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# Transmission-Rate-Adaption Assisted Energy-efficient Resource Allocation with QoS Support in WBANs

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***Abstract*—With the advances in wearable sensors and wireless technologies, wireless body area network (WBAN) has become a promising network to provide health applications such as ubiquitous e-Health services and real-time health monitoring. In these WBANs, Quality of Service (QoS) requirements, including packet loss rate (PLR), throughput and delay, need to be guaranteed for providing reliable and real-time data transmission even under highly dynamic environment due to human mobility and postures. Meanwhile, energy efficiency is another key factor to consider for increasing the network lifetime in such a resource-constrained network. In this paper, a transmission-rate-adaption assisted and energy-efficient resource allocation scheme is proposed in which both constraints of QoS metrics and the characteristics of dynamic links are considered. Specifically, a QoS optimization problem is formulated to optimize the transmission power and time slots for each sensor, which minimizes energy consumption subjected to the QoS constraints. Due to the dynamic link characteristics, the link quality may become poor, and then the QoS requirements of normal packets and emergency packets cannot be satisfied. Besides, the emergency packets should receive more attentions with a high priority and high QoS requirements. To guarantee the QoS requirements when the link is very poor, a transmission rate adaption policy (TRAP) is proposed to carefully adjust the transmission rate at each sensor to assist the QoS optimization problem, and a priority-based retransmission strategy (PRS) is designed to apply the retransmission strategy to further improve the performances of the emergency packets with a high priority. Numerical results demonstrate the effectiveness of the QoS optimization problem, the proposed transmission rate adaption policy, and the priority-based retransmission strategy.**

***Index Terms*—Wireless body area network (WBAN), quality of service (QoS), energy efficiency, transmission rate adaption policy, resource allocation**

## I. Introduction

With the rapid increase of the aging population, healthcare requirements for the elderly are rising and overloading the current healthcare systems [1], [2]. Thanks to the advanced sensor and communication technologies, the wireless body area network (WBAN) has emerged as a key technology to provide healthcare applications with high efficiency, which usually contains one hub (Mobile Phone or PDA) and several on-body sensors. In addition, the WBAN has the potential economic impacts in Electronic Health (e-Health) services and other applications, such as patient monitoring, interactive gaming, and telemedicine [3], [4], thus it has attracted more and more interests from both healthcare communities and industries.

For healthcare applications, physiological data streams should be collected and packetized into the packets by the body sensors, which will have different levels of data fusion to support various applications [5]. Moreover, some abnormal physiological signals will be picked out and treated as the emergency packets which are more important than the normal packets. Besides, a loss or an excessive delay of the vital physiological signals acquired by the body sensors may cause a fatal accident [6]. For example, the heart activity readings, e.g., ECG signals, should be monitored continuously for the detection of a heart attack. Once the heart attack is detected, a warning signal needs to be sent to the health professionals for timely assistance. Hence, a loss of heart activity readings may cause a fatal accident, and even result in the death of the patient. Therefore, guaranteeing the quality of service (QoS) of the WBAN, such as packet loss rate (PLR), throughput, and delay, becomes an important issue, especially when the link quality inside the WBAN is dynamic due to human mobility and posture variation [7], [8], [9].

The QoS issues of the WBAN are different from that of the general wireless sensor network due to the particular characteristics of the WBAN: (1) A WBAN is a heterogeneous system, which consists of several energy-constrained sensors and an energy-rich hub. Different sensors collect a variety of physiological signals, and the QoS requirements of these sensors are different. (2) With considering the requirement of lightweight and non-intrusive, the body sensors have a limited size. Thus the resource of them, such as processing, storage and battery energy supply, are extremely constrained comparing with the conventional wireless sensors. (3) The dynamic link characteristics inside the WBAN should be taken into consideration. Channel fading between sensors and the hub is subject to the link distance and many factors such as clothing, obstructions due to different body segments and so on [10], [11]. When the human posture changes, some link factors will inevitably change. Therefore, on-body sensor networks have to deal with such link dynamism caused by the human posture variations. Furthermore, the link quality may be so

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bad that the QoS requirements are hard to be guaranteed when the communication environment changes or the human posture changes[12]. Apparently, these characteristics and the QoS issue are tightly interdependent and mutually influenced. Thus how to guarantee the QoS requirements is a key challenge while both energy-efficient characteristic and link-dynamic characteristic are carefully considered in the WBAN.

In this paper, we investigate all these issues and provide a unified framework to minimize the system energy consumption, in which we consider both the characteristics of the dynamic links due to different postures and the constraints of the QoS metrics, such as PLR, delay, and throughput. The key contributions of this paper are two-fold:

Firstly, we design a QoS optimization problem to optimally allocate the limited resources to each sensor for maximizing the energy efficiency of the WBAN system. Meanwhile, both the characteristics of the dynamic links and the constraints of the QoS metrics are fully considered. The original optimization problem is nonlinear and non-convex. Then we successfully transform the original problem into the form of Generalized Geometric Programming (GGP), which can be solved efficiently.

Secondly, to cope with the various QoS requirements and dynamic link characteristics, a transmission rate adaption policy (TRAP) is proposed to assist the QoS optimization problem to satisfy much stricter QoS requirements and meet poorer link quality by dynamically adjusting the transmission rates of each sensor, and it can be tuned for the desired trade-off between energy consumption and attainable QoS performance. In addition, to further improve the QoS performance of the emergency packets which usually require a higher priority to be transmitted to the hub, a priority-based retransmission strategy (PRS) is designed to apply the retransmission strategy to the emergency packets.

The remainder of this paper is organized as follows. In Section II, we discuss the related work relevant to this paper. The details of the system model are presented in Section III. In Section IV, we describe the QoS constraints of the WBAN system. The optimization problem is described and solved in Section V. And the transmission rate adaption policy and the priority-based retransmission strategy are shown in Section VI. The simulation results are provided in Section VII, and the conclusion and future work are drawn in Section VIII.

## II. Related works

To improve the energy efficiency of the WBAN with considering some QoS metrics, many strategies have been introduced in the literature [1], [13]. Using the empirical evidence or fixed transmit power would result in wasted energy or low reliability due to the rapidly changing link quality [14]. Thus, the transmission power control (TPC) scheme, as a classic approach to adjust the transmission power for reducing the communication cost, has been studied to improve energy efficiency of the WBAN system in [15], [14], [16], [17], [18], [19]. Generally, the history received signal strength indicator (RSSI) is measured to evaluate the channel state for the adjustment of the transmission power in TPC scheme. In [14], the feedback information from the receiver is used to adjust the transmission power in real-time for practical implementation, and the trade-offs between the energy savings and the reliability can be achieved by tuning the parameters of the scheme. To better utilize the partial-periodicity of the measured WBAN channel, the authors weighted an alternate least-squares estimate for the desired prediction interval using the last 4s of received signal [15]. However, the accuracy of the channel prediction was severely affected by complex and rapid changes of the body postures. Thus, the dynamic nature of on-body channel links with varying body postures was characterized in [16], and then a dynamic postural position inference (DPPI) mechanism was proposed to assign the best possible power level to a link, which was based on the observed linear relationship between the transmission power (TP) and the received signal strength indicator (RSSI) [20]. However, the linear relationship between TP and RSSI was studied in wireless sensor networks, in which the wireless sensors were usually located in a fixed position. Thus it may not be appropriate to be directly adopted in the WBAN case. In order to better adapt to the body posture change and dynamic body motion, both of the long-term and the short-term estimations were designed to adjust the transmission power to improve the system lifetime with satisfying the target RSSI threshold range respectively [17].

Comparing with the adjustment of the transmission power in TPC, the resource allocation methods have been shown to more effective to improve the WBAN performance through tuning not only the transmission power but also some other parameters, such as the transmission rate, the number of allocated slots, the packet size and so on [6], [21], [22], [23], [24]. To improve the energy efficiency of various communication scenarios, the required packet size was evaluated and optimized according to the employed acknowledgment policy [21]. As we know, reducing the transmission rate could improve the packet delivery ratio (PDR) with the same SINR, so the source rate and the transmission power could be optimized to provide a high-quality service in health monitoring systems [6]. However, the optimization problem is formulated based on the data transmission from the hubs to the base station rather than from the sensors to the hub. In addition, the number of allocated slots in the MAC layer was optimized for each sensor to minimize the energy consumption, while the latency as an important QoS metric was taken into consideration [22]. Since the method focused on the polling-based communication protocols, the flexibility was restricted. Furthermore, the packet loss rate, regarded as another vital parameter for the WBAN, was not considered. The global energy consumption and the network lifetime were applied as the objective functions for energy optimization in [23]. However, the path loss was assumed as a specific value in advance while the hub broadcast the beacon to reallocate resources for each sensor at the beginning of every superframe, which seems not suitable due to the dynamic link characteristics in the WBAN.

In summary, the heterogeneous and resource-constrained WBAN system requires that the vital data should be transmitted under the requirements of strict QoS constraints while both the dynamic link characteristics and the energy efficiency

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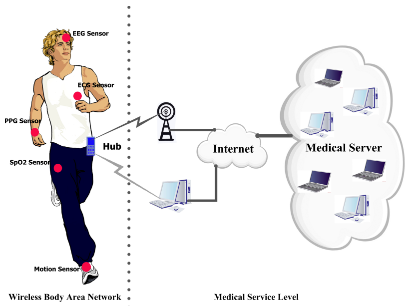


Fig. 1: A classical WBAN architecture

of the WBAN should be considered to improve the system performance. However, the transmission power control methods and the resource allocation methods mentioned above only consider part of requirements in the WBAN whereas failing to consider other specific features. Moreover, none of the above works have introduced a unified framework to deal with these issues such as energy efficiency, dynamic link, and QoS metrics.

