of coexisting WBANs increasing, the channel resource is insufficient. Then, more than one WBAN share the same channel, leading to multiple packets pending to be transmitted. The packet delay of both 2TM-MAC and IEEE 802.15.6 increase.

Figure 6 shows the delay variation as the data arrival rates increase. Delay changes little with the increasing data arrival rates before the network is saturated. 2TM-MAC can transmit data in multiple channels at the same time. Nodes in lower priority have more chance to transmit data, thus the transmission delay is lower than IEEE 802.15.6. When the network is saturated, the hub could not allocate enough slots for arriving data, leading to the sharply increasing average packet delay. The packet delay of IEEE 802.15.6 reaches 95 ms at data rate 10kbps per node. In contrast, the delay of 2TM-MAC with 2 channels is 60 ms while the delay with 8 channels is 8 ms. The delay is reduced by 37% and 91% in saturated condition, respectively.

Figure 7 shows the throughput variation of each WBAN with different number of coexisting WBANs. Throughput is defined the transmitted traffic payload per unit time, and could be expressed as

$$Throughput = \frac{m\lambda_i L_{iMload}}{T_s}. \qquad (11)$$

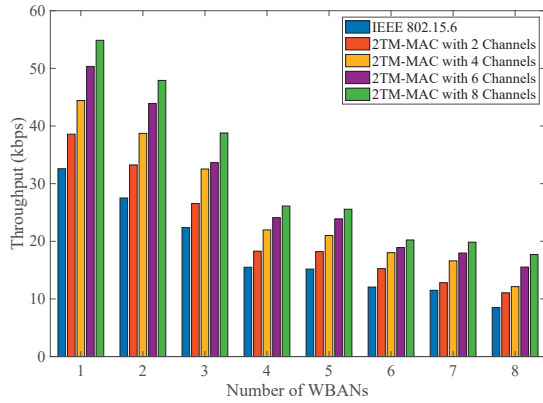As the number of WBANs increases, the throughput of the
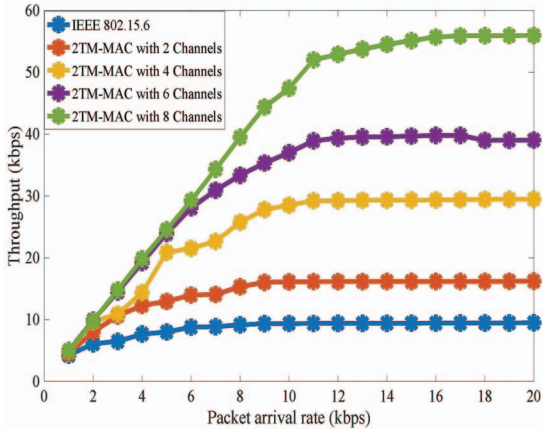
Fig. 7: Throughput vs number of WBANs.

Fig. 8: Throughput vs data arrival rates.

whole network decreases due to the generated by inter-WBAN interference. But the throughput of 2TM-MAC protocol is always higher than that of IEEE 802.15.6, which is owing to the multi-channel mechanism. In Fig. 7, the payload of each packet is 100 bytes. Throughput of 2TM-MAC increases significantly with the increasing number of available channels. Moreover, the design can reduce the effect of low priority starvation in IEEE 802.15.6, helping for network load balancing.

We investigate the changing network throughput with the diversified data arrival rates of intra-WBAN nodes in Fig. 8. For a random WBAN, with the increasing packet arrival rate, the throughput of both IEEE 802.15.6 MAC and 2TM-MAC increase. But the throughput changes little when the network becomes saturated. The single channel IEEE 802.15.6 MAC protocol becomes saturated when the data arrival rates of nodes are 6kbps. The 2TM-MAC become saturated at 9kbps when there are 2 available channels, and become saturated at 13kbps when there are 8 channels for concurrent data transmissions. The throughput of 2TM-MAC outperforms IEEE 802.15.6 significantly.

V. Conclusions

In this paper, we have proposed a two tier interference mitigation MAC (2TM-MAC) protocol to improve network performance for health monitoring in multiple WBANs coexisting scenario. We have designed a multi-channel selection algorithm to assign channels for each WBAN to reduce inter-WBAN interference according to the WBAN priority and interference matrix at the first tier. Moreover, at the second tier, we have calculated the appropriate number of slots for each intra-WBAN node to satisfy diversified QoS requirements. Besides, we have allocated the channel with minimum allocated slot number for nodes in privilege to improve slots and channel utilization. Simulation results verify the 2TM-MAC could highly improve the network throughput and reduce packet delay. In the future, we will consider human movements for time-varying multi-channel mechanism design and consider the burst data in resource allocation.

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