Truthful Mechanism Design for Transmission Scheduling in Beyond Wireless Body Area Networks

by

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Abstract

As an enabling technology for supporting ubiquitous physiological monitoring of human bodies, wireless body area networks (WBANs) has been proposed as a promising paradigm for future wireless communications, and can provide a lot of benefits in various perspectives. One major application of WBANs is the use for healthcare services. The implementation of WBAN-based remote medical systems can significantly alleviate the financial and social burdens resulting from the growth of aging population, the increasing demand for high-quality treatments and the rising costs, as it can offer pervasive healthcare monitoring, computer-assisted rehabilitations and emergency notifications. Because of these, a lot of research efforts have been made in this area. However, the technical issues related to data packet transmissions in beyond-WBAN communications (i.e., the information exchanges between WBAN-gateways and the remote facilities), though of high importance, have not been well studied.

This thesis particularly emphasizes on studying the beyond-WBAN transmission scheduling by applying the mechanism design technique for achieving high network efficiency (e.g., social welfare maximization or operation revenue maximization), ensuring the fulfillment of desired priority-aware quality-of-service (QoS) and preventing any untruthful strategic bahaviors from smart WBAN-gateways. Specifically, i) we start by proposing a truthful mechanism for delay-sensitive transmission scheduling with homogeneous packet transmission time in the beyond-WBAN; ii) by relaxing the assumption of homogeneous packet transmission time and defining a discretized priority classification fitting the existing IEEE standards for WBAN-applications, we then design a novel truthful mechanism for supporting multi-class prioritized delay-sensitive beyond-WBAN transmission scheduling; iii) with the further consideration of a more general transmission service process and the relaxation of the fixed priority requirement, we redesign a truthful mechanism for managing delay-dependent dynamic prioritized transmission scheduling; and iv) for dealing with applications with stringent delay limits in the beyond-WBAN transmission, we extend the previously employed delay-sensitive transmission scheduling framework to a delay-constrained one and develop a corresponding truthful mechanism for delay-constrained prioritized transmission scheduling. Both theoretical analyses and simulations are conducted to evaluate the performance of the proposed mechanisms.

Keywords: WBAN, beyond-WBAN, transmission scheduling, truthful mechanism design, social welfare maximization, revenue maximization, priority-aware QoS, delay sensitivity, delay-dependent dynamic priority, stringent delay limit.

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List of Abbreviations

BAN	Body Area Network
BSN	Body Sensor Network
BS	Base Station
CDF	Cumulative Distribution Function
DCS	Delay Control Scheme
DTM	Dynamic Transmission Mechanism
DPMT	Delay-dependent Prioritized Transmission Mechanism
ECG	Electrocardiography
EEG	Electroencephalography
EMG	Electromyography
FCFS	First-Come First-Serve
IoT	Internet of Things
KKT	Karush-Kuhn-Tucker
NE	Nash Equilibrium
PDF	Probability Density Function
QoS	Quality of Service
SNR	Signal-to-Noise Ratio
TMDC	Transmission Mechanism with Delay Constraints
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Networks
WSN	Wireless Sensor Network

Chapter 1

Introduction

With the development of technologies in various fields of electrical and computer engineering, wireless communication has become increasingly popular and even indispensable in our daily life. As a consequence, wireless technology has experienced rapid evolution in past decades, and has been attracting more and more interests from both academia and industry.

Among all kinds of technical issues in wireless communications, radio resource management is an everlasting problem since the birth of wireless technology. The general goal of radio resource management is to efficiently utilize the limited radio resources in order to enhance the network performance and the quality of service (QoS) for all individuals. Mechanism design technique [1] has been widely discussed in the literature for dealing with conventional resource management problems involved by intelligent, selfish and rational users. Due to the recent advanced technology in human-computer interactions on newly developed wireless devices (such as smart phones and tablets), it becomes necessary and imperative to introduce mechanism design technique for radio resource management in wireless networks.

This thesis particularly focuses on applying mechanism design technique for the radio resource management (or more specifically, the transmission scheduling) in the beyond wireless body area network (beyond-WBAN), which is one of the important tiers of the communication architecture of wireless body area networks (WBANs). In this chapter, an overview of WBANs is first presented. Then, the network characteristics and research challenges of beyond-WBANs are described in detail. After that, a review on mechanism design theory and its existing applications in wireless networks are provided. Last but not least, the motivations and the contributions of this thesis are summarized.

1.1 Overview of Wireless Body Area Networks

Recent advances in physiological sensors, integrated circuits, information processing and wireless communications have enabled a new generation of wireless network technology, called wireless body area network (WBAN). WBAN, also referred as body area network (BAN) or body sensor network (BSN), is a new type of network architecture which aims to utilize a collection of low-power, miniaturized and lightweight devices with wireless communication capabilities that operate in the proximity of a human body for monitoring the human's physiological activities and actions, such as health status and motion patterns [2].

A WBAN commonly consists of a number of wearable, implantable or portable biosensors that are deployed on a human body for continuously tracking his/her physiological conditions, and a gateway that aggregates the sensing data from biosensors and then forwards them to remote facilities, such as medical centers, cloud servers or databases, for interpretation and analysis. Clearly, wireless devices in WBANs can be classified in terms of the functionality as follows:

- *Gateway:* This device is responsible for collecting all the information received by biosensors and handling the interactions with remote network facilities. This device may also be called WBAN-coordinator, hub, sink or local processing unit in different applications [3]. In practice, gateways can be smart phones, tablets or any other smart devices.

- *Biosensors:* These devices are responsible for gathering data on physical stimuli and transmitting them via wireless communications to the gateway. Existing commercially available biosensors used in WBANs include but not limited to [4]: electromyography (EMG), electroencephalography (EEG), electrocardiography (ECG), temperature, humidity, blood pressure and glucose sensors, thermistor, spirometer, magnetic biosensor, accelerometer, etc. Note that the number of biosensors in a WBAN is in the range from tens to hundreds (e.g., a typical medical-based WBAN is stated to have up to 256 biosensors [5]).

Although WBANs share a similar network structure as the conventional wireless sensor networks (WSNs) [6–8], they are fundamentally different in terms of application requirements and communication architectures. In the following, the unique features and applications of WBANs are first discussed. Then, the existing standards and some major requirements of WBANs are briefly reviewed. Finally, the multi-tier communication architecture of WBANs is introduced.

1.1.1 Features and Applications

To better illustrate the unique features of WBANs, the differences between WBANs and conventional WSNs are investigated as follows:

- *Deployment and density:* Each biosensor in WBANs is deployed for a certain application purpose. They are in/on/around human bodies. Therefore, it is not allowed to employ redundant nodes to cope with diverse types of network failures. In contrast, WSNs are commonly used in places that may not be easily accessed by operators so that more sensors are required for potential network failures. This implies that sensors in WBANs are not as dense as WSNs.

- *Data rate:* Most WSNs are employed for event-based monitoring, where events may happen at irregular intervals. WBANs are employed for monitoring physiological activities and actions, which may occur in a more predictable manner. This may lead to data streams in WBANs exhibiting relatively stable rates.

- *Latency and reliability:* This is one of the key differences between WBANs and WSNs. Since the sensors of WSNs are sometimes physically unreachable after deployment, the battery lifetime becomes the primary issue of WSNs. In order to extend the network lifetime, WSNs may be willing to suffer considerably long delays or even high packet losses. However, the biosensors of WBANs are possibly replaceable, which makes the energy efficiency less important than transmission latency and reliability, especially for the transmissions of critical physiological signals.

- *Mobility:* WBANs are accompanied with humans that may move around. Thus, the wireless access technology in WBANs should be capable of dealing with the mobility issue. However, WSNs are usually considered as static.

Because of the deployment of various biosensors on human bodies, WBANs create the opportunity of developing a large number of applications in several fields:

- *Healthcare:* At a first glance, this is the most important and promising application of WBANs. With the biosensors deployed on the human body and the wireless communication technology, WBANs have a huge potential to revolutionize the future medical services by providing real-time healthcare monitoring. WBANs will be a key solution in early diagnosis and treatment of patients with fatal diseases and anomalies. Besides, WBANs can also improve the life style of hearing and visually impaired people by means of cochlear implant and artificial retina, respectively [9].

- *Sports and entertainments:* WBANs can gather information concerning sport activities and help athletes to prevent injuries and improve sport performance. For example, biosensors can be worn at both hands and elbows for accurate feature extraction of sports players' movements. Besides, motion sensors enable game players to perform actual body movements, such as boxing and shooting, that can be feedback to the corresponding gaming console, thereby enhancing their entertainment experience.

- *Military purposes:* WBANs can improve the performance of soldiers engaged in military operations at both individual and squad levels. At the individual level, WBANs can help soldiers in monitoring vital parameters about surrounding environment in order to avoid potential threats. At the squad level, WBANs can help the commanders to acquire more information so as to better coordinate the squad actions.

- *Secure authentication:* Traditionally, this application relies on the utilization of physiological biometrics, such as facial patterns, fingerprints and iris recognition. The potential issues related to secure authentication, e.g., forgery and duplicability, have motivated the design of WBANs integrating new physiological characteristics of humans, such as EEG and gait biometrics [2].

1.1.2 Standards and Major Requirements

The unique features and application requirements of WBANs prompt the need of a standard model for successful implementation of WBANs. IEEE Task Group TG6 was thus established in November 2007 working on the standard specifically designed for WBANs. Till now, several versions of the communication standards for WBANs have been released and the latest one is IEEE std. 802.15.6 [10] which was ratified in February 2012.

According to IEEE std. 802.15.6, some major requirements of WBANs are outlined as follows [11,12]:

- WBAN should support bit rates in the range of 10 Kbps to 10 Mbps.
- Each WBAN should be capable of supporting 256 sensor nodes.
- Reliable communications should be provided by WBANs, even when persons are on the move. Although it is acceptable for network capacity to be reduced,

Table 1.1: An example of priority classification in IEEE std. 802.15.6.

Data priority	**Traffic designation**
0	Background (BK)
1	Best effort (BE)
2	Excellent effort (EE)
3	Video (VI)
4	Voice (VO)
5	Medical data or network control
6	High-priority medical data or network control
7	Emergency or medical implant event report

data should not be frequently lost due to unstable channel conditions.

- WBANs should be able to support delay-sensitive applications. Latency/delay in WBANs should be less than 125 ms for medical applications and less than 250 ms for non-medical applications.
- WBANs should be able to operate in a heterogeneous environment.
- WBANs have to be self-healing and secure.
- WBANs must incorporate QoS management and provide priority services.
- Data packets in WBANs should be categorized into multiple priority classes. An example of the 8-level priority classification defined in IEEE std. 802.15.6 is demonstrated in Table 1.1 [10] (where 0 and 7 represent the lowest and highest priorities, respectively).

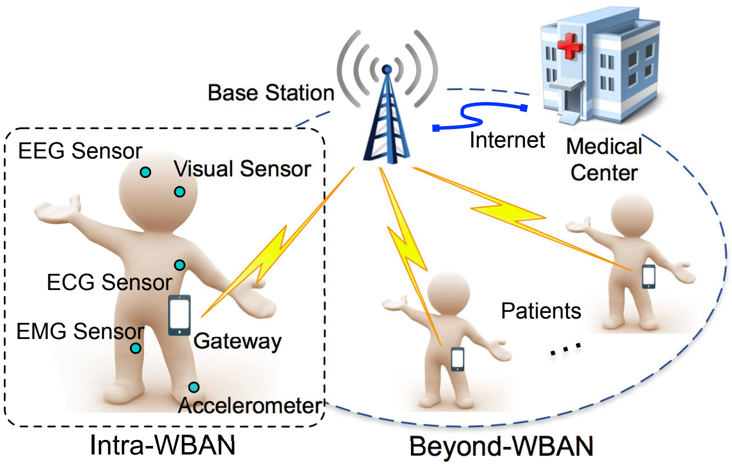

Figure 1.1: An illustration of the WBAN communication architecture.

1.1.3 Communication Architecture

The communication architecture of WBANs can be separated into multiple tiers. Depending on the application scenarios, there are different ways in defining such multi-tier communication architecture [2, 5]. In this thesis, a two-tier WBAN communication architecture is considered, which can be illustrated in Fig. 1.1.

- *Tier-1: Intra-WBAN communication:* This communication tier depicts the radio communications of about 2 meters around the human body [9]. In this tier, i.e., the intra-WBAN, various biosensors transmit their collected physiological signals to the gateway, located in Tier-1. Then, the aggregated data is forwarded by the gateway to the remote facilities in Tier-2.

- *Tier-2: Beyond-WBAN communication:* This communication tier is designed for metropolitan areas and is commonly application-specific [3]. Gateways, e.g., smart phones, can be used to bridge the connection between Tier-1 and Tier-2. Particularly, this communication tier can enhance the coverage of WBAN-based healthcare systems by enabling authorized healthcare personnel (in medical centers) to remotely access patients' medical information.

1.1.4 Potentials and Future Development

WBANs may interact with the Internet and other existing wireless technologies, such as ZigBee [13], WSNs [6], Bluetooth [14], wireless local area networks (WLANs) [15], wireless personal area networks (WPANs) [16], video surveillance systems [17] and cellular networks [18]. Therefore, the potential and future marketing opportunities of WBANs will thoroughly expand, allowing for a new generation of more intelligent and autonomous applications for improving our quality of lives [2]. WBANs are expected to cause a dramatic shift in how people manage and think about their health and body motions, similar to the way that the Internet has changed the way people look for information and communicate with each other [5]. WBANs are capable of transforming how people interact with and benefit from information technology. WBAN sensors are capable of sampling, monitoring, processing and communicating various vital signs as well as providing real time feedback to the remote facilities (e.g., medical personnel) without causing any discomfort [19]. The deployment of a WBAN allows continuous monitoring of one's physiological parameters thereby providing greater mobility and flexibility to facilitate various applications, including medical and non-medical ones. For instance, as WBANs provide large time intervals of data from a patient's natural environment, doctors will have a clearer view of the their health status [3]. These advantages have stimulated the new concepts of m-Health [20] and 4G-Health (through 4G mobile communications) [21], combining with the Internet of Things (IoT) [22], to enable new personalized telemedicine in the healthcare services. However, the technical and social challenges must be well addressed so as to allow the wide implementations of WBANs, and these motivate the research works conducted in this thesis.

1.2 Beyond Wireless Body Area Networks

WBAN has been considered as a promising paradigm which can offer a lot of potential benefits in various perspectives, spanning from telemedicine to entertainment and ambient intelligence. Because of this, the design of WBAN-based systems has become increasingly popular in recent years and has attracted great research interests. However, most of existing works limited their emphases on the intra-WBAN (i.e., Tier-I of WBAN) [23–25], while the beyond-WBAN (i.e., Tier-2 of WBAN), though of equal importance, has rarely been studied [5]. In the following, the network characteristics of beyond-WBAN are first described. Then, the technical issues and research challenges in the beyond-WBAN are explained.

1.2.1 Network Characteristics

Different from the intra-WBAN and any other existing wireless networks (such as WiFi and traditional cellular networks), beyond-WBAN has its unique network characteristics which can be summarized as follows:

- Beyond-WBAN communications mostly refers to the uplink data transmissions from gateways (e.g., smart phones) to the base station (BS) of the remote facilities (e.g., medical centers), as shown in Fig. 1.2 [26].

- As the most important communication units, gateways in the beyond-WBAN have much less stringent constraints on power capabilities and much higher device intelligence compared to biosensors in the intra-WBAN [2] .
- Unlike conventional wireless networks that are mainly designed for throughput maximization, the physiological signals transmitted in the beyond-WBAN have relatively low data rate requirements [27] so that the throughput or transmission capacity is no longer the primary concern. Instead, since data packets in beyond-WBAN are commonly medical related and may be critical for healthcare, it is required that data packets can be transmitted via the beyond-WBAN in a more timely manner.
- Due to the potential mobility issues (caused by the roaming of patients) and the transmission reliability requirements (for supporting pervasive and ubiquitous monitoring), beyond-WBAN should guarantee wireless access at “anywhere” and “anytime” [28].

1.2.2 Beyond-WBAN Transmission Scheduling and Challenges

As illustrated in Fig. 1.2, the implementation of beyond-WBAN requires an efficient transmission scheduling scheme for managing the uplink data transmissions initiated by smart gateways. However, such management is challenged by a number of emerging issues, which have never been addressed in the literature.

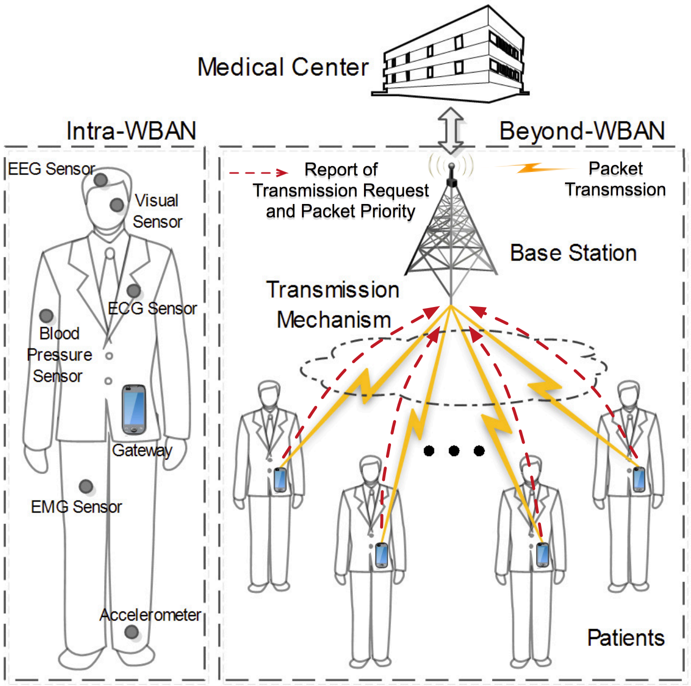

Figure 1.2: An illustration of the Beyond-WBAN.

- It has been envisioned that there will be a large deployment of WBANs in the near future [5], and thus it can be expected that a mass of various bio-sensing data will be generated and the demand for beyond-WBAN transmissions will be explosively increased, leading to a heavy burden on the beyond-WBAN management (e.g., resulting in low transmission rates or long delays).

- WiFi (or any other technologies working on low-frequency bands) is not suitable for beyond-WBAN communications due to its considerably restricted radio coverage [28]. Since WBAN-based systems are widely used in medical applications, any service interruption or packet loss in beyond-WBAN transmissions may result in serious consequences.

- Cellular-like networks are more preferable for beyond-WBAN communications. However, traditional cellular systems have already been crowded with a large number of subscribed mobile users, and the ever-increasing demand in wireless access is rapidly straining the capacity of existing cellular networks [29]. Thus, only very limited radio bandwidths can be allocated for beyond-WBAN communications.

- Another distinctive feature that has to be taken into account in the beyond-WBAN transmission scheduling is the guarantee of priority-aware QoS [30]. This is a fundamental requirement for remote healthcare service (which has been seen as the most promising application of WBANs).

- In addition, as widely discussed in the WBAN-related literature [3,11,31], gateways in the beyond-WBAN are commonly smart devices, and thus they may be intelligent enough (due to the rapid development of device intelligence) to behave strategically and selfishly for benefiting themselves. As the beyond-WBAN transmission scheduling is based on the priority information of data packets that need to be reported by associated gateways, an efficient and robust beyond-WBAN system should be capable of preventing gateways from potentially misreporting their data packets' priorities.

This thesis aims to build management frameworks for scheduling data packet transmissions with different QoS requirements in the beyond-WBAN by applying *mechanism design technique*, which can overcome all aforementioned challenges.

1.3 Truthful Mechanism Design in Wireless Networks

Mechanism design theory is a subfield of game theory. It considers how to implement good system-wide solutions to problems that involve multiple self-interested users. In 2007, the Nobel Prize in economics was awarded to Leonid Hurwicz, Eric Maskin, and Roger Myerson "for having laid the foundations of mechanism design theory". This indicates the importance and popularity of mechanism design in various areas. For instance, mechanism design theory has been extensively applied in practical engineering problems, such as electronic market design [32, 33], distributed scheduling [34–36], and radio resource management [37–40]. In this section, the basics of mechanism design theory are briefly reviewed. In addition, some existing applications of mechanism design technique in wireless networks are discussed.

1.3.1 Mechanism Design Theory

Though mechanism design is originated from game theory, it is fundamentally different in terms of the design objective and the system model. Specifically, traditional game theory emphasizes on the analysis of the outcome of strategic interactions among individual users in a given game, while mechanism design focuses on designing the game which can produce a certain desired outcome. Thus, mechanism design is also known as *reverse game theory*. A key feature of mechanism design is that the determination of the optimal allocation depends on the information which is possessed privately by users. In order to obtain the optimal solution, this private information has to be elicited from users. However, users may strategically misreport their private information rather than truthful telling if they can recognize the potential benefits from such behaviors. Apparently, computing the allocation from incorrect information may result in serious mistakes. Hence, it is challenging to devise a mechanism for information interactions such that the outcome is optimal, even though users may behave strategically. Mechanism design can therefore be considered as the design of rules for guaranteeing desirable outcomes amongst fully strategic users [41].

General Concepts

Generally speaking, mechanism design is an effective approach to incentivize users to participate in the system by choosing their own strategies while guaranteeing certain design goals. As prerequisites, some terminologies and general concepts of mechanism design are first presented in the following.

- *Mechanism and strategy:* A mechanism commonly consists of two steps. The first step is the strategy submission from all participants. Each participant has a type which indicates its own private preference and affects its strategies. The second step is the outcome determination of the system, e.g., the determination of the optimal allocation based on a set of pre-determined rules.

- *Utility, social welfare and incentive design:* In mechanisms for resource allocations, each user who is granted by its requested resource has a utility which equals the difference between its valuation (i.e., a function of its type) and the cost for obtaining such resource. Note that users who are not assigned with any resource have a zero utility. The sum of utilities of all individuals is defined as the social welfare, which represents the profit/gain that the mechanism produces to the system. For each user, a non-negative utility indicates a benefit which can be seen as a kind of incentive to encourage its participation in the system. Naturally, a feasible mechanism should guarantee incentives to all participants. Failing to do so can lead to a collapse of the system since rational users will not take any risk from suffering any potential utility loss.

Desired Properties

Consider a resource management system with N intelligent users and one central controller. Each user i has a private type v_i over its requested resource, and may strategically report $v_i' \neq v_i$ if and only if it can benefit from such behavior. Since the central controller cannot observe the private information of any individual user, the outcome of a mechanism $(\boldsymbol{\mathcal{Z}}, \boldsymbol{\pi})$ is based on the reported information $\boldsymbol{v'} = \{v_1', v_2', \ldots, v_N'\}$, where $\boldsymbol{\mathcal{Z}} = \{\mathcal{Z}_1(v_1'), \mathcal{Z}_2(v_2'), \ldots, \mathcal{Z}_N(v_N')\}$ represents the vector of allocation decisions and $\boldsymbol{\pi} = \{\pi_1(v_1'), \pi_2(v_2'), \ldots, \pi_N(v_N')\}$ stands for the vector of charges on all users. Therefore, the utility function of each user i with an actual type v_i but reporting v_i', denoted by $U_i(v_i'|v_i)$, can be expressed as

$$U_i(v_i'|v_i) = v_i \cdot \mathcal{Z}_i(v_i') - \pi_i(v_i'), \quad \forall i. \tag{1.1}$$

As the most essential requirement for guaranteeing efficiency and robustness, the design of a mechanism $(\boldsymbol{\mathcal{Z}}, \boldsymbol{\pi})$ is required to satisfy the following important property, i.e., *truthfulness.*

Definition 1.1 (**Truthfulness**). A mechanism $(\boldsymbol{\mathcal{Z}}, \boldsymbol{\pi})$ is truthful if no user i can improve its own utility by misreporting $v_i' \neq v_i$, i.e.,

$$v_i = \arg\max_{v_i'} U_i(v_i'|v_i), \ \forall i, \tag{1.2}$$

or equivalently

$$v_i \cdot \mathcal{Z}_i(v_i) - \pi_i(v_i) \geq v_i \cdot \mathcal{Z}_i(v_i') - \pi_i(v_i'),\ \forall i. \tag{1.3}$$

Besides the truthfulness, in order to encourage all users to join the system, a mechanism should also be designed with the guarantee of *individual rationality.*

Definition 1.2 (**Individual Rationality**). A mechanism $(\boldsymbol{\mathcal{Z}}, \boldsymbol{\pi})$ is individual-rational if every user can obtain a non-negative utility when it behaves truthfully (by reporting $v_i' = v_i$), i.e.,

$$U_i(v_i|v_i) = v_i \cdot \mathcal{Z}_i(v_i) - \pi_i(v_i) \geq 0,\ \forall i. \tag{1.4}$$

1.3.2 Applications of Mechanism Design in Wireless Networks

Mechanism design technique has been widely adopted in various wireless applications for dealing with intelligent and selfish mobile users with potential strategic behaviors [42]. In this subsection, a review of existing mechanisms designed for radio resource management in wireless networks is presented.

The most common application scenario in the literature is the one in which radio resources are allocated among mobile users with homogeneous QoS requirements. For instance, Gao et al. in [43] introduced an integrated contract and auction mechanism for secondary spectrum trading under stochastic network information, where each secondary wireless user requested one idle channel. Wu et al. in [44] proposed a privacy-preserving and truthful spectrum sharing mechanism which guaranteed anonymity for wireless users with homogeneous spectrum demands. Zhuo et al. in [45] provided a novel incentive mechanism to motivate mobile users with homogeneous QoS requirements to leverage their delay tolerances for cellular traffic offloading. Wang et al. in [46] formulated a set of spectrum sharing mechanisms that were specifically designed for local spectrum markets, in which wireless users were considered to be homogeneous. Hong et al. in [47] introduced a truthful mechanism for base station association and resource allocation in multi-cell downlink networks, where mobile users with same medium access protocols may misreport their downlink channel states. Sun et al. in [48] proposed a coalition mechanism for spectrum allocation, where wireless users were partitioned into several coalitions based on their homogeneity in spectrum requests and the spectrum reusability was executed within each coalition.

Some recent works have been dedicated in studying mechanism design for radio resource management with heterogeneous mobile users' QoS provisioning. For example, Zheng et al. in [49] designed a truthful combinatorial mechanism for joint spectrum allocation and transmission scheduling in noncooperative wireless networks, where channels were utilized in a time-multiplexing way. Li et al. in [50] developed a truthful and efficient mechanism for radio spectrum sharing, in which the spectrum resource was modeled in a time-frequency division manner. Koutsopoulos et al. in [51] constructed an incentive mechanism for mobile participatory sensing, where the cost information of each wireless user was assumed to follow a known distribution. Feng et al. in [52] proposed a mechanism for secondary wireless service providers, where each of them could flexibly determine the channel demand and corresponding value according to the requirement of its end users. In [53], Kash et al. proposed a truthful and scalable mechanism which aimed to allocate spectrum to both sharers and exclusive-users in secondary networks. In [54], Xu et al. analyzed a semi-truthful online frequency scheduling mechanism, where the network controller could sublease spectrum resource to wireless users and preempt any existing spectrum usages with some compensations.

However, mechanisms developed in all these works cannot be applied for the beyond-WBAN transmission scheduling because i) nearly all of them employed the assumption that the network model was quasi-static, i.e., the radio resource management was conducted in a static manner regardless of the potential temporal dynamics, which does not fit the dynamic nature of the beyond-WBAN; and ii) due to the differences in system settings and application purposes, none of these works can guarantee the priority-aware QoS required by WBAN systems.

1.4 Motivations and Contributions

Unlike existing works, this thesis particularly focuses on the management of data packet transmission scheduling in the beyond-WBAN instead of the commonly discussed intra-WBAN. As illustrated in Section 1.1.3, beyond-WBAN is one of the most essential tiers in the WBAN architecture, and thus beyond-WBAN transmission scheduling plays a vital role in supporting the operation of WBANs. However, the efficient management of beyond-WBAN transmission scheduling faces a number of critical challenges, which have never been addressed in the literature (as explained in Section 1.2.2). These motivate the study and the exploration of beyond-WBAN management frameworks by applying mechanism design technique for not only satisfying desired system requirements but also achieving good overall performance.

It is worth noting that designing feasible and efficient management mechanisms for beyond-WBAN transmission scheduling is very difficult because

a. The beyond-WBAN scheduling management should be capable of offering priority-aware QoS for various data packet transmissions. Such priority requirements bring additional constraints to the management system and increase the complexity of the follow-up analyses.

b. The achieved QoS of data packet transmissions in the beyond-WBAN depends on the designed management mechanism, and this complicated relationship can hardly be explicitly described, and thus a packet-level queueing modeling is required.

c. The designed mechanism should be able to force or induce all gateways in the beyond-WBAN to behave truthfully so as to guarantee the proper execution of the desired prioritized transmission scheduling. This necessitates the redesign of novel mechanisms for the beyond-WBAN transmission scheduling management.

d. In order to facilitate the implementation of WBAN-based systems, the beyond-WBAN transmissions should be well managed with the aim of achieving certain network objectives (such as operation revenue or social welfare maximization).

To tackle all aforementioned difficulties, this thesis starts by designing a mechanism for delay-sensitive transmission scheduling with homogeneous packet transmission time in the beyond-WBAN. Then, by relaxing the assumption of homogeneous packet transmission time and defining a discretized priority classification fitting the IEEE std. 802.15.6, a truthful mechanism for supporting multi-class prioritized delay-sensitive transmission scheduling in the beyond-WBAN is proposed. After that, with the consideration of a more general beyond-WBAN transmission service process and the relaxation of the fixed priority requirement, a truthful mechanism for managing delay-dependent dynamic prioritized transmission scheduling in the beyond-WBAN is devised. To further deal with WBAN-applications with stringent delay limits in transmissions, the previously employed delay-sensitive transmission scheduling scheme is extended and modified to a delay-constrained one and a corresponding truthful mechanism for delay-constrained prioritized transmission scheduling in the beyond-WBAN is developed.

The main contributions of this thesis are summarized as follows.

i) A truthful mechanism for delay-sensitive transmission scheduling with homogeneous packet transmission time in the beyond-WBAN (this work has been published as **[C. Yi, A. S. Alfa and J. Cai, "An incentive-compatible mechanism for transmission scheduling of delay-sensitive medical packets in e-health networks,"** ***IEEE Transactions on Mobile Computing***, **vol. 15, no. 10, pp. 2424–2436, Oct. 2016]**):

   - The management for data packet transmissions in the beyond-WBAN is formulated as a multi-server (i.e., multi-channel) queueing system with deterministic service time (i.e., transmission time) and absolute priorities.
   - Delay sensitivities are introduced to represent the severities of data packets in beyond-WBAN transmissions.
   - Waiting delays of data packets in the prioritized beyond-WBAN queueing scheduling system are analyzed mathematically.
   - A truthful mechanism for scheduling beyond-WBAN data packet transmissions with heterogeneous delay sensitivities is proposed.

- Both theoretical analyses and numerical results are presented to prove that the proposed mechanism is feasible and applicable for the beyond-WBAN transmission scheduling management.

ii) A truthful mechanism for supporting multi-class prioritized delay-sensitive transmission scheduling in the beyond-WBAN (this work has been published as **[C. Yi and J. Cai, "A priority-aware truthful mechanism for supporting multi-class delay-sensitive packet transmissions in e-health networks,"** ***IEEE Transactions on Mobile Computing*****, vol. 16, no. 9, pp. 2422–2435, Sep. 2017]**):

- The dynamic management of delay-sensitive data packet transmissions in the beyond-WBAN is formulated as a multi-class multi-server (i.e., multi-channel) queueing system with absolute priorities.
- A truthful mechanism for data packet transmissions with two priority levels is first proposed, which consists of a deterministic relaxation and a dynamic reconstruction.
- The designed mechanism is then extended to a general form which can support multi-level (i.e., larger or equal to 3) prioritized data transmissions.
- Theoretical analyses and simulation results examine the desired properties of the proposed mechanism, and demonstrate its feasibility and superiority compared to the counterparts.

iii) A truthful mechanism for managing delay-dependent dynamic prioritized transmission scheduling in the beyond-WBAN (this work has been accepted as **[C. Yi and J. Cai, "Transmission management of delay-sensitive data packets**

in beyond wireless body area networks: a queueing game approach", *IEEE Transactions on Mobile Computing*, accepted for publication in 2018]):

- The beyond-WBAN data packet transmission scheduling is modeled by a multi-class multi-server (i.e., multi-channel) queueing system with a generally distributed service time (i.e., transmission time) and a delay-dependent priority discipline.
- With the objective of maximizing the social welfare and the consideration of potential untruthful behaviors of gateways in the beyond-WBAN, a mechanism design problem is formulated.
- As a benchmark, an optimal scheduling scheme is designed for a relaxed pure queueing problem.
- After studying the characteristics of the problem. a truthful mechanism for beyond-WBAN transmission scheduling is proposed, which is based on the outcome of an introduced virtual queueing game.
- Both theoretical analyses and simulations are conducted to evaluate the performance of the proposed mechanism.

iv) A truthful mechanism for scheduling delay-constrained priority-aware data packet transmissions in the beyond-WBAN (this work has been submitted as **[C. Yi and J. Cai, "A truthful mechanism for scheduling delay-constrained transmissions in beyond wireless body area networks", submitted to *IEEE Transactions on Wireless Communications*]**):

- The management of beyond-WBAN data packet transmissions is modeled by a multi-class delay-constrained multi-server priority queueing system.