## III. System model

With considering the special issues of the WBAN, such as dynamic links, energy efficiency, and QoS requirements, the classical ZigBee and Bluetooth are not well suited for these various WBAN requirements [25], [26]. Thus, in this paper, we design the system model based on the IEEE 802.15.6 protocol, which is developed and published specifically for the WBAN to improve the performance of the system. A typical WBAN model is shown in Fig. 1, which contains one hub and several body sensors deployed on the different positions of the human body. The set of body sensors is defined as $\mathcal{N} = 1, 2, \cdots, N$. These sensors collect physiological signals and transmit them to the hub. Then these signals can be sent to medical servers, which can infer many diseases (e.g. chronic or cardiovascular) at an early stage [5]. With considering the resource-constrained body sensors, one-hop star topology is adopted in 2-3m communication range of sensors, which is most commonly deployed WBAN topology [25], [27]. As recommended by IEEE 802.15.6 standards [25], a TDMA-based scheduled access mechanism in beacon mode with superframe boundaries is adopted to avoid collisions, idle listening, and overhearing of sensors. Meanwhile, the Code Division Multiple Access (CDMA) has high computation requirements, and the Frequency Division Multiple Access (FDMA) requires too complex hardware, both of which are not suitable in the context of the WBAN with the energy-constrained, size-limited and limited frequency bands body sensors [28]. Considering that the network topology of the WBAN is not very dynamic, the TDMA-based protocols would outperform CSMA-based protocols in many aspects, such as energy efficiency, bandwidth utilization, preferred traffic level and so on, with a good synchronization scheme [29]. As presented in Fig. 2, the hub broadcasts beacons to allocate the time slots, the transmission power and the transmission rate to all the sensors, and the sensor only turns active in its dedicated slots to transmit data. In physical (PHY) layer, transmission rates can be specified by adjusting the

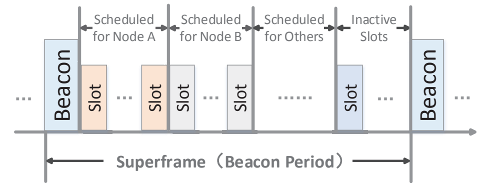


Fig. 2: Scheduled access mechanism in beacon mode with superframe boundaries

parameters of the modulation and coding scheme (MCS). In general, these optional transmission rates are discrete and can be expressed as $\mathcal{R}_{dev} = \{Rate_1, \cdots, Rate_{N_R}\}$ [25]. The notations, summarized in Table I, contain a part of important parameters used in this paper, while other parameters are explained when they first show in the manuscript.

### A. Energy Consumption Model

Since the hub [3] is not as energy critical as the sensors due to its high capacity and easily replaced battery, here we only consider the energy consumption of the on-body sensors. Compared with the energy consumption of the communication for the sensors, the energy used for sensing and processing is much smaller and can be ignored [14], [30]. Therefore, the total energy consumption of the sensor $E_{con}$ mainly consists of the transmitting energy consumption $E_{tran}$ and the receiving energy consumption of the ACK packets $E_{ack}$, which can be expressed as follows,

$$E_{con} = E_{tran} + E_{ack} \tag{1}$$

where $E_{tran} = (1+\alpha) E_{tx} + E_{ct}$ [31]. $\alpha$ is power amplifier inefficiency factor, $E_{tx} = P_{tx} t$ is the transmit energy consumption and $E_{ct} = P_{ct} t$ is the circuitry energy consumption. $P_{ct}$ is the transmission circuitry power, which is a constant depending on the specific transmitter [32], and $P_{tx}$ is the transmission power. $t$ is the time duration of transmitting data packets. $E_{ack} = P_{rx} t_{ack}$ is the receive energy consumption of the small ACK packet, $P_{rx}$ is the receiving power, and $t_{ack}$ is the time duration of receiving ACK packet.

To satisfy the QoS requirements, the transmission power is adjusted according to the path loss of the wireless link. Therefore, the transmit amplifier energy consumption depends on the path loss model in the WBAN. As recommended by the IEEE 802.15.6 standard [25], the path loss in the WBAN can be modeled as

$$PL(d) = PL_{d_0} + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{2}$$

where $d$ is the distance between the sensor and the hub. $PL_{d_0}$ is the path loss at a reference distance $d_0$, and $n$ is the path-loss exponent which is different for different Line-Of-Sight (LOS) channel or Not-Line-Of-Sight (NLOS) channel. The shadowing $X_\sigma$ in $dB$ follows a normal distribution $N\left(0, \sigma^2\right)$ [12]. When the body posture changes, such as from still to run, the mean and the standard deviation of the shadowing $X_\sigma$ varies [33]. As for the posture detection, the distributed and centralized recognition methods have been proposed to classify the human posture and activity in real time with

TABLE I: Notations

| Symbol | Definition |
|---|---|
| $d$ | distance between the sensor and the hub |
| $PL_{d_0}$ | Path loss at a reference distance $d_0$ |
| $\mathcal{N}$ | Set of body sensors |
| $\mathcal{R}_{dev}$ | Set of optimal transmission rates of the sensor |
| $X_\sigma$ | Shadowing of path loss in dB |
| $\gamma$ | Bit Signal to Noise Ratio (bit SNR) |
| $B$ | System bandwidth |
| $PL(d)$ | Path loss with the distance $d$ between the sensor and the hub |
| $\lambda_{i,n}, \lambda_{i,m}$ | Arrival rates of normal packets and emergency packets at sensor i, respectively |
| $\mu_{i,n}, \mu_{i,m}$ | Service rates of normal packets and emergency packets at sensor i, respectively |
| $W_{q,i,n}, W_{q,i,m}$ | Average queuing delays of normal packets and emergency packets at sensor i, respectively |
| $S_{i,n}, S_{i,m}$ | Source rates of normal packets and emergency packets at sensor i, respectively |
| $R_{i,n}, R_{i,m}$ | Transmission rates of normal packets and emergency packets at sensor i, respectively |
| $L_{i,n}, L_{i,m}$ | Lengths of normal packets and emergency packets at sensor i, respectively |
| $P_{tx,i,n}, P_{tx,i,m}$ | Allocated transmission powers for normal packets and emergency packets at sensor i, respectively |
| $t_{i,n}, t_{i,m}$ | Lengths of the scheduled time slots of normal packets and emergency packets at sensor i, respectively |
| $\vec{P}$ | Vector of the transmission powers $P_{tx,i,n}, P_{tx,i,m}, i = 1, .., N,$ for normal packets and emergency packets of all sensors |
| $\vec{T}$ | Vector of the allocated time $t_{i,n}, t_{i,m}$ for normal packets and emergency packets of all sensors |
| $T$ | Length of the superframe in seconds |
| $PLR_{i,n}, PLR_{i,m}$ | Packet loss rates of normal packets and emergency packets at sensor i, respectively |
| $\overline{PLR}$ | Average packet loss rate |
| $\overline{PLR_{i,n}}, \overline{PLR_{i,m}}$ | Average packet loss rate of normal packets and emergency packets at sensor i, respectively |
| $PLR_{i,n,th}, PLR_{i,m,th}$ | Thresholds of the packet loss rate for normal packets and emergency packets at sensor i, respectively |
| $D_{i,n,th}, D_{i,m,th}$ | Thresholds of the delay for normal packets and emergency packets at sensor i, respectively |
| $P_{tx,min}, P_{tx,max}$ | Minimum and Maximum transmission powers in the optional transmission rate set respectively |
| $\mu_{\gamma_{dB}}$ | Mean of bit SNR $\gamma$ in dB |
| $\mu_R$ | Mean of bit SNR when a sensor adopts the transmission rate $R$ with the maximum transmission power $P_{tx,max}$ |
| $\mu_{th}$ | The mean of bit SNR $\gamma$ in dB just satisfy the equation $\overline{PLR\left(\mu_{th}, \sigma_{\gamma_{dB}}\right)} = PLR_{th}$ |
| $\sigma_{\gamma_{dB}}$ | Standard deviation of bit SNR $\gamma$ in dB |

the physiological signals and several extra motion sensors [34], [35], [36], in which the centralized posture detection mechanisms are more suitable for the WBAN system with the resource-rich hub. The hub can collect motion data from its motion sensors in real time, and then extract useful features to describe characteristics of postures. Finally, well-trained classifiers with low complexity can identify current posture in real time by the hub [34]. Therefore, in this paper, we assume the posture can be detected in real time by the hub, and the details of the detection strategy are out of the scope of this paper.

## B. Queuing Model

In the WBAN system, each sensor usually collects the physiological signals, packetizes them into the packets, stores them in the data queue and waits for the assigned time slots to transmit them. However, some abnormal physiological signals may occur, and they need to be picked out and treated with stricter QoS requirements. For example, in hospital, different kinds of sensors are placed on the body of patients to monitor ECG, heart rate, blood oxygen saturation and so on. Once some abnormal signals, such as high heart rate, should be sent to the hub with high "priority", which will be further transmitted to the medical server for timely analysis and treatment. Therefore, we assume that each sensor contains a packet classifier module which can simply classify the packets into one of the two classes, normal packets and emergency packets, based on a preset threshold at each sensor [37]. Correspondingly, these normal packets and emergency packets are put into the normal queue and the emergency queue, respectively. Packets in different queues are treated with different QoS requirements. For example, the delay requirement of the emergency packets is shorter than that of the normal packets.

