WBAN on NS-3: Novel Implementation with High Performance of IEEE 802.15.6

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***Abstract*—Wireless Body Area Networks (WBAN) are becoming increasingly important for health care with the development of health consciousness and health detection requirements. A lot of researches have been devoted to the progress of WBAN, for example, the improvement of protocols designed for WBAN, the optimization of parameters and the system performance evaluation. However, the main premise of all the directions above is to provide an efficient and reliable simulation platform, since the existing platforms cannot respond to accord with the reality with high performance. To work this issue out, we construct the WBAN simulation platform on Network Simulation 3 (NS-3) which specifies in good expandability and resources saving and agrees with real networks in many aspects comparing with the other simulators. In this paper, we propose our implementation of WBAN module based on IEEE 802.15.6 standard. Our simulation platform consists of Medium Access Control (MAC) and Physical (PHY) layer of IEEE 802.15.6. Then in order to make the simulation more objective, we design a proper simulation scenario according to the practical application and analyze the simulation results. Finally, we compare the throughput saturation threshold on NS-2 and NS-3 with the analysis results respectively to indicate the superiorities of NS-3 and verify the validity and effectiveness of our WBAN module.**

I. Introduction

With the rapid growth of global population and the ageing effect, people's demands of health care and health forecasts are arising. However, many medical resources in the medical systems cannot keep pace with the increasing health consciousness, such as budget expenditure, medical workers. In this case, developing an efficient and convenient health care systems becomes more essential. Furthermore, owing to the rapid development of Internet, people are not just satisfied with the basic Internet services, such as surfing the Internet and handling e-mails, instead that they are eager for personalized, intelligentized and convenient "Internet lifestyles" which promote the development of medical industry. Under this circumstances, the development of WBAN [1][2] becomes more and more necessary.

WBAN is one of the emerging cross-technologies and closely related to Wireless Personal Area Network (WPAN), Wireless Sensor Network (WSN) [3][4], short distance wireless communication and sensor technology [5]. Owing to the special application scenario, WBAN has its own characteristics compared to the traditional WSN [6]. Firstly, WBAN is primarily used in human bodies and communicates on a small scale. Then the businesses in WBAN are relevant. In other words, data changes in a node might result in the variation of the other nodes. Finally, the low-latency and high reliability of data should be guaranteed. WBAN could continuously monitor the health indexes for human beings conveniently and efficiently, it is practical in disease prevention and diagnosis. But nowadays, most of people take treatments after onset of illness which is far from the precautions and real-time diagnoses, whereas WBAN can make up the shortfalls exactly. And due to its convenience and accuracy, WBAN has profound realistic significance to health care. Therefore WBAN is mainly utilized in various fields, such as medical field, danger occasions and entertainment applications.

In order to develop WBAN conveniently and rapidly, the IEEE 802.15 has established Task Group 6 (TG6) for an appropriate communication standard for WBAN, called IEEE 802.15.6 [7] which is the first international standard in WBAN field and has overcome limitations of IEEE 802.15.4 [8]. In the IEEE 802.15.6 protocol, a node may initiate frame transactions in different contended-based access phases using Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA) [9] or Slotted Aloha. A hub in WBAN has the ability of arranging committed scheduled allocation intervals, unscheduled bilink allocation interval on a best-effort basis, and improvised polled and posted allocation intervals in contention free access phases. The detailed overview of medium access control (MAC) [10][11] and physical (PHY) [12] functionalities in IEEE 802.15.6 was presented in [13]. The real WBAN scenario is variable with different influence factors, so it is difficult to evaluate the influence of a certain factor on protocol performance. However, we can obtain them by changing the parameters setting in a simulation scenario to improve protocol performance when we construct a reliable and effective simulation platform.

NS-3 has been developed to provide an open, extensible network simulation platform for networking research. Some of reasons to use NS-3 include to perform studies that are more difficult or not possible to perform with real system and to achieve system behaviors in a highly controlled, reproducible environment. NS-3 is better than most of the other simulators in completeness, openness, usability and expandability. Moreover, NS-3 provides more realistic network simulations for all kinds of networks, protocols and layers. In this case, it gradually gains greater adoption and more acceptance in the academic circle [14].