- Taking into account the potential untruthfulness of gateways, a mechanism design problem for beyond-WBAN transmission scheduling is formulated.
- Besides studying the characteristics of the problem, the performance of the considered queueing scheduling system is extensively analyzed.
- Based on the derived queueing outcome, a truthful mechanism for scheduling data packet transmissions with delay constraints is proposed.
- Theoretical analyses and simulation results show that the proposed mechanism can meet all design requirements, and can achieve a superior performance compared to the counterparts.

1.5 Organization of the Thesis

The rest of the thesis is organized as follows. In Chapter 2, truthful mechanism design is first introduced for delay-sensitive beyond-WBAN transmission scheduling with homogeneous packet transmission time. In Chapter 3, the design of priority-aware truthful mechanisms for multi-class delay-sensitive beyond-WBAN transmission scheduling is studied. Chapter 4 presents the truthful mechanism for managing delay-dependent prioritized beyond-WBAN transmissions. The scheduling of delay-constrained data packet transmissions in the beyond-WBAN is discussed in Chapter 5, followed by conclusions of this thesis and a summary of future works in Chapter 6.

Chapter 2

Delay-Sensitive Transmission Scheduling with Homogeneous Packet Transmission Time

In this chapter, a truthful mechanism for delay-sensitive data packet transmission scheduling in the beyond-WBAN is studied. In the considered system, data packets collected by biosensors are aggregated randomly at each gateway and are stamped with different delay sensitivities based on their data information severities (e.g., the degree of deviations [55] or the importance of data types [56]). Each gateway immediately declares the beyond-WBAN transmission requests of its data packets upon their arrivals and temporarily stores the packet in its own buffer before it is completely transmitted. The BS, who acts as the network regulator, then determines the scheduling order of beyond-WBAN transmissions by formulating a priority queue. In this chapter, the beyond-WBAN transmissions of all data packets are assumed to be conducted in homogeneous time lengths. With the construction of the utilities of data packet transmissions in the beyond-WBAN and the network revenue (i.e., the operating profit of the BS), the characteristics of the system is investigated and a truthful mechanism is designed. Theoretical analyses and simulation results show that the proposed mechanism can induce all gateways to truthfully report the actual delay sensitivities of their data packets and can also maximize the network revenue, while always guaranteeing higher beyond-WBAN transmission priorities to more emergent data packets.

2.1 System Model and Problem Description

In this section, the considered system model is first described. After that, the problem of designing a truthful mechanism for scheduling delay-sensitive data packet transmissions in the beyond-WBAN is formulated.

2.1.1 System Model

As introduced in Chapter 1, the WBAN communication architecture consists of two tiers, i.e., intra-WBAN and beyond-WBAN. Each intra-WBAN includes a gateway and a number of heterogeneous biosensors worn on different parts of the human body, where each biosensor monitors one specific physiological information and transmits its sensed signal to the gateway. Such intra-WBAN communications have been defined and regulated by existing standards, such as IEEE std. 802.15.4 [57] and IEEE std. 802.15.6 [10]. As a hub or an aggregator, the gateway collects all sensed information from biosensors, temporarily stores data in its buffer (i.e., data storage), and then forwards it to a BS (which connects to remote facilities through Internet) via the beyond-WBAN. For explanation purpose, in this chapter and all follow-up chapters, the details of the intra-WBAN are ommited, and the research focus of this thesis is on the transmission scheduling in beyond-WBAN communications.

Here, consider a cellular-like beyond-WBAN with a single BS[1] and K gateways. The BS owns N homogeneous channels that are fixed and dedicated for beyond-WBAN communications, and is responsible to manage the scheduling of data packet transmissions from all associated gateways. In WBAN-based pervasive monitoring systems, each WBAN is required to support up to 256 biosensors [11], and it is expected that with the future advancements in lightweight sensors and the low-power transmission technology, the number of biosensors associated with a WBAN may even increase for fulfilling more comprehensive and accurate physiological monitoring [5]. Thus, the aggregate arrival of data packets from a relatively large number of independent biosensors at each gateway k (i.e., receiving from intra-WBAN communications) can be well approximated by a Poisson process with an average rate λ_k. However, the proposed mechanism can be applied to more general arrival processes. Each gateway will declare a transmission request to the BS when it receives a data packet from any of its biosensors. All received packets are stored in gateways' buffers before they are completely transmitted to the BS. In this thesis, buffer overflows are ignored[2]. Fig. 2.1 depicts the queueing model of the beyond-WBAN transmission scheduling studied in this chapter.

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[1] For a network with multiple BSs, an additional BS association algorithm [58, 59] can be applied to decouple the network into multiple subnetworks, each of which has a single BS.

[2] In practice, the effect of buffer overflow at gateways is generally negligible because data packets in WBANs are in commonly hundred kilobits while the storages of current mobile devices (i.e., gateways) are in hundred gigabytes.

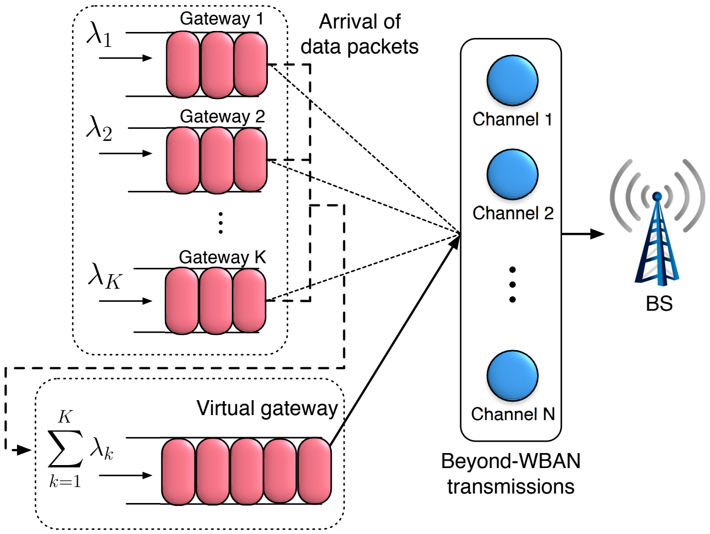

Figure 2.1: Queueing model of the delay-sensitive transmission management.

In addition, to describe the priority-aware QoS requirement in WBANs, in this chapter, an absolute priority rule (which is commonly required for medical applications) is adopted for scheduling beyond-WBAN data packet transmissions, i.e., more critical data packets have to always be transmitted prior to the ones with less emergency [30]. Therefore, from the view of the BS, data packets for beyond-WBAN transmissions are differentiated by their severities rather than the gateways where they are originated. Thus, the BS can treat all packet transmission requests from a single virtual gateway as shown in Fig. 2.1. Since all gateways are independent with each other, the aggregate arrival of data packets' transmission requests at the virtual gateway is still a Poisson process with an average rate:

$$\lambda = \sum_{k=1}^{K} \lambda_k. \tag{2.1}$$

Furthermore, consider that the beyond-WBAN transmissions of all data packets are conducted in time frames with equal length T, and further define that the minimum resource allocation unit is one time-frequency chunk (a single time frame on one channel), which can support one beyond-WBAN data packet transmission. Then, the beyond-WBAN management system can be formulated as an $M/d/N$ queue with a *Poisson/Markovian* arrival of data packets at a rate λ, a *deterministic* service time (i.e., the homogeneous transmission time length T), and N servers (i.e., N channels).

2.1.2 Problem Formulation

For simplicity, it is assumed that the value of transmitting each data packet in the beyond-WBAN is a constant[3], denoted by v. However, data packets may be heterogeneous in terms of delay sensitivity. As a result, the value of transmitting one data packet may decrease differently with the increase of the transmission delay. In other words, each data packet may suffer a waiting cost in the beyond-WBAN transmission, which is defined as a function of its delay sensitivity as [55]

$$c(\theta) = \theta \mathbb{E}[D(\theta)], \tag{2.2}$$

where θ indicates the cost per unit of waiting time in the beyond-WBAN transmission scheduling, and reflects the delay sensitivity of packets. $\mathbb{E}[D(\theta)]$ represents the mean waiting time given the delay sensitivity θ. Thus, the data packet with a larger value of θ has more concern on the potential delay since it will suffer more waiting cost (i.e., larger $c(\theta)$). In practice, θ can be defined based on the importance of data packets. For instance, a severity index of a data packet can be defined as

$$\delta = \xi \left| \frac{(\Phi_u - \Phi)^2 - (\Phi - \Phi_l)^2}{(|\Phi_u| + |\Phi_l|)^2} \right|, \tag{2.3}$$

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[3] This assumption is only employed in this chapter for simplification and will be relaxed in the following chapters.

where Φ is the sensed signal. Φ_u and Φ_l are the upper and lower bounds of the normal range for a particular physiological signal, respectively. ξ denotes a weight coefficient where a more important application has a larger ξ. Apparently, δ reflects the severity of a data packet by measuring the deviation of the sensed signal from its normal range. Naturally, θ can be defined as a continuous function of δ, i.e., $\theta = \mathcal{F}(\delta)$. Note that the proposed model is not restricted to any form of $\mathcal{F}(\cdot)$.

For each data packet i, θ_i is a private information, i.e., it is only available to its associated gateway while unknown to all other gateways and the BS. Thus, data packets are heterogeneous in terms of delay sensitivities, and their *types*[4] are parameterized by θ. However, since it is intuitive that the severities of data packets are random, one can assume that the delay sensitivities (which is a function of data severities) of all packets are drawn from a known distribution with a probability density function (PDF) $f_\theta(\cdot)$ and a cumulative distribution function (CDF) $F_\theta(\cdot)$ on an interval $\boldsymbol{\theta} = [0, \bar{\theta}]$, where $\bar{\theta}$ is an upper bound. In practice, this distribution can be estimated from empirical measurements.

Upon the arrival of a data packet i with type θ_i, the gateway who receives it will immediately declare a beyond-WBAN transmission request to the BS by reporting the delay sensitivity of this packet. However, it is possible that the gateway may report θ'_i, rather than θ_i. This is because, as an intelligent entity, each gateway may strategically misreport the delay sensitivities of its own data packets if and only if it can benefit from such behavior. Moreover, taking into account the absolute priority requirement, the beyond-WBAN transmission management system is defined as a

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[4] In this chapter, *type* refers to the truthful private information (i.e., actual delay sensitivity) of each data packet.

priority queue where the packet with higher reported delay sensitivity will always be scheduled for transmission with a higher priority (i.e., a shorter waiting time/delay). Besides, gateways will be charged for beyond-WBAN transmissions. Since such charge should be based on the achieved QoS (i.e., waiting time) of each data packet in the beyond-WBAN transmission, it becomes a function of the reported delay sensitivity, denoted as $\pi(\theta'_i)$. In summary, the utility gained by gateways for transmitting a data packet i with truthful type θ_i but reporting type θ'_i can be expressed as

$$U(\theta'_i|\theta_i) = v - \theta_i \mathbb{E}[D(\theta'_i)] - \pi(\theta'_i), \tag{2.4}$$

where v is the initial value, $\theta_i \mathbb{E}[D(\theta'_i)]$ and $\pi(\theta'_i)$ are the waiting cost and the charge for transmitting packet i, respectively. In order to maximize the utility gained from the beyond-WBAN transmission of the packet, the gateway may misreport a higher delay sensitivity to decrease the waiting time in the transmission scheduling so as to reduce the waiting cost. However, with an appropriate pricing design, reporting a higher delay sensitivity may also need to be charged by a higher price for the data transmission. Thus, it is required to design an appropriate pricing function $\pi(\cdot)$ such that all gateways will be induced to report the truthful types of their data packets (i.e., the utility of transmitting each packet in the beyond-WBAN is always maximized when its type is reported truthfully). Such solution is called to be truthful.

Meanwhile, the BS aims to maximize its profit (i.e., the network revenue) gained from gateways for serving the beyond-WBAN transmissions of their data packets. If all packets are reported with their actual delay sensitivities, the expected profit of the BS can be calculated as

$$\mathcal{R} = \lambda \int_{\boldsymbol{E}} \pi(\theta) f_{\theta}(\theta) d\theta, \tag{2.5}$$

where λ is the aggregate arrival rate of data packets defined in (2.1), $\pi(\theta)$ and $f_{\theta}(\theta)$ are the pricing and distribution functions associated with the delay sensitivity θ, respectively. Generally, gateways are only willing to transmit the data packet which could produce non-negative utility. Thus, $\boldsymbol{E}$ represents the set of data packets which satisfies such individual rationality, i.e., $\boldsymbol{E} = \{\theta | U(\theta|\theta) \geq 0\}$. As illustrated in (2.4), the utility of each data packet largely depends on the pricing function $\pi(\cdot)$. Considering the application to critical medical systems which require no packet loss, the formulation of the pricing function should also ensure that $\boldsymbol{E} = \boldsymbol{\theta}$.

In summary, the problem of designing a truthful mechanism for beyond-WBAN transmission scheduling with delay-sensitive data packets can be formulated as

$$\begin{aligned} \underset{\pi(\cdot)}{\arg\max} \quad & \lambda \int_{\boldsymbol{E}} \pi(\theta) f_{\theta}(\theta) d\theta \\ s.t. \quad & U(\theta'|\theta) \leq U(\theta|\theta),\ \forall \theta, \theta' \in \boldsymbol{\theta}, \\ & \boldsymbol{E} = \boldsymbol{\theta}, \end{aligned} \tag{2.6}$$

where the first constraint indicates the condition of truthfulness, i.e., the utility gained by the gateway from transmitting the packet with type θ can never be increased with a misreport $\theta' \neq \theta$. The second constraint imposes the requirement of no packet loss.

2.2 Truthful Mechanism Design

In this section, the characteristics of the mechanism is first studied. Then, the relationship between the expected waiting time in the beyond-WBAN transmission scheduling and the reported delay sensitivity is analyzed in detail. Finally, a pricing function is proposed which completes the design of the mechanism.

2.2.1 Characteristics of the Mechanism

Unlike conventional models [46, 49, 53, 60–62] in mechanism design, the random arrival of data packet transmission requests and the strategic report of delay sensitivities are considered in this chapter. In the following, some properties of the mechanism are first investigated by assuming that the truthfulness has been satisfied.

Proposition 2.1. If the designed mechanism satisfies the truthfulness condition, then for any two data packets with types θ_i and θ_j, we must have

$$\pi(\theta_i) \geq \pi(\theta_j), \quad \text{if } \theta_i > \theta_j, \forall \theta_i, \theta_j \in \boldsymbol{E}. \tag{2.7}$$

Proof. First, assume by the way of contradiction that

$$\pi(\theta_i) < \pi(\theta_j), \quad \text{if } \theta_i > \theta_j, \forall \theta_i, \theta_j \in \boldsymbol{E}. \tag{2.8}$$

Since $\theta_j \in \boldsymbol{E}$ and the mechanism is assumed to satisfy the truthfulness condition, i.e., the first constraint in (2.6), we must have

$$U(\theta_j|\theta_j) > 0 \text{ and } U(\theta_j|\theta_j) \geq U(\theta_i|\theta_j). \tag{2.9}$$

Moreover, $\mathbb{E}[D(\cdot)]$ is decreasing on $\boldsymbol{\theta}$ because a larger value of delay sensitivity will never lead to a longer waiting time in expectation according to the absolute prioritized scheduling. Thus,

$$\mathbb{E}[D(\theta_i)] < \mathbb{E}[D(\theta_j)], \quad \text{if } \theta_i > \theta_j, \forall \theta_i, \theta_j \in \boldsymbol{E}. \tag{2.10}$$

With (2.8) and (2.10), for any two types $\theta_i > \theta_j$, we have

$$v - \theta_j \mathbb{E}[D(\theta_j)] - \pi(\theta_j) < v - \theta_j \mathbb{E}[D(\theta_i)] - \pi(\theta_i), \tag{2.11}$$

which implies that $U(\theta_j|\theta_j) < U(\theta_i|\theta_j)$. Apparently, it contradicts (2.9). Hence, the assumption in (2.8) does not hold, which proves the proposition. $\square$

Proposition 2.1 indicates the fact that the data packet with a higher delay sensitivity (which means that it is more emergent) so as to gain a better service (i.e., a shorter delay) is required to be charged by a higher price for the beyond-WBAN transmission service. Furthermore, with the satisfaction of truthfulness, it can also be shown that data packets will be scheduled for the beyond-WBAN transmission according to a threshold condition.

Proposition 2.2. Considering that the mechanism satisfies the truthfulness condition, if the transmission utility of a data packet with type $\theta_0 \in \boldsymbol{\theta}$ is non-negative, then the transmission utility of any data packet with type $\theta \leq \theta_0$ is also non-negative.

Proof. Given that a packet with $\theta_0 \in \boldsymbol{E}$, we have

$$U(\theta_0|\theta_0) = v - \theta_0 \mathbb{E}[D(\theta_0)] - \pi(\theta_0) \geq 0. \tag{2.12}$$

Since $\theta \leq \theta_0$, we have

$$v - \theta_0 \mathbb{E}[D(\theta_0)] - \pi(\theta_0) \leq v - \theta \mathbb{E}[D(\theta_0)] - \pi(\theta_0). \tag{2.13}$$

Moreover, with the satisfaction of truthfulness, the following inequality holds:

$$v - \theta \mathbb{E}[D(\theta_0)] - \pi(\theta_0) = U(\theta_0|\theta) \leq U(\theta|\theta). \tag{2.14}$$

Combining (2.12), (2.13) and (2.14), we can obtain that

$$U(\theta|\theta) \geq U(\theta_0|\theta_0) \geq 0, \quad \text{if } \theta \leq \theta_0, \tag{2.15}$$

which means that the transmission utility of the packet with θ is also non-negative. □

With Proposition 2.2, it can be expected that the pricing function should be designed in accordance with the upper bound of delay sensitivity, $\bar{\theta}$, so as to guarantee that $\boldsymbol{\theta} = \boldsymbol{E}$ (i.e., no packet loss).

2.2.2 Analysis of the Expected Waiting Delay

From (2.4), it can be observed that the design of the mechanism requires the expression of the mean waiting time/scheduling delay, $\mathbb{E}[D(\theta)]$. As described previously, the beyond-WBAN transmission service system can be formulated as an $M/d/N$ queue with priorities (the data packet with a higher delay sensitivity has a higher queueing priority). In this chapter, the preemptive priority discipline is employed so that the arriving data packets with higher priorities can preempt the transmissions of packets with lower priorities which are already in the system (no matter whether they are in the queue or in the service). The preempted transmissions will resume their service when there are no high-priority packets. This preemptive-resume priority queueing discipline meets the requirement of the absolute priority rule, i.e., more emergent data packets have to be transmitted right away no matter whether the transmissions of lower-priority packets have been completed or not.

Unlike the traditional analysis of priority queues [63], in which customers are classified into different pre-determined priority levels, the priorities of data packets in the considered problem are determined by their delay sensitivities which follow a probability distribution. Here, the expected waiting time $\mathbb{E}[D(\theta)]$ includes two different parts:

i) When the data packet with type θ just arrives, beyond-WBAN transmissions of all other packets with lower priorities will be preempted even if they are being served, but the early arrived packets with priorities higher or equal to θ in the system cannot be ignored. This part of waiting time can be denoted as $\mathbb{E}[D_1(\theta)]$. Equivalently, we can simply consider all data packets with priority higher or equal to θ in one priority class, and the mean waiting time for these packets is exactly $\mathbb{E}[D_1(\theta)]$. Since the low-priority packets will not affect the service of high-priority packets, $\mathbb{E}[D_1(\theta)]$ equals $\mathbb{E}[D_{fcfs}(\theta)]$. Here, $\mathbb{E}[D_{fcfs}(\theta)]$ represents the mean waiting time of a first-come first-serve (FCFS) $M/d/N$ queue with the arrival rate $\lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)]$, where $F_\theta(\bar{\theta}) - F_\theta(\theta)$ is the probability of having a packet with type less than $\bar{\theta}$ but larger than or equal to θ.

ii) After the data packet with type θ has already been in the system, there will be newly arrived packets with priorities higher than θ. Since they have higher preemptive priorities, their service time will definitely contribute to the waiting time of the packet with type θ. We denote this part of waiting time as $\mathbb{E}[D_2(\theta)]$. Then, we have

$$\mathbb{E}[D_2(\theta)] = \mathbb{E}[T_{res}(\theta)] \cdot \lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)] \cdot T/N, \tag{2.16}$$

where $\mathbb{E}[T_{res}(\theta)] = \mathbb{E}[D(\theta)] + T$ is the mean response time which includes the waiting time and the transmission service time of the data packet, and N/T is the mean service rate of the beyond-WBAN transmission system. Thus, (2.16) indicates the total transmission time of packets with priorities higher than θ, arriving during the waiting and the transmission of the packet with type θ.

In summary, the expression of $\mathbb{E}[D(\theta)]$ can be written as

$$\mathbb{E}[D(\theta)] = \mathbb{E}[D_{fcfs}(\theta)] + (\mathbb{E}[D(\theta)] + T)\lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)]\frac{T}{N}. \tag{2.17}$$

After some mathematical manipulations,

$$\mathbb{E}[D(\theta)] = \frac{\mathbb{E}[D_{fcfs}(\theta)] + \lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)] \cdot T^2/N}{1 - \lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)] \cdot T/N}, \tag{2.18}$$

where the only unknown term remaining is the expected waiting time in a FCFS $M/d/N$ queue, i.e., $\mathbb{E}[D_{fcfs}(\theta)]$. Deriving $\mathbb{E}[D_{fcfs}(\theta)]$ is difficult due to the deterministic service time (i.e., beyond-WBAN transmission time), multiple servers (i.e., N channels) and more importantly the requirement for the closed-form expression. In the following, the detailed derivation is presented.

For notation simplicity, let $\lambda' = \lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)]$ and $\mathbb{E}[D_q] = \mathbb{E}[D_{fcfs}(\theta)]$. Furthermore, define $\mathbb{E}[L_q]$ as the average number of packets that are already in the queue when a new packet arrives. In fact, $\mathbb{E}[D_q]$, also consists of two parts, i.e., the mean waiting time due to the packets which arrived earlier, but are still waiting in the queue, and the mean waiting time for any one of the N channels becoming free. The former part can be directly calculated as $\mathbb{E}[L_q] \cdot T/N$, and let us denote the later part as $\mathbb{E}[D_0]$. Then,

$$\mathbb{E}[D_q] = \mathbb{E}[L_q] \cdot T/N + \mathbb{E}[D_0]. \tag{2.19}$$

By the Little's law [64], we have

$$\mathbb{E}[L_q] = \lambda' \cdot \mathbb{E}[D_q]. \tag{2.20}$$

Substituting (2.20) into (2.19) yields

$$\mathbb{E}[D_q] = \frac{\mathbb{E}[D_0]}{1 - \lambda' T/N}. \tag{2.21}$$

To further analyze $\mathbb{E}[D_0]$, let us introduce two random variables, X and Y, where X represents the remaining busy period of a channel, and Y is the time between two successive transmission service completion on one channel. As pointed out by [65], the relationship between X and Y can be demonstrated as

$$f_X(x) = \frac{1 - F_Y(x)}{\mathbb{E}[Y]}, \tag{2.22}$$

where $f_X(\cdot)$ and $F_Y(\cdot)$ are the PDF of X and the CDF of Y, respectively; and $\mathbb{E}[Y]$ denotes the mean value of Y.

Since the beyond-WBAN transmission time of each data packet is deterministic in the formulated $M/d/N$ queue, the random variable Y has the following properties:

$$F_Y(y) = \begin{cases} 1, & \text{if } \ y \geq T, \\ 0, & \text{if } \ y < T; \end{cases} \quad \text{and } \ \mathbb{E}[Y] = T. \tag{2.23}$$

Thus, the PDF of X in (2.22) can be rewritten as

$$f_X(x) = \begin{cases} 1/T, & \text{if } \ x < T, \\ 0, & \mathit{Otherwise}. \end{cases} \tag{2.24}$$

For all N channels, let their respective remaining busy periods be $X_1, X_2, \ldots, X_N$. Then, the remaining time for one of these channels becoming free can be expressed as

$$Z = \min\{X_1, X_2, \ldots, X_N\}. \tag{2.25}$$

With the heavy traffic approximation [66], $X_1, \ldots, X_N$ are independent and identically distributed. Thus, the distribution of Z can be calculated as

$$\begin{aligned} F_Z(z) &= \Pr.(Z \le z) \\ &= 1 - \Pr.(X_1 > z, X_2 > z, \ldots, X_N > z) \\ &= 1 - \Pr.(X_1 > z) \cdots \Pr.(X_N > z) \\ &= 1 - (1 - F_X(z))^N. \end{aligned} \tag{2.26}$$

From (2.24), we have

$$1 - F_X(z) = \int_z^{\infty} f_X(z)dx = \int_z^{T} 0dx + \int_T^{\infty} \frac{1}{T}dx = 1 - \frac{z}{T}. \tag{2.27}$$

Thus, substituting (2.27) into (2.26) yields

$$F_Z(z) = 1 - \left(1 - \frac{z}{T}\right)^N = 1 - \frac{(T-z)^N}{T^N}, \tag{2.28}$$

and

$$f_Z(z) = \frac{dF_Z(z)}{dz} = \frac{N(T-z)^{N-1}}{T^N} \quad 0 \le z \le T. \tag{2.29}$$

Then, the expectation of Z can be calculated as

$$\begin{aligned} \mathbb{E}[Z] &= \int_0^T z f_Z(z)dz \\ &= \frac{N}{T^N}\int_0^T z(T-z)^{N-1}dz \\ &= \frac{N}{T^N}\int_0^T -[(T-z)-T](T-z)^{N-1}dz \\ &= \frac{N}{T^N}\left(\frac{T^{N+1}}{N} - \frac{T^{N+1}}{N+1}\right) = \frac{T}{N+1}. \end{aligned} \tag{2.30}$$

Therefore, given that all N channels are currently busy (i.e., the system is overloaded), the mean waiting time for any one of them becoming free should be

$$\mathbb{E}[D_0] = \sum_{\ell=N}^{\infty} \chi_\ell \mathbb{E}[Z] = \frac{T}{N+1}\sum_{\ell=N}^{\infty} \chi_\ell, \tag{2.31}$$

where χ_ℓ represents the stationary probability that there are ℓ data packets in the system, and $\sum_{\ell=N}^{\infty}\chi_\ell$ indicates the queueing probability (i.e., the probability that the number of packets in the system is larger or equal to the total number of channels).

With (2.21) and (2.31), the mean waiting time of the FCFS $M/d/N$ queue with an arrival rate of $\lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)]$ can now be expressed as

$$\mathbb{E}[D_{fcfs}(\theta)] = \frac{[T/(N+1)]\sum_{\ell=N}^{\infty}\chi_\ell}{1-\lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)]T/N}. \tag{2.32}$$

Substituting (2.32) into (2.18), the mean waiting time for data packets with type θ in the considered beyond-WBAN transmission scheduling system becomes

$$\mathbb{E}[D(\theta)] = \frac{[T/(N+1)]\sum_{\ell=N}^{\infty}\chi_\ell}{(1-\lambda' T/N)^2} + \frac{\lambda' T^2/N}{1-\lambda' T/N}, \tag{2.33}$$

where $\lambda' = \lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)]$.

In order to get a closed-from expression and avoid burdensome calculations, one can use the *Erlang-C formula* [67] to approximate the queueing probability of the formulated $M/d/N$ queue, i.e,

$$\sum_{\ell=N}^{\infty}\chi_\ell \approx \frac{\frac{(N\rho)^N}{N!}}{(1-\rho)\sum_{\ell=0}^{N-1}\frac{(N\rho)^\ell}{\ell!} + \frac{(N\rho)^N}{N!}}, \tag{2.34}$$

where $\rho = \lambda[F_\theta(\bar{\theta}) - F_\theta(\theta)]T/N$ denotes the utilization factor which is assumed to be less than 1. It is well known that such approximation has a relatively good performance for calculating the queueing probability of multi-server queueing systems with the deterministic service time [68].

2.2.3 Design of the Pricing Function

With the characteristics obtained in Section 2.2.1 and the expression of $\mathbb{E}[D(\theta)]$ derived in Section 2.2.2, it is now able to design the pricing function for the mechanism. Inspired by [69] for a static single-item allocation mechanism, the pricing function is formulated as follows.

- ***Pricing function formulation:*** *For any data packet with delay sensitivity $\theta \in \boldsymbol{\theta}$, the charge for its beyond-WBAN transmission is set as*

$$\pi(\theta) = v - \theta\mathbb{E}[D(\theta)] - \int_{\theta}^{\bar{\theta}} \mathbb{E}[D(t)]dt. \tag{2.35}$$

Clearly, the problem studied in this chapter is more complicated than the one in [69] because of the considerations of the dynamic arrival of beyond-WBAN data packet transmission requests and the strategy of delay sensitivity. To verify that the mechanism with the pricing function proposed in (2.35) is feasible and applicable, some important theorems are given in the following.

Theorem 2.1. *The mechanism with the designed pricing function (2.35) is truthful.*

Proof. To prove the truthfulness, it is required to show that $U(\theta'|\theta) \leq U(\theta|\theta), \forall \theta, \theta' \in \boldsymbol{\theta}$. With the utility function defined in (2.4) and the expression of pricing function in (2.35), $U(\theta'|\theta)$ can be written as

$$\begin{aligned} U(\theta'|\theta) &= v - \theta\mathbb{E}[D(\theta')] - \pi(\theta') \\ &= \left(\theta'\mathbb{E}[D(\theta')] + \int_{\theta'}^{\bar{\theta}} \mathbb{E}[D(t)]dt\right) - \theta\mathbb{E}[D(\theta')]. \end{aligned} \tag{2.36}$$

Taking the first order derivative of $U(\theta'|\theta)$ with respect to θ',

$$\begin{aligned}\frac{dU(\theta'|\theta)}{d\theta'} &= \left(\mathbb{E}[D(\theta') + \theta' \frac{d\mathbb{E}[D(\theta')}{d\theta'} - \mathbb{E}[D(\theta')\right) - \theta \frac{d\mathbb{E}[D(\theta')]}{d\theta'} \\ &= (\theta' - \theta)\frac{d\mathbb{E}[D(\theta')]}{d\theta'}.\end{aligned} \tag{2.37}$$

Since the mean waiting time is a strictly decreasing function of the reported delay sensitivity θ', i.e., $d\mathbb{E}[D(\theta')]/d\theta' < 0$, $U(\theta'|\theta)$ can reach an extreme point only when $\theta' = \theta$ (which results in $dU(\theta'|\theta)/d\theta' = 0$). To further confirm that $\theta' = \theta$ will lead to the maximum instead of the minimum value of $U(\theta'|\theta)$, we check the second order derivative as

$$\begin{aligned}\left.\frac{d^2U(\theta'|\theta)}{d\theta'^2}\right|_{\theta'=\theta} &= \left.\frac{d}{d\theta'}\left((\theta' - \theta)\frac{d\mathbb{E}[D(\theta')]}{d\theta'}\right)\right|_{\theta'=\theta} \\ &= \left.\left(\frac{d\mathbb{E}[D(\theta')]}{d\theta'} + \theta' \frac{d^2\mathbb{E}[D(\theta')]}{d\theta'^2}\right)\right|_{\theta'=\theta} - \left.\theta \frac{d^2\mathbb{E}[D(\theta')]}{d\theta'^2}\right|_{\theta'=\theta} \\ &= \left.\frac{d\mathbb{E}[D(\theta')]}{d\theta'}\right|_{\theta'=\theta} + \left.(\theta' - \theta)\frac{d^2\mathbb{E}[D(\theta')]}{d\theta'^2}\right|_{\theta'=\theta} \\ &= \left.\frac{d\mathbb{E}[D(\theta')]}{d\theta'}\right|_{\theta'=\theta} < 0.\end{aligned} \tag{2.38}$$

The above inequality holds because $d\mathbb{E}[D(\theta')]/d\theta' < 0$. In summary, we must have

$$\theta = \arg\max_{\theta'} U(\theta'|\theta), \ \forall \theta \in \boldsymbol{\theta}. \tag{2.39}$$

Hence, to maximize the transmission utilities, all gateways will be induced to truthfully report the actual delay sensitivities of their data packets in the beyond-WBAN transmission management system. □

As required in the problem formulation, the designed mechanism has to also satisfy the condition $\boldsymbol{\theta} = \boldsymbol{E}$ (i.e., $U(\theta|\theta) \geq 0, \forall \theta \in \boldsymbol{\theta}$). The following theorem demonstrates that the proposed mechanism can indeed meet such requirement.

Theorem 2.2. *The mechanism with the designed pricing function (2.35) can guarantee no packet loss in the beyond-WBAN transmission scheduling system, i.e.,* $U(\theta|\theta) \geq 0, \forall \theta \in \boldsymbol{\theta}$.