For normal packets, we assume that they arrive at sensor $i$ periodically with a constant rate $\lambda_{i,n}$ during a superframe. The normal packet transmission process can then be modeled as a $D/G/1$ queuing model, and the service rate $\mu_{i,n}$ follows a Binomial Distribution in consideration of the existence of the packet loss. The upper bound of the average queuing delay $W_{q,i,n}$ of the $D/G/1$ queuing model can be expressed as follows,

$$W_{q,i,n} \le \frac{\lambda_{i,n}\sigma^2_{i,n,B}}{2\left(1-\rho_{i,n}\right)}T \tag{3}$$

where $\rho_{i,n} = \frac{\lambda_{i,n}}{\mu_{i,n}}$, $\lambda_{i,n} = \frac{S_{i,n}T}{L_{i,n}}$, $\mu_{i,n} = \frac{(1-PLR_{i,n})R_{i,n}t_{i,n}}{L_{i,n}}$, and $\sigma^2_{i,n,B} = \frac{PLR_{i,n}(1-PLR_{i,n})R_{i,n}t_{i,n}}{L_{i,n}}$. Here $S_{i,n}$ is the average source rate of normal packets at sensor i. $R_{i,n}$ is the data rate of transmitting the normal packets to the hub at sensor $i$, $t_{i,n}$ is the length of the scheduled time slots at sensor $i$ for normal packets, and $PLR_{i,n}$ is the packet loss rate of normal packets at sensor $i$. $L_{i,n}$ is the length of the normal packets in bits at sensor $i$ and $T$ is the length of the superframe in seconds.

For emergency packets, we assume that the arrivals of them at sensor $i$ follow a Poisson process with an average rate $\lambda_{i,m}$ during a superframe. Then the service rate $\mu_{i,m}$ follows a Binomial Distribution due to the packet loss at sensor $i$. Thus we can model the emergency packet transmission process as an $M/G/1$ queuing model. The average queuing delay of the emergency packet is given by [38]:

$$W_{q,i,m} = \frac{\rho^2_{i,m}\big/\lambda_{i,m} + \lambda_{i,m}\sigma^2_{i,m,B}}{2(1-\rho_{i,m})}T \tag{4}$$

where $\lambda_{i,m} = \frac{S_{i,m}T}{L_{i,m}}$, $\mu_{i,m} = \frac{(1-PLR_{i,m})R_{i,m}t_{i,m}}{L_{i,m}}$, $\rho_{i,m} = \frac{\lambda_{i,m}}{\mu_{i,m}}$, and $\sigma^2_{i,m,B} = \frac{PLR_{i,m}(1-PLR_{i,m})R_{i,m}t_{i,m}}{L_{i,m}}$. Here $S_{i,m}$ is the average source rate of emergency packets. $R_{i,m}$ is the data rate of emergency packets at sensor $i$, $t_{i,m}$ is the length of

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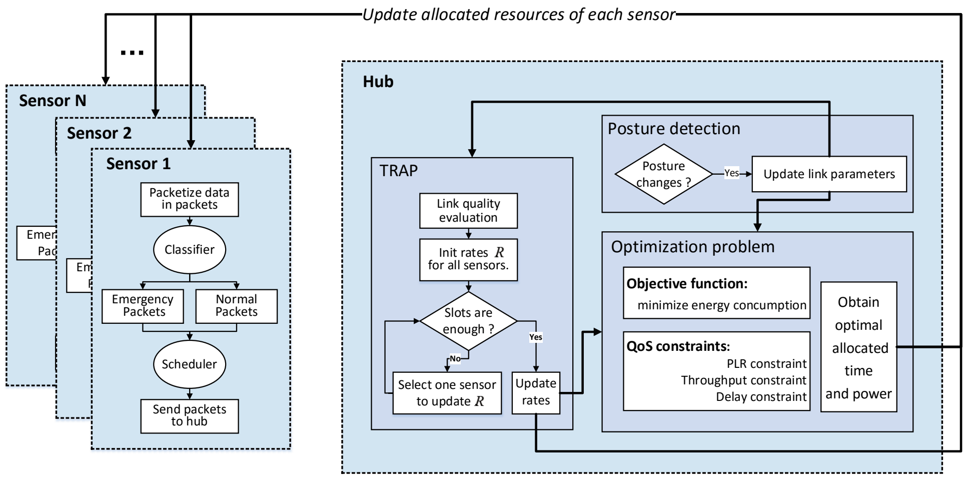


Fig. 3: The proposed unified framework to minimize energy consumption with fully considering both dynamic link characteristic and constraints of QoS metrics.

scheduled time slots at sensor $i$ for emergency packets, and $PLR_{i,m}$ is the packet loss rate of emergency packets at sensor $i$. $L_{i,m}$ is the length of the emergency packets in bits at sensor $i$. In this paper, we denote with $W_{q,i,y}$ the queuing delay of the normal or emergency packets for sensor $i$, $y \in \{n, m\}$. In the remaining of the paper, for the sake of readability, when it is not strictly necessary to distinguish between the normal and emergency packets, the queuing delay of the normal and emergency packets $\{W_{q,i,n}, W_{q,i,m}\}$ will be simply denoted with $W_{q,i}$ for sensor $i$.

## IV. QoS Constraints

In this section, we introduce several QoS metrics, such as the packet loss rate, the throughput, and the delay. And we treat them as the QoS constraints, which should be satisfied while we design the resource allocation scheme. Besides, the different QoS requirements for normal and emergency packets are also taken into consideration.

### A. Packet Loss Rate Constraint

As recommended by IEEE 802.15.6 standard [25], in the ISM band, the Differential Phase Shift Keying (DPSK) modulation and BCH channel coding scheme are adopted in WBAN system. Moreover, three bits for MCS parameters are introduced in PHY frame structure to configure the desired transmission rate. The extension to the case with other kinds of channel codes and modulator is straightforward. Therefore, with the assumption of the bit error occurs independently in a packet transmission, the packet loss rate $PLR$ can be expressed as follows,

$$PLR(\gamma) = 1 - \left(1 - P_{b,B}(\gamma)\right)^L \tag{5}$$

where $\gamma = 10^{\frac{P_{tx,dB} - PL(d) - P_N}{10}} \frac{B}{R}$ is the bit Signal to Noise Ratio (bit SNR). $L$ is the length of a packet in bits. $P_{tx,dB}$ indicates the transmission power in $dB$, $P_N$ is the power of noise in $dB$, $B$ is the system bandwidth, and $R$ is the transmission rate. $P_{b,B}$ is the equivalent bit error rate (BER) using DPSK modulation and BCH coding and the details of $P_{b,B}$ can be found in [10], [39].

Considering the time-varying channel, the average packet loss rate $\overline{PLR}$ can then be calculated as follows,

$$\overline{PLR} = \int_0^{+\infty} PLR(\gamma) P(\gamma | \mu_{\gamma_{dB}}, \sigma_{\gamma_{dB}}) d\gamma \tag{6}$$

where $P(\gamma | \mu_{\gamma_{dB}}, \sigma_{\gamma_{dB}})$ indicates the probability density function of bit SNR, and follows a log-normal distribution as the shadowing $X_\sigma$. $\mu_{\gamma_{dB}}$ is the mean of $\gamma$ in $dB$, and $\sigma_{\gamma_{dB}}$ denotes the standard deviation of $\gamma$ in $dB$. When the human posture changes, the statistic characteristics of shadowing changes correspondingly [33]. Therefore, the packet loss rate constraint can be expressed as follows,

$$\overline{PLR} < PLR_{th} \tag{7}$$

where $PLR_{th}$ is a preset threshold of the average packet loss rate, and it is different for the normal packets and the emergency packets, respectively. Generally, $PLR_{th}$ of the emergency packets is smaller than that of the normal packets due to the importance of the emergency packets.

### B. Throughput Constraint

For both normal packets and emergency packets, the queuing system needs to satisfy the throughput condition, i.e., $\mu \geq \lambda$, in order to be stable [38]. For the normal packets, the throughput constraint $\mu_{i,n} \geq \lambda_{i,n}$ at sensor $i$ can be expressed as,

$$\frac{\left(1 - PLR_{i,n,th}\right) R_{i,n} t_{i,n}}{L_{i,n}} \geq \frac{S_{i,n} T}{L_{i,n}} \tag{8}$$

For the emergency packets, the throughput constraint $\mu_{i,m} \geq \lambda_{i,m}$ is formulated as

$$\frac{\left(1 - PLR_{i,m,th}\right) R_{i,m} t_{i,m}}{L_{i,m}} \geq \frac{S_{i,m} T}{L_{i,m}} \tag{9}$$

### C. Delay Constraint

For each sensor, the total delay that a packet suffers contains three parts: the access delay $W_a$, the queuing delay $W_q$ and the propagation delay $W_p$. The access delay $W_a$ is the time between the packet arrival at the end of the queue and the beginning of the scheduled slots for the first packet in the queue to be transmitted. The queuing delay $W_q$ is the average number of superframes that the packet stays in the queue, and the propagation delay $W_p$ is the time from transmitting the first bit of the packet to the end of the packet. The average access delay is half of the superframe time $T/2$ when we assume the packets arrive uniformly during each superframe period. The propagation delay can be expressed as $W_p = \frac{L}{R}$. Therefore, the delay constraint can be formulated as,

$$W = W_a + W_q + W_p \le D_{th} \tag{10}$$

where $D_{th}$ is a preset threshold for the delay constraint and its value for the emergency packets is usually smaller than that of the normal packets since the emergency packets should have the higher priority for transmission.