In this paper, we analyze the characteristics of NS-3 and WBAN and implement a more accurate and practical WBAN platform on NS-3, in hopes of facilitating researchers and manufacturers to develop products based upon this new standard and helping promoting a set of future works in WBAN or IEEE 802.15.6. However, to the best of our knowledge, there are

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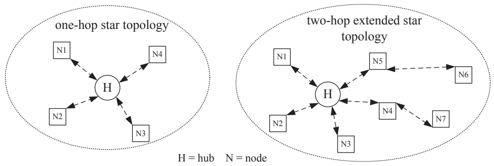

Fig. 1: Network topology

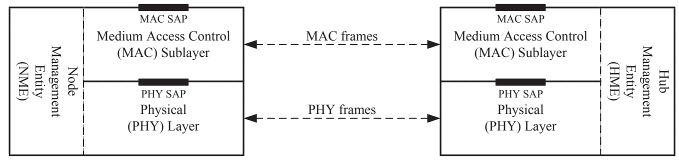

Fig. 2: Reference model

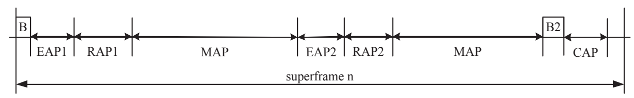

Fig. 3: Superframe format

no simulations available so far to implement WBAN or IEEE 802.15.6 module in NS-3, and this is the first implementation of IEEE 802.15.6 on NS-3. The contributions of this paper are presented below:

- Designing and implementing some modules such as CSMA/CA module, PHY module and MAC module to develop an NS-3 simulator for IEEE 802.15.6.
- According to the built platform and actual situation, we carry out several sets of simulation scenarios to evaluate its performances. In order to verify the validity of our WBAN platform, we record the throughput under different information data rates and arrival rates and note the transmission time under different size of packets and information data rates.
- According to the comparison between some simulators, we can realize the advantages of NS-3 on many aspects obviously, such as simulation time and memory usage. Furthermore, we compare the throughput saturation threshold among NS-2, NS-3 and the analysis results, which not only indicates the superiorities of NS-3, but verifies the effectiveness of our WBAN module.

The rest of the paper is organized as follows: Section II is a brief introduction to MAC layer of the IEEE 802.15.6 standard. Next, we outline the details of the implementation of IEEE 802.15.6 standard on NS-3 in Section III. Then Section IV shows the simulation results and performance analysis. Finally, we present conclusions and future works in Section V.

II. A Brief Description of IEEE 802.15.6 MAC

IEEE 802.15.6 can be widely used in the wearable sensors and a lot of medical devices. In addition, it considers the body effects on the channel and the safety due to the specific absorption rate into the body. In this section, we give a brief overview of the network topology, the reference model and the frame format.

IEEE 802.15.6 defines two kinds of network topology: one-hop star topology and two-hop extended star topology, as illustrated in Fig. 1. There is one hub in a WBAN, whereas the number of nodes in a WBAN is to range from 0 to 64. In a one-hop star BAN, frame exchanges are to occur directly between nodes and the hub of the WBAN. IEEE 802.15.6 also supports the two-hop extended star topology in which the hub and a node are to exchange frames optionally via a relay-capable node.

All nodes and hubs are internally partitioned into a PHY layer and a MAC sublayer [12], in accordance with the IEEE 802.15.6 reference model, as shown in Fig. 2. Direct communications between a node and a hub are to transpire at the PHY layer and MAC layer [15] as specified in this standard; the PHY layer and MAC sublayer of a node or a hub are to use only one operating channel at any given time. Within a node or a hub, the MAC provides its services to the MAC client (higher layer) through the MAC service access point (SAP) located immediately above the MAC sublayer, while the PHY provides its service to the MAC through the PHY SAP located between them.

The structure of the superframe as illustrated in Fig. 3 is divided into seven access phases: exclusive access phase 1 (EAP1), random access phase 1 (RAP1), managed access phase (MAP), exclusive access phase 2 (EAP2), random access phase 2 (RAP2), managed access phase (MAP), and contention access phase (CAP). In RAP and CAP, all the nodes can compete for contended allocations using CSMA/CA access, while the committed scheduled access, improvised access, and unscheduled access on a best-effort basis can be used for periodic and quasi-periodic traffics in MAP. Thus we only consider the EAP1, RAP1, EAP2 and RAP2, and the length of MAP is zero.