Proof. With the proposed pricing function (2.35), the transmission utility of each data packet can be written as

$$U(\theta|\theta) = v - \theta\mathbb{E}[D(\theta)] - \pi(\theta) = \int_{\theta}^{\bar{\theta}} \mathbb{E}[D(t)]dt. \tag{2.40}$$

Obviously, the utility equals zero when $\theta = \bar{\theta}$. Since the value of θ is within the range of $\boldsymbol{\theta} = [0, \bar{\theta}]$, we must have $U(\theta|\theta) \geq 0, \forall \theta \in \boldsymbol{\theta}$, which completes the proof. □

Last but not least, it is also necessary to analyze the optimality of the mechanism in maximizing the network revenue (i.e, the profit of the BS). By substituting the proposed pricing function (2.35) into the objective function in (2.6), and after doing some mathematical manipulations, we have

$$\begin{aligned} \mathcal{R} &= \lambda \int_0^{\bar{\theta}} \pi(\theta) f_\theta(\theta) d\theta \\ &= \lambda \int_0^{\bar{\theta}} \left(v - \theta\mathbb{E}[D(\theta)] - \int_{\theta}^{\bar{\theta}} \mathbb{E}[D(t)]dt \right) f_\theta(\theta) d\theta \\ &= \lambda v - \lambda \int_0^{\bar{\theta}} f_\theta(\theta) \left(\theta + \frac{F_\theta(\theta)}{f_\theta(\theta)} \right) \mathbb{E}[D(\theta)] d\theta. \end{aligned} \tag{2.41}$$

Let $\eta(\theta) = \theta + F_\theta(\theta)/f_\theta(\theta)$. Equation (2.41) can be rewritten as

$$\mathcal{R} = \lambda v - \lambda \int_0^{\bar{\theta}} f_\theta(\theta)\eta(\theta)\mathbb{E}[D(\theta)]d\theta. \tag{2.42}$$

Theorem 2.3. *When the distribution of delay sensitivity satisfies a mild condition that* $\eta(\theta)$ *monotonically increases with* θ*, the proposed mechanism can maximize* $\mathcal{R}$.

Proof. Consider two data packets with $\theta_i > \theta_j$. If $\eta(\theta)$ is monotonically increased with θ, we must have $\eta(\theta_i) > \eta(\theta_j)$. In the proposed mechanism, since $d\mathbb{E}[D(\theta)]/d\theta < 0$, we also have $\mathbb{E}[D(\theta_i)] < \mathbb{E}[D(\theta_j)]$. If the service priorities of these two packets are exchanged, their mean waiting time will be exchanged accordingly. In this case, $\mathcal{R}$ will be reduced by

$$\begin{aligned}\Delta &= (v - \theta_i\mathbb{E}[D(\theta_i)] + v - \theta_j\mathbb{E}[D(\theta_j)]) - (v - \theta_i\mathbb{E}[D(\theta_j)] + v - \theta_j\mathbb{E}[D(\theta_i)]) \\ &= (\theta_i - \theta_j)(\mathbb{E}[D(\theta_j)] - \mathbb{E}[D(\theta_i)]).\end{aligned} \tag{2.43}$$

Apparently, Δ is positive. Hence, the proposed mechanism maximizes $\mathcal{R}$ by serving the beyond-WBAN transmissions of data packets with higher delay sensitivities ahead of the others. Note that it can be easily proved that most of the random distributions which are commonly used in wireless networks (e.g., uniform and exponential distributions) satisfies the mild condition that $\eta(\theta)$ increases with θ. □

2.3 Simulation Results

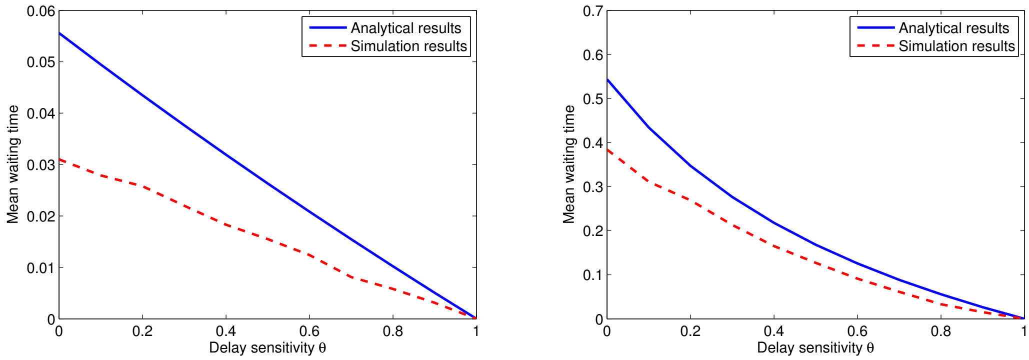
In this section, simulations are conducted by MATLAB to evaluate the performance of the proposed mechanism in the delay-sensitive beyond-WBAN transmission scheduling. The performance analysis of the mean waiting time/delay is first examined by comparing analytical and simulation results under different scenarios. Then, some characteristics of the designed pricing function are demonstrated numerically. Finally, the superiority of the proposed mechanism is illustrated.

2.3.1 Simulation Settings

Consider a beyond-WBAN with one BS who owns $N = 5$ channels. Since the size of WBAN data packets at gateways is normally under 100 Kb [27] and the average uplink transmission rate of 3G cellular networks is commonly under 500 Kpbs [70], it is assumed that the time length for serving the beyond-WBAN transmission of each data packet, T, is 0.2 second. The average arrival rate of the overall packets' transmission requests is λ per second, where λ is chosen as an integer from 0 to 10. Similar settings have also been employed in [28]. For all data packets, let us define that the initial value for each of their transmission is a unified constant, i.e., $v = 1$. Their heterogeneous delay sensitivities are uniformly determined within the interval $[0, \bar{\theta}]$, where $\bar{\theta} = 1$. In the following, all results are obtained by taking averages over 100 runs. Note that some parameters may vary according to evaluation scenarios.

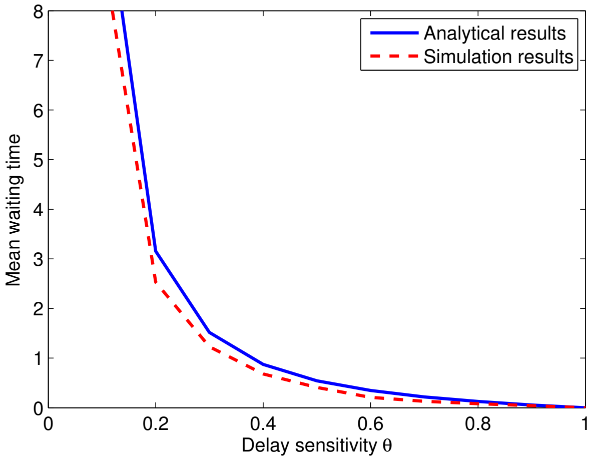
2.3.2 Performance Evaluations

Fig. 2.2 shows the mean waiting time/delay (in seconds) for data packets with different delay sensitivities in the designed mechanism. From this figure, we can first see that the analytical results can well match the simulation results, especially for a busier transmission scheduling system (i.e., a larger λ). The performance gap mostly results from the approximation made in the mathematical analyses. Besides, the higher delay sensitivity the packet has, the shorter mean waiting time it obtains. This is because the data packet with more critical information (i.e., which has to be transmitted promptly) will always be scheduled for the beyond-WBAN transmission prior to the others with less emergency. By further comparing Fig. 2.2a-Fig. 2.2c with



(a) $\lambda = 1$

(b) $\lambda = 5$



(c) $\lambda = 10$

Figure 2.2: Mean waiting time of data packets in beyond-WBAN transmissions.

different packet arrival rate λ, we can observe that the waiting time for packets with the same delay sensitivity is longer when λ increases. Intuitively, a larger λ implies that more packets need to be transmitted by the system so that the waiting probability increases. Moreover, these figures also illustrate that the mean transmission delay of a packet is decreased exponentially with the increase of the delay sensitivity, and such trend becomes more obvious for a larger λ.

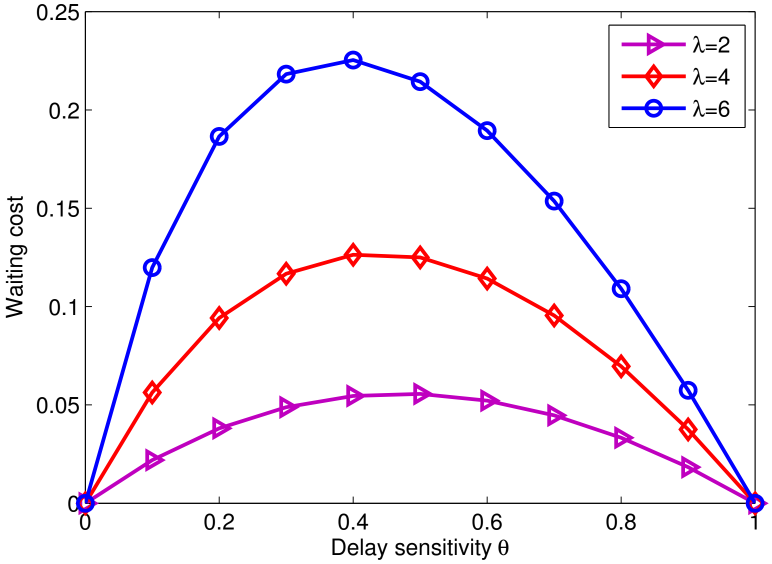


Figure 2.3: Waiting costs for data packets with different delay sensitivity θ.

In Fig. 2.3, the waiting costs for data packets with different delay sensitivities are investigated. It is shown that the waiting cost first increases with the delay sensitivity, and then decreases when θ continuously increases from 0 to $\bar{\theta} = 1$. According to the expression in (2.2), the waiting cost is defined as a product of the delay sensitivity and the mean waiting delay. Thus, the waiting cost tends to 0 for two extreme cases: i) when $\theta \to 0$, it indicates that the packet is not important so that it does not care about the potential delay; ii) when $\theta \to \bar{\theta}$, it means that the packet has the highest transmission priority so that it will be served without any delay. Furthermore, since the waiting time increases with the packet arrival rate as demonstrated in Fig. 2.2, the waiting cost shown in Fig. 2.3 also becomes larger when λ increases.

Fig. 2.4 reveals the relationship between the transmission service charge/payment and the delay sensitivity of the data packet in the beyond-WBAN. It can be seen from

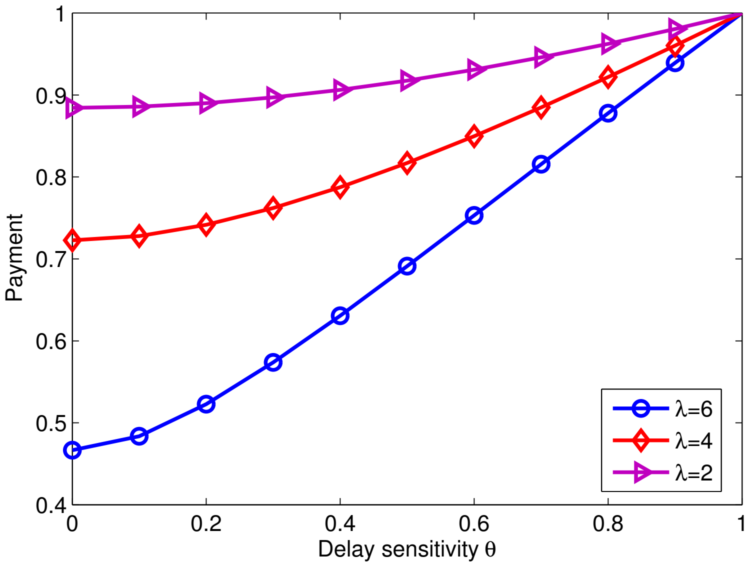


Figure 2.4: Beyond-WBAN transmission charge for data packets with different θ.

the figure that the transmission service charge increases with the delay sensitivity, which matches the observation from the Proposition 2.1 that the packet with a larger θ so as to receive a better service (i.e., a shorter delay) will be charged by a higher price for its transmission. Moreover, the curve is increased more dramatically for a high packet arrival rate. This is because the service is improved significantly when λ is large (i.e., the waiting time is decreased exponentially as shown in Fig. 2.2c). Besides, it is intuitive that a larger packet arrival rate always leads to a lower payment for the same data packet transmission since the overall system is more congested.

In Fig. 2.5, the truthfulness of the proposed mechanism is verified. Given the absolute priority queueing discipline, gateways can strategically report the delay sensitivity of each data packet so as to maximize their utility gains. The trend of the curves in Fig. 2.5 indicates that the transmission utility of an individual packet is

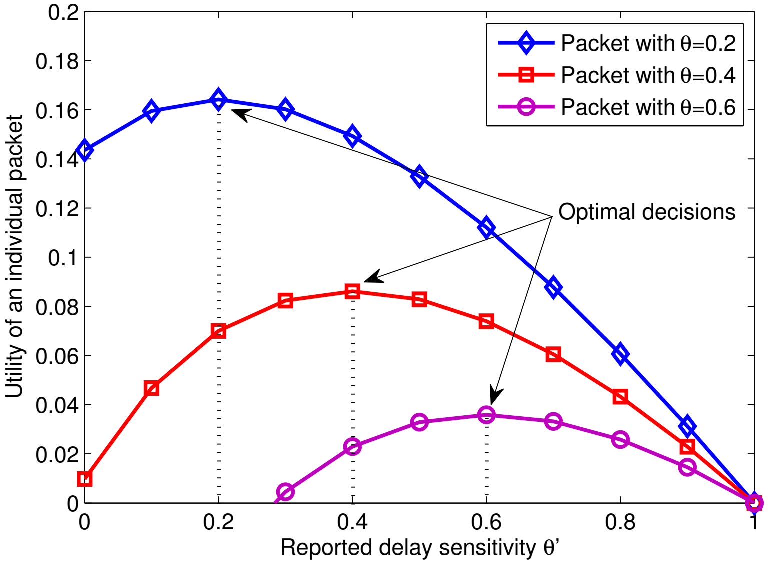


Figure 2.5: Optimal decisions in reporting the delay sensitivities of data packets.

first increased with the reported θ'. This is because with the increase of θ', a shorter delay is achieved so that it gains more utility. However, after a certain point (i.e., $\theta' = \theta$), since the delay requirement has already been satisfied, the transmission service charge becomes dominant so that the utility decreases. Intuitively, the θ' which results in the highest utility is the optimal decision that will be adopted. Thus, the delay sensitivities of all data packet will be reported truthfully in the designed mechanism. In addition, Fig. 2.5 shows that the packet with a larger θ produces less utility. The reason is that the initial value of all packets' transmissions are defined to be homogeneous, while the transmission service charge for the packet with a larger θ is higher as shown in Fig. 2.4.

For comparison purpose, in the following, the mechanism without the consideration of priority is simulated as the benchmark, which ignores the heterogeneous delay

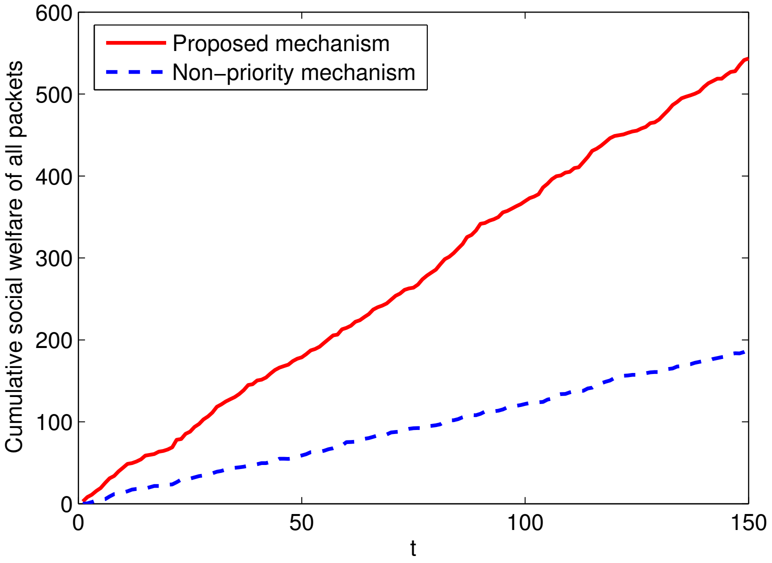


Figure 2.6: Cumulative social welfare of beyond-WBAN packet transmissions.

sensitivities of data packets and transmits them based on the FCFS manner.

Fig. 2.6 compares the cumulative social welfare of all data packets in the beyond-WBAN transmissions under the proposed mechanism and the non-priority mechanism from 0 to 150 seconds. Here, the cumulative social welfare is defined as [71]

$$\text{Welfare}(t) = \sum_{t} \sum_{i} v - \theta_i \mathbb{E}[D(\theta_i)], \tag{2.44}$$

which represents the total utility gain from all packet transmissions regardless of their transmission service charges. It is intuitive that such cumulative social welfare increases with the time. However, these curves are not smooth since both the arrival of the packets' transmission requests and their associated types are random. Moreover, it can be seen that the proposed mechanism achieves a much better performance than the non-priority mechanism. The explanation is twofold: i) The non-priority mechanism cannot offer appropriate transmission services for data packets with different

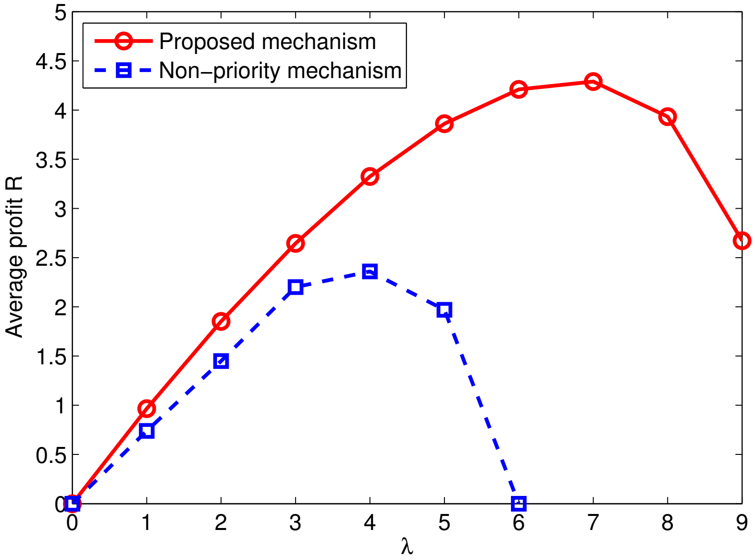


Figure 2.7: Performance comparison on the network revenue.

delay sensitivities, so that high delay-sensitive packets may suffer large waiting costs; ii) The non-priority mechanism cannot guarantee that the utility of each individual packet is always non-negative, which means that some packets may be dropped so that the amount of successfully transmitted packets is smaller than that under the proposed mechanism.

As a proof for Theorem 2.3, Fig. 2.7 illustrates the expected profits of the BS under the proposed mechanism and the non-priority mechanism. It is shown that the proposed mechanism outperforms the non-priority mechanism, and such superiority is more obvious with the increase of λ. This is because more data packets can be granted with desirable services under the proposed mechanism, and thus the total revenue increases. In addition, we can observe that the profit of the BS is not continuously increased with λ. Even though a larger λ indicates a larger amount of packets' transmission requests, the transmission service charge for each individual packet transmission is actually decreased as examined in Fig. 2.4. When λ is increasing over a certain value, such reduction becomes dominant because most of the packets are suffering relatively long waiting time due to the service congestion, and thus the profit of the BS decreases. However, Fig. 2.7 shows that such profit reduction happens in a much heavier traffic load under the proposed mechanism than the non-priority mechanism.

Chapter 3

Multi-Class Delay-Sensitive Prioritized Transmission Scheduling

In Chapter 2, mechanism design technique was first introduced for handling dynamic management of data packet transmissions in the beyond-WBAN with the guarantee of truthfulness from smart gateways. However, the mechanism proposed in Chapter 2 may be too primitive for the practical implementation due to the following assumptions: i) the priorities of WBAN data packets were defined as continuous values (reflected by their packet delay sensitivities) and this does not fit the existing IEEE std. 802.15.6 [10], in which data packet priorities are ordinarily categorized into discrete classes; ii) the beyond-WBAN transmission time of different data packets was assumed to be homogeneous, which may not be realistic.

To address these impractical assumptions, in this chapter, a novel priority-aware truthful mechanism for *multi-class* delay-sensitive data packet transmissions in the beyond-WBAN is redesigned. In the considered system model, different data packets collected by biosensors are aggregated randomly at each gateway, and all packets are categorized into finite discrete priority classes. Upon receiving a data packet, the associated gateway immediately declares a beyond-WBAN transmission request to the BS, and temporarily stores the packet in its buffer before it is completely transmitted. Data packets take heterogeneous time lengths for beyond-WBAN transmissions, and their delay-sensitivities are represented by different costs per unit of waiting delay. As the network regulator/controller, the BS determines a scheduling mechanism for dynamically managing the data packet transmissions in the beyond-WBAN with the consideration of the priority-aware QoS requirement. The packet-level operation is then formulated as a multi-class priority queueing system. Based on this, a truthful mechanism is proposed which can guarantee that all gateways will truthfully report their packet priority classes and can maximize the expected network revenue gained by the BS in running the management system.

3.1 System Model and Problem Description

In this section, the system model is first described. Then, the problem of designing a priority-aware truthful mechanism for scheduling multi-class delay-sensitive data packet transmissions in the beyond-WBAN is formulated.

3.1.1 System Model

Similar to the model studied in Chapter 2, a cellular-like beyond-WBAN with a single BS and K gateways is considered. The BS owns N homogeneous channels that are dedicated for beyond-WBAN communications, and is responsible for managing data packet transmissions from all associated gateways. Each gateway may receive a variety of data packets belonging to different applications (e.g., EEG, ECG and blood pressure) from its own biosensors. According to IEEE std. 802.15.6 [10], data packets are categorized into $\mathcal{L} = \{0, 1, \ldots, L\}$ discrete priority classes, where 0 and L represents the lowest and highest priority levels, respectively. Following the conventions in the literature [28, 72] and the justification provided in Chapter 2, the aggregate arrival of data packets at each gateway k is assumed as a Poisson process with an average rate λ_k. However, the proposed mechanism can be applied to more general arrival processes. Besides, by monitoring the long-term physiological conditions of humans/patients, it is reasonable to assume that there is a known distribution $\boldsymbol{P}_k = (P_{k,0}, P_{k,1}, \ldots, P_{k,L})$ for packets arrived at each gateway k, where $\sum_{\ell=0}^{L} P_{k,\ell} = 1$, and $P_{k,\ell}$ indicates the probability that the arrived packet are in priority level $\ell, \forall \ell \in \mathcal{L}$. Thus, the average arrival rate of data packets in priority level ℓ at gateway k can be calculated as $\lambda_k P_{k,\ell}$. Fig. 3.1 depicts the queueing model of the multi-class beyond-WBAN data packet transmission scheduling system.

Each gateway will immediately declare a beyond-WBAN transmission request to the BS when it receives a data packet from any of its biosensors. All received data packets are stored in gateways' buffers before they are completely transmitted to the BS. Again, we do not consider buffer overflow. In addition, the scheduling order of packet transmissions is required to guarantee the absolute priority, i.e., more critical data packets (in higher priority levels) have to always be transmitted prior to the ones with less emergency (in lower priority levels) [30]. Therefore, from the view of the BS, data packets are differentiated by their priorities rather than the gateways where

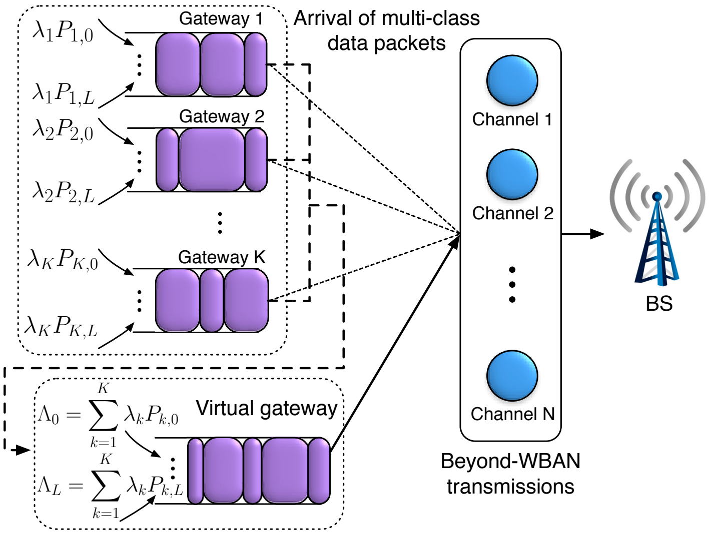


Figure 3.1: Queueing model of the multi-class prioritized transmission management.

they are originated. Thus, the BS can treat all packet transmission requests from a single virtual gateway as shown in Fig. 3.1, which also consists of multi-class arrival processes with respect to $\mathcal{L}$ priority levels. Since all gateways are independent from each other, the aggregate packet arrivals at the virtual gateway still follow Poisson distribution, and the average packet arrival rate can be denoted by

$$\Lambda_\ell = \sum_{k=1}^{K} \lambda_k P_{k,\ell}, \ \forall \ell \in \mathcal{L}. \tag{3.1}$$

In reality, data packets may experience different beyond-WBAN transmission time due to the heterogeneities in terms of physiological signal packet size and achievable signal-to-noise ratios (SNRs) at different gateways. Here, for simplicity, we employ the common assumption [73, 74] that the packet transmission time on each channel $n, \forall n = 1, 2 \ldots, N$, is exponentially distributed with mean $1/\mu$. Then, the packet-level operation can be formulated as a multi-class multi-server queueing system, where there are $\mathcal{L}$ Poisson-distributed packet arrival processes, $\mathcal{L}$ prioritized service classes,

Table 3.1: Sensing frequencies of different biosensors.

Biosensors	**Sensing Frequency**
ECG/EEG/EMG sensor	500Hz (Very high)
Respiration sensor	20Hz (High)
Blood-PH	4Hz (Low)
Temperature sensor	0.2Hz (Very low)

exponentially distributed transmission times, and N servers (i.e., N channels).

3.1.2 Problem Formulation

Different from data packets in general communication networks, data packets in WBANs may be differentiated by not only their priorities, but also their timeliness [75, 76]. Here, the packet timeliness is defined as the time length before the information carried by this data packet becomes outdated. For instance, respiration sensors have higher sensing frequencies than temperature sensors as shown in Table 3.1 [77], and thus the status of respiration will be more quickly updated with the generation of new packets. As a result, the packet with respiratory signals will be easier to become outdated, i.e., it has shorter timeliness. Naturally, humans/patients (represented by gateways) will benefit from the beyond-WBAN data packet transmissions. To describe such benefits (or utility gains), let us define a value, denoted by v_i, for successfully transmitting data packet i, where v_i is determined by both the packet priority level and timeliness. Commonly, data packets with higher priorities should have higher values than the ones with lower priorities. For packets within the same priority level, their values may further be differentiated by their heterogeneous timeliness. Since the arrivals and severities of data packets are both random, the values of data packets in each priority level $\ell, \forall \ell \in \mathcal{L}$, can be modeled by a distribution, represented by a CDF $F_\ell(\cdot)$ and a PDF $f_\ell(\cdot)$. In practice, these distributions may be estimated from empirical measurements.

There are potential waiting/scheduling delays for packet transmissions in the beyond-WBAN, and such delay will incur a waiting cost on the value of each packet transmission. In other words, the value of transmitting one data packet will decrease with the increase of the waiting delay. Since the beyond-WBAN transmission order is solely determined by packet priorities due to the absolute priority rule, the waiting cost of data packet i with priority ℓ_i can be defined as

$$C_i = \theta_{\ell_i} \cdot D(\ell_i), \ \forall \ell_i \in \mathcal{L}, \tag{3.2}$$

where θ_{ℓ_i} is the cost per unit of waiting delay, and $D(\ell_i)$ represents the experienced waiting delay of packet i in beyond-WBAN transmissions. Intuitively, data packets with higher priorities have more concerns on potential delays. Thus, let us define

$$\theta_x \leq \theta_y, \ \text{for } 0 \leq x < y \leq L, \tag{3.3}$$

which indicates that the data packet with a higher priority suffer more cost per unit of waiting delay.

It is intuitive that for any data packet i, its priority level ℓ_i is a private information that is only available to its associated gateway, while unknown to all the other gateways and the BS. Upon the arrival of data packet i with priority ℓ_i, the associated gateway will declare a transmission request to the BS by reporting the packet priority level. However, it is possible that the gateway may report $\ell_i' \neq \ell_i$. This is because, as an intelligent entity, the gateway may strategically misreport the priority levels of its data packets if and only if it can benefit from such behavior. By considering all gains and costs of a data packet transmission, the net utility obtained by the gateway from transmitting packet i with truthful priority ℓ_i but reporting ℓ_i' can be expressed as

$$U_i(\ell_i'|\ell_i) = v_i - \theta_{\ell_i} D(\ell_i') - \pi(\ell_i'), \tag{3.4}$$

where v_i, $\theta_{\ell_i} D(\ell_i')$ and $\pi(\ell_i')$ are the value, the cost due to the waiting delay and the charge by the BS for beyond-WBAN transmission service, respectively. Since the BS is unaware of the truthful priorities of data packets, the resulted delay and price (i.e., $D(\ell_i')$ and $\pi(\ell_i')$) for transmitting packet i are both based on the reported priority level ℓ_i'. Therefore, as an essential requirement for realizing absolutely prioritized scheduling for beyond-WBAN data packet transmissions, ensuring that all gateways report truthful priorities of their data packets is necessary in the design of the transmission mechanism. Note that the utility given by (3.4) is actually an ex-post value because delays cannot be known in advance. Thus, when declaring the priority level of the arrived packet i, the gateway can only intend to maximize the expected utility, $\mathbb{E}[U_i(\ell_i'|\ell_i)]$, according to the mean waiting delay for transmitting data packets with priority ℓ_i' in the queueing system. Hence, the condition of truthfulness can be described as

$$\ell_i = \arg\max_{l_i' \in \mathcal{L}} \{\mathbb{E}[U_i(\ell_i'|\ell_i)]\}, \quad \text{for any packet } i. \tag{3.5}$$

Namely, the expected utility of transmitting packet i should only be maximized when the gateway behaves truthfully by reporting its actual priority (i.e., $\ell_i' = \ell_i$). With the utility function (3.4), the condition (3.5) is equivalent to

$$\theta_\ell \mathbb{E}[D(\ell)] + \pi(\ell) \leq \theta_\ell \mathbb{E}[D(\ell')] + \pi(\ell'), \ \forall \ell, \ell' \in \mathcal{L}. \tag{3.6}$$

Meanwhile, the BS aims to maximize its revenue gained from gateways for successfully serving the transmissions of their data packets. However, it is possible that the number of successful packet transmissions may not be the same as that of total arrivals because gateways will not be willing to continue transmitting any data packet which produces a negative utility (due to the consideration of individual rationality). Such situation may happen when a packet has been waited too long in the buffer and become much less important than newly emerged packets. By considering this potential packet loss[1], the actual admission rate of packet transmission requests in beyond-WBAN system should be calculated as

$$\varphi_\ell = \Lambda_\ell \bar{F}_\ell\big(\pi(\ell) + \theta_\ell \mathbb{E}[D(\ell)]\big),\ \forall \ell \in \mathcal{L}, \tag{3.7}$$

where $\bar{F}_\ell\big(\pi(\ell) + \theta_\ell \mathbb{E}[D(\ell)]\big) = 1 - F_\ell\big(\pi(\ell) + \theta_\ell \mathbb{E}[D(\ell)]\big)$ denotes the probability of having a non-negative utility for a data packet in priority level ℓ. With (3.7), the expected revenue of the BS can be defined as

$$\mathcal{R} = \sum_{\ell=0}^{L} \varphi_\ell \cdot \pi(\ell), \tag{3.8}$$

where $\varphi_\ell \pi(\ell)$ represents the average profit gained for transmitting packets in priority level ℓ. As the network regulator, the BS will determine the transmission scheduling scheme denoted by $\boldsymbol{\zeta}(\varphi_0, \dots \varphi_L)$ (which includes a prioritized queueing discipline and a delay control scheme as described later) and the transmission service charge $\boldsymbol{\pi} = [\pi(0), \dots, \pi(L)]$ with the objective that $\mathcal{R}$ is maximized.