## V. QoS Optimization Problem

### A. Statement of QoS Optimization Problem

In this section, the resource allocation in the WBAN is optimized to guarantee the QoS requirements and the energy efficiency of the WBAN system. The QoS optimization problem can be stated as: to minimize sum energy consumption of all the sensors in the WBAN for both normal packets and emergency packets, subject to the constraints of QoS metrics, such as PLR, throughput, and delay. Mathematically, the problem is formulated as follows,

$$\begin{aligned}
\min_{(\vec{P},\vec{T})} \quad & \sum_{i=1}^{i\in N} \left(E_{con,i,n} + E_{con,i,m}\right) \qquad (11)\\
s.t \quad & \overline{PLR_{i,n}} \le PLR_{i,n,th},\\
& \overline{PLR_{i,m}} \le PLR_{i,m,th},\\
& \mu_{i,n} \ge \lambda_{i,n},\\
& \mu_{i,m} \ge \lambda_{i,m},\\
& W_{i,n} \le D_{i,n,th},\\
& W_{i,m} \le D_{i,m,th},\\
& t_{i,n}, t_{i,m} \ge 0,\\
& \sum_{i=1}^{N} \left(t_{i,n} + t_{i,m}\right) \le T,\\
& P_{tx,\min} \le P_{tx,i,n} \le P_{tx,\max},\\
& P_{tx,\min} \le P_{tx,i,m} \le P_{tx,\max},
\end{aligned}$$

where $\vec{P}$ is the vector of the transmission powers $P_{tx,i,n}, P_{tx,i,m}, i \in \mathcal{N}$ for normal packets and emergency packets of all sensors. $\vec{T}$ is the vector of the allocated time $t_{i,n}, t_{i,m}$ for normal packets and emergency packets of all sensors.

In above Qos optimization problem (11), the PLR threshold of emergency packets $PLR_{i,m,th}$ is generally smaller than that of normal packets $PLR_{i,n,th}$. In addition, the average delay of emergency packets $D_{i,m,th}$ should also be smaller than that of normal packets $D_{i,n,th}$.

### B. The QoS optimization problem in the form of GGP

The above optimization problem is a nonlinear and non-convex problem, and it is difficult to solve. Fortunately, we find that the optimization problem (11) is very similar to the form of Generalized Geometric Programming (GGP), which can be solved reliably and efficiently [40]. The Generalized Geometric Programming (GGP) can be expressed as follows[41],

$$\begin{aligned}
\min \quad & f_0(x)\\
s.t \quad & f_i(x) \le 1, i = 1, ..., m\\
& g_i(x) = 1, i = 1, ..., p
\end{aligned}$$

where $g_1, ..., g_p$ are monomials and $f_0, ..., f_m$ are generalized posynomials. The GGP can be mechanically converted to the equivalent Geometric Programming (GP) by a parser using the transformations described in [41], while the GP can be transformed into a convex optimization problem. Then the convex optimization problem can be solved by using many solvers[42].

Thus, we need to transform all the constraints in the QoS optimization problem (11) into the form of generalized posynomials, while the objective function is originally a generalized posynomial. Apparently, all constraints, except the PLR constraint (7) and the delay constraint (10), are all generalized posynomials. Fortunately, both the PLR constraint and the delay constraint can be successfully transformed into the form of generalized posynomials through the following methods.

Firstly, the PLR constraint (7) can not be given as an analytical expression, but the monotone property of the average PLR can be used. Since the average PLR is a monotone decreasing function of the mean of bit SNR $\mu_{\gamma_{dB}}$, which is proved in Appendix A, the PLR constraint is equivalent to $\mu_{\gamma_{dB}} \ge \mu_{th}$, where $\mu_{th}$ satisfies the equation $\overline{PLR(\mu_{th})} = PLR_{th}$. Therefore, the equivalent PLR constraint can be expressed as follows,

$$\mu_{\gamma_{dB}} = E\left[10\log_{10}\left(\frac{B}{R}\right) + P_{tx,dB} - PL(d) - P_N\right] \ge \mu_{th} \tag{12}$$

where $E[\cdot]$ is the expectation operator. Furthermore, the equivalent PLR constraint in the form of generalized posynomials can be derived as follows,

$$P_{tx}R^{-1} \ge B^{-1}10^{\frac{\mu_{th}+PL_{d_0}+10n\log_{10}\left(\frac{d}{d_0}\right)+P_N}{10}} = \theta_{th} \tag{13}$$

Secondly, as for the delay constraints of normal packets and emergency packets, both of them are in the form of the following inequality, which can be successfully transformed in the form of generalized posynomials [41],

$$\frac{p(x)}{r(x) - q(x)} + f(x) \le 1 \tag{14}$$

where $r(x)$ is a monomial, $p(x)$, $q(x)$ and $f(x)$ are generalized posynomials. $q(x) < r(x)$ is the constraint. Then we define a new intermediate variable $v$ as the upper bounder of the first term of (14), which can be expressed as the inequality $\frac{p(x)}{r(x)-q(x)} \le v$. Then the inequality can be expressed as the generalized posynomial inequality $q(x) + \frac{p(x)}{v} \le r(x)$. Finally, we replace the inequality (14) with two generalized posynomials as follows,

$$v + f(x) \le 1, \ q(x) + \frac{p(x)}{v} \le r(x) \tag{15}$$

Using the above decomposition method, the delay constraint of the normal packets can be transformed to the following equivalent form of generalized posynomials,

$$v_{i,n} + \frac{L_{i,n}(R_{i,n})^{-1}}{1 - PLR_{i,n,th}} \leq \left(D_{i,n,th} - \frac{T}{2}\right),$$

$$\frac{2L_{i,n}S_{i,n}T}{1 - PLR_{i,n,th}} + \frac{(PLR_{i,n,th} - PLR_{i,n,th}^2)S_{i,n}TR_{i,n}^2 t_{i,n}^2}{L_{i,n}\cdot v_{i,n}} \leq 2L_{i,n}R_{i,n}t_{i,n}$$

where $v_{i,n}$ is the new intermediate variable. And the delay constraint for the emergency packets can be converted to the following form,

$$v_{i,m} + \frac{L_{i,m}\left(R_{i,m}\right)^{-1}}{(1 - PLR_{i,m,th})} \leq \left(D_{i,m,th} - \frac{T}{2}\right),$$

$$\left(\frac{L_{i,m}S_{i,m}TR_{i,m}^{-1}t_{i,m}^{-1}}{(1 - PLR_{i,m,th})^2} + \frac{PLR_{i,m,th}S_{i,m}TR_{i,m}t_{i,m}}{L_{i,m}}\right)v_{i,m}^{-1} + \frac{2S_{i,m}T}{(1 - PLR_{i,m,th})} \leq 2R_{i,m}t_{i,m},$$

where $v_{i,m}$ is the new intermediate variable. Finally, the delay constraints are transformed to the form of generalized posynomials.

Finally, the QoS optimization problem (11) is successfully transformed to the form of Generalized Geometric Programming (GGP) and formulated as follows,

$$\min_{\left(\vec{P},\vec{T}\right)} \sum_{i=1}^{N} \left((\alpha+1)\, P_{tx,i,n}t_{i,n} + (\alpha+1)\, P_{tx,i,m}t_{i,m}\right)$$

$s.t.$

$$\begin{aligned}
& P_{tx,i,n}\left(R_{i,n}\right)^{-1} \geq \theta_{i,n,th},\\
& P_{tx,i,m}\left(R_{i,m}\right)^{-1} \geq \theta_{i,m,th},\\
& \frac{\left(1 - PLR_{i,n,th}\right)R_{i,n}t_{i,n}}{L_{i,n}} \geq \frac{S_{i,n}T}{L_{i,n}},\\
& \frac{\left(1 - PLR_{i,m,th}\right)R_{i,m}t_{i,m}}{L_{i,m}} \geq \frac{S_{i,m}T}{L_{i,m}},\\
& v_{i,n} + \frac{L_{i,n}\left(R_{i,n}\right)^{-1}}{1 - PLR_{i,n,th}} \leq \left(D_{i,n,th} - \frac{T}{2}\right),\\
& \frac{(PLR_{i,n,th} - PLR_{i,n,th}^2)S_{i,n}TR_{i,n}^2t_{i,n}^2}{L_{i,n}\cdot v_{i,n}} + \frac{2L_{i,n}S_{i,n}T}{1 - PLR_{i,n,th}} \leq 2L_{i,n}R_{i,n}t_{i,n}\\
& v_{i,m} + \frac{L_{i,m}\left(R_{i,m}\right)^{-1}}{\left(1 - PLR_{i,m,th}\right)} \leq \left(D_{i,m,th} - \frac{T}{2}\right),\\
& \left(\frac{L_{i,m}S_{i,m}TR_{i,m}^{-1}t_{i,m}^{-1}}{\left(1 - PLR_{i,m,th}\right)^2} + \frac{PLR_{i,m,th}S_{i,m}TR_{i,m}t_{i,m}}{L_{i,m}}\right)v_{i,m}^{-1}\\
& \qquad + \frac{2S_{i,m}T}{\left(1 - PLR_{i,m,th}\right)} \leq 2R_{i,m}t_{i,m},\\
& \sum_{i=1}^{N}\left(t_{i,n} + t_{i,m}\right) \leq T,\ t_{i,n}, t_{i,m} \geq 0,\\
& P_{tx,\min} \leq P_{tx,i,n} \leq P_{tx,\max},\\
& P_{tx,\min} \leq P_{tx,i,m} \leq P_{tx,\max},
\end{aligned}$$

Efficient solution solvers for the Generalized Geometric Programming (GGP) are well developed. In this paper, we use the YALMIP [40], a toolbox for modeling and optimization in MATLAB, to solve the transformed QoS optimization problem and obtain the optimal power and time slots allocation, $\vec{P}^*, \vec{T}^*$, for all the sensors in the WBAN system.