III. Design and Implementation of WBAN Module on NS-3

As we all known that WBAN module have been achieved on many kinds of simulators. However, because of some irreplaceable advantages, NS-3 should certainly find its place in the area of network simulation. As shown in Fig. 4 and Fig. 5, the simulation time and memory usage under different packet drop rates on NS-3 show better performances than that on other simulators [16]. In this case, we can implement the more efficient and more accurate simulation on NS-3 to approve real networks with high performance.

The fundamental model of a node on NS-3 is illustrated in Fig. 6. Node is the principal part in NS-3. A computer equipment connected to Internet is called host or terminal system in the physical network. Because NS-3 is a network simulator rather than a specified Internet simulator, a host is replaced by a node in the simulation system. As a computer, we can add a set of functions in a node, e.g., applications, protocol stacks and network devices with driver, to make the computer work better. The concept of channels represents the

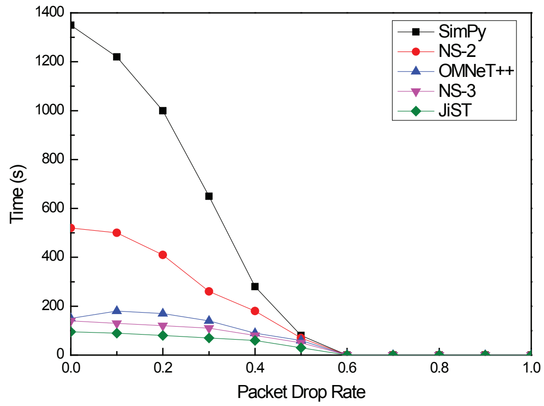

Fig. 4: Simulation time under different packet drop rates and simulators

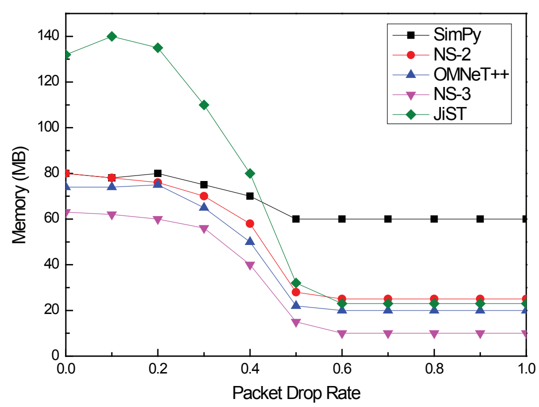

Fig. 5: Memory usage under different packet drop rates and simulators

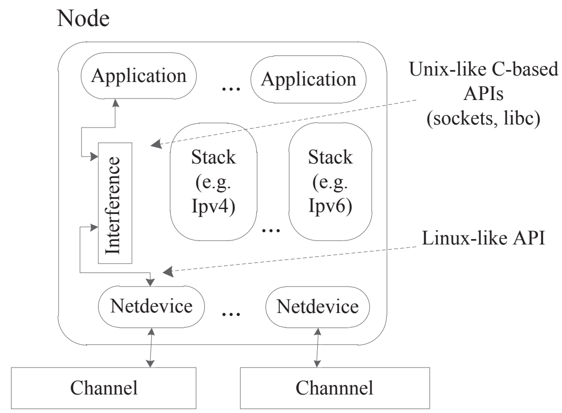

Fig. 6: NS-3 node constructed structure

transmission medium in NS-3 and we can also configure the channel attributes, such as delay and error rate. Moreover, network devices correspond with channels, e.g., the CSMA network device corresponds with the CSMA channel and the Wi-Fi network device corresponds with the Wi-Fi channel.

A. IEEE 802.15.6 System Construction on NS-3

In order to understand the structure of IEEE 802.15.6 and the detailed design process of the communication system, we introduce IEEE 802.15.6 system construction on NS-3, as shown in Fig. 7.