In summary, the problem of designing a priority-aware truthful mechanism for multi-class delay-sensitive data packet transmissions in beyond-WBANs can be for-

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[1] Unlike Chapter 2, in this chapter, we do not impose the strict requirement of no packet loss.

mulated as

$$(\mathcal{P}1): \quad [\boldsymbol{\zeta}, \boldsymbol{\pi}] = \arg\max \sum_{\ell=0}^{L} \varphi_\ell \cdot \pi(\ell) \tag{3.9}$$

$$s.t., \theta_\ell \mathbb{E}[D(\ell)] + \pi(\ell) \leq \theta_\ell \mathbb{E}[D(\ell')] + \pi(\ell'), \forall \ell, \ell' \in \mathcal{L}, \tag{3.10}$$

$$\varphi_\ell = \Lambda_\ell \bar{F}_\ell\big(\pi(\ell) + \theta_\ell \mathbb{E}[D(\ell)]\big), \forall \ell \in \mathcal{L}, \tag{3.11}$$

$$\big(\mathbb{E}[D(0)], \ldots, \mathbb{E}[D(L)]\big) \in \boldsymbol{\zeta}(\varphi_0, \ldots \varphi_L), \tag{3.12}$$

$$D(\ell) \leq D(\ell'), \ \forall \ell \geq \ell' \text{ and } \ell, \ell' \in \mathcal{L}, \tag{3.13}$$

where constraint (3.10) induces all gateways to report truthful priorities of their data packets, and (3.11) indicates the actual admission rate. Constraints (3.12) and (3.13) are the requirements that the expected waiting delays for transmissions of data packets in all priority levels should follow the determined transmission scheduling scheme, and the absolute priority should always be guaranteed instantaneously. It is obvious that solving problem ($\mathcal{P}1$) directly is challenging because i) $\boldsymbol{\zeta}$ is not a simple decision variable (or vector) but a complicated management scheme of the queue; and ii) any adjustment on $\boldsymbol{\zeta}$ or $\boldsymbol{\pi}$ will affect the queueing dynamics, which will in turn change the final decisions. Hence, in the following, a novel method is proposed to construct the mechanism, i.e., $[\boldsymbol{\zeta}, \boldsymbol{\pi}]$, which can meet all design requirements in ($\mathcal{P}1$).

3.2 Two-Class Prioritized Transmission Mechanism

In this section, let us first consider to design a mechanism for the beyond-WBAN transmission scheduling with two-class prioritized data packets, i.e., *normal* and *emergency*, which are represented by $\ell = 0$ and 1, respectively. Such 2-level priority classification has been widely discussed in the WBAN-related literature [55, 78]. Later, in Section 3.3, the extension to multi-class data packet transmissions will be discussed.

3.2.1 Deterministic Relaxation

By ignoring the complications introduced by the queueing dynamics, a *deterministic relaxation* can be first conducted. Specifically, with $\mathcal{L} = \{0, 1\}$, the original problem $(\mathcal{P}1)$ can be deterministically relaxed as

$$(\mathcal{P}2): \quad \underset{D(0),D(1),\pi(0),\pi(1)}{\arg\max} \quad \varphi_0\pi(0) + \varphi_1\pi(1) \tag{3.14}$$

$$s.t., \ \theta_\ell D(\ell) + \pi(\ell) \leq \theta_\ell D(\ell') + \pi(\ell'), \forall \ell, \ell' \in \{0, 1\}, \tag{3.15}$$

$$\varphi_\ell = \Lambda_\ell \bar{F}_\ell\big(\pi(\ell) + \theta_\ell D(\ell)\big), \forall \ell \in \{0, 1\}, \tag{3.16}$$

$$\varphi_0 + \varphi_1 \leq N \cdot \mu, \tag{3.17}$$

$$0 \leq D(1) \leq D(0). \tag{3.18}$$

Compared to $(\mathcal{P}1)$, the objective function and the first two constraints are same except that delays (i.e., $D(0)$ and $D(1)$) become decision variables in $(\mathcal{P}2)$ instead of endogenous factors generated by the queueing dynamics. Constraints (3.12) and (3.13) in $(\mathcal{P}1)$ are replaced by (3.17) and (3.18), which guarantee that the total admission rate of packet transmission requests cannot exceed the total service rate of N channels, and emergent data packets should always experience a shorter non-negative waiting delay than normal ones. Though the relaxed problem $(\mathcal{P}2)$ seems oversimplified, it actually captures essential features of the original problem $(\mathcal{P}1)$. As discussed in the following subsections, the optimal solution of $(\mathcal{P}2)$ can provide an upper-bound performance and will be used in designing the dynamic transmission mechanism.

Since $(\mathcal{P}2)$ is obviously a standard convex programming problem, various existing software-based optimization tools [71] can be applied to numerically solve this problem. Let the corresponding optimal solution be $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$, and define $\tilde{\varphi}_\ell = \Lambda_\ell \bar{F}_\ell\big(\tilde{\pi}(\ell) + \theta_\ell \tilde{D}(\ell)\big), \forall \ell \in \{0, 1\}$.

Proposition 3.1. If $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$ leads to the optimality of $(\mathcal{P}2)$, then we must have

$$\tilde{D}(1) = 0, \text{ and } \tilde{D}(0) = \frac{\tilde{\pi}(1) - \tilde{\pi}(0)}{\theta_1}. \tag{3.19}$$

Proof. Let us assume by the way of contradiction that $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$ is a feasible and optimal solution to $(\mathcal{P}2)$, but $\tilde{D}(1) \neq 0$ or $\tilde{D}(0) \neq \frac{\tilde{\pi}(1)-\tilde{\pi}(0)}{\theta_1}$.

If $\tilde{D}(1) \neq 0$, we can build another solution $(\hat{D}(0), \hat{D}(1), \hat{\pi}(0), \hat{\pi}(1))$ such that

$$\hat{D}(0) = \tilde{D}(0), \; \hat{\pi}(0) = \tilde{\pi}(0), \tag{3.20}$$

$$\hat{D}(1) = 0, \; \hat{\pi}(1) = \tilde{\pi}(1) + \theta_1 \tilde{D}(1). \tag{3.21}$$

Substituting (3.20) and (3.21) into $(\mathcal{P}2)$, it is easy to prove that $\hat{\varphi}_\ell = \tilde{\varphi}_\ell, \forall \ell \in \{0, 1\}$, and all constraints are still satisfied, i.e., the solution $(\hat{D}(0), \hat{D}(1), \hat{\pi}(0), \hat{\pi}(1))$ is also feasible. Moreover, $\hat{\mathcal{R}} = \hat{\varphi}_0 \hat{\pi}(0) + \hat{\varphi}_1 \hat{\pi}(1) > \tilde{\mathcal{R}} = \tilde{\varphi}_0 \tilde{\pi}(0) + \tilde{\varphi}_1 \tilde{\pi}(1)$ because $\theta_1 \neq 0$ and $\tilde{D}(1) \neq 0$ so that $\hat{\pi}(1) > \tilde{\pi}(1)$. Hence, $(\hat{D}(0), \hat{D}(1), \hat{\pi}(0), \hat{\pi}(1))$ represents a better solution than $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$.

If $\tilde{D}(0) \neq \frac{\tilde{\pi}(1)-\tilde{\pi}(0)}{\theta_1}$, we can also build another solution $(\breve{D}(0), \breve{D}(1), \breve{\pi}(0), \breve{\pi}(1))$ with

$$\breve{D}(0) = \frac{\tilde{\pi}(1) + \theta_1 \tilde{D}(1) - \tilde{\pi}(0) - \theta_0 \tilde{D}(0)}{\theta_1 - \theta_0}, \tag{3.22}$$

$$\breve{\pi}(0) = \frac{\theta_1(\tilde{\pi}(0) + \theta_0\tilde{D}(0)) - \theta_0(\tilde{\pi}(1) + \theta_1\tilde{D}(1))}{\theta_1 - \theta_0}, \tag{3.23}$$

$$\breve{D}(1) = \tilde{D}(1),\ \breve{\pi}(1) = \tilde{\pi}(1). \tag{3.24}$$

Similarly, it is easy to prove that $\breve{\varphi}_\ell = \tilde{\varphi}_\ell, \forall \ell \in \{0, 1\}$, and $(\breve{D}(0), \breve{D}(1), \breve{\pi}(0), \breve{\pi}(1))$ is feasible to $(\mathcal{P}2)$. By some simple manipulations, we can derive that $\breve{D}(0) = \frac{\breve{\pi}(1)-\breve{\pi}(0)}{\theta_1}$. Moreover, we have

$$\breve{\pi}(0) - \tilde{\pi}(0) = \frac{\theta_0[(\tilde{\pi}(0) + \theta_1\tilde{D}(0)) - (\tilde{\pi}(1) + \theta_1\tilde{D}(1))]}{\theta_1 - \theta_0} > 0, \tag{3.25}$$

because $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$ is a feasible solution that meets the first constraint of $(\mathcal{P}2)$. Thus, $\breve{\mathcal{R}} > \tilde{\mathcal{R}}$ and $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$ cannot be optimal.

Thus, the assumption does not hold, and this in turn proves the proposition. □

Proposition 3.1 indicates that if the queueing dynamics were ignored, the best choice is to transmit all emergent data packets (in priority level 1) without waiting (i.e., $\tilde{D}(1) = 0$), and defer the transmissions of all normal packets (in priority level 0) by a waiting time $\tilde{D}(0) = \frac{\tilde{\pi}(1)-\tilde{\pi}(0)}{\theta_0}$. Note that the purpose of deferring the normal packet transmissions is to differentiate the beyond-WBAN transmission services for packets in different priority levels so as to guarantee that gateways have no incentive to behave untruthfully. However, by taking into account the queueing dynamics, it is difficult to find a dynamic transmission scheduling scheme $\boldsymbol{\zeta}$ such that $\mathbb{E}[D(\ell)] = \tilde{D}(\ell), \forall \ell \in \{0, 1\}$. This is because the mean waiting delays in queueing systems highly depend on the random arrivals of data packets and the prioritized queueing discipline. In Section 3.2.2, we will address this issue by proposing a delay control scheme based on $(\tilde{D}(0), \tilde{D}(1))$, and discuss the design of $\boldsymbol{\zeta}$ in detail.

Notice that without carefully setting the delay sensitivity parameter $\theta_\ell, \forall \ell \in \{0,1\}$, it is possible that we may obtain $\tilde{D}(0) = \tilde{D}(1)$, $\tilde{\pi}(0) = \tilde{\pi}(1)$ after solving ($\mathcal{P}2$), which indicates that all packet transmissions (including both emergent and normal ones) will be treated equally by the BS. Though this solution meets all constraints in the deterministically relaxed problem, it implies that the BS will adopt the first-come-first-serve (FCFS) discipline in the queueing system for all packet transmissions regardless of their different priorities. Obviously, this violates the absolute priority rule which is required in dynamic circumstances. If this happens, we must have $\tilde{D}(0) = \tilde{D}(1) = 0$ (according to Proposition 3.1) and $\tilde{\pi}(0) = \tilde{\pi}(1) = \pi^s_{0,1}$, where $\pi^s_{0,1}$ can be calculated from

$$\pi^s_{0,1} = \arg\max_{\pi} \ \pi(\varphi_0 + \varphi_1) \tag{3.26}$$

$$s.t., \ \ \varphi_\ell = \Lambda_\ell \bar{F}_\ell(\pi), \ \forall \ell \in \{0,1\}, \tag{3.27}$$

$$\varphi_0 + \varphi_1 \leq N \cdot \mu. \tag{3.28}$$

In order to avoid this situation, the setting of $\theta_\ell, \forall \ell \in \{0,1\}$, has to follow a delicate condition as shown in Proposition 3.2.

Proposition 3.2. Let $\pi^s_{0,1}$ be the optimal solution of (3.26). To ensure $\tilde{D}(0) \neq \tilde{D}(1)$, $\tilde{\pi}(0) \neq \tilde{\pi}(1)$, we must set

$$\theta^r_{0,1} < \frac{\Lambda_1[\bar{F}_1(\pi^s_{0,1}) f_0(\pi^s_{0,1}) - \bar{F}_0(\pi^s_{0,1}) f_1(\pi^s_{0,1})]}{f_0(\pi^s_{0,1})[\Lambda_1 \bar{F}_1(\pi^s_{0,1}) + \Lambda_0 \bar{F}_0(\pi^s_{0,1})]}, \tag{3.29}$$

where $\theta^r_{0,1} = \theta_0/\theta_1$.

Proof. Please see Appendix A.1 for the proof. □

3.2.2 Dynamic Transmission Mechanism (DTM-2)

Given the optimal solution $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$ to the deterministically relaxed problem $(\mathcal{P}2)$, our next step is to consider how such results can help us design the two-class prioritized dynamic transmission mechanism for the formulated beyond-WBAN queueing management system. For convenience, this mechanism is named as DTM-2.

Since the absolute priority has to be guaranteed instantaneously, we adopt the preemptive-resume priority queueing discipline in DTM-2 so that the arriving emergent data packets can always preempt the transmissions of normal packets which are already in the system (no matter they are in the queue or in the service). However, the waiting delays of emergent and normal packet transmissions may not always be sufficiently differentiated for maintaining truthfulness in the queueing system with the preemptive-resume priority discipline only. For example, if the queueing system is significantly underloaded, all data packets will experience negligible waiting delays so that the transmission services for emergent and normal packets become very similar. According to the deterministic analysis in Section 3.2.1, this may violate the condition of truthfulness since it is possible that gateways will misreport emergent packets as normal ones in order to lower the transmission service charge while experiencing similar QoS. Thus, motivated by the observation from the solution of $(\mathcal{P}2)$, an additional delay control scheme is introduced with the consideration of specific queueing conditions. Before presenting the proposed delay control scheme, we first introduce a new definition, called *deterministic load factor*.

Definition 3.1. Given the optimal solution $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$ to $(\mathcal{P}2)$, the deterministic load factor of data packets in each priority level is defined as

$$\xi_\ell = \frac{\tilde{\varphi}_\ell}{N\mu}, \ \forall \ell \in \{0,1\}, \tag{3.30}$$

where $\tilde{\varphi}_\ell = \Lambda_\ell \bar{F}_\ell\big(\tilde{\pi}(\ell) + \theta_\ell \tilde{D}(\ell)\big)$. Based on this, we classify the queueing system to be *deterministically capacitated* if $\xi_0 + \xi_1 = 1$, and *incapacitated* if $\xi_0 + \xi_1 < 1$. Note that $\xi_0 + \xi_1$ cannot be larger than 1 due to the feasibility constraint (3.17).

With Definition 3.1, the delay control scheme (DCS-2) is designed as follows:

DCS-2: *If the system is deterministically incapacitated (i.e.,* $\xi_0 + \xi_1 < 1$*), the BS will first intentionally defer the transmission of each normal data packet by an extra delay* $\tilde{D}(0)$*, and then follow the preemptive-resume priority queueing discipline for serving all packet transmissions. Otherwise (i.e.,* $\xi_0 + \xi_1 = 1$*), the preemptive-resume priority discipline will be executed directly without applying any extra delay.*

This scheme introduces an additional delay control for the incapacitated system to differentiate the beyond-WBAN transmission services between different priorities so as to ensure that gateways have no incentive to misreport their data packet priorities. Note that if the system is deterministically capacitated, the preemptive priority discipline is sufficient to introduce large enough delay difference between normal and emergent data packet transmissions so that no more delay control is required.

In summary, the constructed DTM-2 consists of the transmission scheduling scheme, i.e., $\boldsymbol{\zeta}$, which includes the combination of the preemptive-resume priority queueing discipline and the proposed DCS-2, and the transmission service charge, i.e., $\boldsymbol{\pi}$, which equals $(\tilde{\pi}(0), \tilde{\pi}(1))$. In the next subsection, the rationality of the constructed DTM-2 will be justified.

The detailed procedure of the implementation of DTM-2 is described in the following.

(1) The BS formulates the deterministically relaxed problem ($\mathcal{P}2$) and obtains the corresponding optimal solution $(\tilde{D}(0), \tilde{D}(1), \tilde{\pi}(0), \tilde{\pi}(1))$.

(2) The BS decides to i) adopt the preemptive-resume priority queueing discipline for transmitting data packets in different priority levels; and ii) charge $\tilde{\pi}(0)$ and $\tilde{\pi}(1)$ for the successful transmission of normal and emergent packets, respectively.

(3) If the system is deterministically incapacitated (i.e., $\xi_0 + \xi_1 < 1$), the BS will intentionally defer the transmission of each normal packet (in priority level 0) with an extra delay $\tilde{D}(0)$. Otherwise (i.e., $\xi_0 + \xi_1 = 1$), no additional delay will be applied.

(4) The BS broadcasts its dynamic transmission mechanism, i.e., $(\boldsymbol{\zeta}, \boldsymbol{\pi})$, to all gateways, where $\boldsymbol{\zeta}$ and $\boldsymbol{\pi}$ are determined by steps (2) and (3).

(5) Upon the arrival of data packets, gateways will immediately send transmission requests to the BS by reporting the packet priorities.

(6) The BS manages the beyond-WBAN transmissions by following the aforementioned mechanism $(\boldsymbol{\zeta}, \boldsymbol{\pi})$.

(7) All arrived data packets are temporarily stored in gateways' buffers until they are completely transmitted.

3.2.3 Performance Analyses

To examine the feasibility and applicability of the proposed DTM-2, a general definition of ν*-scaling* systems, given a fixed traffic intensity $\rho_\ell = \Lambda_\ell / N\mu, \forall \ell \in \mathcal{L}$, is first introduced.

Definition 3.2 (ν-scale)**.** Given $\rho_\ell, \forall \ell \in \mathcal{L}$, a ν-scaling beyond-WBAN transmission system is characterized by $N^\nu = \nu$ available channels and average packet arrival rate $\Lambda_\ell^\nu = \nu \rho_\ell \mu, \forall \ell \in \mathcal{L}$, where $\nu \in \mathbb{Z}^+$.

Obviously, for any value of ν, the problem formulation of $(\mathcal{P}1)$ holds, except that the considered queueing system (i.e., both arrival and service rates) is scaled proportionally by a parameter ν. We redefine all notations in ν-scale system by introducing a superscript ν, and let $\eta_\ell^\nu = \varphi_\ell^\nu / N^\nu \mu$ be the stochastic load factor of data packets in priority level $\ell, \forall \ell \in \mathcal{L}$, and symbol "→" denote "tends to". In the following, the performance of DTM-2 in terms of the scale parameter ν will be analyzed.

Theorem 3.1 (Queueing stability)**.** *In a* ν*-scaling system implementing DTM-2, if all data packets are reported truthfully with their actual priorities, then*

i) there exists a unique stationary state with $(\eta_0^\nu, \eta_1^\nu, \mathbb{E}[D^\nu(0)] = \mathbb{E}[W^\nu(0)] + \delta, \mathbb{E}[D^\nu(1)] = \mathbb{E}[W^\nu(1)])$*;*

ii) $\eta_\ell^\nu \to \xi_\ell$ *and* $\mathbb{E}[D^\nu(\ell)] \to \tilde{D}(\ell), \forall \ell \in \{0,1\}$*, as* $\nu \to \infty$*.*

where $\mathbb{E}[W^\nu(\ell)], \forall \ell \in \{0,1\}$*, is the mean waiting time/delay in the preemptive-resume priority queue, and* δ *is the extra delay (where* $\delta = \tilde{D}(0)$ *if the system is incapacitated, and* $\delta = 0$ *otherwise).*

Proof. Please see Appendix A.2 for the proof. □

Theorem 3.1 illustrates that DTM-2 can always lead to a unique stationary state. In addition, as $\nu \to \infty$, the mean waiting delays in the dynamic queueing model tend to the optimal solution of ($\mathcal{P}2$).

Theorem 3.2 (Absolute priority-aware QoS). *For a ν-scaling system implementing DTM-2, if all data packets are reported truthfully with their actual priorities, emergent packets will always be transmitted prior to the normal ones, i.e.,*

$$D(0) \geq D(1). \tag{3.31}$$

Proof. This can be directly observed from the management scheme $\boldsymbol{\zeta}$ of DTM-2. □

Theorem 3.3 (Truthfulness). *In a ν-scaling system implementing DTM-2, there exists a threshold ν_{th} such that if $\nu \geq \nu_{th}$, all gateways will be induced to truthfully report the actual priority levels of their data packets, i.e.,*

$$\theta_\ell \mathbb{E}[D^\nu(\ell)] + \tilde{\pi}(\ell) \leq \theta_\ell \mathbb{E}[D^\nu(\ell')] + \tilde{\pi}(\ell'), \forall \ell, \ell' \in \{0, 1\}, \tag{3.32}$$

where $(\tilde{\pi}(0), \tilde{\pi}(1))$ is the transmission service charge defined in DTM-2.

Proof. By applying Proposition 3.1 to (3.32), we have

$$\tilde{D}(0) \leq \mathbb{E}[D^\nu(0)] - \mathbb{E}[D^\nu(1)] \leq \theta_1/\theta_0 \cdot \tilde{D}(0). \tag{3.33}$$

Thus, the remaining goal is to prove that (3.33) holds.

From Theorem 3.1, we know that $\mathbb{E}[D^\nu(0)] \to \tilde{D}(0)$ and $\mathbb{E}[D^\nu(1)] \to 0$, as $\nu \to 0$. Since $\theta_1/\theta_0 > 1$ by definition, there must exist a ν_{th}^1 such that

$$\mathbb{E}[D^\nu(0)] - \mathbb{E}[D^\nu(1)] \leq \theta_1/\theta_0 \cdot \tilde{D}(0),\ \forall \nu \geq \nu_{th}^1. \tag{3.34}$$

To prove $\tilde{D}(0) \leq \mathbb{E}[D^\nu(0)] - \mathbb{E}[D^\nu(1)]$, we consider two separate cases, i.e., the system is deterministically incapacitated ($\xi_0 + \xi_1 < 1$) or capacitated ($\xi_0 + \xi_1 = 1$).

If the system is incapacitated, $\mathbb{E}[D^\nu(1)] = \mathbb{E}[W^\nu(1)]$ and $\mathbb{E}[D^\nu(0)] = \mathbb{E}[W^\nu(0)] + \tilde{D}(0)$. The priority discipline indicates that $\mathbb{E}[W^\nu(1)] \leq \mathbb{E}[W^\nu(0)]$, and thus

$$\mathbb{E}[D^\nu(0)]-\mathbb{E}[D^\nu(1)]=\tilde{D}(0)+\mathbb{E}[W^\nu(0)]-\mathbb{E}[W^\nu(1)]\geq\tilde{D}(0). \tag{3.35}$$

If the system is capacitated, $\mathbb{E}[D^\nu(1)] = \mathbb{E}[W^\nu(1)]$ and $\mathbb{E}[D^\nu(0)] = \mathbb{E}[W^\nu(0)]$, then

$$\mathbb{E}[D^\nu(0)]-\mathbb{E}[D^\nu(1)]=\tilde{D}(0) + (\mathbb{E}[W^\nu(0)] - \tilde{D}(0)) - \mathbb{E}[W^\nu(1)]. \tag{3.36}$$

Since $\mathbb{E}[W^\nu(0)] \geq \tilde{D}(0)$ and $\mathbb{E}[W^\nu(1)] \to 0$, there must exist a ν_{th}^2 such that $\mathbb{E}[D^\nu(0)] - \mathbb{E}[D^\nu(1)] \geq \tilde{D}(0), \forall \nu \geq \nu_{th}^2$.

Therefore, (3.33) holds for any system with scale $\nu \geq \nu_{th} = \max\{\nu_{th}^1, \nu_{th}^2\}$. □

Theorem 3.4 (Revenue optimality)**.** *For any ν-scaling system with the implementation of DTM-2, we have*

$$\mathcal{R}^\nu_{\textit{DTM-2}}/\mathcal{R}^\nu_{\textit{OPT}} \to 1, \ \ \textit{as } \nu \to \infty, \tag{3.37}$$

where $\mathcal{R}^\nu_{\textit{DTM-2}}$ and $\mathcal{R}^\nu_{\textit{OPT}}$ represent the network revenue achieved by DTM-2 and the optimal solution of ($\mathcal{P}1$), respectively.

Proof. By implementing DTM-2, the expected revenue of the BS in ν-scale system can be expressed as

$$\begin{aligned}\mathcal{R}^\nu_{\text{DTM-2}} &= \varphi_0\tilde{\pi}(0) + \varphi_1\tilde{\pi}(1) \\ &= N^\nu\mu(\eta_0^\nu\tilde{\pi}(0) + \eta_1^\nu\tilde{\pi}(1)) \\ &= \tilde{\mathcal{R}}^\nu - N^\nu\mu\tilde{\pi}(0)(\xi_0 - \eta_0^\nu) - N^\nu\mu\tilde{\pi}(1)(\xi_1 - \eta_1^\nu),\end{aligned} \tag{3.38}$$

where $\tilde{\mathcal{R}}^{\nu} = N^{\nu}\mu\big(\tilde{\pi}(0)\xi_0 + \tilde{\pi}(1)\xi_1\big)$ is the optimal revenue in the deterministically relaxed ν-scale system. By Theorem 3.1, we have $\eta_0^{\nu} \to \xi_0$ and $\eta_1^{\nu} \to \xi_1$, as $\nu \to \infty$, and thus

$$\mathcal{R}^{\nu}_{\text{DTM-2}} \to \tilde{\mathcal{R}}^{\nu}, \text{ as } \nu \to \infty. \tag{3.39}$$

Since it is intuitive that $\tilde{\mathcal{R}}^{\nu} \geq \mathcal{R}^{\nu}_{\text{OPT}}$ and $\mathcal{R}^{\nu}_{\text{OPT}} \geq \mathcal{R}^{\nu}_{\text{DTM-2}}$, (3.39) implies (3.37). $\square$

Theorems 3.2, 3.3 and 3.4 indicate that for any beyond-WBAN system with a sufficiently large scale, the proposed DTM-2 can not only meet all design requirements, but also achieve a near-optimal revenue for the BS. In reality, it is expected that the future WBAN-based systems will involve a large number of humans/patients equipped with WBANs, so that the aggregate arrival rate of data packet transmission requests may be sufficiently high. In addition, the size of each data packet is ordinarily small, and thus it is more efficient to utilize more narrowband channels to support beyond-WBAN transmissions. All these features demonstrate that the scales of future beyond-WBAN systems are tremendously large. Moreover, simulations in Section 3.4 will also show that the large-scale requirement of DTM-2 can easily be satisfied under practical network settings. Therefore, we can conclude that the proposed DTM-2 is indeed practically feasible and applicable.

3.3 Multi-Class Prioritized Transmission Mechanism

In this section, DTM-L is extended to the general DTM-L which can well handle the beyond-WBAN transmission management with data packets in multi-class (i.e., more than two) priority levels.

3.3.1 Deterministic Relaxation

With $\mathcal{L}=\{0,1,\dots,L\}$, $(\mathcal{P}1)$ can be relaxed as

$$(\mathcal{P}3):\quad \arg\max_{\boldsymbol{D},\boldsymbol{\pi}} \sum_{\ell=0}^{L} \varphi_\ell \pi(\ell) \tag{3.40}$$

$$s.t.,\ \theta_\ell D(\ell)+\pi(\ell) \le \theta_\ell D(\ell')+\pi(\ell'),\ \forall \ell,\ell' \in \mathcal{L}, \tag{3.41}$$

$$\varphi_\ell = \Lambda_\ell \bar{F}_\ell\big(\pi(\ell)+\theta_\ell D(\ell)\big),\ \forall \ell \in \mathcal{L}, \tag{3.42}$$

$$\sum_{\ell=0}^{L} \varphi_\ell \le N\cdot\mu, \tag{3.43}$$

$$D(\ell) \le D(\ell'),\ \forall \ell \ge \ell' \text{ and } \ell,\ell' \in \mathcal{L}, \tag{3.44}$$

where $\boldsymbol{D}=[D(\ell)|\ell\in\mathcal{L}]$, $\boldsymbol{\pi}=[\pi(\ell)|\ell\in\mathcal{L}]$. Let the optimal solution of $(\mathcal{P}3)$ be $(\tilde{D}(\ell),\tilde{\pi}(\ell))$ and $\tilde{\varphi}_\ell=\Lambda_\ell\bar{F}_\ell\big(\tilde{\pi}(\ell)+\theta_\ell\tilde{D}(\ell)\big)$, $\forall\ell\in\mathcal{L}$. Note that $(\mathcal{P}3)$ is a general form of $(\mathcal{P}2)$, and thus its optimal solution satisfies the following properties which are analogous to Propositions 3.1 and 3.2.

Proposition 3.3. If $(\tilde{D}(\ell),\tilde{\pi}(\ell)),\forall\ell\in\mathcal{L}$, leads to the optimality of $(\mathcal{P}3)$, then we must have

$$\tilde{D}(L)=0, \tag{3.45}$$

$$\tilde{D}(\ell)=\frac{\tilde{\pi}(\ell+1)-\tilde{\pi}(\ell)}{\theta_{\ell+1}}+\tilde{D}(\ell+1),\ \forall\ell\in\{0,1,\dots,L-1\}. \tag{3.46}$$

Proof. Similar to the proof for Proposition 3.1, we assume that $(\tilde{D}(\ell),\tilde{\pi}(\ell)),\forall\ell\in\mathcal{L}$, is an optimal solution to $(\mathcal{P}3)$, but (3.45) or (3.46) does not hold.

If (3.45) does not hold, we can find a better solution $(\hat{D}(\ell),\hat{\pi}(\ell)),\forall\ell\in\mathcal{L}$, with

$$\hat{D}(L)=0,\ \hat{\pi}(L)=\tilde{\pi}(L)+\theta_L\tilde{D}(L), \tag{3.47}$$

$$\hat{D}(\ell)=\tilde{D}(\ell),\ \hat{\pi}(\ell)=\tilde{\pi}(\ell),\ \forall\ell\in\{0,1,\ldots,L-1\}. \tag{3.48}$$

If (3.46) does not hold, we can also find another better solution $(\breve{D}(\ell),\breve{\pi}(\ell)),\forall\ell\in\mathcal{L}$, with

$$\breve{D}(\ell)=\frac{\tilde{\pi}(\ell+1)+\theta_{\ell+1}\tilde{D}(\ell+1)-\tilde{\pi}(\ell)-\theta_{\ell}\tilde{D}(\ell)}{\theta_{\ell+1}-\theta_{\ell}}, \tag{3.49}$$

$$\breve{\pi}(\ell)=\frac{\theta_{\ell+1}(\tilde{\pi}(\ell)+\theta_{\ell}\tilde{D}(\ell))-\theta_{\ell}(\tilde{\pi}(\ell+1)+\theta_{\ell+1}\tilde{D}(\ell+1))}{\theta_{\ell+1}-\theta_{\ell}}, \tag{3.50}$$

for any $\ell\in\{0,1,\ldots,L-1\}$, and $\breve{D}(\ell')=\tilde{D}(\ell')$, $\breve{\pi}(\ell')=\tilde{\pi}(\ell')$, $\forall\ell'\neq\ell$.

Thus, the assumption cannot be true, and this in turn proves the proposition. □

Proposition 3.4. To ensure $\tilde{D}(\ell)\neq\tilde{D}(\ell')$, $\tilde{\pi}(\ell)\neq\tilde{\pi}(\ell')$, $\forall\ell\neq\ell'$ and $\ell,\ell'\in\mathcal{L}$, we can set

$$\theta^{r}_{\ell-1,\ell}<\frac{\Lambda_{\ell}[\bar{F}_{\ell}(\pi^{s}_{\ell-1,\ell})f_{\ell-1}(\pi^{s}_{\ell-1,\ell})-\bar{F}_{\ell-1}(\pi^{s}_{\ell-1,\ell})f_{\ell}(\pi^{s}_{\ell-1,\ell})]}{f_{\ell-1}(\pi^{s}_{\ell-1,\ell})[\Lambda_{\ell}\bar{F}_{\ell}(\pi^{s}_{\ell-1,\ell})+\Lambda_{\ell-1}\bar{F}_{\ell-1}(\pi^{s}_{\ell-1,\ell})]}, \tag{3.51}$$

where $\theta^{r}_{\ell-1,\ell}=\theta_{\ell-1}/\theta_{\ell},\forall\ell\in\{1,2,\ldots,L\}$, and $\pi^{s}_{\ell-1,\ell}$ is calculated from

$$\pi^{s}_{\ell-1,\ell}=\arg\max_{\pi}\ \pi(\varphi_{\ell-1}+\varphi_{\ell}) \tag{3.52}$$

$$s.t.,\ \ \varphi_{\ell-1}=\Lambda_{\ell-1}\bar{F}_{\ell-1}(\pi),\ \varphi_{\ell}=\Lambda_{\ell}\bar{F}_{\ell}(\pi), \tag{3.53}$$

$$\varphi_{\ell-1}+\varphi_{\ell}\leq N\cdot\mu-\sum_{\ell'\neq\ell-1,\ell}\Lambda_{\ell'}. \tag{3.54}$$

Proof. Because of the definition in (3.3), if $\tilde{D}(\ell)\neq\tilde{D}(\ell-1)$, $\tilde{\pi}(\ell)\neq\tilde{\pi}(\ell-1)$, $\forall\ell\in\{1,2,\ldots,L\}$, then automatically we have $\tilde{D}(\ell)\neq\tilde{D}(\ell')$, $\tilde{\pi}(\ell)\neq\tilde{\pi}(\ell')$, $\forall\ell\neq\ell'$. This indicates that we only need to regulate the setting of $\theta_{\ell-1}/\theta_{\ell}$. Then, Proposition 3.4 can be proved similar to Proposition 3.2. □

3.3.2 Generalized Transmission Mechanism (DTM-L)

Now, it is ready to design a generalized mechanism, namely DTM-L, based on the optimal solution $(\tilde{D}(\ell), \tilde{\pi}(\ell)), \forall \ell \in \mathcal{L}$, of $(\mathcal{P}3)$, for dynamically managing multi-class prioritized data packet transmissions in the beyond-WBAN queueing system. Note that $\ell = 0$ and $\ell = L$ denote the lowest and the highest priority levels, respectively.