## VI. Transmission-Rate-Adaption and Priority-based Retransmission Strategies

In the above QoS optimization problem, QoS metrics are treated as the constraints which need to be strictly satisfied. However, due to the dynamic link characteristics inside the

**Algorithm 1** Transmission Rate Adaption Policy (TRAP)

**Require:**

Calculate $\theta_{i,n,th}$, $\theta_{i,m,th}$ for normal packets and emergency packets at sensor $i$ respectively.
$\theta_{th} = B^{-1}10^{\frac{\mu_{th}+PL_{d_0}+10n\log_{10}\left(\frac{d}{d_0}\right)+P_N}{10}}$

Calculate the transmission rate threshold $R_{i,n,th}, R_{i,m,th}$ according to (16).

Obtain initial $R_{i,n,cur}, R_{i,m,cur}, \mu_{i,n,R_{cur}}, \mu_{i,m,R_{cur}}$ in accordance with $R_{i,n,th}, R_{i,m,th}$ at sensor $i$.

$$R_{cur} = \begin{cases} Rate_1 & R_{th} < Rate_1\\ Rate_h & Rate_{N_R} \leq R_{th}\\ Rate_j & Rate_j \leq R_{th} < Rate_{j+1},1 \leq j < N_R \end{cases}$$

$$\mu_{R_{cur}} = \begin{cases} \mu_{th} & Rate_{N_R} \leq R_{th}\\ \mu_{th} & Rate_j \leq R_{th} < Rate_{j+1},\ 1 \leq j < N_R\\ 10\log_{10}\left(\frac{P_{tx,max}}{R_{cur}}B\right) - PL_{d_0} - 10n\log_{10}\left(\frac{d}{d_0}\right) - P_N & R_{th} < Rate_1 \end{cases}$$

Calculate $N_{alloc}$, the summation of the number of slots allocated to the sensors to satisfy throughput constraints with $R_{i,n,cur}, R_{i,m,cur}$.

**Ensure:**

**while** $N_{alloc} > \beta \cdot N_{total}$ **do**

  Update the candidate of the transmission rate $R_{i,n,cad}, R_{i,m,cad}$ at sensor $i$ according to the following equation.

$$R_{cad} = \begin{cases} R_{cur} & R_{cur} = Rate_{N_R}\\ Rate_{j+1} & Rate_j \leq R_{cur} < Rate_{j+1},1 \leq j < N_R \end{cases}$$

  Recalculate the PLR cost $\omega_{i,n}$, $\omega_{i,m}$ for normal packets and emergency packets at sensor $i$, respectively.

$$\omega = \begin{cases} \frac{\left|\mu_{th}-\mu_{R_{cad}}\right|}{\mu_{th}} & R_{cur} < Rate_{N_R}\\ \text{inf} & R_{cur} = Rate_{N_R} \end{cases}$$

  **if** $\omega$ of each sensor is equal to inf **then**

    break;

  **end if**

  Select the sensor which has the minimum cost for normal or emergency packets by $ind = \arg\left(\min_{i\in\mathcal{N}}\left(\omega_{i,n}, \omega_{i,m}\right)\right)$.

  Set $R_{ind,cur}$ to $R_{ind,cad}$,and reset $\mu_{ind,R_{cur}}$ to $\mu_{ind,R_{cad}}$.

  Recalculate $N_{alloc}$.

**end while**

**return**

Update transmission rates $R_{i,n}, R_{i,m}$, and then reset $\theta_{i,n,th}, \theta_{i,m,th}$ of the PLR constraint for the QoS optimization problem.
$R_{i,n} = R_{i,n,cur}, \quad R_{i,m} = R_{i,m,cur}$
$\theta_{th} = B^{-1}10^{\frac{\mu_{R_{cur}}+PL_{d_0}+10n\log_{10}\left(\frac{d}{d_0}\right)+P_N}{10}}$

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WBAN, the QoS constraints, especially the packet loss rate (PLR), sometimes cannot be satisfied even with the maximum transmission power when the link quality becomes much worse, and then the QoS optimization problem would not have a solution to allocate the resources for all sensors. In addition, compared with the normal packets, the emergency packets, which contain the information of vital abnormal signals, should have a higher priority to be transmitted with higher QoS performances. In this section, the transmission-rate-adaption policy and the priority-based retransmission strategy are designed to solve these problems.

### A. Transmission Rate Adaption Policy

As we know, reducing transmission rate can gain better PLR performance with same signal-to-noise (SNR) [43], while it also will cost more energy due to longer transmission time. Thus, when the link has a good quality, transmission rate adaption policy prefers to set transmission rates to the maximum for improving energy efficiency. Once QoS optimization problem cannot satisfy the QoS requirements by adjusting transmission power, transmission rate adaption policy will explore adjusting transmission rate to satisfy current QoS requirements with worse link quality. Besides, reducing the transmission rate is at the cost of more energy consumption. In some cases, the longer system lifetime is more important than the stricter QoS requirements. Thus the algorithm should be able to have a trade-off between the energy consumption and the PLR requirements. In this paper, we propose the transmission rate adaption policy (TRAP) to deal with the above problems caused by the dynamic link characteristic and various QoS requirements.

Firstly, we need to obtain the initial transmission rate $R_{cur}$ for each sensor which can just satisfy the PLR threshold. As seen in the equivalent PLR constraint (13), the transmission rate $R_{cur}$ should satisfy the following inequality to meet the PLR constraint,

$$R_{cur} \leq R_{th} = \frac{P_{tx,max}}{\theta_{th}} \tag{16}$$

where $R_{th}$ is the transmission rate threshold which meets the PLR constraint with the maximum transmission power. When $R_{th}$ is larger than the maximum transmission rate $Rate_{N_p} \in \mathcal{R}_{dev}$, it means that the PLR constraint can be satisfied by adjusting the transmission power even with the maximum transmission rate in the current link quality. Then the initial transmission rate $R_{cur}$ is set to the maximum rate $Rate_{N_p}$ to save energy. When $R_{th}$ is smaller than the minimum transmission rate $Rate_1 \in \mathcal{R}_{dev}$, $R_{cur}$ is set to the minimum transmission rate $Rate_1$. Otherwise, $R_{cur}$ is chosen from the transmission rate set $\mathcal{R}_{dev}$, which is just smaller than $R_{th}$. Since the $R_{cur}$ is smaller than $R_{th}$, the PLR constraint (13) can be satisfied in the QoS optimization problem.

Secondly, turning down the transmission rate means increasing the number of allocated slots in the superframe to satisfy the throughput constraint and thus consuming more energy. Therefore, we need to check whether the total number of allocated slots $N_{alloc}$ with the initial transmission rate $R_{cur}$ exceeds the preset number $\beta \cdot N_{total}$. Here, the parameter $\beta \in [0, 1]$ is designed to tune the desired trade-off between energy consumption and average PLR, and $N_{total}$ is a total number of slots in a superframe. When $N_{alloc}$ is larger than $\beta{\cdot}N_{total}$, it means throughput constraints of some sensors with current transmission rate $R_{cur}$ can not be satisfied. Therefore, we need to choose some sensors to raise the transmission rate step by step until $N_{alloc} \leq \beta \cdot N_{total}$. Which sensors should be chosen to raise the transmission rates $R_{cur}$ to satisfy the slot number limitation is the key issue in TRAP. Once a sensor is chosen to raise its transmission rate $R_{cur}$, it means its PLR constraint cannot be guaranteed. Thus, we define the following PLR cost parameter to evaluate the PLR increment compared with the excepted PLR while raising transmission rate,

$$\omega = \frac{\left|\mu_{th} - \mu_R\right|}{\mu_{th}} \tag{17}$$

$$\mu_R = 10\log_{10}\left(\frac{P_{tx,max}}{R}B\right) - PL_{d_0} - 10n\log_{10}\left(\frac{d}{d_0}\right) - P_N \tag{18}$$

where $\mu_R$ is the mean of bit SNR when a sensor adopts the transmission rate $R$ with the maximum transmission power $P_{tx,max}$. Since the average PLR is a monotone decreasing function of the mean of bit SNR $\mu_{\gamma_{dB}}$, which is proved in Appendix A, the difference between $\mu_R$ and $\mu_{th}$ can be used to estimate the difference between $PLR$ with transmission rate $R$ and $PLR_{th}$, where $\mu_{th}$ satisfies the equation $PLR(\mu_{th}) = PLR_{th}$. In each loop, the sensor which has the minimum PLR cost is chosen to raise its transmission rate. This way can avoid that one sensor has much larger PLR cost than the others.