The two circles on the left represent the MAC layer and PHY layer of a node respectively and the right two circles are for hub. The MAC layer is used to coordinate the bandwidth resources among the nodes to achieve higher throughput and lower system delay in the system. Meanwhile, the PHY layer provides transmission medium and interconnection devices for the data transmission among the nodes. Firstly, when a node need to send messages to a hub, the application layer of a node should transmit the required information to the MAC layer via the MAC SAP, and the required information will be taken as the MAC frame body in the MAC frame structure. Next, the MAC header and MAC trailer are added respectively behind and in front of the MAC frame body to make up an integrated frame, then the frame is pushed into the transmit queue preparing to pass to the PHY layer. After that, the frame contends with other frames to obtain access to the channel in the CSMA/CA mode. Therefore, the PHY layer will provide the MAC layer [17] with the channel messages and the MAC layer will decide whether it should send the frame or not and change the transceiver state according to the channel messages. When it matches the transmission conditions, the frame will be past to the PHY layer via PHY SAP and then it will be transmitted to the PHY layer of a hub through the channel. Then the frame is past from the PHY layer to the MAC layer of a hub, and the MAC header and MAC trailer are removed in the MAC layer. Finally, the frame is transmitted to the application layer of a hub to finish the whole communication process.

B. CSMA/CA

In our work, all the nodes and the hub operate in an one-hop star network in the assumption of all nodes supporting the CSMA/CA access in IEEE 802.15.6. All the nodes support the CSMA/CA access to obtain the channel. At a certain time, a packet arrives, and the maximums of the contention window (CW) and the minimum of CW are set according to the priority of the packet. Next, the node sets the value of CW depending on a set of regulations which are described in detail in [18]. Then the node uniformly selects a random integer from the interval [1, CW] as the backoff counter value. The backoff counter is decreased by one once the CSMA/CA slot is idle and there is long enough to complete a packet transaction during the remaining time. Each CSMA/CA slot has fixed duration and the hub considers the CSMA/CA slot to be idle if the channel is monitored idle for a period of time equal to 63 symbol duration time. When the backoff counter is decreased to zero, the node starts to transmit data. The CSMA/CA procedure is as briefly described by the pseudo code Algorithm 1.

As we can see in the pseudo code above, we cannot scan the channel all the time, so we just scan start time point and end time point of the period. If two time points are both idle, we

Algorithm 1 CSMA/CA

```
get data from queue.
get the value of CW.
get the value of backoff counter from [1, CW].
if the priority is seven then
    if the current time is EAP or RAP then
        if the channel is idle then
            backoff counter decrements by one.
            if backoff counter is zero then
                transmit data.
            else
                scan channel in the next slot.
            end if
        else
            lock the backoff counter.
        end if
    else
        lock the backoff counter.
    end if
else if the current time is RAP then
    if the channel is idle then
        backoff counter decrements by one.
        if backoff counter is zero then
            transmit data.
        else
            scan channel in the next slot.
        end if
    else
        lock the backoff counter.
    end if
else
    lock the backoff counter.
end if
```

Algorithm 2 Channel Scan

```
channel scan.
if channel is idle then
    if this is the first channel scan then
        scan channel after 105 μs.
    else
        backoff counter decrements by one.
        if backoff counter is zero then
            transmit data
        else
            scan channel after 40 μs.
        end if
    end if
else
    if this is the first channel scan then
        scan channel after 145 μs.
    else
        scan channel after 40 μs.
    end if
end if
```

consider this period is idle. The specific procedure is described by the pseudo code Algorithm 2.

IV. Simulation Scenario and Discussion

In order to verify the validity and effectiveness of the W-BAN platform, in this section, firstly we design the simulation scenario according to the practical application. Then we record the throughput under different information data rates and the arrival rates and analyze the transmission time under different size of packets and information data rates. Finally, we analyze the simulation results and draw some conclusions.