Similar to DTM-2, the preemptive-resume priority queueing discipline is employed in DTM-L, and an additional delay control scheme (DCS-L) should be adopted to guarantee that all gateways behave truthfully. Following the idea of DCS-2 in Section 3.2.2, the BS should add an extra delay $\tilde{D}(\ell_p)$ for each data packet in priority level $\ell_p, \forall \ell_p \in \{0, 1, \ldots, L-1\}$, in the queueing system, if and only if $\sum_{\ell=\ell_p}^{L} \xi_\ell < 1$, where $\xi_\ell = \tilde{\varphi}_\ell / N\mu$ is the deterministic load factor of packets in priority level ℓ. However, unlike DCS-2 that extra delays are applied only when the overall system is deterministically incapacitated (i.e., $\sum_{\ell=0}^{L} \xi_\ell < 1$), in DCS-L, the transmissions of data packets in priority levels 1 to $L-1$ (i.e., all intermediate priority levels) should always be deferred by additional delays due to the following proposition.

Proposition 3.5. Given the solution $(\tilde{D}(\ell), \tilde{\pi}(\ell))$, $\forall \ell \in \mathcal{L}$, of $(\mathcal{P}3)$, we must have

$$\sum_{\ell=\ell_p}^{L} \xi_\ell < 1, \ \forall \ell_p \in \{1, 2, \ldots, L-1\}. \tag{3.55}$$

Proof. Since $\sum_{\ell=0}^{\ell_p-1} \xi_\ell \neq 0, \forall \ell_p \in \{1, 2, \ldots, L-1\}$, the contradiction of (3.55), i.e., $\sum_{\ell=\ell_p}^{L} \xi_\ell \geq 1, \forall \ell_p \in \{1, 2, \ldots, L-1\}$ indicates that

$$\sum_{\ell=0}^{L} \xi_\ell = \sum_{\ell=0}^{\ell_p-1} \xi_\ell + \sum_{\ell=\ell_p}^{L} \xi_\ell > 1, \ \forall \ell_p \in \{1, 2, \ldots, L-1\}. \tag{3.56}$$

Clearly, (3.56) violates the feasibility constraint (3.43) in $(\mathcal{P}3)$, and thus the contradiction of this proposition cannot hold. □

Therefore, before employing the preemptive-resume priority queueing discipline for serving data packet transmissions in all priority levels, an additional delay control scheme (DCS-L) is applied as follows:

DCS-L: *If the overall system is deterministically incapacitated (i.e., $\sum_{\ell=0}^{L} \xi_\ell < 1$), the BS will intentionally defer the transmission of each data packet in priority level $\ell, \forall \ell \in \{0, 1, \ldots, L-1\}$, by an extra delay $\tilde{D}(\ell)$. Otherwise (i.e., $\sum_{\ell=0}^{L} \xi_\ell = 1$), the BS will only defer the transmission of each data packet in priority levels 1 to $L-1$ by an extra delay $\tilde{D}(\ell)$.*

In summary, in the constructed DTM-L, the transmission scheduling scheme, i.e., $\boldsymbol{\zeta}$, includes the combination of the preemptive-resume priority queueing discipline and the proposed delay control scheme DCS-L, and the transmission service charge, i.e., $\boldsymbol{\pi}$, is $(\tilde{\pi}(\ell)), \forall \ell \in \mathcal{L}$. The implementation of DTM-L is similar to that of DTM-2 in Section 3.2.2.

The feasibility and applicability of the proposed DTM-L can be examined by the following theorems in terms of the system scale ν introduced in Definition 3.2.

Theorem 3.5 (Queueing stability)**.** *In a ν-scaling system implementing DTM-L, if all data packets are reported truthfully with their actual priorities, then*

i) there exists a unique stationary state with $(\eta_0^\nu, \eta_1^\nu, \ldots, \eta_L^\nu, \mathbb{E}[D^\nu(0)] = \mathbb{E}[W^\nu(0)] + \delta, \mathbb{E}[D^\nu(1)] = \mathbb{E}[W^\nu(1)]) + \tilde{D}(1), \ldots, \mathbb{E}[D^\nu(L-1)] = \mathbb{E}[W^\nu(L-1)]) + \tilde{D}(L-1), \mathbb{E}[D^\nu(L)] = \mathbb{E}[W^\nu(L)]))$;

ii) $\eta_\ell^\nu \to \xi_\ell$, $\mathbb{E}[D^\nu(\ell)] \to \tilde{D}(\ell), \forall \ell \in \mathcal{L}$, as $\nu \to \infty$.

where $\mathbb{E}[W^\nu(\ell)], \forall \ell \in \mathcal{L}$, is the mean waiting time/delay in the preemptive-resume priority queue, and $\delta = \tilde{D}(0)$ if the system is incapacitated, and $\delta = 0$ otherwise.

Proof. This is a general form of Theorem 3.1 for multi-class packet priority levels, and thus its proof is omitted. □

Theorem 3.6 (Absolute priority-aware QoS)**.** *For a ν-scaling system implementing DTM-L, if all data packets are reported truthfully, higher-priority data packets will always be transmitted prior to the ones in lower priority levels, i.e.,*

$$D(\ell) \leq D(\ell'),\ \forall \ell \geq \ell' \text{ and } \ell, \ell' \in \mathcal{L}. \tag{3.57}$$

Proof. This can be directly observed from the management scheme $\boldsymbol{\zeta}$ of DTM-L. □

Theorem 3.7 (Truthfulness)**.** *In a ν-scaling system implementing DTM-L, there exists a threshold ν_{th} such that if $\nu \geq \nu_{th}$, all gateways will be induced to truthfully report the actual priority levels of their data packets, i.e.,*

$$\theta_\ell \mathbb{E}[D^\nu(\ell)] + \tilde{\pi}(\ell) \leq \theta_\ell \mathbb{E}[D^\nu(\ell')] + \tilde{\pi}(\ell'),\ \forall \ell, \ell' \in \mathcal{L}, \tag{3.58}$$

where $\tilde{\pi}(\ell), \forall \ell \in \mathcal{L}$, is the transmission service charge defined in DTM-L.

Proof. Let $\ell' - \ell = \Delta\ell$. Then, (3.58) can be rewritten as

$$\theta_\ell \mathbb{E}[D^\nu(\ell)] + \tilde{\pi}(\ell) \leq \theta_\ell \mathbb{E}[D^\nu(\ell + \Delta\ell)] + \tilde{\pi}(\ell + \Delta\ell),\ \forall |\Delta\ell| \geq 1. \tag{3.59}$$

By following the similar proof procedure for Theorem 3.3, we can easily verify that no packet will be misreported by a priority which is one level higher or lower than the truthful one ($|\Delta\ell| = 1$), i.e.,

$$\theta_\ell \mathbb{E}[D^\nu(\ell)] + \tilde{\pi}(\ell) \leq \theta_\ell \mathbb{E}[D^\nu(\ell \pm 1)] + \tilde{\pi}(\ell \pm 1), \forall \nu \geq \nu_{th}. \tag{3.60}$$

Thus, the remaining job is to prove that (3.59) holds for $|\Delta\ell| \geq 2$. Consider that $|\Delta\ell| = 2$, and assume by the way of contradiction that (3.59) does not hold, i.e.,

$$\theta_\ell \mathbb{E}[D^\nu(\ell)] + \tilde{\pi}(\ell) > \theta_\ell \mathbb{E}[D^\nu(\ell \pm 2)] + \tilde{\pi}(\ell \pm 2). \tag{3.61}$$

Combining (3.61) and (3.60) produces

$$\theta_\ell \mathbb{E}[D^\nu(\ell \pm 1)] + \tilde{\pi}(\ell \pm 1) > \theta_\ell \mathbb{E}[D^\nu(\ell \pm 2)] + \tilde{\pi}(\ell \pm 2). \tag{3.62}$$

By substituting Proposition 3.3 and Theorem 3.5 into (3.62), we can derive that

$$\theta_{\ell+1} < \theta_\ell. \tag{3.63}$$

Clearly, (3.63) contradicts the definition in (3.3), and thus (3.61) cannot be true. Subsequently, it can be proved that (3.59) holds for $|\Delta\ell| = 3, 4, \ldots$. □

Theorem 3.8 (Revenue optimality)**.** *For any ν-scaling system with the implementation of DTM-L, we have*

$$\mathcal{R}^\nu_{\textit{DTM-L}} / \mathcal{R}^\nu_{OPT} \to 1, \ \textit{as } \nu \to \infty, \tag{3.64}$$

where $\mathcal{R}^\nu_{\textit{DTM-L}}$ and $\mathcal{R}^\nu_{OPT}$ are the revenue achieved by DTM-L and the optimal solution of ($\mathcal{P}1$), respectively.

Proof. This can be proved by following the same proof procedure for Theorem 3.4. □

3.4 Simulation Results

In this section, simulations are conducted by MATLAB to evaluate the performance of the proposed mechanisms in dynamically scheduling multi-class delay-sensitive data packet transmissions in the beyond-WBAN.

3.4.1 Simulation Settings

Consider a beyond-WBAN with one base station who owns N channels. According to IEEE std. 802.15.6 [10], all data packets are categorized into $\mathcal{L} = \{0, 1, \ldots, 7\}$

discrete priority classes. Since the size of WBAN data packets aggregated at gateways is normally less than 100 Kb [27] and the average uplink transmission rate of 3G cellular networks is commonly under 500 Kbps [70], let us assume that the average beyond-WBAN transmission time, $1/\mu$, is 0.2 second. The traffic intensity of data packets, i.e., $\rho_\ell, \forall \ell \in \mathcal{L}$, is selected from 0 to 1, while ensuring that $\sum_{\ell=0}^{\ell=7} \rho_\ell \leq 1$. Thus, the system may be deterministically capacitated or incapacitated. Given a fixed $\rho_\ell, \forall \ell \in \mathcal{L}$, the data packet arrival rates and the total number of channels are both varied with the scale parameter ν according to Definition 3.2, where ν is chosen as an integer from 1 to 20. Similar settings have also been employed in [28, 79]. For data packets in priority level $\ell, \forall \ell \in \mathcal{L}$, the values for their transmissions are uniformly distributed within the intervals $[\ell + 1, \ell + 2]$. In addition, let $\theta_0 = 0.4$ and $\theta_{\ell-1}/\theta_\ell = 1/2, \forall \ell \in \{1, 2, \ldots, 7\}$, so that the system requirement in Proposition 3.4 can always be satisfied. In the following, all results are obtained by taking averages over 100 runs.

3.4.2 Performance of DTM-2

Fig. 3.2 illustrates the mean waiting delays (in seconds) of data packets in different priority levels under the designed DTM-2. It is shown that emergent packets always have shorter mean waiting delays than normal ones. This is because the data packet with more critical information (i.e., in a higher priority level) will always be transmitted prior to those with less emergency. Besides, it can be observed that the packet mean waiting delays decrease exponentially with the increase of system scale ν. When ν is sufficiently large (e.g., $\nu > 12$ for incapacitated system, and $\nu > 18$

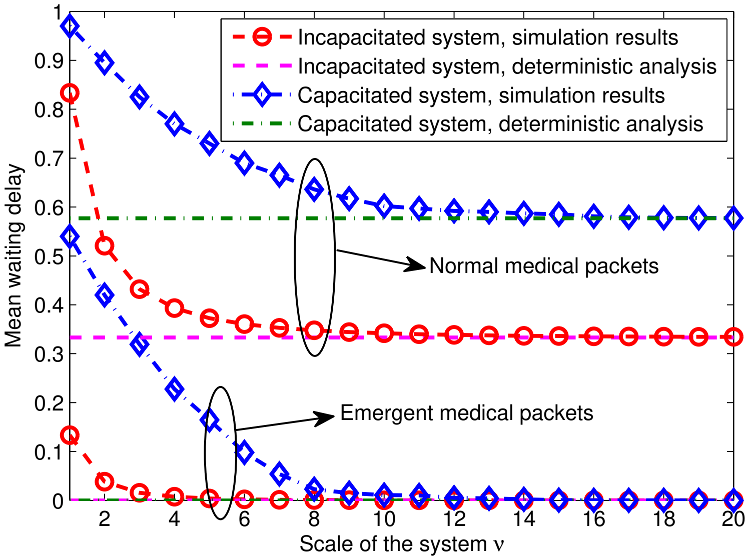
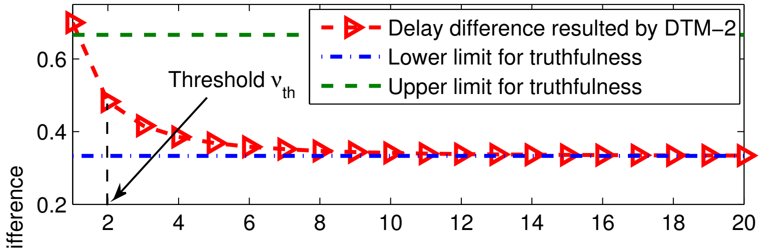


Figure 3.2: Mean waiting delays of data packet transmissions in DTM-2.

for capacitated system), the mean waiting delays of either emergent or normal data packets converge to the corresponding optimal solutions of the deterministically relaxed systems (i.e., $\tilde{D}(1) = 0$ and $\tilde{D}(0) = \frac{\tilde{\pi}(1)-\tilde{\pi}(0)}{\theta_1}$). This confirms the theoretical analysis in Theorem 3.1.

In Fig. 3.3, the truthfulness of DTM-2 is examined by analyzing the delay differences (in seconds) between normal and emergent data packets in incapacitated and capacitated systems, respectively. The upper and lower bounds for truthfulness are calculated according to the condition derived in (3.33). For the incapacitated system as shown in Fig. 3.3(a), since the normal packet transmission is always deferred by an extra delay in DTM-2, the delay difference between normal and emergent packet transmissions is ordinarily large. However, such difference decreases with the increase of system scale ν, and when $\nu \geq \nu_{th} = 2$, the condition of truthfulness is satisfied. For the capacitated system as shown in Fig. 3.3(b), since there is no additional delay con-

(a) Incapacitated system



(b) Capacitated system

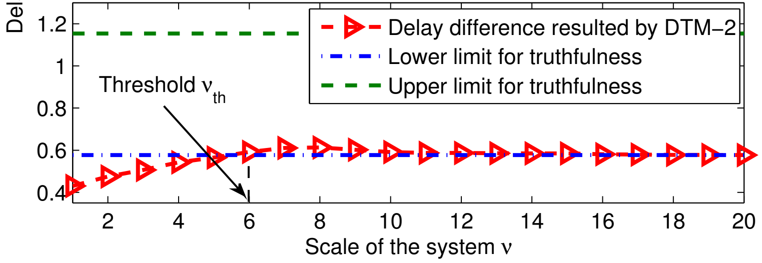


Figure 3.3: Truthfulness analysis of DTM-2.

trol, the delay difference between normal and emergent packet transmissions resulted by DTM-2 actually increases with ν, and when $\nu \geq \nu_{th} = 6$, such difference meets the condition of truthfulness. These results prove the theoretical analysis in Theorem 3.3. Notice that the values of ν_{th} in both Figs. 3.3(a) and 3.3(b) are considerably small compared to the practical network settings. Thus, the truthfulness of DTM-2 can be easily guaranteed for practical applications.

Fig. 3.4 shows the performance of DTM-2 on the BS's expected network revenue. The upper bound of the optimal solution is obtained by solving ($\mathcal{P}2$). Intuitively, the revenue increases with the system scale ν, and such increasing trend is linear for the optimal solution of ($\mathcal{P}2$). From this figure, we can see that the gap between the revenue achieved by DTM-2 and its upper bound is large when the system scale ν is small. However, the performance of DTM-2 approaches the upper bound as ν

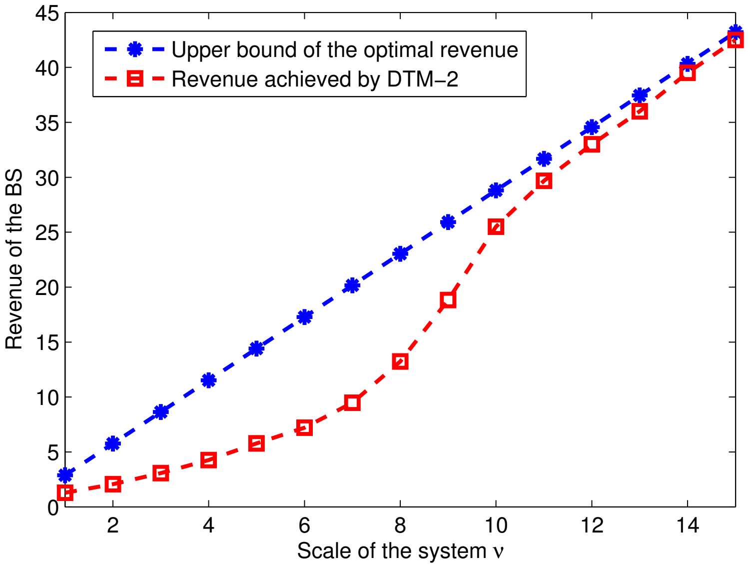


Figure 3.4: Performance of DTM-2 on the network revenue.

continues increasing. This is because the decision of transmission service charges in DTM-2 is same as that in the optimal solution of ($\mathcal{P}2$) so that the performance of DTM-2 becomes close to optimality when mean waiting delays in the queueing system tend to the optimal solutions of the deterministically relaxed system (i.e., $\tilde{D}(1)$ and $\tilde{D}(0)$) as shown in Fig. 3.2.

3.4.3 Performance of DTM-L

In this subsection, the performance of DTM-L is demonstrated by fixing $\nu = 20$. For comparison purpose, the preemptive-priority and non-priority mechanisms are simulated as benchmarks, where the preemptive-priority mechanism does not include any extra delay control to prevent potential untruthful behaviours from gateways, and the non-priority mechanism transmits all data packets based on the FCFS manner

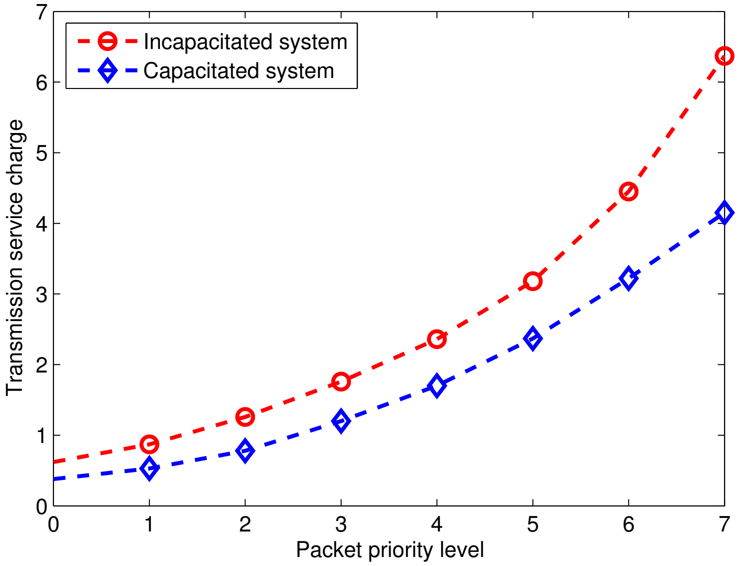


Figure 3.5: Beyond-WBAN transmission charge for packets with different priorities.

without considering the priority requirement.

Fig. 3.5 reveals the relationship between the beyond-WBAN transmission service charge and the priority level of the data packet. It can be seen from the figure that the service charge increases with the packet priority level, which matches the intuition that the packet with a higher priority so as to receive a better service (i.e., a shorter delay) has to be charged a higher price for its transmission. In addition, this figure also shows that the transmission service charge for the same packet in the capacitated system is lower than that in the incapacitated system. This is because the waiting delays for data transmissions in the beyond-WBAN are naturally longer in more congested systems.

In Fig. 3.6, the truthfulness of DTM-L is examined by showing the transmission utility of one packet with different reported priority levels. In the system imple-

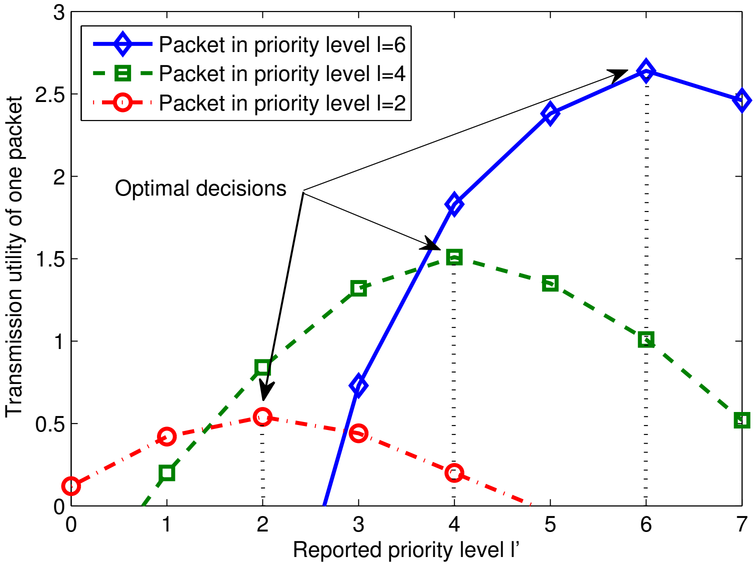


Figure 3.6: Optimal decisions in reporting the data packet priorities.

menting DTM-L, gateways may strategically report the packet priority level so as to maximize the transmission utility of each data packet. The trend of the curves in Fig. 3.6 indicates that the utility of one packet transmission first increases with the reported priority level ℓ'. This is because with the increase of ℓ', a shorter waiting delay is granted for the packet transmission so that a higher utility can be obtained. However, after a certain point (i.e., $\ell' = \ell$), since the delay requirement has already been satisfied, the transmission service charge becomes dominant so that the utility decreases. Intuitively, the ℓ' which leads to the highest utility is the optimal decision that will be adopted. This indicates that all gateways will be induced to truthfully report the actual the priority levels of their data packets under DTM-L.

Fig. 3.7 shows the cumulative social welfare of all priority classes of data packet transmissions from 0 to 100 seconds achieved by DTM-L, preemptive-priority and

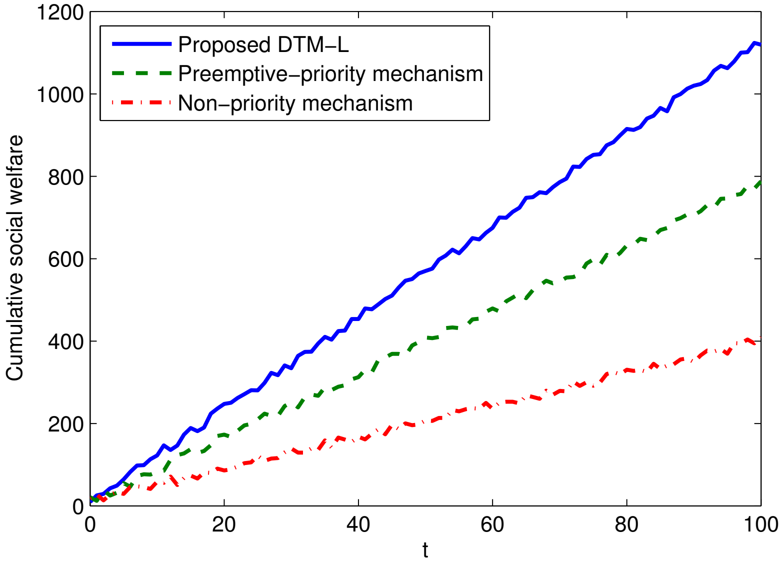


Figure 3.7: Cumulative social welfare of multi-class packet transmissions.

non-priority mechanisms, respectively. Similar to that in Chapter 2, the cumulative social welfare is defined as

$$\text{Welfare}(t) = \sum\nolimits_t \sum\nolimits_i v_i - \theta_{\ell_i} \mathbb{E}[D(\ell_i)], \tag{3.65}$$

which represents the total utility gain from all data packet transmissions regardless of their transmission service charges. It is intuitive that such welfare increases with the time. More importantly, it can be observed that the proposed DTM-L achieves the best performance. This is because the preemptive-priority mechanism cannot guarantee truthfulness due to the insufficient QoS differentiation among multi-class data packet transmissions and the non-priority mechanism cannot offer prioritized transmission services for heterogeneous data packets, so that both of them will result in large waiting costs on critical data packet transmissions in the beyond-WBAN.

Fig. 3.8 illustrates the expected revenue of the BS under different mechanisms. It

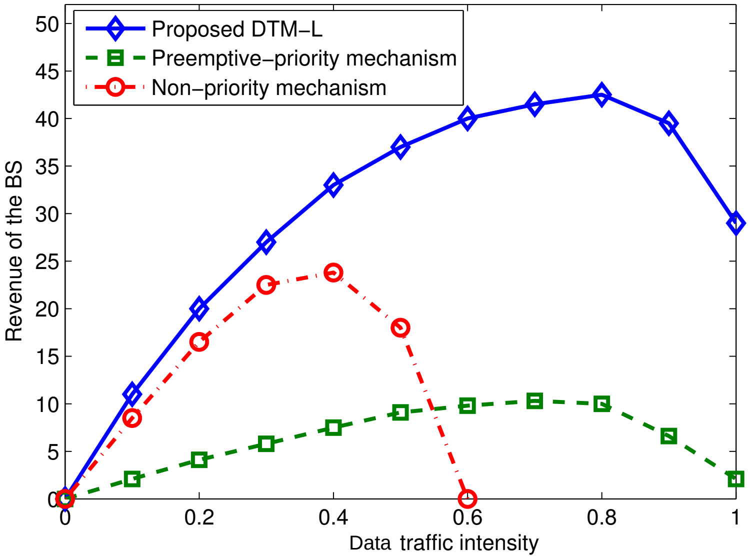


Figure 3.8: Comparison on the expected revenue of the BS.

is shown that the revenue first increases and then decreases with the data traffic intensity. This is because even though a larger traffic implies more packets' transmission requests, the beyond-WBAN transmission service charge for each individual packet actually becomes lower due to longer waiting delays. However, the proposed DTM-L obviously outperforms the preemptive-priority and non-priority mechanisms because all gateways will report their data packet priorities truthfully and more packets can be granted with desirable beyond-WBAN transmission services under DTM-L.

Chapter 4

Delay-Dependent Dynamic Prioritized Transmission Scheduling

It is worth noting that Chapters 2 and 3 impose a common requirement of the absolute priority in the beyond-WBAN transmission scheduling, i.e., data packets with higher priority levels or larger delay sensitivities should always be scheduled for beyond-WBAN transmissions in prior to the others. This is essential for protecting critical WBAN data transmissions, such as emergent medical information deliveries. However, for non-emergent routines with similar importance, applying such absolute and fixed priority rule will lead to tremendously large waiting delays on certain types (e.g., the lowest-priority class) of data packets' transmissions, which may not be beneficial to the overall network performance. In practice, these "less important" data information may also be useful in improving the accuracy of profiling the physiological conditions or motions of humans/patients. Thus, excessive delays (or starving) in their transmissions may at the end deteriorate the WBAN-based services. This prompt the necessity of adopting a delay-dependent dynamic prioritized beyond-WBAN transmission scheduling, where the original packet criticality and the experienced waiting delays can be jointly considered [80].

Moreover, the mechanisms devised in Chapters 2 and 3 relied on a relatively strong assumption that the beyond-WBAN transmission time of different data packets was either homogeneous or exponentially distributed, and neither of them aimed to directly maximize the network social welfare, so that the overall performance of the beyond-WBAN transmission scheduling may not be good enough.

To address the aforementioned limitations, in this chapter, a novel truthful mechanism for scheduling delay-dependent prioritized data packet transmissions in the beyond-WBAN is proposed. In the considered model, sensed data packets collected by biosensors are aggregated randomly at each gateway, and all packets are categorized into different classes (which consist of one class of emergent alarms and multiple classes of non-emergent routines). Upon receiving a data packet, each gateway immediately reports a beyond-WBAN transmission request to the BS, and temporarily stores the packet in its own buffer before it is completely transmitted. Data packets may experience different beyond-WBAN transmission time due to their heterogeneities in terms of packet sizes and achievable SNRs at different gateways. As the network regulator, the BS manages the scheduling of beyond-WBAN data packet transmissions according to the specific priority-aware QoS requirements. The packet-level operation is then formulated as a queueing system with dynamic priority disciplines. For maximizing the social welfare of the beyond-WBAN transmission scheduling (i.e., the total waiting cost of all data packet transmissions) and ensuring that all gateways can truthfully report the actual classes of their data packets, a truthful and efficient mechanism is derived and analyzed.

4.1 System Model and Problem Description

In this section, the network and queueing models are first introduced. Then, the problem of designing a truthful and efficient mechanism for scheduling delay-dependent prioritized data packet transmissions in the beyond-WBAN is formulated.

4.1.1 Network Model

Again, consider a cellular-like beyond-WBAN with a single BS and K gateways. There are N homogeneous channels that are dedicated for beyond-WBAN communications, and the BS is responsible to schedule uplink data packet transmissions from all gateways. Each gateway may receive a variety of data packets generated by its connected biosensors via intra-WBAN communications. To be consistent with the IEEE std. 802.15.6 [10], all data packets are categorized into a finite set of classes which consists of one class for emergency and multiple classes for non-emergency. In this chapter, this packet class set is defined as $\mathcal{L} = \{0, 1, 2, \ldots, L\}$, where $\{L\}$ and $\{0, 1, \ldots, L-1\}$ stand for the sets of classes for emergent alarms and non-emergent routines, respectively. Intuitively, different data packets may also be heterogeneous in terms of packet size, and thus let us assume that the size (in bits) of data packets in each class $\ell, \forall \ell \in \mathcal{L}$, is characterized by a random variable S_ℓ following a general distribution with a PDF $f_{S_\ell}(\cdot)$ and a finite mean $\mathbb{E}[S_\ell]$.

The uplink beyond-WBAN transmission rate of each gateway $k, \forall k \in \{1, \ldots, K\}$, on each channel can be expressed as [81]

$$x_k = B \cdot \log_2 \left(1 + \frac{|h_k|^2 \cdot P_t \cdot y_k^{-\eta}}{\sigma^2} \right), \tag{4.1}$$

where B, P_t and σ^2 denote the channel bandwidth, the transmission power and the variance of the additive Gaussian noise, respectively; $|h_k|^2$ captures the Rayleigh fading effect and follows an exponential distribution with a unity mean; y_k specifies the distance between gateway k and the BS, so that $y_k^{-\eta}$ signifies the path loss effect, where $\eta \geq 2$ is the path loss exponent. With proper uplink transmission scheduling and resource management, each gateway can transmit its data packets to the BS through different and possibly multiple channels.

Furthermore, consider that humans/patients (represented by gateways in the beyond-WBAN) are randomly distributed in the cell, e.g., following a Poisson point distribution [82,83] or a random waypoint model [84]. Then, from the view of the BS, the distances between gateways and the BS, i.e., $y_k, \forall k \in \{1, \ldots, K\}$, can be modeled by a random variable Y. Substituting this into (4.1), the beyond-WBAN transmission rates of all data packets (regardless of particular gateway) can be represented as a random variable, denoted by X, with a PDF $f_X(\cdot)$ and a finite mean $\mathbb{E}[X]$. Similar definition can also be found in [18, 85].

4.1.2 Queueing Model

Similar to that in Chapters 2 and 3, the aggregate arrival of data packets at each gateway $k, \forall k \in \{1, \ldots, K\}$, is approximated by a Poisson process with an average rate λ_k. However, the proposed mechanism can also be applied to scenarios with more general arrival processes. Besides, through a long-term tracking, it is reasonable to

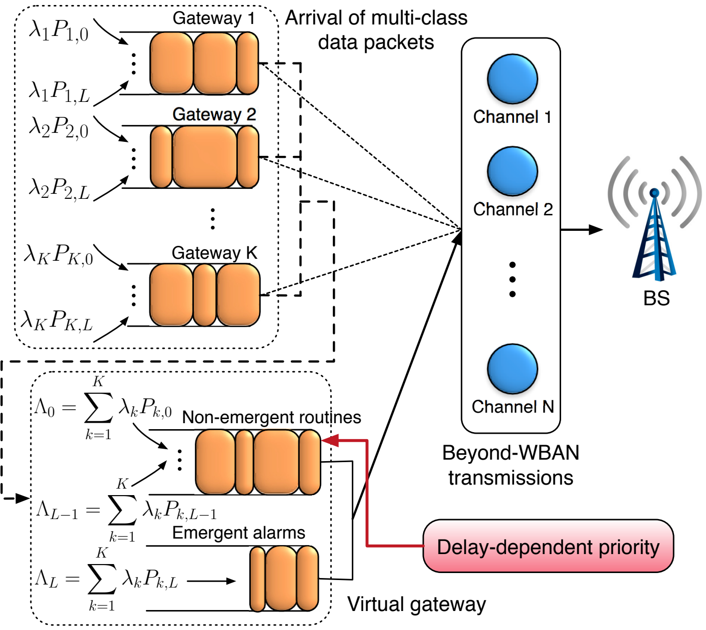


Figure 4.1: Queueing model of the delay-dependent prioritized scheduling.

assume that there is a known distribution $\boldsymbol{P}_k = (P_{k,0}, P_{k,1}, \ldots, P_{k,L})$ on the arrival of data packets from different classes at each gateway k, where $P_{k,\ell}$ indicates the probability that an arrived packet at gateway k belongs to class $\ell, \forall \ell \in \mathcal{L}$, and obviously $\sum_{\ell=0}^{L} P_{k,\ell} = 1$. Note that in practice, we must have $P_{k,L} \ll \sum_{\ell=0}^{L-1} P_{k,\ell}$, which implies that emergent events seldom happen. Given $\boldsymbol{P}_k, \forall k \in \{1, \ldots, K\}$, the average arrival rate of the ℓ-th class data packets at any gateway k can be calculated as $\lambda_k P_{k,\ell}, \forall \ell \in \mathcal{L}$. When a gateway receives a packet from its connected biosensors, it will immediately declare a beyond-WBAN transmission request to the BS. All packets that have not been scheduled for beyond-WBAN transmissions are temporarily stored in gateways' buffers. By ignoring the buffer overflow (which barely exits in the considered system, as explained in Chapter 2), the queueing model of the beyond-WBAN transmission scheduling studied in this chapter can be constructed as Fig. 4.1.