Finally, we can adjust the parameter $\beta$ to tune the desired trade-off between energy consumption and average PLR. The smaller $\beta$ is, the stricter the slot number limitation is. Thus more sensors need to be set to the larger transmission rate in the transmission rate set $\mathcal{R}_{dev}$, correspondingly average PLR is larger, but less energy is consumed, and vice verse. The details of the proposed TRAP are described in Algorithm 1.

### B. Priority-based Retransmission Strategy

After obtaining the allocated slots from the hub, each sensor adjusts the allocated slots for the normal packets and the emergency packets, respectively. Considering that the emergency packets are more important than the normal packets, the emergency packets should be given more high priority to access the allocated slots for timely transmission. In addition, the number of the emergency packets in one superframe is time-variant while the arrivals of the normal packets are stable, thus the utilization of the allocated slots for the emergency packets is limited. In this paper, we combine the allocated slots for the normal packets and the emergency packets and then reallocate these slots to improve the performance of the WBAN system.

At the beginning of each superframe, each sensor will check whether the emergency queue is empty. If there are emergency packets in the emergency queue, they will be firstly transmitted by the sensor. Besides, when an emergency packet is lost due to the path loss of the channel, it will be retransmitted by the sensor. And when the maximum number of retransmission of the emergency packet is reached, the emergency packet will be

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**Algorithm 2** Priority-based Retransmission Strategy (PRS)

**Require:**

The number of emergency packets and normal packets of sensor $i$ at the beginning of current superframe are $N_{i,q,n}$ and $N_{i,q,m}$.

The maximum number of retransmission of emergency packets of sensor $i$ is $N_{i,q,th}$.

The rest allocated time in current superframe is $t_{i,rest} = t_{i,n} + t_{i,m}$. And the number of retransmissions is $N_{i,retran} = 0$.

**Ensure:**

```
while (N_{i,q,m} > 0) and (R_{i,m} * t_{i,rest} > L_{i,m}) do
  if N_{i,retran} ≥ N_{i,q,th} then
    Discard the first emergency packet.
    Update N_{i,q,m} = N_{i,q,m} − 1 and N_{i,retran} = 0.
  else
    Try to send the first emergency packet to the hub.
    if the transmission is successful then
      Update N_{i,q,m} = N_{i,q,m} − 1 and N_{i,retran} = 0.
    else
      Update N_{i,retran} = N_{i,retran} + 1.
    end if
    Update t_{i,rest} = t_{i,rest} − L_{i,m}/R_{i,m}.
  end if
end while
while (N_{i,q,n} > 0) and (R_{i,n} * t_{i,rest} > L_{i,n}) do
  Try to send the first normal packet to the hub.
  if the transmission is successful then
    Update N_{i,q,n} = N_{i,q,n} − 1.
  else
    Discard the first normal packet and update N_{i,q,n} = N_{i,q,n} − 1.
  end if
  Update t_{i,rest} = t_{i,rest} − L_{i,n}/R_{i,n}.
end while
```

discarded and then the first emergency packet in the emergency queue will be transmitted following the FIFO strategy. Once the emergency queue is empty, the normal packets will be transmitted. The details of the proposed PRS are described in Algorithm 2.

In the system implementation, the resource-rich hub performs the QoS optimization problem while the posture state changes. The parameters $(\beta, \vec{T}, \overrightarrow{PLR}_{th}, \vec{D}_{th})$ are set by the administrator at the hub, where $\overrightarrow{PLR}_{th}$ is the vector of the $PLR$ thresholds $PLR_{i,n,th}, PLR_{i,m,th}, i \in \mathcal{N}$ of normal packets and emergency packets for all sensors, and $\vec{D}_{th}$ is the vector of the delay thresholds $D_{i,n,th}, D_{i,m,th}, i \in \mathcal{N}$ of normal packets and emergency packets for all sensors. The parameters $(L_{i,n}, L_{i,m})$ are provided by the sensor $i$. While the change of postures is detected, the hub recalculates the $\vec{R}$ with current link parameters by using the TRAP scheme, and then computes the optimal transmission power $\vec{P}^*$ and the optimally allocated time slots $\vec{T}^*$ by solving the QoS optimization problem with the rates $\vec{R}$. Then the hub feeds back the parameters $(\vec{R}, \vec{P}^*, \vec{T}^*)$ to each sensor through the broadcasting beacons at the beginning of the superframe once the posture changes. Then each sensor can schedule the normal packets and emergency packets based on the PRS strategy. The details of the proposed unified framework are given in Fig. 3.

## VII. Simulations

### A. Simulation Setting

In this section, considering that there is no IEEE 802.15.6-based hardware to implement the proposed resource allocation scheme, a variety of simulations are designed to evaluate the performance of the proposed QoS optimization problem and the transmission rate adaption policy (TRAP). We built an event-driven WBAN system based on MATLAB. The application module generates a constant rate of normal packets and Poisson arrival rate of emergency packets. The MAC module supports the scheduled access mechanism in beacon model with superframe boundaries as recommended by IEEE 802.15.6 [25]. Also, the PHY module can set specific transmission rate by adjusting the parameters of MCS. For solving the proposed QoS optimization problem (11), an MATLAB-based optimization toolbox, YALMIP [40], is also embedded in the simulation environment. The channel module generates the path loss in each slot with using the reference code by IEEE 802.15.6 standard [44].

A classical WBAN as shown in Fig. 1 is adopted, which consists of five on-body sensors and a hub. The deployed positions and the corresponding body link parameters of all sensors are given in Table II [33], [12]. All sensors have the battery capacity $100J$. In the simulations, the variation of the postures is modeled as a Markov chain, and the probability of different posture change can be determined from real human posture trace [45]. For convenience, we only consider three types of body postures, i.e., still, walk and run, and their steady-state probabilities are set to 0.5, 0.3 and 0.2, respectively. The extension to the case with more body postures is straightforward. In addition, we assume that these postures can be identified with high accuracy in real time by the hub [34], [35], [36]. In this paper, the standard derivation $\sigma_s$ of the shadowing will be changed with the postures as shown in Table III, which are set based on the measurement results in [33], [12]. We assume that the path loss for each sensor remains unchanged during a superframe period, since the duration of the slow fading is larger than the typical length of one superframe, e.g., $100ms$ [33]. Other simulation parameters are summarized in Table IV. Note that, all the simulations are based on the IEEE 802.15.6 standard [25].

In order to better evaluate the performance, we compare the performances of five different approaches:

- The proposed optimal resource allocation (ORA) scheme **without** transmission rate adaption policy (TRAP) and priority-based retransmission strategy (PRS), abbreviated ***ORA without TRAP-PRS***.
- The proposed optimal resource allocation (ORA) scheme **with** transmission rate adaption policy (TRAP) and priority-based retransmission strategy (PRS), abbreviated ***ORA with TRAP-PRS***.

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TABLE II: Parameters of the sensors

| Sensor Index | Location | $d$ (cm) | LOS/NLOS | $n$ | $PL_{d_0}$ |
|---|---|---|---|---|---|
| 1 | Head | 69 | LOS | 3.11 | 35.2 |
| 2 | Chest | 36 | LOS | 3.23 | 41.2 |
| 3 | R wrist | 48 | NLOS | 3.35 | 32.2 |
| 4 | Thigh | 34 | NLOS | 3.45 | 32.5 |
| 5 | Foot | 100 | LOS | 3.11 | 35.2 |

TABLE III: Standard deviation $\sigma_S$ and Source Rate

| | $\sigma_S(dB)$ | | | Source Rate (kbps) | |
|---|---|---|---|---|---|
| Sensor Index | Still | Walk | Run | $S_n$ | $S_m$ |
| 1 | 6.054 | 5.4153 | 6.1118 | 20 | 10 |
| 2 | 4.8497 | 7.4276 | 7.8011 | 68 | 25 |
| 3 | 5.113 | 4.9736 | 4.5625 | 34 | 18 |
| 4 | 2.6356 | 4.4678 | 4.0395 | 50 | 25 |
| 5 | 2.2796 | 3.6547 | 2.6646 | 35 | 20 |

- The uniform power allocation (UPA) approach, in which each sensor has the same transmission power and the transmission rates are all set to the maximum $Rate_{N_R}$ in transmission rate set $\mathcal{R}_{dev}$, abbreviated ***UPA***.
- The general transmission power control (TPC) approach [14], in which the transmission power is adjusted in real time based on the feedback information from the receiver, and the allocated time slots can satisfy the throughput constraint for the system stability, abbreviated ***TPC***.
- The Link-State-Estimation-based transmission power control (LSEPC) [17] is the enhanced transmission power control approach, in which not only the short-term link estimation but also the long-term link estimation is used to adapt the transmission power, abbreviated ***LSEPC***.

In this paper, we want to evaluate the role of the TRAP and PRS in improving the performance of the WBAN, so both *ORA without TRAP-PRS* and *ORA with TRAP-PRS* are compared in the simulations.

For various scenarios, the demands for the PLR performance and the energy efficiency are determined according to the specific needs of the scenarios. As we know, the stricter PLR threshold is at cost of more energy consumption, and the requirements of PLR performances are different with considering the energy efficiency in different scenarios. In order to simulate the demands of different scenarios, the PLR threshold is set in the range from 0.5% and 15% to cover enough scenarios. And the PLR threshold of the emergency packets is smaller than that of the normal packets considering that the emergency packets are more important. Here, we set the threshold of the queuing delay for the normal packets as $1000ms$ and the threshold of the queuing delay for the emergency packets as $200ms$. In the simulations, we study the performance comparison of the five approaches with different PLR thresholds.