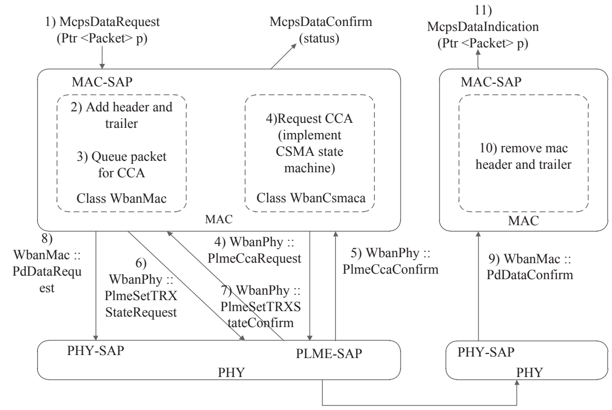

Fig. 7: IEEE 802.15.6 system construction

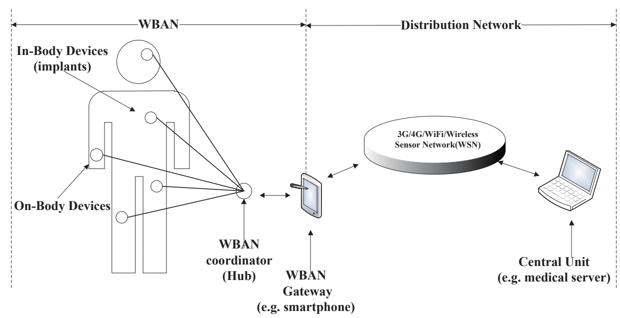

Fig. 8: Simulation scenario

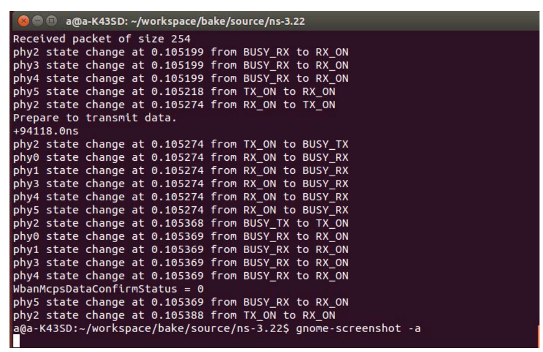

Fig. 9: Logging

A. Simulation Scenario

We build our simulation scenario based on WBAN platform illustrated above. As we can see in Fig. 8, there are five nodes located in, on or around human body which are connected with a hub. Nodes transmit the medical data periodically to a hub, e.g., heart rate data and body temperature data. Then the data is sent from a hub to a smartphone. Next, they are sent to the Central Unit via the 3G, 4G or the Wireless Sensor Network to be calculated and analyzed. Finally, the analysis results will be transmitted to the owner accurately and timely. In this paper, we choose the one-hop star topology as our network topology. Moreover, there are two assumed conditions in the simulation. Firstly, we ignore the bit errors caused by channel factors. That is to say, packet loss is due to packet collision and buffer overflow of nodes. Secondly, the service model we adopt in the simulation is the Constant Bit Rate (CBR) model. The proposed approach could also be applied to large scale wireless networks [19][20].

B. Simulation Results

As we can see in the Section III all nodes send packets to hub simultaneously. The transceiver state of all nodes are illustrated in Fig. 9, the size of packets hub received and the I-ACK nodes received are also shown in it.

Firstly, the transceiver state of all nodes and a hub are close. When a node prepares to send packets to hub, the receiver of node turns on, meanwhile, the transmitter of hub switches on too. Next, the transceiver state of node and hub keep busy until a packet is sent and received respectively. When hub sends I-ACK to the node and the node receives the I-ACK successfully, the entire point-to-point communication process is finished.

Fig. 10 shows throughput under different information data rates and arrival rates. The horizontal axis describes the arrival rate in the network and the arrival rate means the payloads of all the nodes sending to a hub in a second. The vertical axis describes the throughput in the network and the throughput means the receiving payloads of a hub from all the nodes in a second. The four different information data rates is 971.4 kbps, 485.7 kbps, 242.9 kbps and 121.4 kbps in frequency 2.4 GHz. As we can see in Fig. 10, the throughput increases as the transmission rate gets higher under the same arrival rate. The highest throughput under 971.4 kbps is about twice higher than that under 485.7 kbps, four times higher than that under 242.9 kbps, eight times higher than that under 121.4 kbps. Moreover, the throughput under different transmission rates increase linearly at first and then reach the highest points in sequence with the increase of arrival rate. When the arrival rate do not reach its saturation threshold [21][22], all packets arrived can be transmitted successfully in the network. With the increase of arrival rates, the networks under different transmission rates reach their saturation thresholds in sequence. The saturation threshold of different transmission rates is about 450, 250, 130 and 70 kbps, respectively.

Fig. 11 shows the delay under different packet sizes and information data rates. The horizontal axis describes the payload of all the packets transmitted to the hub. The vertical axis describes the delay which includes all the propagation delay, transmission delay and processing delay. Under the same packet size, the delay decreases gradually with the increase of the information data rate. Above all, the delay increases slowly as packet size gets larger under 242.9, 485.7, 971.4 kbps. However, it increases rapidly under 121.4 kbps because in the mentioned case, arrival rate should be $255 \times 10 \times 5 \times 8 = 102$ kbps which is far from the saturation threshold under 242.9, 485.7, 971.4 kbps but is over the saturation threshold under 121.4 kbps. Therefore, the collision between packets increases and delay raises sharply.