As the network regulator, the BS schedules the beyond-WBAN data packet transmissions initiated by all associated gateways. Obviously, such transmission scheduling should be based only on the criticality of data packets, and independent of the gateways where they are originated. Thus, the BS can treat all packet transmission requests from a single virtual gateway, as illustrated in Fig. 4.1, which consists of two specific virtual buffers, i.e., one for emergent packets and the other for non-emergent ones. Accordingly, there are multiple different packet arrival processes at the virtual gateway with respect to $\mathcal{L}$ packet classes. Due to the independency among gateways, their aggregate packet arrival processes at the virtual gateway are still Poisson distributed, and the average arrival rates are

$$\Lambda_\ell = \sum_{k=1}^{K} \lambda_k P_{k,\ell}, \ \forall \ell \in \mathcal{L}. \tag{4.2}$$

Note that even though all data packets may be sensitive to the potential waiting delays in the beyond-WBAN transmission [86] (such delay sensitivity will be further characterized in Section 4.1.3), there is a fundamental requirement in most WBAN-applications that the critical information delivery has to be protected with a strictly higher priority over those with regular importance [30]. This implies an inherent constraint that the QoS of beyond-WBAN transmissions for emergent packets has to always be guaranteed irrespective of the existence of non-emergent ones. In other words, it is required to ensure that

$$\mathbb{E}[D(L)] \leq \alpha_{th}, \tag{4.3}$$

where $\mathbb{E}[D(L)]$ and α_{th} are the expected waiting delay for the beyond-WBAN transmission of emergent packets (in class L) in the beyond-WBAN and its desired QoS threshold, respectively. Intuitively, in order to meet this condition, the BS can grant N_L channels for exclusively serving emergent packet transmissions. Note that N_L can be obtained according to different QoS requirements. For explicitly analysis, in this chapter, the derivation of N_L is based on the mean delay requirement (i.e., the satisfaction of inequality (4.3)). In practice, N_L can also be numerically calculated by imposing a requirement on higher-order statistics of the waiting delay for emergent packet transmissions.

Then, the transmission scheduling for emergent alarms can be modeled as a FCFS $M/G/N_L$ queue with a Poisson-distributed arrival at a rate of Λ_L and a general-distributed service at a rate of $N_L\mu_L$, where $1/\mu_L$ is the expected beyond-WBAN transmission time for one emergent data packet on one channel, and can be directly calculated as

$$1/\mu_L = \mathbb{E}[S_L/X] = \mathbb{E}[S_L]\int_{-\infty}^{\infty}\frac{1}{x}f_X(x)dx, \tag{4.4}$$

where S_L and X are the size of emergent data packets and the per-channel beyond-WBAN transmission rate, respectively.

According to [87], the delay performance of the constructed $M/G/N_L$ queue can be well approximated by

$$\mathbb{E}[D(L)] = \mathbb{E}[D^{M/G/N_L}] \approx \left(\frac{\mathcal{C}^2+1}{2}\right)\mathbb{E}[D^{M/M/N_L}], \tag{4.5}$$

where $\mathbb{E}[D^{M/G/N_L}]$ and $\mathbb{E}[D^{M/M/N_L}]$ denote the expected waiting delays of the considered $M/G/N_L$ queue and an $M/M/N_L$ queue with an exponential-distributed service at the same rate; $\mathcal{C}^2$ is the coefficient-of-variation of the transmission time, which can be derived as

$$\mathcal{C}^2 = \frac{\mathrm{Var}[S_L/X]}{\mathbb{E}[S_L/X]^2} = \mu_L^2 \left(\mathbb{E}[S_L^2] \int_{-\infty}^{\infty} \frac{1}{x^2} f_X(x)dx - 1/\mu_L^2 \right). \tag{4.6}$$

Besides, according to [88], $\mathbb{E}[D^{M/M/N_L}]$ can be expressed in a closed-form as

$$\mathbb{E}[D^{M/M/N_L}] = \frac{Q_{(N_L,G_L)}}{\mu_L(N_L - G_L)}, \tag{4.7}$$

where $G_L = \Lambda_L/\mu_L$ and $Q_{(N_L,G_L)}$ stands for the corresponding queueing probability:

$$Q_{(N_L,G_L)} = \frac{G_L^{N_L}/N_L!}{[(N_L - G_L)/N_L] \sum_{n=0}^{N_L-1} (G_L^n/n!) + G_L^{N_L}/N_L!}. \tag{4.8}$$

Thus, substituting (4.4) – (4.8) in (4.3), the minimum number of channels, i.e., $N_L^{\min}$, required for protecting emergent data packet transmissions can be obtained as

$$N_L^{\min} = \arg\min_{N_L} \mathbb{E}[D(L)] \le \alpha_{th}. \tag{4.9}$$

The numerical calculation and analysis of $N_L^{\min}$ will be presented in Section 4.3.

Since Λ_L is relatively small because $P_{k,L} \ll \sum_{\ell=0}^{L-1} P_{k,\ell}$, $\forall k \in \{1, \ldots, K\}$, we can assume that $N_L^{min} < N$ always holds. Then, the transmission scheduling for non-emergent routines can be formulated as another queueing system, in which the service time for non-emergent data packets in each class $\ell, \forall \ell \in \mathcal{L} \backslash \{L\}$, is

$$Z_\ell = \frac{S_\ell}{X(N - N_L^{\min})}, \tag{4.10}$$

where S_ℓ is the size of the ℓ-th class non-emergent data packets. Accordingly, the first and second moment of $Z_\ell, \forall \ell \in \mathcal{L} \backslash \{L\}$, can be derived as

$$\mathbb{E}[Z_\ell] = \frac{\mathbb{E}[S_\ell] \int_{-\infty}^{\infty} \frac{1}{x} f_X(x)dx}{N - N_L^{\min}}; \quad \mathbb{E}[Z_\ell^2] = \frac{\mathbb{E}[S_\ell^2] \int_{-\infty}^{\infty} \frac{1}{x^2} f_X(x)dx}{(N - N_L^{\min})^2}. \tag{4.11}$$

Note that even though all non-emergent data packets are considered to be stored in the same virtual buffer, their service orders (i.e., their transmission orders) depend on their packet criticality and their experienced waiting delays. To characterize the joint effects from these two factors, a new concept, called *delay-dependent priority*, is introduced in the following.

Definition 4.1 (DP)**.** For any non-emergent data packet in class $\ell, \forall \ell \in \mathcal{L} \backslash \{L\}$, which entered the system at time τ, its delay-dependent priority at time $t, \forall t \geq \tau$, is calculated as $\beta_\ell (t - \tau)$, where $\beta_\ell \in [0, \infty)$ is the criticality coefficient for the ℓ-th class packets.

According to this definition, DP is a linear combination of the criticality coefficient and the experienced waiting delay. However, the formulation of DP is actually not restricted to linear functions, and the only necessary requirement is the implication of a *class-dependent priority*[1]. In this chapter, the linear form of DP is adopted as an example to show the analysis procedure, while any other forms, which guarantee the class-dependent priority, can also be employed.

Thus, the instantaneous transmission order of any two non-emergent data packets i and j under a scheduling scheme $\boldsymbol{\zeta}$ follows

$$O^t_{\boldsymbol{\zeta}}(i) \geq O^t_{\boldsymbol{\zeta}}(j), \text{ if } \beta_{\ell_i}(t - \tau_i) \geq \beta_{\ell_j}(t - \tau_j), \ \forall t, \tag{4.12}$$

where $O^t_{\boldsymbol{\zeta}}(\cdot)$ denotes the transmission priority under $\boldsymbol{\zeta}$ at time t. Hereafter, we call (4.12) as *delay-dependent priority discipline* and $\boldsymbol{\zeta}$ which satisfies (4.12) as *delay-dependent prioritized scheduling scheme.*

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[1] As a common requirement for WBAN data transmissions [89, 90], packets in a class with higher emergency should always have higher priorities than the ones in other classes with less importance, if they have experienced the same waiting delays.

With such discipline, non-emergent packets with larger criticality coefficients or longer waiting delays may have higher transmission priorities in beyond-WBAN scheduling. Note that $\beta_\ell, \forall \ell \in \mathcal{L}\backslash\{L\}$, is an important parameter which has to be carefully determined by the BS.

4.1.3 Problem Formulation

Because of the limited amount of channels for beyond-WBANs, there exists potential waiting delays in beyond-WBAN transmissions. Since the value of transmitting a data packet may decrease with the increase of its waiting delay, similar to the previous chapters, we introduce a parameter θ_ℓ as the cost per unit of waiting delay for data packets in each class $\ell, \forall \ell \in \mathcal{L}\backslash\{L\}$, called the delay sensitivity of the ℓ-th class non-emergent packets. Without loss of generality, let us assume that

$$\theta_0 \leq \theta_1 \leq \ldots \leq \theta_{L-1}. \tag{4.13}$$

Then, the expected waiting cost of a non-emergent packet can be written as

$$\mathbb{E}[\phi(\ell)] = \theta_\ell \cdot \mathbb{E}[D(\ell)],\ \forall \ell \in \mathcal{L}\backslash\{L\}, \tag{4.14}$$

where $\mathbb{E}[D(\ell)]$ denotes the expected waiting delay of the ℓ-th class packets in beyond-WBAN transmissions. Note that we do not consider waiting costs on emergent packet transmissions since their QoS has been guaranteed from the satisfaction of condition (4.3). For notation consistency, we define $\mathbb{E}[\phi(L)] = 0$.

It is intuitive that for any data packet, the class it belongs to is the private information that is only known by its associated gateway, while unknown to the other gateways and the BS. Upon receiving a data packet, the associated gateway will immediately declare a beyond-WBAN transmission request to the BS along with the corresponding packet class. However, as an intelligent and rational entity, a smart gateway may strategically misreport another class ℓ' (instead of the actual class ℓ) if and only if it can benefit from such behavior, e.g., minimizing its expected transmission cost. Here, the total cost for transmitting a data packet in class ℓ but reporting class ℓ' is defined as

$$\mathbb{E}[C(\ell'|\ell)] = \mathbb{E}[\phi(\ell'|\ell)] + \pi(\ell'),\ \forall \ell, \ell' \in \mathcal{L}, \tag{4.15}$$

where $\mathbb{E}[\phi(\ell'|\ell)]$ and $\pi(\ell')$ are the expected cost due to the waiting delay and the charge by the BS for beyond-WBAN transmission, respectively. Obviously, the scheduling made by the BS can only based on the reported class ℓ' (since the BS is unaware of gateways' private information in advance), and thus both $\mathbb{E}[\phi(\ell'|\ell)]$ and $\pi(\ell')$ are functions of ℓ'. As the essential requirement to guarantee robustness and efficiency of a scheduling mechanism, it is always necessary to ensure that all gateways are induced to truthfully report the actual classes of their data packets. Hence, the designed mechanism has to meet the following truthfulness condition:

$$\ell = \arg\min_{\forall \ell' \in \mathcal{L}} \{\mathbb{E}[C(\ell'|\ell)]\},\ \forall \ell \in \mathcal{L}, \tag{4.16}$$

which indicates that the expected cost of transmitting a data packet in the beyond-WBAN should only be minimized when its class is reported truthfully (i.e., $\ell' = \ell$). Note that gateways will never take the risk to misreport any emergent packet as a non-emergent one because doing so may break condition (4.3) and lead to serious consequences. Besides, by adopting the *two-class prioritized dynamic transmission mechanism (DTM-2)* as proposed in Chapter 3, the possibility of misreporting any non-emergent packet as an emergent one can also be prevented. Thus, in this chapter, we limit our discussions on the truthfulness requirement among non-emergent packet classes. With (4.14) and (4.15), condition (4.16) can be rewritten as

$$\mathbb{E}[C(\ell|\ell)] \leq \mathbb{E}[C(\ell'|\ell)], \ \forall \ell, \ell' \in \mathcal{L} \backslash \{L\}, \tag{4.17}$$

where

$$\mathbb{E}[C(\ell'|\ell)] = \theta_\ell \mathbb{E}[D(\ell')] + \pi(\ell'). \tag{4.18}$$

The objective is to minimize the expected waiting costs of all data packet transmissions in the beyond-WBAN (i.e., to enhance the overall network performance or social welfare), which is defined as

$$W = \sum_{\ell \in \mathcal{L}} \Lambda_\ell \mathbb{E}[\phi(\ell)] = \sum_{\ell=0}^{L-1} \Lambda_\ell \theta_\ell \mathbb{E}[D(\ell)], \tag{4.19}$$

where $\Lambda_\ell \mathbb{E}[\phi(\ell)]$ represents the expected waiting costs of the ℓ-th class data packets in the queueing system. As the network regulator, the BS will aim to minimize W by jointly determining i) the criticality coefficients $\boldsymbol{\beta} = [\beta_0, \beta_1, \ldots, \beta_{L-1}]$, and ii) the transmission service charge $\boldsymbol{\pi} = [\pi(0), \pi(1), \ldots, \pi(L-1)]$, under a delay-dependent prioritized scheduling scheme $\boldsymbol{\zeta}$.

In summary, the problem of designing an efficient and truthful mechanism for scheduling delay-dependent prioritized beyond-WBAN transmissions can be formulated as

$$(\mathcal{P}1): \ [\boldsymbol{\beta}, \boldsymbol{\pi}] = \arg\min \sum\nolimits_{\ell=0}^{L-1} \Lambda_\ell \theta_\ell \mathbb{E}[D(\ell)], \tag{4.20}$$

$$s.t., \ \mathbb{E}[C(\ell|\ell)] \leq \mathbb{E}[C(\ell'|\ell)], \ \forall \ell, \ell' \in \mathcal{L} \backslash \{L\}, \tag{4.21}$$

$$O^t_{\boldsymbol{\zeta}}(i) \geq O^t_{\boldsymbol{\zeta}}(j), \ \text{if} \ \beta_{\ell_i}(t - \tau_i) \geq \beta_{\ell_j}(t - \tau_j), \ \forall i, j, t, \tag{4.22}$$

$$(\mathbb{E}[D(0)], \mathbb{E}[D(1)], \ldots, \mathbb{E}[D(L-1)]) \in \boldsymbol{\mathcal{Q}}(\Lambda, Z, \boldsymbol{\beta}, \boldsymbol{\pi}, \boldsymbol{\zeta}), \tag{4.23}$$

where constraint (4.21) induces gateways to behave truthfully in reporting the actual classes of their data packets; (4.22) imposes the requirement of delay-dependent priority discipline for $\boldsymbol{\zeta}$; and (4.23) indicates that the expected waiting delays for multi-class packet transmissions are obtained from the constructed queueing system, denoted by $\boldsymbol{\mathcal{Q}}$. Obviously, solving problem ($\mathcal{P}1$) directly is challenging because i) delays, i.e., $E[D(\ell)], \forall \ell$, are endogenous factors of the queueing system, which depend on the resulted queueing dynamics; ii) any adjustment on $\boldsymbol{\beta}$ and $\boldsymbol{\pi}$ will vary the queueing dynamics, which will in turn change the final decisions; and iii) instead of simple decision variables or vectors, $\boldsymbol{\pi}$ is an undetermined pricing rule or function with respect to $\boldsymbol{\beta}$. Thus, in the following, a novel approach is proposed to devise the mechanism which can satisfy all design requirements in ($\mathcal{P}1$).

4.2 Delay-Dependent Prioritized Mechanism

In this section, a delay-dependent prioritized mechanism for the beyond-WBAN transmission scheduling (DPMT) is proposed. First, a pure queueing scheduling scheme (without the guarantee of truthfulness and delay-dependent priority) is presented, which can achieve a lower-bound performance in solving ($\mathcal{P}1$). Then, the relationships between $\boldsymbol{\beta}$ and $\boldsymbol{\pi}$ is established. After that we formulate a virtual queueing game and devise DPMT (i.e., $[\boldsymbol{\beta}, \boldsymbol{\pi}]$) based on the corresponding Nash equilibrium (NE). Finally, the rationality and the feasibility of DPMT are justified.

4.2.1 Pure Queueing Scheduling

By considering the scheduling scheme as a decision, a pure queueing scheduling problem with the same objective function of problem ($\mathcal{P}1$) can be formulated as

$$(\mathcal{P}2): \ [\boldsymbol{\zeta}^*] = \arg\min \sum_{\ell=0}^{L-1} \Lambda_\ell \theta_\ell \mathbb{E}[D(\ell)] \tag{4.24}$$

$$s.t., \quad (\mathbb{E}[D(0)], , \mathbb{E}[D(1)], \ldots, \mathbb{E}[D(L-1)]) \in \boldsymbol{\mathcal{Q}}(\Lambda, Z, \boldsymbol{\zeta}^*). \tag{4.25}$$

Compared to ($\mathcal{P}1$), the constraints for guaranteeing truthfulness and delay-dependent priority (i.e., (4.21) and (4.22)) are ignored. Besides, constraint (4.25) is similar to (4.23) in ($\mathcal{P}1$) except that the queueing system $\boldsymbol{\mathcal{Q}}$ no longer depends on $\boldsymbol{\beta}$ and $\boldsymbol{\pi}$. Note that although the relaxed problem ($\mathcal{P}2$) seems oversimplified, its optimal solution can provide a lower bound on the minimum expected waiting costs of beyond-WBAN transmission scheduling in solving ($\mathcal{P}1$) and will be used as a benchmark for evaluating the efficiency of the proposed DPMT in Sections 4.2.4 and 4.3.

Inspired by [91, 92], the optimal prioritized scheduling scheme $\boldsymbol{\zeta}^*$ for ($\mathcal{P}2$) can be designed according to the following theorem.

Theorem 4.1. *Given a set of* $\{0, 1, \ldots, L-1\}$ *classes of data packets, reindex them based on a decreasing order of* $\theta_\ell / \mathbb{E}[Z_\ell], \forall \ell \in \{0, 1, \ldots, L-1\}$*, i.e.,*

$$\frac{\theta_0}{\mathbb{E}[Z_0]} \leq \frac{\theta_1}{\mathbb{E}[Z_1]} \leq \cdots \leq \frac{\theta_{L-1}}{\mathbb{E}[Z_{L-1}]}. \tag{4.26}$$

Then, to minimize the expected waiting cost, $\boldsymbol{\zeta}^*$ *will always grant a higher transmission priority to packets in class* ℓ *than those in class* $\ell - 1, \forall \ell \in \{1, \ldots, L-1\}$ *with the new indices defined by (4.26).*

Proof. This is equivalent to prove that for data packets belonging to any two consecutive classes (with indices defined by (4.26)), e.g., ℓ and $\ell - 1$, under the optimal scheduling scheme $\boldsymbol{\zeta}^*$, packets in class ℓ will always be transmitted in an absolutely higher priority over the ones in class $\ell - 1$.

The waiting costs for packets in both classes ℓ and $\ell - 1$ can be written as

$$\begin{aligned} W_{(\ell,\ell-1)} &= \Lambda_\ell \theta_\ell \mathbb{E}[D(\ell)] + \Lambda_{\ell-1}\theta_{\ell-1}\mathbb{E}[D(\ell-1)] \\ &= \frac{\theta_\ell}{\mathbb{E}[Z_\ell]}\rho_\ell \mathbb{E}[D(\ell)] + \frac{\theta_{\ell-1}}{\mathbb{E}[Z_{\ell-1}]}\rho_{\ell-1}\mathbb{E}[D(\ell-1)], \end{aligned} \tag{4.27}$$

where $\rho_\ell = \Lambda_\ell \mathbb{E}[Z_\ell]$. By the Little's law [64], we have

$$\rho_\ell \mathbb{E}[D(\ell)] = \Lambda_\ell \mathbb{E}[Z_\ell]\mathbb{E}[D(\ell)] = \mathbb{E}[Z_\ell]\mathbb{E}[Q_\ell], \tag{4.28}$$

where $\mathbb{E}[Q_\ell]$ represents the expected queue length of the ℓ-th class packets, and thus $\mathbb{E}[Z_\ell]\mathbb{E}[Q_\ell]$ denotes the mean workload of the ℓ-th class packets in the queue. Obviously, the total workload of both the ℓ-th and the $\ell - 1$-th class data packets in the queue remains a constant, i.e., $\mathbb{E}[Z_\ell]\mathbb{E}[Q_\ell] + \mathbb{E}[Z_{\ell-1}]\mathbb{E}[Q_{\ell-1}]$ is a constant, regardless of $\boldsymbol{\zeta}^*$. Hence, $\rho_\ell \mathbb{E}[D(\ell)] + \rho_{\ell-1}\mathbb{E}[D(\ell-1)]$ is also a constant.

Thus, if $\theta_\ell/\mathbb{E}[Z_\ell] \geq \theta_{\ell-1}/\mathbb{E}[Z_{\ell-1}]$, the only way to minimize $W_{(\ell,\ell-1)}$ is to decrease $\mathbb{E}[D(\ell)]$ as much as possible (even though $\mathbb{E}[D(\ell-1)]$ will increase accordingly). In other words, data packets in class ℓ should be granted by a higher beyond-WBAN transmission priority over those in class $\ell - 1$. $\square$

Theorem 4.1 indicates that for achieving expected cost minimization, data packets in a class with a higher cost per unit of transmission delay or a shorter expected service time should be given a higher beyond-WBAN transmission priority. In Section 4.2.4, it will be shown that the proposed DPMT can lead to a similar transmission order as that in $\boldsymbol{\zeta}^*$.

4.2.2 Characteristics of the Mechanism

In this subsection, some characteristics of DPMT is first investigated by assuming that the resulted $[\boldsymbol{\beta}, \boldsymbol{\pi}]$ can meet all requirements in $(\mathcal{P}1)$.

Proposition 4.1. For any two classes of non-emergent data packets (e.g., ℓ and ℓ') under DPMT, we always have

$$\pi(\ell) \geq \pi(\ell'), \text{ if } \beta_\ell \geq \beta_{\ell'}, \ \forall \ell, \ell' \in \mathcal{L} \backslash \{L\}. \tag{4.29}$$

Proof. Assume by the way of contradiction that

$$\pi(\ell) < \pi(\ell'), \text{ if } \beta_\ell \geq \beta_{\ell'}, \ \forall \ell, \ell' \in \mathcal{L} \backslash \{L\}. \tag{4.30}$$

Since DPMT is assumed to satisfy the truthfulness condition (4.21), the expected cost of transmitting any ℓ'-th class data packet should be minimized when its class ℓ' is reported truthfully, i.e.,

$$\mathbb{E}[C(\ell'|\ell')] \leq \mathbb{E}[C(\ell|\ell')], \ \forall \ell', \ell. \tag{4.31}$$

By employing the delay-dependent priority discipline (4.22), we have

$$\mathbb{E}[D(\ell)] \leq \mathbb{E}[D(\ell')], \text{ if } \beta_\ell \geq \beta_{\ell'}, \ \forall \ell, \ell' \in \mathcal{L} \backslash \{L\}. \tag{4.32}$$

This inequality can be proved by analyzing the delay performance of the delay-dependent prioritized queueing system.

Thus, from (4.30) and (4.32), we can derive that if $\beta_\ell \geq \beta_{\ell'}, \ \forall \ell, \ell' \in \mathcal{L} \backslash \{L\}$,

$$\theta_{\ell'} \mathbb{E}[D(\ell)] + \pi(\ell) < \theta_{\ell'} \mathbb{E}[D(\ell')] + \pi(\ell'). \tag{4.33}$$

which is equivalent to $\mathbb{E}[C(\ell|\ell')] < \mathbb{E}[C(\ell|\ell')]$ based on the cost function defined in (4.15). Obviously, this contradicts the truthfulness condition illustrated in (4.31), and hence the assumption in (4.30) does not hold. □

Proposition 4.1 implies that $\pi(\ell), \forall \ell \in \mathcal{L}\backslash\{L\}$, should be an increasing function of β_ℓ. This matches the intuition that any ℓ-th class data packet with a larger β_ℓ so as to obtain a better beyond-WBAN transmission service (i.e., a smaller $\mathbb{E}[D(\ell)]$) has to be charged by a higher price for its transmission. Besides, it is intuitive that the service charge for each packet transmission should depend on not only the waiting delay but also the service length (i.e., the time length in occupying certain beyond-WBAN radio resources). In other words, $\pi(\ell), \forall \ell \in \mathcal{L}\backslash\{L\}$, should also be an increasing function of $\mathbb{E}[Z_\ell]$. Thus, $\pi(\ell), \forall \ell \in \mathcal{L}\backslash\{L\}$, can be rewritten as

$$\pi(\ell) \triangleq \pi(\beta_\ell, \mathbb{E}[Z_\ell]), \ \forall \ell \in \mathcal{L}\backslash\{L\}, \tag{4.34}$$

with

$$\frac{\partial \pi(\beta_\ell, \mathbb{E}[Z_\ell])}{\partial \beta_\ell} \geq 0 \ \text{ and } \ \frac{\partial \pi(\beta_\ell, \mathbb{E}[Z_\ell])}{\partial \mathbb{E}[Z_\ell]} \geq 0. \tag{4.35}$$

4.2.3 A Virtual Queueing Game Approach

From the formulation of problem ($\mathcal{P}1$) and the characteristics of DPMT shown in previous sections, it can be observed that the key of the design is the determination of $\boldsymbol{\beta} = \{\beta_\ell\}_{\ell \in \mathcal{L}\backslash\{L\}}$. Even though $\beta_\ell, \forall \ell \in \mathcal{L}\backslash\{L\}$, is a centralized decision made by the BS, its value has to be carefully chosen in order to guarantee that each individual smart gateway will report the actual classes of its data packets, i.e., satisfying the truthfulness condition (4.21). As explained in Section 4.1.3, directly deriving $\boldsymbol{\beta}$ is difficult because of the queueing dynamics and the interactions among different packet classes (reflected by the potential untruthful behaviors of strategic gateways). A natural way to model and deal with radio resource managements (e.g., the transmission scheduling) involving multi-agent interactions is through game theory [93]. Therefore, in order to obtain $\boldsymbol{\beta}$, a novel approach is proposed, in which the BS first formulates a *virtual queueing game* by treating each packet class ℓ as a *virtual player* and β_ℓ as its associated strategy. After running the game and computing the corresponding NE (such that the costs of transmitting all classes of data packets can be minimized), the BS can then design the mechanism exactly based on the outcome of the game. The details are explained in the following.

Game Formulation

As the central controller, the BS can virtually consider that there are L intelligent players with respect to L packet classes in $\{0, 1, \ldots, L-1\}$, i.e., each packet class ℓ is represented by a virtual player, also denoted by ℓ for notation simplicity. Each virtual player ℓ strategically determines β_ℓ with the objective of maximizing its own benefit or minimizing its own cost. Let β_ℓ, $\boldsymbol{\beta}_{-\ell}$ and $\boldsymbol{\beta}$ be the strategy of virtual player ℓ, strategies of all other virtual players and the strategy profile of all virtual players, respectively. Obviously, the cost function of each virtual player ℓ can be formulated according to the expected cost of transmitting any ℓ-th class data packet in the beyond-WBAN. Thus, with (4.18), (4.34) and the delay-dependent priority discipline, the cost of each virtual player ℓ under strategy profile $\boldsymbol{\beta}$ can be written as

$$C_\ell(\beta_\ell, \boldsymbol{\beta}_{-\ell}) = \theta_\ell \mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})] + \pi(\beta_\ell, \mathbb{E}[Z_\ell]). \tag{4.36}$$

Intuitively, in order to minimize $C_\ell(\beta_\ell, \boldsymbol{\beta}_{-\ell})$, a virtual player ℓ may increase β_ℓ for potentially decreasing the expected waiting delay, i.e., $\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]$, in beyond-WBAN transmission scheduling. However, choosing a larger β_ℓ may also lead to a higher service cost, i.e., a larger $\pi(\beta_\ell, \mathbb{E}[Z_\ell])$, according to the relationship obtained in (4.35). For mathematical tractability, we define $\pi(\beta_\ell, \mathbb{E}[Z_\ell]) = \xi\beta_\ell\mathbb{E}[Z_\ell]$, where ξ is a system-determined parameter. Then, all L virtual players will compete with each other to minimize their own costs by adjusting their strategies, which results in a non-cooperative game over a delay-dependent prioritized queueing system. Formally, such virtual queueing game can be denoted by

$$\mathcal{G} \triangleq \{L, \boldsymbol{\mathcal{E}}, \{C_\ell\}_{\forall\ell}\}, \tag{4.37}$$

where L and $\{C_\ell\}$ are the number of players in the game, the strategy set and the cost function of each player ℓ, respectively. The NE of $\mathcal{G}$ can be defined as follows.

Definition 4.2 (NE)**.** A strategy profile $\boldsymbol{\beta}^e$ is a Nash equilibrium of game $\mathcal{G}$ if for every virtual player ℓ, we have

$$C_\ell(\beta_\ell^e, \boldsymbol{\beta}_{-\ell}^e) \leq C_\ell(\tilde{\beta}_\ell, \boldsymbol{\beta}_{-\ell}^e),\ \forall\tilde{\beta}_\ell \in \boldsymbol{\mathcal{E}}. \tag{4.38}$$

Note that unlike traditional non-cooperative game frameworks [94, 95], analyzing the formulated delay-dependent prioritized virtual queueing game, i.e., $\mathcal{G}$, is much more challenging because it can be seen from (4.36) that the cost function of each virtual player largely depends on the delay performance resulted by the queueing system, and it is difficult, if not impossible, to explicitly derive a closed-form expression of the corresponding expected waiting delay.

Game Analyses

To address the aforementioned challenges, let us first explore the relationships between the packets' criticality coefficients and their expected waiting delays in the queueing system with the delay-dependent priority discipline.

Lemma 4.1. *Let $\boldsymbol{\beta}$ be the strategy profile of all virtual players, which denotes the criticality coefficients of all classes of non-emergent packets. Then, the expected waiting delay of a ℓ-th class data packet, represented by a virtual player ℓ with a strategy β_ℓ, can be expressed in a recursive form as*

$$\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})] = \frac{\frac{\kappa}{1-\rho} - \sum_{\{\ell' | \beta_{\ell'} < \beta_\ell\}} \rho_{\ell'}(1 - \frac{\beta_{\ell'}}{\beta_\ell})\mathbb{E}[D(\beta_{\ell'}, \boldsymbol{\beta}_{-\ell'})]}{1 - \sum_{\{\ell' | \beta_{\ell'} \geq \beta_\ell\}} \rho_{\ell'}(1 - \frac{\beta_\ell}{\beta_{\ell'}})}, \tag{4.39}$$

where

$$\rho_\ell = \Lambda_\ell \mathbb{E}[Z_\ell], \ \rho = \sum_{\ell=0}^{L-1} \rho_\ell \text{ and } \kappa = \sum_{\ell=0}^{L-1} \frac{\rho_\ell \mathbb{E}[Z_\ell^2]}{2\mathbb{E}[Z_\ell]}.$$

Proof. Please see Appendix B.1 for the proof. □

Since the waiting delay expression given by (4.39) is not in a closed form due to a recursive term in the numerator, the cost functions of virtual players, i.e., (4.36), cannot be explicitly expressed. However, the properties of game $\mathcal{G}$ can still be analyzed based on the corresponding queueing performance.

Lemma 4.2. *For any virtual player ℓ in game $\mathcal{G}$, its expected waiting delay, i.e., $\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]$, is a non-increasing and convex function of β_ℓ.*

Proof. Please see Appendix B.2 for the proof. □

With Lemmas 4.1 and 4.2, it can be shown that there exits at least one NE in game $\mathcal{G}$.

Theorem 4.2. *The formulated virtual queueing game $\mathcal{G}$ has at least one NE.*

Proof. As defined in (4.36), the cost function can be expressed as

$$C_\ell(\beta_\ell, \boldsymbol{\beta}_{-\ell}) = \theta_\ell \mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})] + \xi \beta_\ell \mathbb{E}[Z_\ell]. \tag{4.40}$$

With Lemma 4.2, it can be easily proved that $\frac{\partial C_\ell(\beta_\ell,\boldsymbol{\beta}_{-\ell})}{\partial \beta_\ell} \geq 0$, which means that $C_\ell(\beta_\ell,\boldsymbol{\beta}_{-\ell})$ is convex with respect to β_ℓ.