### *B. Simulation Results*

We first evaluate the energy efficiency performance under different PLR thresholds. We vary the PLR threshold of all sensors to simulate different scenarios. Note that, the *UPA*, *TPC* and *LSEPC* schemes can obtain the different PLR performance by adjusting the parameters in their algorithms. In Fig. 4, we illustrate the relationship between the average PLR

TABLE IV: Simulation Parameters

| Parameters | Value |
|---|---|
| Bandwidth | 1MHz |
| Noise Power $P_N$ | -94dBm |
| Rate Set $\mathcal{R}_{dev}$ | [121,243,486,971]Kbps |
| Transmission power range $P$ | -30dBm to 0dBm |
| One slot length $t_{slot}$ | 0.5 ms |
| One superframe length $T$ | 100 ms |
| Transmission circuitry power $P_{ct}$ | 0.5uW |
| Number of Sensors $N$ | 5 |
| Factor $\alpha$ | 1.4 |

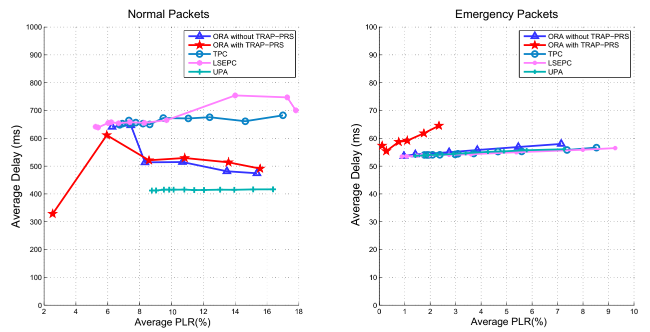


Fig. 4: Relationship between the average delay and the average PLR for normal packets and emergency packets, respectively.

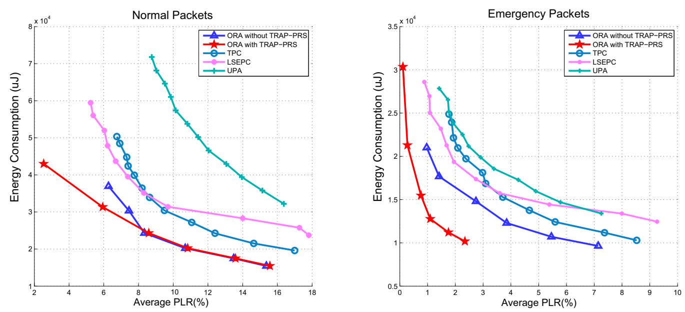


Fig. 5: Relationship between the total energy consumption and the average PLR for normal packets and emergency packets, respectively.

and the average delay of all sensors for the normal packets and the emergency packets, while the relationship between the total energy consumption and the average PLR of all sensors is illustrated in Fig. 5. In this paper, we preset the delay thresholds of normal packets and emergency packets. A packet will be discarded once its delay exceeds the preset delay threshold for each sensor. Thus the average delay of all algorithms is under the delay threshold as seen in Fig. 4. Hence, the average PLR and the energy consumption can be used to evaluate the performance of these approaches. We can see from Fig. 5 that all approaches achieve a reduction of energy consumption with the degradation of PLR performance and the proposed two approaches have the highest energy efficiency performance. That means the proposed two approaches can obtain a lower energy consumption with a same average PLR performance. This is because the proposed optimization problem is carefully designed to minimize the energy consumption under the QoS constraints, meanwhile dynamic link characteristics are considered into the optimization problem for improving the robustness of the system.

In addition, only the proposed *ORA with TRAP-PRS* ap-

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proach can obtain the stricter PLR performance, which is smaller than 5% for the normal packets and 1% for the emergency packets as shown in Fig. 4 and Fig. 5. This is because that at some poor link scenarios, even if the transmission powers are set to the maximum value, the PLR threshold cannot attain the minimum 0.5% with the constant transmission rates. So the other four approaches, including the proposed *ORA without TRAP-PRS*, cannot satisfy some strict PLR constraints in some scenarios, which may be vital in health monitoring applications. Fortunately, the proposed *optimal resource allocation (ORA)* approach can satisfy the stricter PLR constraint with adopting the *transmission rate adaption policy (TRAP)* and the *priority-based retransmission strategy (PRS)*. It is because that the transmission rates of all sensors can be adjusted to gain better PLR performance with same SINR by *TRAP*, and *PRS* can also further improve the PLR performance of the emergency packets by adopting the re-transmission strategy. Furthermore, although the transmission rate has to be adjusted in the *ORA with TRAP-PRS* to satisfy the PLR constraint, which results in more time slots requirement and thus more energy consumption, the performance of the *ORA with TRAP-PRS* is still similar to that of the *ORA without TRAP-PRS* for the normal packets. It is because the proposed transmission rate adjusting strategy in TRAP is designed to minimize the penalty introduced by adjusting transmission rate. Moreover, it should be pointed out that TRAP only adjusts the transmission rate when the channel condition becomes worse. And when the channel is good, the transmission rate will be set to the maximum value for saving energy and channel resource.

We now evaluate the performance of optimal resource allocation (ORA) with and without the re-transmission policy in detail, when the PLR threshold is varied to simulate different scenarios. As shown in Fig. 6, we observe that the PLR performances of both two schemes become better with the decrease of the PLR threshold, while the total energy consumption gradually increases. It is because the optimal resource allocation scheme will increase the transmission power and allocate more channel resources to meet the higher PLR requirements, which leads to more energy consumption. On the other hand, although average PLR of normal packets using ORA with re-transmission policy has a slight increase compared with using ORA without re-transmission policy, the PLR performance of emergency packets with re-transmission policy has been significantly improved. With the re-transmission policy, the total energy consumption has a small increase to re-transmit the lost emergency packets. However, to obtain the same PLR performance level, the ORA without re-transmission policy will cost more energy as shown in Fig. 5. The reason for this phenomenon is that the improved PLR performances by the re-transmission policy will cause much energy with the adjustment of transmission power by optimizing the resource allocation problem.

To analyze the effect of *TRAP*, the allocated transmission rates for different sensors in different postures are shown in Fig. 7. We can easily find that the results for different sensors by *TRAP* are different with different postures. It is because that *TRAP* can adjust the transmission rates of each sensor to satisfy their PLR constraint corresponding to their respective link quality. Besides, the allocated transmission rates of different sensors versus the PLR requirements are given in Fig. 8, and we can find that different sensors have different transmission rate allocations. Because different sensors have different link quality, the transmission rates are allocated by TRAP to each sensor for satisfying the dedicated PLR requirements. In addition, for a single sensor, the allocated transmission rate increases as the PLR constraint becomes relaxed with

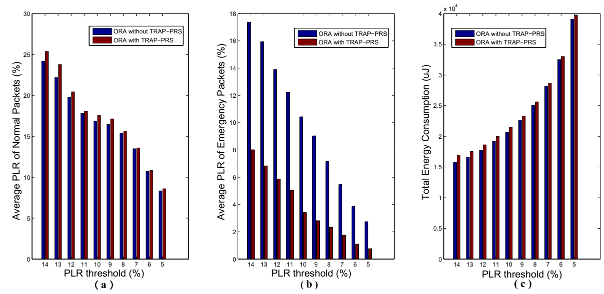


Fig. 6: a) Relationship between the PLR threshold and average PLR of normal packets; b) Relationship between the PLR threshold and average PLR of emergency packets; c) Total energy consumption of the system versus the PLR threshold.

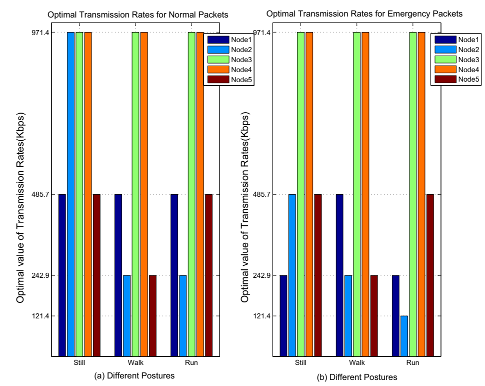


Fig. 7: Comparison of the allocated transmission rates of five sensors in different postures using TRAP with PLR threshold of 1% :(a) for normal packets. (b) for emergency packets.

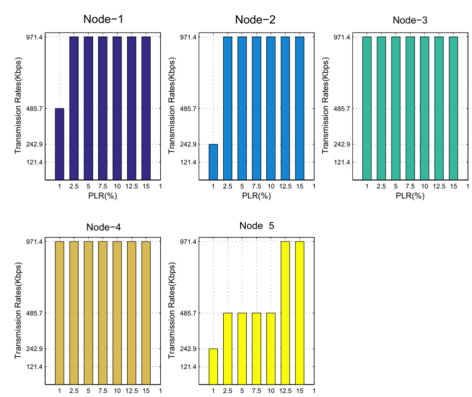


Fig. 8: Relationship between the transmission rate allocation results and PLR of normal packets at each sensor in the walking posture using TRAP.

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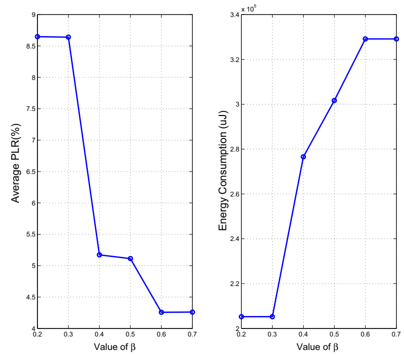


Fig. 9: Average PLR with expectations of 0.5% and Total energy consumption versus the value of $\beta$ using Transmission Rate Adaption Policy (TRAP) and Priority-based Retransmission Strategy (PRS) over 10000 superframes.