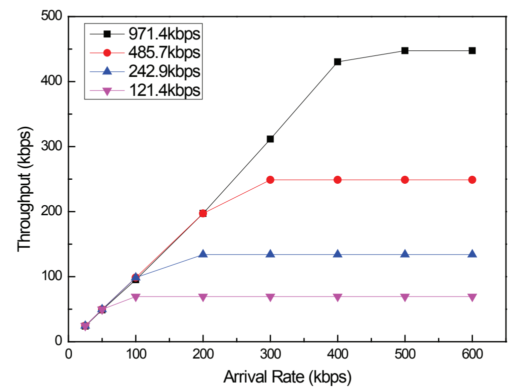

Fig. 10: Average throughput under different transmission rate and arrival rate

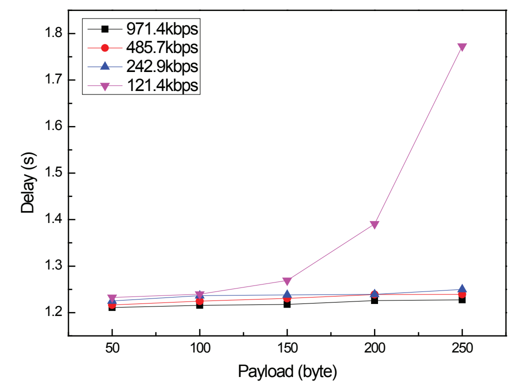

Fig. 11: Average transmission time under different transmission rate and packet size

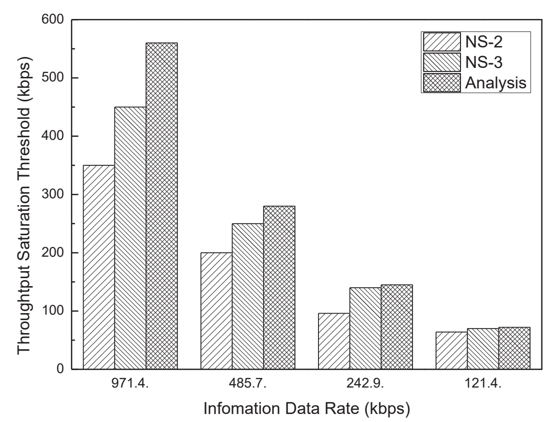

Fig. 12: Average throughput under different information data rate among NS-2, NS-3 and analysis

However, the top priority to implement a simulation is to access to the reality. Moreover, as a suitable network simulator, NS-2 has its advantages in simulation and is widely used in the academic circles. According to the analysis results in [23], the normalized throughput for 5 nodes in priority class 2 is about 0.58. In this case, in order to highlight the advantages of NS-3, we compare the throughput saturation threshold on NS-2 and NS-3 with the analysis results respectively. Fig. 12 shows the throughput saturation threshold of different information data rates among NS-2, NS-3 and the analysis results respectively. The horizontal axis describes the four different information data rates and the vertical axis describes the saturation threshold of NS-2, NS-3 and the analysis results. Because of the lower packet drop rate and the higher transmission efficiency, the saturation threshold of different information data rates on NS-3 are higher than that on NS-2 and closer to the analysis results, which indicates the advantages of NS-3 in network simulation and shows the effectiveness of our WBAN module on NS-3.

V. Conclusion

In order to provide a more effective WBAN simulation platform for more researchers and contribute to evaluating and improving the protocol performance, in the paper we choose NS-3 as our simulator and implement the WBAN module on it. Then we construct simulation scenario and model on our built platform to analyze the performance of IEEE 802.15.6 to verify the validity of the WBAN platform. The simulations show the throughput under different information data rates and arrival rates and manifest the transmission time under different sizes of packets and information data rates. Moreover, we compare the throughput of NS-2, NS-3 and the analysis results respectively based on the same simulation scenario to indicate the effectiveness of our WBAN module and the advantages of NS-3 on some aspects.

In our built WBAN module, as mentioned above, the frame contends with other frames to obtain access to the channel in the CSMA/CA mode. Therefore, adding the Time Division Multiple Access (TDMA) mode in our platform will be part of our future work, which highlights the advantages of the multiple access modes in IEEE 802.15.6 and achieves the more effective and reliable data transmission.

VI. Acknowledgment

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