Moreover, since $\beta_\ell, \forall \ell \in \boldsymbol{\mathcal{L}}\backslash\{L\}$ is in the range of $[0,\infty)$, in order to minimize $C_\ell(\beta_\ell,\boldsymbol{\beta}_{-\ell})$, it is intuitive that for any virtual player ℓ, the determined strategy β_ℓ should satisfy

$$C_\ell(\beta_\ell,\boldsymbol{\beta}_{-\ell}) \leq C_\ell(0,\boldsymbol{\beta}_{-\ell}). \tag{4.41}$$

Substituting (4.40) into (4.41) yields

$$\theta_\ell \mathbb{E}[D(\beta_\ell,\boldsymbol{\beta}_{-\ell})] + \xi\beta_\ell\mathbb{E}[Z_\ell] \leq \theta_\ell\mathbb{E}[D(0,\boldsymbol{\beta}_{-\ell})]. \tag{4.42}$$

According to Lemma 4.1 and by considering that $\beta_\ell = 0$, we have

$$\begin{aligned}\mathbb{E}[D(0,\boldsymbol{\beta}_{-\ell})] &= \frac{\frac{\kappa}{1-\rho} - \sum_{\{\ell'|\beta_{\ell'}<0\}}\rho_{\ell'}(1-\frac{\beta_{\ell'}}{\beta_\ell})\mathbb{E}[D(\beta_{\ell'},\boldsymbol{\beta}_{-\ell'})]}{1-\sum_{\{\ell'|\beta_{\ell'}\geq 0\}}\rho_{\ell'}(1-\frac{\beta_\ell}{\beta_{\ell'}})},\\ &= \frac{\frac{\kappa}{1-\rho}-0}{1-\sum_{\ell'\in\mathcal{L}\backslash\{0\}}\rho_{\ell'}} = \frac{\kappa}{(1-\rho)^2}.\end{aligned} \tag{4.43}$$

Substituting (4.43) back into inequality (4.42), we have

$$\begin{aligned}\beta_\ell &\leq \frac{\theta_\ell}{\xi\mathbb{E}[Z_\ell]}\big(\mathbb{E}[D(0,\boldsymbol{\beta}_{-\ell})] - \mathbb{E}[D(\beta_\ell,\boldsymbol{\beta}_{-\ell})]\big)\\ &\leq \frac{\theta_\ell}{\xi\mathbb{E}[Z_\ell]}\mathbb{E}[D(0,\boldsymbol{\beta}_{-\ell})] = \frac{\theta_\ell\kappa}{\xi\mathbb{E}[Z_\ell](1-\rho^2)} \triangleq \bar{\beta}_\ell,\end{aligned} \tag{4.44}$$

which implies that the strategies of all virtual players can be limited in a compact and convex set, denoted by a Cartesian product as

$$\boldsymbol{\mathcal{E}} = \prod_{\ell\in\mathcal{L}\backslash\{L\}} [0,\bar{\beta}_\ell] \subset \mathbb{R}^L. \tag{4.45}$$

Since the cost function of each virtual player is continuous and convex, and the strategy set $\boldsymbol{\mathcal{E}}$ is nonempty, convex and compact, the game $\mathcal{G}$ has at least one NE. □

Because of the existence of NE for game $\mathcal{G}$, in the proposed DPMT, $\boldsymbol{\beta}$ can be determined as

$$\boldsymbol{\beta} \triangleq \boldsymbol{\beta}^e, \tag{4.46}$$

so that the expected cost of transmitting every class of data packets can be minimized. Note that for practical implementations, $\boldsymbol{\beta}^e$ can be computed by using existing numerical methods [96–98], and the convergence speed is not a primary concern because the BS can always run the virtual game (by simulation) in advance before it starts the beyond-WBAN transmission scheduling. Moreover, even if the NE of the virtual queueing game $\mathcal{G}$ is not unique, the BS can select any resulted NE as its decision for $\boldsymbol{\beta}$ in DPMT.

4.2.4 Performance Analyses

The timeline for the implementation of DPMT is described in the following.

(1) According to the QoS requirements, the BS first determines the assignments of $N_L^{\min}$ and $N - N_L^{\min}$ channels for serving the beyond-WBAN transmissions of emergent and non-emergent data packets, respectively.

(2) The BS formulates and runs a virtual queueing game $\mathcal{G}$ by simulation to obtain an equilibrium strategy profile $\boldsymbol{\beta}^e$.

(3) The BS constructs a mechanism $[\boldsymbol{\beta}, \boldsymbol{\pi}]$, in which $\beta_\ell = \beta_\ell^e$ and $\pi_\ell = \xi\beta_\ell^e\mathbb{E}[Z_\ell]$.

(4) The BS broadcasts the scheduling scheme (i.e., FCFS for emergent alarms and delay-dependent priority discipline for non-emergent routines) and the corresponding mechanism (i.e., $[\boldsymbol{\beta}, \boldsymbol{\pi}]$) to all gateways in the beyond-WBAN.

(5) Whenever a gateway collects a packet from its biosensors, it will immediately declare a beyond-WBAN transmission request to the BS by reporting the class of this packet. All data packets are stored in gateways' buffers until they are completely transmitted.

(6) The BS manages beyond-WBAN transmissions following the aforementioned scheduling schemes and the devised mechanism.

Theorem 4.3 (Truthfulness)**.** *By applying DPMT, all gateways will be induced to report the actual classes of their data packets to the BS when declaring beyond-WBAN transmission requests, i.e.,*

$$\theta_\ell \mathbb{E}[D(\ell)] + \pi(\ell) \leq \theta_\ell \mathbb{E}[D(\ell')] + \pi(\ell'), \forall \ell, \ell' \in \mathcal{L} \backslash \{L\}. \tag{4.47}$$

Proof. From the view of a gateway, misreporting a packet in class ℓ as another class ℓ' can manipulate its packets' criticality coefficient from β_ℓ to $\beta_{\ell'}$ (since the BS assigns different criticality coefficients to different data packets based on their reported classes). Note that the BS charges for each packet transmission only after it has been completed, and both the delay sensitivity and the transmission time of this packet are inherent parameters. Thus, the truthfulness condition (4.47) can be rewritten as

$$\theta_\ell \mathbb{E}[D(\beta_\ell)] + \xi \beta_\ell \mathbb{E}[Z_\ell] \leq \theta_\ell \mathbb{E}[D(\beta_{\ell'})] + \xi \beta_{\ell'} \mathbb{E}[Z_\ell], \tag{4.48}$$

which only depends on β_ℓ and $\beta_{\ell'}$.

In DPMT, the criticality coefficient $\beta_\ell, \forall \ell \in \mathcal{L} \backslash \{L\}$, is determined as the NE of game $\mathcal{G}$ with

$$\theta_\ell \mathbb{E}[D(\beta_\ell)] + \xi \beta_\ell \mathbb{E}[Z_\ell] \leq \theta_\ell \mathbb{E}[D(\tilde{\beta}_\ell)] + \xi \tilde{\beta}_\ell \mathbb{E}[Z_\ell], \ \forall \tilde{\beta}_\ell. \tag{4.49}$$

Since (4.49) obviously implies the satisfaction of (4.48), it can be concluded that all gateways will behave truthfully by reporting the actual classes of their data packets in the beyond-WBAN employing DPMT. □

Theorem 4.4. *Consider that DPMT results in a criticality coefficient* β_ℓ *for data packets in each class* $\ell, \forall \ell \in \mathcal{L}\backslash\{L\}$*, and without loss of generality, assume that packet classes are ordered in accordance with*

$$\beta_0 \leq \beta_1 \leq \ldots \leq \beta_L - 1. \tag{4.50}$$

Then, it can be shown that this order coincides with (4.26), i.e.,

$$\frac{\theta_0}{\mathbb{E}[Z_0]} \leq \frac{\theta_1}{\mathbb{E}[Z_1]} \leq \ldots \leq \frac{\theta_{L-1}}{\mathbb{E}[Z_{L-1}]}. \tag{4.51}$$

based on which the corresponding absolutely prioritized scheduling can lead to a lower-bound performance of $(\mathcal{P}1)$ *on the minimum expected waiting costs.*

Proof. Assume by the way of contradiction that there exists two classes $\ell, \ell', \forall \ell, \ell' \in \mathcal{L}\backslash\{L\}$, such that

$$\beta_\ell \geq \beta_{\ell'}, \text{ while } \frac{\theta_\ell}{\mathbb{E}[Z_\ell]} < \frac{\theta_{\ell'}}{\mathbb{E}[Z_{\ell'}]}. \tag{4.52}$$

Since β_ℓ and $\beta_{\ell'}$ are obtained as the NE of virtual players ℓ and ℓ', respectively, we must have

$$\theta_\ell \mathbb{E}[D(\beta_\ell)] + \xi\beta_\ell \mathbb{E}[Z_\ell] \leq \theta_\ell \mathbb{E}[D(\beta_{\ell'})] + \xi\beta_{\ell'} \mathbb{E}[Z_\ell], \tag{4.53}$$

$$\theta_{\ell'} \mathbb{E}[D(\beta_{\ell'})] + \xi\beta_{\ell'} \mathbb{E}[Z_{\ell'}] \leq \theta_{\ell'} \mathbb{E}[D(\beta_\ell)] + \xi\beta_\ell \mathbb{E}[Z_{\ell'}]. \tag{4.54}$$

With some simple mathematical manipulations, we have

$$\xi(\beta_\ell - \beta_{\ell'}) \leq \frac{\theta_\ell}{\mathbb{E}[Z_\ell]}(\mathbb{E}[D(\beta_{\ell'})] - \mathbb{E}[D(\beta_\ell)]) < \frac{\theta_{\ell'}}{\mathbb{E}[Z_{\ell'}]}(\mathbb{E}[D(\beta_{\ell'})] - \mathbb{E}[D(\beta_\ell)]), \tag{4.55}$$

where the first and second inequalities holds because of (4.53) and (4.52), respectively.

Clearly, inequality (4.55) can be rewritten as

$$\theta_{\ell'}\mathbb{E}[D(\beta_{\ell'})] + \xi\beta_{\ell'}\mathbb{E}[Z_{\ell'}] > \theta_{\ell'}\mathbb{E}[D(\beta_{\ell})] + \xi\beta_{\ell}\mathbb{E}[Z_{\ell'}], \tag{4.56}$$

which contradicts (4.54), and thus the assumption in (4.52) cannot be true. □

Theorem 4.4 states that the criticality coefficients of all classes of packets determined by DPMT share a same order as the transmission order in the optimal solution to the relaxed pure queueing scheduling problem ($\mathcal{P}2$). This implies that DPMT can achieve a relatively good performance in minimizing the expected costs of all packet transmissions in the beyond-WBAN. In Section 4.3, the efficiency of DPMT will be further illustrated by simulations.

4.3 Simulation Results

In this section, simulations are conducted by MATLAB to evaluate the performance of the proposed DPMT in scheduling delay-dependent prioritized data packet transmissions in the beyond-WBAN.

4.3.1 Simulation Settings

Consider a beyond-WBAN with one BS and K gateways ($K \in [10, 100]$). There are $N = 10$ channels for scheduling both emergent and non-emergent packet transmissions. Following the definition in IEEE 802.15.6 [10], all data packets are categorized into $\mathcal{L} = \{0, 1, \ldots, 7\}$ classes with $\{7\}$ and $\{0, 1, \ldots, 6\}$ denoting the sets of emergent alarms and non-emergent routines, respectively. According to the characteristics

Table 4.1: Channels assigned for emergent packet transmissions.

(a) $N_L^{\min}$ with different probabilities of emergency.

P_0	0.05	0.1	0.15	0.2	0.25
$N_L^{\min}$	1	2	3	3	4

(b) $N_L^{\min}$ with different QoS thresholds.

α_{th} (sec.)	0.01	0.05	0.1	0.15	0.2
$N_L^{\min}$	3	2	2	1	1

of WBANs [27], the size of each packet is chosen from 50 to 100 Kb, and the QoS threshold α_{th} (i.e., the delay requirement) of emergent information delivery is set as 0.2 seconds. The beyond-WBAN transmission rate of each gateway is assumed to be randomly distributed over $[250, 500]$ Kbps, which is identical to the uplink transmission rate in 3G networks [70]. The aggregate arrival rate of data packets at each gateway k is taken within the range of $[5, 25]$ packets per minutes, and the probability distribution $\boldsymbol{P}_k$ is assumed as $(0.2, 0.15, 0.15, 0.15, 0.1, 0.1, 0.1, 0.05)$. Furthermore, let $\xi = 10^2$ and delay sensitivities of all classes of non-emergent packets, i.e., $\theta_1, \theta_2, \ldots, \theta_7$, be $0.5, 1, 1.5, 2, 2.5, 3, 3.5$, respectively. In the following, all numerical results are obtained by taking averages over 100 runs, and some parameters may vary depending on simulation scenarios.

4.3.2 Performance Evaluations

Table 4.1 shows the calculation results of the number of channels that are exclusively assigned in DPMT for emergent packet transmissions. With different settings, at least $N_L^{\min}$ channels have to be reserved for protecting the QoS of emergent alarms.

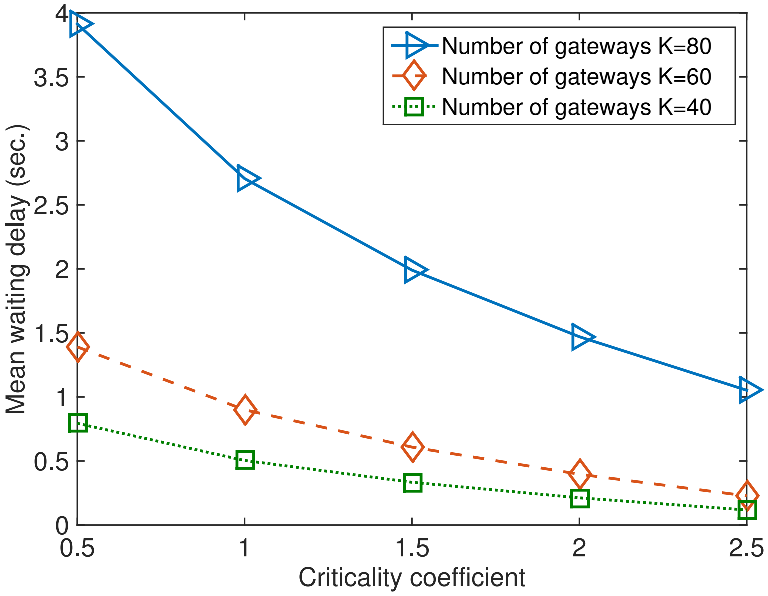

Figure 4.2: Delay performance of the constructed delay-dependent priority queue.

It can be seen from Table 4.1 (a) that $N_L^{\min}$ increases with increment of P_0 (which denotes the average probability of emergency), while decreases with the relaxation of the QoS requirement on emergent alarms (i.e., the increase of α_{th}) as demonstrated by Table 4.1 (b). As a typical example, we can observe that, in the scenario that $P_0 = 0.05$ and $\alpha_{th} = 0.2$ [27], $N_L^{\min} = 1$ is enough to guarantee the QoS of emergency, and the rest of $N - N_L^{\min} = 9$ channels can be allocated for non-emergency. Note that the results obtained in Table 4.1 will be used for follow-up simulations.

Fig. 4.2 illustrates the waiting delay performance of the constructed transmission scheduling system with delay-dependent priorities. It is shown that the waiting delay of a non-emergent data packet with a larger criticality coefficient is shorter. In other words, the larger criticality coefficient a packet has, a better beyond-WBAN transmission service it obtains. Moreover, we can see that the decreasing trend of curves in

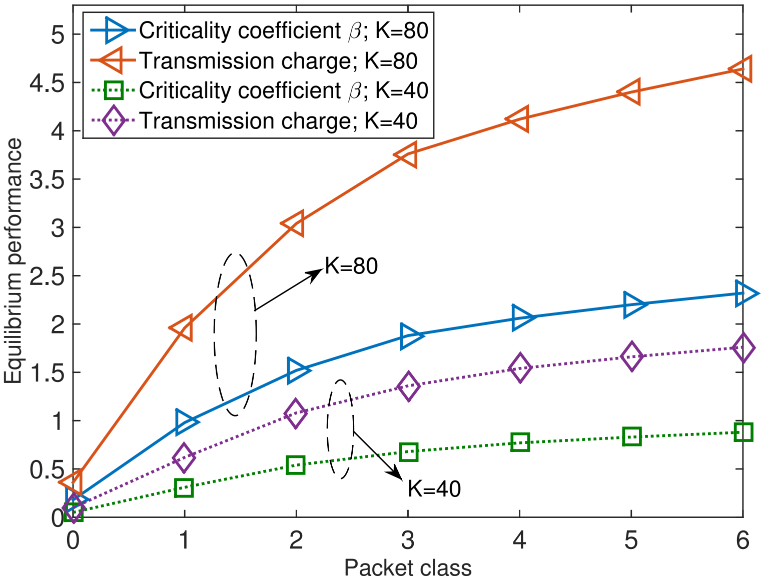

Figure 4.3: Equilibrium performance of the virtual queueing game $\mathcal{G}$.

Fig. 4.2 becomes less obvious when packets' criticality coefficients are larger. These verify the theoretical analysis in Lemma 4.2 that the waiting delay of a non-emergent packet is non-increasing and convex with respect to the criticality coefficient. In addition, Fig. 4.2 also shows that the waiting delay is longer when the number of gateways K increases. This is because a larger K indicates more beyond-WBAN transmission requests and leads to a busier management system.

In Fig. 4.3, the equilibrium performance of the formulated virtual queueing game $\mathcal{G}$ is investigated. From this figure, we can observe that for any data packet in a class with a larger ℓ, both its criticality coefficient (i.e., β^e) and transmission service charge (i.e., π) are larger. According to the simulation settings, the delay sensitivity θ increases with the packet class and the expected packet size is homogeneous among all classes. Therefore, the trend of curves in Fig. 4.3 reveals that the order of

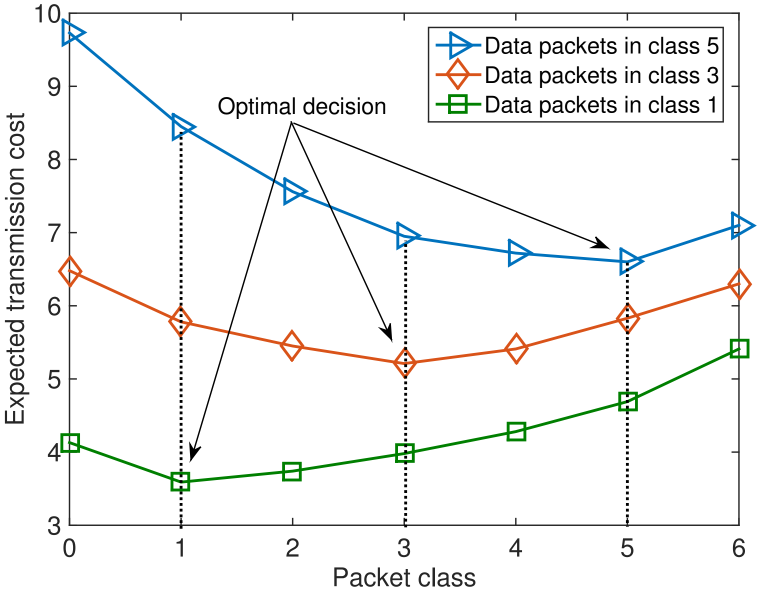

Figure 4.4: Truthfulness analysis of DPMT.

$\beta_\ell, \forall\ell$, corresponds to that of $\theta_\ell/\mathbb{E}[Z_\ell], \forall\ell$, which verifies Theorem 4.4. Besides, as depicted by Fig. 4.2, a higher-class data packet with a larger criticality coefficient can obtain a better beyond-WBAN transmission service (i.e., experience a shorter waiting delay), and thus has to be charged by a higher service price. Furthermore, since the competition in game $\mathcal{G}$ becomes more and more intense when the scheduling system is increasingly busier, it is also shown in Fig. 4.3 that a larger number of gateways results in larger β^e and π.

Fig. 4.4 examines the truthfulness of DPMT by evaluating the expected transmission cost of a data packet with different reported classes ℓ'. In beyond-WBANs, smart gateways can strategically report the class of each packet so as to minimize its transmission cost. The trend of curves in Fig. 4.4 indicates that the packet's expected transmission cost first decreases with the increase of the reported class ℓ'.

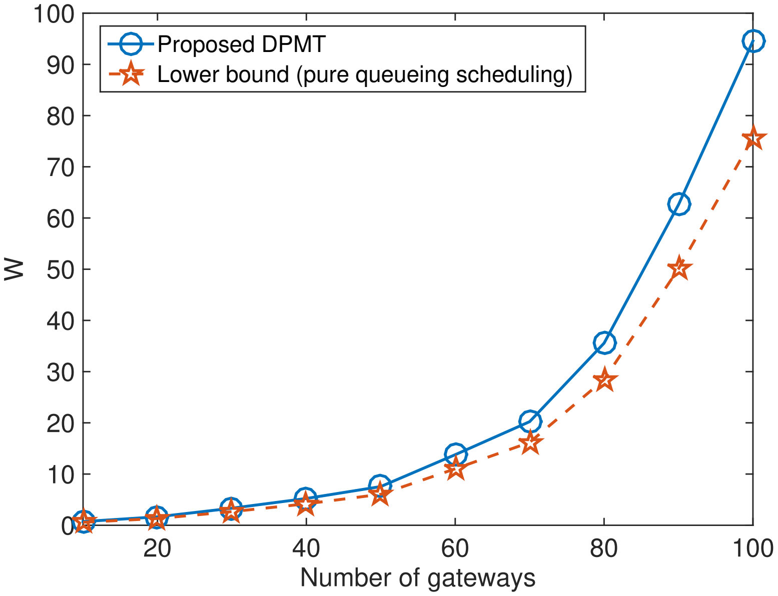

Figure 4.5: Performance of DPMT in minimizing W.

This is because reporting a larger ℓ' can result in a lower transmission service charge for the beyond-WBAN transmission as explained in Fig. 4.3. However, after a certain point (i.e., the reported packet class equals the actual packet class), since the waiting delay performance is getting much worse than expectation, the waiting cost becomes dominant so that the total transmission cost increases. Intuitively, the optimal decision (of gateways) is to report a data packet in a class which leads to the lowest transmission cost, i.e., truthfully report the actual class of every data packet, and thus Theorem 4.3 holds.

Fig. 4.5 shows the performance of DPMT in minimizing W (i.e., the total waiting costs of all data packet transmissions in the beyond-WBAN) by comparing it with the lower bound obtained by the pure queueing scheduling scheme discussed in Section 4.2.1. From this figure, we can see that W increases with the number of gateways K.

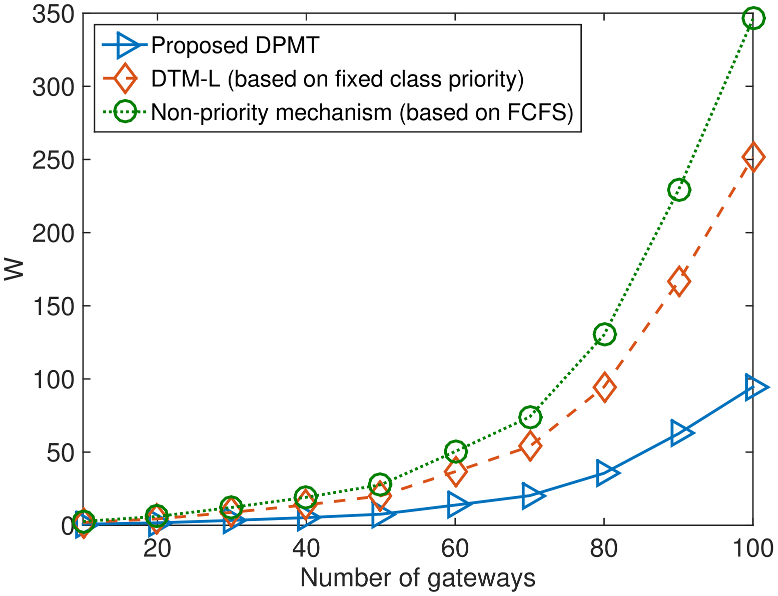

Figure 4.6: Comparison with existing mechanisms on minimizing W.

This is because, as defined in (4.19), W depends on the average arrival rate of the beyond-WBAN packet transmission requests and their waiting delays, and both of them increase when the scheduling system becomes busier (i.e., K increases). More importantly, it can be observed that DPMT results in a slightly larger W than the lower bound, which clearly indicates the efficiency of DPMT in minimizing W. This is mainly because DPMT schedules the beyond-WBAN transmissions of data packets based on both their criticality coefficients and experienced waiting delays, and the determined criticality coefficients of all packet classes are ordered in accordance with the optimal transmission orders in the pure queueing scheduling scheme.

In Fig. 4.6, the superiority of the proposed DPMT on minimizing the expected waiting cost of the overall beyond-WBAN transmission system is demonstrated. For comparison purpose, the transmission scheduling mechanisms based on the absolute and fixed class priority (i.e., DTM-L) [99] and FCFS discipline (i.e., non-priority mechanism) [100] are also simulated as benchmarks, where DTM-L always maintains a fixed class-dependent transmission order regardless of packets' experienced waiting delays and their potential heterogeneities in terms of transmission time, and the non-priority mechanism treats all transmission requests equally without taking into account the QoS requirements. It is shown that the non-priority mechanism based on FCFS has the worst performance (i.e., the largest W) because the potential priorities among different classes of data packets are ignored. It is obvious that DTM-L achieves a better performance than that of the non-priority mechanism due to the consideration of class-dependent packet priorities. Moreover, it can be seen that the proposed DPMT outperforms both DTM-L and non-priority mechanism on overall expected cost minimization. This is because DPMT aims to enhance the social welfare of the beyond-WBAN, and can well balance the waiting costs of all classes of data packets by providing the delay-dependent prioritized transmission services.

Chapter 5

Delay-Constrained Priority-Aware Transmission Scheduling

In all previous chapters, data packet transmissions in the beyond-WBAN were considered as delay-sensitive, i.e., the value of transmitting each packet would decrease with the increase of its waiting/scheduling delay in the beyond-WBAN. However, in some WBAN applications, such as sports and entertainments [101], data packets may not be that sensitive to relatively tiny changes in the waiting delay. Instead, the effectiveness (or value) of each piece of information can lasts for a certain limit period of time [102], and thus it is only required to transmit the data packet within its required delay limit (so as to avoid any loss). This encourages us to study the delay-constrained priority-aware transmission scheduling for the beyond-WBAN.

Extended from the mechanisms designed in previous chapters, in this chapter, a novel priority-aware truthful mechanism for scheduling delay-constrained data packet transmissions in the beyond-WBAN is proposed. In the considered system model, multi-class data packets collected by biosensors are aggregated randomly at each gateway (via the intra-WBAN communication). Upon receiving a data packet, the associated gateway immediately declare a beyond-WBAN transmission request to the BS, and temporarily stores the packet in its own buffer until it has been successfully transmitted or dropped due to excessive delays (i.e., waiting longer than its required delay limit). Different data packets may experience different beyond-WBAN transmission time and are constrained by different delay requirements. As the network regulator, the BS manages the beyond-WBAN data packet transmissions with the guarantee of priority-aware QoS. The packet-level operation is then formulated as a multi-class delay-constrained priority queueing system. Based on this model, an efficient mechanism is devised, which can ensure that all gateways will truthfully report the priority classes of their data packets and can incentivize the BS to run the beyond-WBAN management system by maximizing its operation revenue.

5.1 System Model and Problem Description

In this section, the system model is first described. Then, the problem of designing a truthful mechanism for priority-aware beyond-WBAN transmission scheduling of data packets with delay constraints is formulated.

5.1.1 System Model

As usual, consider a cellular-like beyond-WBAN consisting of one BS and K gateways. The BS is responsible to mange the scheduling of data packet transmissions from all gateways on N homogeneous channels that are dedicated for beyond-WBAN communications. Each gateway aggregates a variety of data packets generated by its connected biosensors via the intra-WBAN and then forward them to the BS through the beyond-WBAN. According to the IEEE std. 802.15.6 [10], data packets are categorized into a finite set of classes, denoted by $\mathcal{L} = \{0, 1, \ldots, L\}$, where 0 and L represent the lowest and the highest priority levels, respectively.

At each gateway $k, \forall k \in \{1, 2, \ldots, K\}$, the aggregate arrival of data packets collected from many independent biosensors is again approximated by a Poisson process with an average rate λ_k. However, the proposed mechanism can also be applied to scenarios where packet arrivals are more generally distributed. Besides, with a long-term condition tracking, it is reasonable to assume that there is a known distribution $\boldsymbol{P}_k = (P_{k,0}, P_{k,1}, \ldots, P_{k,L})$ on the data packet arrival from different priority classes at each gateway $k, \forall k \in \{1, 2, \ldots, K\}$, where $P_{k,\ell}$ indicates the probability that an arrived data packet at gateway k is in priority level $\ell, \forall \ell \in \mathcal{L}$. Obviously, $\sum_{\ell=0}^{L} P_{k,\ell} = 1$. Thus, the average arrival rate of data packets in priority class ℓ at gateway k can be calculated as $\lambda_k P_{k,\ell}, \forall k \in \{1, 2, \ldots, K\}, \forall \ell \in \mathcal{L}$.

To join the beyond-WBAN for transmitting any data packet to the BS, each gateway is required to immediately declare a transmission request along with the corresponding packet class when it receives a packet from any of its connected biosensors. All data packets that have not been scheduled for beyond-WBAN transmissions are temporarily stored in gateways' buffers. Similar to that in previous chapters, the buffer overflow is ignored. However, since data packet transmissions are considered to be delay-constrained (i.e., there is a stringent delay requirement for each data packet transmission), a data packet will be dropped by the gateway (and will no longer be transmitted in the beyond-WBAN) whenever it has been waiting longer than its required delay limit. Since delay limits of various data packets may be different, let us define a generic random variable D to describe packets' delay limits observed by the BS. These delay limits result in potential packet loss in the beyond-WBAN transmission scheduling system.

As the network regulator, the BS schedules the uplink transmissions of all data packets from all gateways in the beyond-WBAN. For simplicity, in this chapter, the absolute priority rule (i.e., data packets in higher priority levels should always be transmitted before the others in lower priority levels), which has been considered in Chapters 2 and 3, is adopted as the QoS requirement for the beyond-WBAN transmission scheduling. To guarantee the fulfillment of such priority-aware QoS, the BS will determine the beyond-WBAN transmission order purely based on data packets' priorities, and independent of the identities of gateways. Thus, the BS can treat all data packet transmission requests from a single virtual gateway, as depicted in Fig. 5.1, which consists of multi-class packet arrival processes with respect to the $\mathcal{L}$ priority classes. Because of the independency among gateways, the packet arrivals at the virtual gateway are still Poisson distributed with average rates:

$$\Lambda_\ell = \sum_{k=1}^{K} \lambda_k P_{k,\ell}, \ \forall \ell \in \mathcal{L}. \tag{5.1}$$

Considering the diversities in term of the packet sizes and the achievable SNRs at different gateways, data packets may experience different beyond-WBAN transmission time. From the view of the network scheduler (i.e., the BS), the transmission time of data packets on a beyond-WBAN channel can also be represented by a random variable T. Then, the operation of the beyond-WBAN transmission scheduling

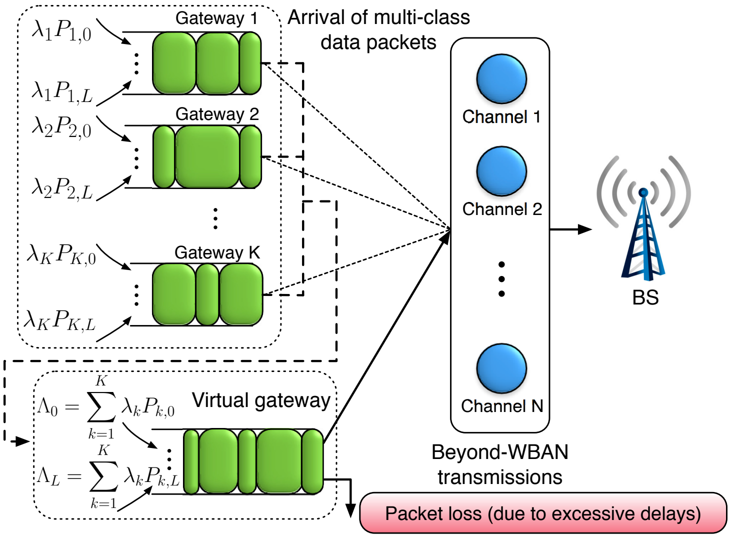

Figure 5.1: Queueing model of the delay-constrained transmission management.

can be formulated as a multi-class delay-constrained multi-server priority queue with multi-class Poisson-distributed packet arrivals, different service time (i.e., transmission time), heterogeneous delay limits for data packet transmissions, and N servers (i.e., N channels). Fig. 5.1 shows the formulated queueing model of the beyond-WBAN transmission scheduling system.