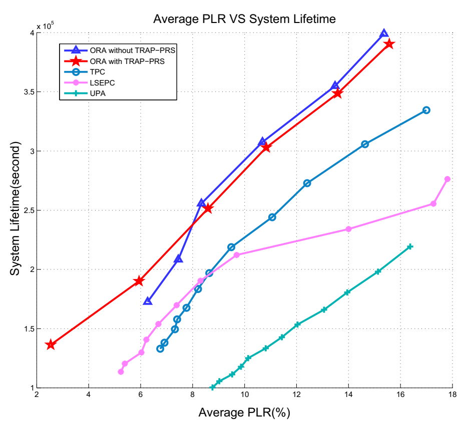


Fig. 10: Relationship between the average PLR and the system lifetime with $\beta = 0.5$ in TRAP.

larger PLR threshold. This is because lower transmission rate means more energy consumption, thus the transmission rate adjusting strategy in TRAP will turn the rate up once the PLR threshold becomes larger to save energy. As for the sensor 3 and the sensor 4, their transmission rates remain unchanged at the maximum transmission rate, and it is because the link quality of the sensor 3 and the sensor 4 is so good that the PLR threshold can be satisfied with the maximum transmission rate.

The lower average PLR is at the cost of more energy consumption as seen in Fig. 5, in which the energy consumption increases shapely when the average PLR becomes smaller. However, in some cases, we may prefer the longer system lifetime rather than the stricter QoS requirements. Thus, the parameter $\beta$ in *TRAP* is used to be tuned for the desired trade-off between the energy consumption and the average PLR. As shown in Fig. 9, when the value of $\beta$ is raised, the lower PLR can be attained, while the energy consumption is larger. To evaluate the energy efficiency performance, we illustrate the relationship between the average PLR and the system lifetime with $\beta = 0.5$ in Fig. 10. We can see that the system lifetime of the proposed *ORA with TRAP-PRS* and *ORA without TRAP-PRS* approaches outperform the other approaches under different average PLR, with almost 100% more lifetime than *UPA* approach and about 30% more lifetime than *LSEPC* approach with the average PLR of 10%. In addition, when the average PLR is close to 10%, the system lifetime of our proposed approaches is 22% more than that of *TPC* approach.

## VIII. Conclusion and Future Work

In the paper, we design a unified optimization framework to maximize the energy efficiency while considering both the characteristics of the dynamic links and the QoS constraints, such as the delay constraint, the throughput constraint, and the packet loss rate constraint, in the WBAN system. A QoS optimization problem is formulated and solved, in which we jointly optimize the transmission power and the scheduled slots at each sensor to ensure QoS performance and energy efficiency. To guarantee more strict PLR constraints, a Transmission Rate Adaption Policy (TRAP) is proposed to allocate the transmission rates of each sensor, and a Priority-based Retransmission Scheme (PRS) is designed to improve the performances of the emergency packets with a higher priority. The simulation results demonstrate that the optimal resource allocations improve the system energy efficiency while satisfying QoS constraints the TRAP scheme can guarantee more strict PLR constraint, and the effectiveness of the proposed transmission rate adaption policy and the priority-based retransmission strategy.

In the future, when the commercial IEEE 802.15.6 protocol-based hardware is produced, we will carry out real-world experiment to validate and optimize the resource allocation scheme. And not only the dynamic postures but also the changing environment will be considered in the resource allocation scheme to address more complex and realistic scenarios. Besides, an online learning process of channel model parameters can be also designed to update the channel parameters.

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## Appendix

### *A. The average PLR in eq.* (7) *is a monotonically decreasing function of the mean of bit SNR* $\mu_{\gamma_{dB}}$.

*Proof:* The average packet loss rate is the function of the mean of bit SNR $\mu_{\gamma_{dB}}$ and the standard deviation of bit SNR $\sigma_{\gamma_{dB}}$, which can be expressed as follows,

$$\begin{aligned} &\overline{PLR\left(\mu_{\gamma_{dB}}, \sigma_{\gamma_{dB}}\right)} \\ &= 1 - \int_{0}^{+\infty} PLR(\gamma) \frac{10/\ln 10}{\sqrt{2\pi}\sigma_{\gamma_{dB}}\gamma} \exp\left[-\frac{(10log_{10}(\gamma) - \mu_{\gamma_{dB}})^2}{2\sigma^2_{\gamma_{dB}}}\right] d\gamma \\ &= 1 - h\left(\mu_{\gamma_{dB}}, \sigma_{\gamma_{dB}}\right) \end{aligned}$$

Here, we fix the variable $\sigma_{\gamma_{dB}}$ to study the relationship between the average packet loss rate $\overline{PLR}$ and the mean of bit SNR $\mu_{\gamma_{dB}}$. Thus we only need to prove that $h\left(\mu_{\gamma_{dB}}\right)$ is a monotonically increasing function of the mean of bit SNR $\mu_{\gamma_{dB}}$ with a constant $\sigma_{\gamma_{dB}}$. Therefore, if $\forall\ \mu_{\gamma_{dB,1}}, \mu_{\gamma_{dB,2}},\ \mu_{\gamma_{dB,1}} \geq \mu_{\gamma_{dB,2}}$, we need to prove that $h\left(\mu_{\gamma_{dB,1}}\right) \geq h\left(\mu_{\gamma_{dB,2}}\right)$ is permanent establishment. We set $x_1 = \frac{\gamma}{10^{\frac{\mu_{\gamma_{dB,1}}}{10}}}, x_2 = \frac{\gamma}{10^{\frac{\mu_{\gamma_{dB,2}}}{10}}}$, then the $h\left(\mu_{\gamma_{dB,1}}\right)$ and $h\left(\mu_{\gamma_{dB,2}}\right)$ can be shown as follows,

$$h\left(\mu_{\gamma_{dB,1}}\right) = \int_0^{+\infty} PLR(10^{\frac{\mu_{\gamma_{dB,1}}}{10}} x_1) \frac{10/\ln 10}{\sqrt{2\pi}\sigma_{\gamma_{dB}} x_1} \exp\left[-\frac{\left(10\log_{10} x_1\right)^2}{2\sigma^2_{\gamma_{dB}}}\right] dx_1 \tag{19}$$

$$h\left(\mu_{\gamma_{dB,2}}\right) = \int_0^{+\infty} PLR(10^{\frac{\mu_{\gamma_{dB,2}}}{10}} x_2) \frac{10/\ln 10}{\sqrt{2\pi}\sigma_{\gamma_{dB}} x_2} \exp\left[-\frac{\left(10\log_{10} x_2\right)^2}{2\sigma^2_{\gamma_{dB}}}\right] dx_2 \tag{20}$$

Then, the difference between $h\left(\mu_{\gamma_{dB,1}}\right)$ and $h\left(\mu_{\gamma_{dB,2}}\right)$ can be obtained as follows,

$$h\left(\mu_{\gamma_{dB,1}}\right) - h\left(\mu_{\gamma_{dB,2}}\right) = \int_0^{+\infty} PLR_\Delta(x) \frac{10/\ln 10}{\sqrt{2\pi}\sigma_{\gamma_{dB}} x} \exp\left[-\frac{\left(10\log_{10}(x)\right)^2}{2\sigma^2_{\gamma_{dB}}}\right] dx \tag{21}$$

where $PLR_\Delta(x) = PLR(10^{\frac{\mu_{\gamma_{dB,1}}}{10}} x) - PLR(10^{\frac{\mu_{\gamma_{dB,2}}}{10}} x)$. $x$ is larger than or equal to 0. $10^{\frac{\mu_{\gamma_{dB,1}}}{10}}, 10^{\frac{\mu_{\gamma_{dB,2}}}{10}}$ are larger than 0 and $10^{\frac{\mu_{\gamma_{dB,1}}}{10}} \geq 10^{\frac{\mu_{\gamma_{dB,2}}}{10}}$ with the assumption $\mu_{\gamma_{dB,1}} \geq \mu_{\gamma_{dB,2}}$. Therefore, $10^{\frac{\mu_{\gamma_{dB,1}}}{10}} x \geq 10^{\frac{\mu_{\gamma_{dB,2}}}{10}} x$. Apparently, the packet loss rate $PLR(x)$ is a monotonically decreasing function of the bit SNR $x$. So $PLR_\Delta(x) \geq 0$ is permanent establishment with $10^{\frac{\mu_{\gamma_{dB,1}}}{10}} x \geq 10^{\frac{\mu_{\gamma_{dB,2}}}{10}} x$. Thus, $h\left(\mu_{\gamma_{dB,1}}\right) \geq h\left(\mu_{\gamma_{dB,2}}\right), \forall\ \mu_{\gamma_{dB,1}}, \mu_{\gamma_{dB,2}}, \mu_{\gamma_{dB,1}} \geq \mu_{\gamma_{dB,2}}$. So we prove that $h\left(\mu_{\gamma_{dB}}\right)$ is a monotonously increasing function of the mean of bit SNR $\mu_{\gamma_{dB}}$. Further, we can prove that the average PLR is a monotonically decreasing function of the mean of bit SNR $\mu_{\gamma_{dB}}$. ■

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