5.1.2 Problem Formulation

Naturally, WBAN applications rely on the support of beyond-WBAN communications. This can be implied by a utility gain at each gateway for successfully transmitting a data packet in the beyond-WBAN. To characterize this, let us introduce v_ℓ as the valuation for the successful beyond-WBAN transmission of a packet in priority class $\ell, \forall \ell \in \mathcal{L}$. Intuitively, data packets with in higher priority levels have higher valuations. Thus, we must have

$$v_0 < v_1 < v_2 < \ldots < v_L. \tag{5.2}$$

Denote $\mathcal{V} = \{v_0, v_1, \ldots, v_L\}$. In practice, $\mathcal{V}$ can be pre-determined from empirical measurements, and hence can be considered as a common knowledge to all gateways and the BS in the network. For explanation purpose in later analyses, let $v_{\ell+1} - v_\ell = \delta,\ \forall \ell \in \{0, 1, \ldots, L-1\}$, where $\delta > 0$ is a pre-defined system parameter.

For each data packet i, its priority class $\ell_i \in \mathcal{L}$ is a private information that is only available to the gateway which collects this packet, while unknown to all other gateways and the BS. According to the network model, upon receiving packet i with priority ℓ_i, the associated gateway will immediately declare a beyond-WBAN transmission request to the BS by reporting the priority class of this packet. However, as an intelligent and rational entity, a smart gateway may strategically report $\ell_i' \neq \ell_i$ if and only if it can benefit more from such behavior. By taking into account all gains and costs of a data packet transmission in the beyond-WBAN, the net utility obtained by the gateway for transmitting packet i with actual priority ℓ_i but reporting ℓ_i' can be defined as

$$U_i(\ell_i' | \ell_i) = v_{\ell_i} \cdot (1 - x(\ell_i')) - \pi(\ell_i'), \tag{5.3}$$

where $x(\ell_i') \in \{0, 1\}$ is the indicator of packet loss (i.e., $x(\ell_i') = 1$ means that packet i is dropped due to the over-limit waiting delay, and $x(\ell_i') = 0$ otherwise); v_{ℓ_i} and $\pi(\ell_i')$ are the valuation of successful packet transmission and the charge by the BS for beyond-WBAN transmission service, respectively. Since the BS is unaware of gateways' private information, it is intuitive that the scheduling outcomes (i.e., $x(\ell_i')$ and $\pi(\ell_i')$) for packet i's beyond-WBAN transmission are based on the reported priority ℓ_i'.

Obviously, as an essential requirement to guarantee the proper execution of the required absolutely prioritized transmission scheduling, the designed mechanism should be able to induce all gateways to truthfully report the actual priorities of their data packets. Note that (5.3) is an ex-post utility function because the packet loss indicator $x(\ell_i')$ depends on the instantaneous queueing performance of the system, which is unknown in advance. Thus, a smart gateway will consider to potentially misreport the priority of a packet only for maximizing its expected utility (according to the packet loss probabilities of the queueing system). To prevent this, the following truthfulness condition should always hold:

$$\ell_i = \underset{0 \le \ell_i' \le L}{\arg\max} \{\mathbb{E}[U_i(\ell_i'|\ell_i)]\}, \quad \text{for any packet } i. \tag{5.4}$$

Namely, the expected utility of transmitting packet i, i.e., $\mathbb{E}[U_i(\ell_i'|\ell_i)]$, is maximized when the gateway behaves truthfully by reporting $\ell_i' = \ell_i$. With the utility function (5.3), $\mathbb{E}[U_i(\ell_i'|\ell_i)]$ can be expressed as

$$\mathbb{E}[U_i(\ell_i'|\ell_i)] = v_{\ell_i} \cdot (1 - Q(\ell_i')) - \pi(\ell_i'), \tag{5.5}$$

where $Q(\ell_i')$ indicates the packet loss probability given priority level ℓ_i'. Substituting (5.5) into (5.4), we can rewrite the truthfulness condition in a general form as

$$v_\ell(1 - Q(\ell)) - \pi(\ell) \ge v_\ell(1 - Q(\ell')) - \pi(\ell'), \ \forall \ell, \ell' \in \mathcal{L}. \tag{5.6}$$

In addition, to encourage data packet transmissions in the beyond-WBAN, the designed mechanism should also ensure individual rationality, i.e., non-negative expected utility for transmitting any packet that is reported truthfully:

$$\mathbb{E}[U(\ell|\ell)] = v_\ell(1 - Q(\ell)) - \pi(\ell) \ge 0, \ \forall \ell \in \mathcal{L}. \tag{5.7}$$

Meanwhile, the BS aims to maximize its operation revenue gained from beyond-WBAN transmissions of all data packets. If packets' priorities are reported truthfully, the expected revenue of the BS can be calculated as

$$\mathcal{R} = \sum_{\ell=0}^{L} \Lambda_\ell \cdot \pi(\ell), \tag{5.8}$$

where $\Lambda_\ell \pi(\ell)$ represents the average transmission service charge on beyond-WBAN transmissions of data packets in priority level $\ell, \forall \ell \in \mathcal{L}$. It is worth noting that the packet loss probability, $Q(\ell), \forall \ell \in \mathcal{L}$, is not necessary to be included in (5.8). This is because $\pi(\ell), \forall \ell \in \mathcal{L}$, is actually a function of $Q(\ell), \forall \ell \in \mathcal{L}$ (which will be discussed in Section 5.2.3), so that the definition of $\mathcal{R}$ already implies the expected revenue charged from successful beyond-WBAN packet transmissions. Then, as the network regulator, the BS will determine the scheduling discipline $\boldsymbol{\zeta}$ and the transmission service charge $\boldsymbol{\pi} = [\pi(0), \ldots, \pi(L)]$ with the objective of maximizing $\mathcal{R}$ subject to required system constraints.

In summary, the problem of designing a truthful mechanism for managing the priority-aware beyond-WBAN transmission scheduling of delay-constrained data packets can be formulated as

$$[\boldsymbol{\zeta}, \boldsymbol{\pi}] = \arg\max \sum_{\ell=0}^{L} \Lambda_\ell \cdot \pi(\ell) \tag{5.9}$$

$$s.t., \; v_\ell Q(\ell') + \pi(\ell') \geq v_\ell Q(\ell) + \pi(\ell), \; \forall \ell, \ell' \in \mathcal{L}, \tag{5.10}$$

$$v_\ell (1 - Q(\ell)) - \pi(\ell) \geq 0, \; \forall \ell \in \mathcal{L}, \tag{5.11}$$

$$O_{\boldsymbol{\zeta}}(\ell) \geq O_{\boldsymbol{\zeta}}(\ell'), \; \forall \ell \geq \ell' \text{ and } \forall \ell, \ell' \in \mathcal{L}, \tag{5.12}$$

$$(Q(0), \ldots, Q(L)) \in \boldsymbol{S}(\boldsymbol{\Lambda}, T, D, \boldsymbol{\zeta}), \tag{5.13}$$

where constraint (5.10) is derived from the truthfulness condition (5.6) which can induce all gateways to report the actual priorities of their data packets; (5.11) imposes the requirement of individual rationality; (5.12) indicates that the scheduling discipline $\boldsymbol{\zeta}$ should lead to an absolutely prioritized transmission order, i.e., data packets in a higher priority level should always be granted with a higher transmission priority ($O_{\zeta}(\cdot)$) than the ones with a lower priority; and (5.13) states that packet loss probabilities are obtained from the beyond-WBAN queueing system, denoted by $\boldsymbol{S}$. Obviously, solving this problem directly is very challenging because i) $Q(\ell), \forall \ell \in \mathcal{L}$, is an endogenous factor of the priority-aware delay-constrained queueing system $\boldsymbol{S}$ (depending on the queueing discipline $\boldsymbol{\zeta}$ and the delay limits of data packets D); ii) $\boldsymbol{\pi}$ is not a simple decision vector but an undetermined pricing function highly relying on the resulted queueing dynamics; and iii) exhaustive searching, if not impossible, will result in an immeasurable computational complexity. Therefore, in the following, a novel approach is proposed to construct the mechanism, i.e., $[\boldsymbol{\zeta}, \boldsymbol{\pi}]$, which can meet all design requirements.

5.2 Transmission Mechanism with Delay Constraints

In this section, a truthful mechanism for scheduling beyond-WBAN data packet transmissions with delay constraints (named as TMDC) is desiged. The characteristics of the mechanism is first investigated. Then, the performance of the considered priority-aware delay-constrained queueing system is studied in detail. After that, an efficient pricing function is devised and the performance of TMDC is analyzed.

5.2.1 Characteristics of the Mechanism

By assuming that all requirements (i.e., (5.9) - (5.13)) are satisfied under the designed mechanism TMDC (denoted by $[\boldsymbol{\zeta}, \boldsymbol{\pi}]$), some important characteristics of this mechanism can be observed as follows.

Proposition 5.1. If TMDC (i.e., $[\boldsymbol{\zeta}, \boldsymbol{\pi}]$) satisfies (5.9) - (5.13), then we must have

$$\pi(\ell) \leq \pi(\ell'), \ \forall \ell \leq \ell' \text{ and } \ell, \ell' \in \mathcal{L}. \tag{5.14}$$

Proof. By the way of contradiction, let us assume that

$$\pi(\ell) > \pi(\ell'), \ \forall \ell \leq \ell' \text{ and } \ell, \ell' \in \mathcal{L}. \tag{5.15}$$

Since TMDC guarantees truthfulness (i.e., satisfies constraint (5.10)), the expected utility of transmitting a data packet in priority level ℓ is maximized when its priority ℓ is reported truthfully, i.e.,

$$\mathbb{E}[U(\ell|\ell)] \geq \mathbb{E}[U(\ell'|\ell)], \ \forall \ell, \ell' \in \mathcal{L}. \tag{5.16}$$

Besides, since TMDC also ensures that more critical data packets (in a higher priority level) are granted with a higher transmission priority as required by (5.12), and given that D is a random variable, it is intuitive that

$$Q(\ell) \geq Q(\ell'), \ \forall \ell \leq \ell' \text{ and } \ell, \ell' \in \mathcal{L}. \tag{5.17}$$

This inequality can also be verified numerically as shown in Section 5.3.

With (5.15) and (5.17), we can derive that

$$v_\ell Q(\ell) + \pi(\ell) > v_\ell Q(\ell') + \pi(\ell'), \ \forall \ell \leq \ell' \text{ and } \ell, \ell' \in \mathcal{L}, \tag{5.18}$$

which is equivalent to

$$\mathbb{E}[U(\ell|\ell)] < \mathbb{E}[U(\ell'|\ell)],\ \forall \ell \leq \ell' \text{ and } \ell, \ell' \in \mathcal{L}. \tag{5.19}$$

Clearly, the resulted inequality (5.19) contradicts the truthfulness condition (5.16), and thus the assumption in (5.15) does not hold. □

Proposition 5.1 indicates a fact that a data packet in a higher priority level so as to obtain a better beyond-WBAN transmission service should be charged by a higher price. Furthermore, the following proposition shows that, with the satisfaction of truthfulness condition (5.10), the individual rationality (5.11) will be guaranteed based on a threshold condition.

Proposition 5.2. Let TMDC (i.e., $[\boldsymbol{\zeta}, \boldsymbol{\pi}]$) be a mechanism that meets the truthfulness condition (5.10). If the transmission utility of a data packet in the priority level ℓ_0 is non-negative, then the utility of any data packet in a higher priority level $\ell, \forall \ell > \ell_0$, is also non-negative.

Proof. For any data packet in the priority level ℓ_0, we have

$$\mathbb{E}[U(\ell_0|\ell_0)] = v_{\ell_0}(1 - Q(\ell_0)) - \pi(\ell_0) \geq 0. \tag{5.20}$$

By the definition in (5.2), we have $v_\ell > v_{\ell_0}, \forall \ell > \ell_0$, and hence

$$v_\ell(1 - Q(\ell_0)) - \pi(\ell_0) > v_{\ell_0}(1 - Q(\ell_0)) - \pi(\ell_0). \tag{5.21}$$

Moreover, the satisfaction of truthfulness constraint (5.10) implies that

$$v_\ell(1 - Q(\ell_0)) - \pi(\ell_0) = \mathbb{E}[U(\ell_0|\ell)] \leq \mathbb{E}[U(\ell|\ell)]. \tag{5.22}$$

Combining inequalities (5.20) - (5.22) yields

$$\mathbb{E}[U(\ell|\ell)] > \mathbb{E}[U(\ell_0|\ell_0)] \geq 0, \tag{5.23}$$

which completes this proof. □

Proposition 5.2 reveals an important design idea of TMDC, i.e., constraint (5.11) will be satisfied automatically if the transmission utility of any data packet with the lowest priority (in priority level 0) can be constructed as a non-negative function.

With above observations, in the following, we will first determine an appropriate priority queueing discipline and conduct an extensive analysis on the queueing model for deriving the packet loss probabilities (in terms of priority levels); and then an efficient pricing function will be devised according to the obtained characteristics of the mechanism and the resulted queueing dynamics. Finally, it will proved that the proposed TMDC can indeed satisfy all design requirements.

5.2.2 Analysis of the Queueing Scheduling System

As explained in Section 5.1.2, the design of TMDC requires the analysis of the formulated queueing scheduling system $\boldsymbol{S}(\boldsymbol{\Lambda}, T, D, \boldsymbol{\zeta})$ and its corresponding performance $Q(\ell), \forall \ell \in \boldsymbol{\mathcal{L}}$. In order to provide an absolutely prioritized transmission order (5.12), in this chapter, the *non-preemptive priority queueing discipline* is adopted as the realization of $\boldsymbol{\zeta}$. With such scheduling discipline, arriving data packets in higher priority levels will always be put in front of the packets with lower priorities that are waiting in the queue/buffer. Compared to the *preemptive priority queueing discipline* which was employed in Chapters 2 and 3, the non-preemptive priority queueing discipline ensures that data packets that are currently under beyond-WBAN transmissions will never be interrupted so that the continuity and the completeness of each piece of information can be easily maintained.

Unlike existing studies on priority queues [103], analyzing the considered beyond-WBAN queueing scheduling system is much more difficult because i) each data packet has a required delay limit so that the potential packet loss due to unsatisfied services has to be taken into account; and ii) there are multiple channels available for beyond-WBAN packet transmissions, which necessitates the investigation of a multi-server queueing model. To analyze this complicated queueing system so as to obtain the packet loss probabilities $Q(\ell), \forall \ell \in \mathcal{L}$, we will first derive the steady-state probabilities; then construct an absorbing Markov chain to describe the serving and the dropping processes of the queue; and eventually calculate the packet transmission/loss probabilities by recursions. For explicit expressions, in this chapter, the detailed analysis is illustrated by assuming that D and T are both exponentially distributed random variables with means $1/\eta$ and $1/\mu$, respectively. However, the proposed TMDC is actually compatible with any forms of random distributions[1].

For notation simplicity, let us denote $\Lambda = \sum_{\ell=0}^{L} \Lambda_\ell$, $\rho_\ell = \frac{\Lambda_\ell}{N\mu}$ and $\rho = \sum_{\ell=0}^{L} \rho_\ell$. Furthermore, define $A_m^\ell(t)$ as the probability that all servers are busy (i.e., all N channels are temporarily occupied) and there are m data packets with priorities higher than or equal to ℓ in the waiting buffer at time t, and $B_m(t)$ as the probability that there are totally m data packets (of all priorities) in the overall beyond-WBAN transmission scheduling system (including packets under transmissions and in buffers) at time t.

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[1] This is because the design of TMDC only requires $Q(\ell), \forall \ell \in \mathcal{L}$, as an essential input in the pricing function, which can always be obtained either analytically or numerically for all kinds of queueing models with different distributions.

Then, considering all possible events that may occur during a short interval $(t, t+\Delta t)$, we have

$$\begin{aligned}
B_0(t+\Delta t) &= B_0(t)(1-\Lambda\Delta t) + B_1(t)\mu\Delta t + o(t),\\
B_m(t+\Delta t) &= B_{m-1}(t)\Lambda\Delta t + B_m(t)(1-(\Lambda+m\mu)\Delta t)\\
&\quad + B_{m+1}(t)(m+1)\mu\Delta t + o(\Delta t), \quad \forall m < N,\\
B_m(t+\Delta t) &= B_{m+1}(t)(N\mu+(m+1-N)\eta)\Delta t\\
&\quad + B_m(t)(1-(\Lambda+N\mu+(m-N)\eta)\Delta t)\\
&\quad + B_{m-1}(t)\Lambda\Delta t + o(\Delta t), \qquad \forall m \geq N;
\end{aligned}$$

and

$$\begin{aligned}
A_0^{\ell}(t+\Delta t) &= A_1^{\ell}(t)(N\mu+\eta)\Delta t + B_{N-1}(t)\Lambda\Delta t\\
&\quad + (A_0^{\ell}(t) - B_N(t))N\mu\Delta t\\
&\quad + A_0^{\ell}(t)(1-(N\mu+\textstyle\sum_{h=\ell}^{L}\Lambda_h)\Delta t) + o(\Delta t),\\
A_m^{\ell}(t+\Delta t) &= A_{m+1}^{\ell}(t)(N\mu+(m+1)\eta)\Delta t\\
&\quad + A_m^{\ell}(t)(1-(N\mu+m\eta+\textstyle\sum_{h=\ell}^{L}\Lambda_h)\Delta t)\\
&\quad + A_{m-1}^{\ell}(t)\textstyle\sum_{h=\ell}^{L}\Lambda_h\Delta t + o(\Delta t), \quad \forall m \geq 1.
\end{aligned}$$

By letting $\Delta t \to 0$, we can obtain the following two sets of differential equations:

$$\begin{aligned}
\frac{dB_0(t)}{dt} &= -\Lambda B_0(t) + \mu B_1(t),\\
\frac{dB_m(t)}{dt} &= \Lambda B_{m-1}(t) - (\Lambda+m\mu)B_m(t) + (m+1)\mu B_{m+1}(t), \quad \forall m < N,\\
\frac{dB_m(t)}{dt} &= \Lambda B_{m-1}(t) - (\Lambda+N\mu+(m-N)\eta)B_m(t)\\
&\quad + (N\mu+(m+1-N)\eta)B_{m+1}(t), \quad m \geq N;
\end{aligned}$$

and

$$\begin{aligned}\frac{dA_0^\ell(t)}{dt} &= (N\mu+\eta)A_1^\ell(t) - \sum\nolimits_{h=\ell}^{L}\Lambda_h A_0^\ell(t)\\ &\quad + \Lambda B_{N-1}(t) - N\mu B_N(t),\\ \frac{dA_m^\ell(t)}{dt} &= \sum\nolimits_{h=\ell}^{L}\Lambda_h A_{m-1}^\ell(t) + (N\mu+(m+1)\eta)A_{m+1}^\ell(t)\\ &\quad - (N\mu+m\eta+\sum\nolimits_{h=\ell}^{L}\Lambda_h)A_m^\ell(t), \quad \forall m\ge 1.\end{aligned}$$

In the steady state (i.e., as $t\to\infty$), it is expected that $dA_m^\ell(t)/dt\to 0, dB_m(t)/dt\to 0, \forall m$. Defining $A_m^\ell=\lim_{t\to\infty}A_m^\ell(t)$ and $B_m=\lim_{t\to\infty}B_m(t),\forall m$, we can derive

$$\Lambda B_0 = \mu B_1, \tag{5.24}$$

$$(\Lambda+m\mu)B_m = \Lambda B_{m-1}+(m+1)\mu B_{m+1},\ \forall m<N, \tag{5.25}$$

$$(\Lambda+N\mu+(m-N)\eta)B_m = \Lambda B_{m-1}+(N\mu+(m+1-N)\eta)B_{m+1},\forall m\ge N; \tag{5.26}$$

and

$$N\mu B_m + \sum\nolimits_{h=\ell}^{L}\Lambda_h A_0^\ell = \Lambda B_{N-1}+(N\mu+\eta)A_1^\ell, \tag{5.27}$$

$$\begin{aligned}&(N\mu+m\eta+\sum\nolimits_{h=\ell}^{L}\Lambda_h)A_m^\ell\\ &=\sum\nolimits_{h=\ell}^{L}\Lambda_h A_{m-1}^\ell+(N\mu+(m+1)\eta)A_{m+1}^\ell,\forall m\ge 1.\end{aligned} \tag{5.28}$$

Solving equation set (5.24) - (5.26) yields

$$B_m=\begin{cases} B_0\frac{(N\rho)^m}{m!}, & m\le N,\\ B_N\frac{\rho^{m-N}}{\prod_{i=0}^{m-N}(1+i\eta/N\mu)}, & m>N.\end{cases} \tag{5.29}$$

Furthermore, by applying the normalized condition $\sum_{m=0}^{\infty}B_m=1$, we have

$$\frac{1}{B_0}=\sum_{m=0}^{N-1}\frac{(N\rho)^m}{m!}+\frac{(N\rho)^m}{N!}\sum_{m=0}^{\infty}\frac{\rho^m}{\prod_{i=0}^{m}(1+i\eta/N\mu)}, \tag{5.30}$$

where B_0 shows the probability that the system is empty.

From (5.24) - (5.26), we can also derive a relationship that $\Lambda B_{m-1} = m\mu B_m, \forall m \leq N$. Substituting this into equation set (5.27) - (5.28) and after some mathematical manipulations, we have

$$\sum_{h=\ell}^{L} \Lambda_h A_{m-1}^{\ell} = (N\mu + m\eta) A_m^{\ell}, \tag{5.31}$$

which can be transformed as

$$A_m^{\ell} = A_0^{\ell} \frac{(\sum_{h=\ell}^{L} \rho_h)^m}{\prod_{i=1}^{m}(1 + i\eta/N\mu)}. \tag{5.32}$$

Taking summations from $m = 0$ to ∞ on both sides of (5.32), we have

$$\sum_{m=0}^{\infty} A_m^{\ell} = A_0^{\ell} \sum_{m=0}^{\infty} \frac{(\sum_{h=\ell}^{L} \rho_h)^m}{\prod_{i=1}^{m}(1 + i\eta/N\mu)}. \tag{5.33}$$

Here, $\sum_{m=0}^{\infty} A_m^{\ell}$ implies the probability that all channels are busy, and thus can be calculated as

$$\sum_{m=0}^{\infty} A_m^{\ell} = \sum_{m=N}^{\infty} B_m = B_0 \frac{(N\rho)^N}{N!} \sum_{m=0}^{\infty} \frac{\rho^m}{\prod_{i=0}^{m}(1 + i\eta/N\mu)}. \tag{5.34}$$

Substituting (5.34) into (5.33), A_0^{ℓ} can be explicitly expressed as

$$A_0^{\ell} = \sum_{m=N}^{\infty} B_m \Bigg/ \sum_{m=0}^{\infty} \frac{(\sum_{h=\ell}^{L} \rho_h)^m}{\prod_{i=1}^{m}(1 + i\eta/N\mu)} . \tag{5.35}$$

Clearly, with the help of (5.32) and (5.35), the expression of A_m^{ℓ} can also be explicitly derived.

Now, define $H(\ell)$ as the probability that an arriving data packet in priority level $\ell, \forall \ell \in \mathcal{L}$, will be transmitted in the beyond-WBAN, i.e.,

$$H(\ell) = 1 - Q(\ell), \quad \forall \ell \in \mathcal{L}, \tag{5.36}$$

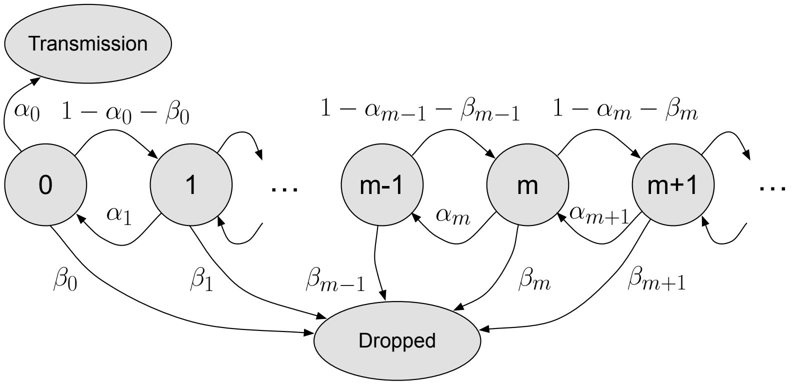

Figure 5.2: Absorbing Markov chain given packet of priority ℓ.

where $Q(\ell)$ is the packet loss probability. Furthermore, denote $H_m(\ell)$ as the probability that a data packet with priority $\ell, \forall \ell \in \mathcal{L}$, which is currently waiting after m packets with higher priorities, will be eventually transmitted. Obviously, the relationship between $H(\ell)$ and $H_m(\ell)$ can be established as

$$H(\ell) = \sum_{m=0}^{N-1} B_m + \sum_{m=0}^{\infty} A_m^\ell \cdot H_m(\ell), \quad \forall \ell \in \mathcal{L}, \tag{5.37}$$

where $\sum_{m=0}^{N-1} B_m$ is the probability that there is at least one idle channel (or at most $N-1$ data packets in the system) when the considered data packet with priority ℓ arrives (so that it can be transmitted immediately); and $\sum_{m=0}^{\infty} A_m^\ell \cdot H_m(\ell)$ is the probability that the considered packet will be scheduled for transmission even though the system is always busy. In (5.37), the only unknown variable is $H_m(\ell)$ while B_m and A_m^ℓ have already been derived in (5.29) and (5.32), respectively. Thus, to obtain $H(\ell)$ so as to determine $Q(\ell)$, the remaining problem is to calculate $H_m(\ell)$, which is solved in the following by Markov chain analysis [104].

Here, let us focus on a tagged packet in priority level ℓ, and consider m as the *state* which indicates that there are m packets in front of the tagged one with priorities higher than or equal to ℓ waiting for transmission. Define *packet in transmission* and *packet dropped* as two absorbing states. Then, the Markov chain which illustrates the state transition process can be drawn as in Fig. 5.2. To analyze this absorbing Markov chain so as to derive $H_m(\ell)$, two different cases should be considered.

Case I: If the considered data packet has the highest priority (i.e., $\ell = L$), the associated transition probabilities of the Markov chain are

$$\alpha_m = \frac{N\mu + m\eta}{N\mu + (m+1)\eta}, \tag{5.38}$$

$$\beta_m = \frac{\eta}{N\mu + (m+1)\eta}, \tag{5.39}$$

$$1 - \alpha_m - \beta_m = 0. \tag{5.40}$$

Obviously, the transition probabilities in (5.38) - (5.40) imply that the states of the Markov chain can be converted in a single direction only (i.e., from $m+1$ to m), as $1 - \alpha_m - \beta_m = 0$. Thus, we have

$$H_0(L) = \alpha_0, \tag{5.41}$$

$$H_m(L) = \alpha_m H_{m-1}(L), \quad \forall m \geq 1. \tag{5.42}$$

Substituting the expression of α_m in (5.38) into (5.41) and (5.42), we can get

$$\begin{aligned} H_m(L) &= \alpha_0 \alpha_1 \cdots \alpha_m \\ &= \frac{N\mu}{N\mu + \eta} \frac{N\mu + \eta}{N\mu + 2\eta} \cdots \frac{N\mu + m\eta}{N\mu + (m+1)\eta} = \frac{N\mu}{N\mu + (m+1)\eta}. \end{aligned} \tag{5.43}$$

Case II: If the considered packet is in priority level $\ell, \forall \ell \in \{0, 1, \ldots, L-1\}$, the associated transition probabilities of the Markov chain are

$$\alpha_m = \frac{N\mu + m\eta}{N\mu + (m+1)\eta + \sum_{h=\ell+1}^{L} \Lambda_h}, \tag{5.44}$$

$$\beta_m = \frac{\eta}{N\mu + (m+1)\eta + \sum_{h=\ell+1}^{L} \Lambda_h}, \tag{5.45}$$

$$1 - \alpha_m - \beta_m = \frac{\sum_{h=\ell+1}^{L} \Lambda_h}{N\mu + (m+1)\eta + \sum_{h=\ell+1}^{L} \Lambda_h}. \tag{5.46}$$

The transition probabilities in (5.44) - (5.46) imply that the states of the Markov chain can be converted from m to $m+1$ or vice versa (because newly arrived packets may have either higher or lower priorities than the tagged one). Hence, in this case, we have

$$H_0(\ell){=}\alpha_0 + (1-\alpha_0-\beta_0)H_1(\ell), \tag{5.47}$$

$$H_m(\ell){=}\alpha_m H_{m-1}(\ell){+}(1{-}\alpha_m{-}\beta_m)H_{m+1}(\ell), \forall m \geq 1. \tag{5.48}$$

Substituting (5.44), (5.45) into (5.47) and (5.48) yields

$$H_0(\ell) - \xi_1 H_1(\ell) = \varphi_0(1 - \xi_0 H_0(\ell)), \tag{5.49}$$

$$H_m(\ell){-}\xi_{m+1}H_{m+1}(\ell) = \varphi_m(H_{m-1}(\ell){-}\xi_m H_m(\ell)), \tag{5.50}$$

where

$$\xi_m = \frac{\sum_{h=\ell+1}^{L} \Lambda_h}{N\mu + m\eta}, \text{ and } \varphi_m = \frac{N\mu + m\eta}{N\mu + (m+1)\eta}.$$

Here, ξ_m and φ_m are introduced to simplify expressions. Based on (5.49) and (5.50), we can derive that

$$\begin{aligned} & H_{m-1}(\ell) - \xi_m H_m(\ell) \\ & = \varphi_0\varphi_1 \cdots \varphi_{m-1}(1 - \xi_0 H_0(\ell)) \\ & = \frac{N\mu}{N\mu + m\eta}\left(1 - \frac{\sum_{h=\ell+1}^{L} \Lambda_h}{N\mu} H_0(\ell)\right) \\ & = \frac{N\mu}{N\mu + m\eta} - \frac{\sum_{h=\ell+1}^{L} \Lambda_h}{N\mu + m\eta} H_0(\ell) \\ & = \xi_m/\xi_0 - \xi_m H_0(\ell), \end{aligned} \tag{5.51}$$

from which we can get by recursions that ($\forall m \geq 1$)

$$\begin{aligned} H_m(\ell) &= \frac{H_{m-1}(\ell)}{\xi_m} + H_0(\ell) - 1/\xi_0 \\ &= \frac{H_{m-2}(\ell)}{\xi_m \xi_{m-1}} + (H_0(\ell) - 1/\xi_0)(1/\xi_m + 1) \\ &\vdots \\ &= \left(H_0(\ell) + \big(H_0(\ell) - \frac{1}{\xi_0}\big) \sum_{i=1}^{m} \prod_{j=1}^{i} \xi_j\right) \Bigg/ \prod_{i=1}^{m} \xi_i \,. \end{aligned} \tag{5.52}$$

In order to determine $H_0(\ell)$, let us take $m \to \infty$ on both sides of (5.52). Since $\lim_{m\to\infty} H_m(\ell) = 0$ (it is intuitive that the transmission probability of a packet with an infinite number of other packets before it tends to zero), we have

$$0 = H_0(\ell) + \Big(H_0(\ell) - \frac{1}{\xi_0}\Big) \sum_{i=1}^{\infty} \prod_{j=1}^{i} \xi_j. \tag{5.53}$$

By some further mathematical manipulations, (5.53) can be rewritten as

$$H_0(\ell) = \sum_{i=1}^{\infty} \prod_{j=1}^{i} \xi_j \Bigg/ \sum_{i=0}^{\infty} \prod_{j=0}^{i} \xi_j \,. \tag{5.54}$$

Substituting (5.54) back into (5.52) eventually results in

$$H_m(\ell) = \sum_{i=m+1}^{\infty} \prod_{j=m+1}^{i} \xi_j \Bigg/ \sum_{i=0}^{\infty} \prod_{j=0}^{i} \xi_j \,, \forall \ell \in \mathcal{L} \backslash \{L\}. \tag{5.55}$$

Finally, after obtaining $H_m(\ell), \forall \ell \in \mathcal{L}$, as illustrated in (5.43) and (5.55), the packet transmission probability $H(\ell), \forall \ell \in \mathcal{L}$, can be expressed according to (5.37), and thus the packet loss probability $Q(\ell), \forall \ell \in \mathcal{L}$, can be directly calculated by

$$Q(\ell) = 1 - H(\ell), \quad \forall \ell \in \mathcal{L}. \tag{5.56}$$

5.2.3 Design of the Mechanism

Based on the obtained characteristics of the mechanism, i.e., Propositions 5.1 and 5.2, and the derived packet loss probabilities of the queueing scheduling system, i.e., $Q(\ell), \forall \ell \in \mathcal{L}$, the pricing function $\boldsymbol{\pi}$ is formulated as follows.

- ***Pricing function formulation:*** *For any data packet in priority level $\ell, \forall \ell \in \mathcal{L}$, the beyond-WBAN transmission service charge is*

$$\pi(\ell) = v_\ell(1 - Q(\ell)) - \sum_{h=0}^{\ell}(1 - Q(h))\delta,\ \forall \ell \in \mathcal{L}. \tag{5.57}$$

Thus, in summary, the proposed TMDC consists of the adopted non-preemptive priority queueing discipline $\boldsymbol{\zeta}$ and the pricing function constructed in (5.57). To examine the feasibility and efficiency of this design, some important theorems are given in the following.

Theorem 5.1 (Absolute priority-aware QoS)**.** *With the implementation of TMDC, if all data packets are reported truthfully with their actual priorities, packets with higher priorities will always be transmitted prior to the ones in lower priority levels, i.e.,*

$$O_{\boldsymbol{\zeta}}(\ell) \geq O_{\boldsymbol{\zeta}}(\ell'),\ \forall \ell \geq \ell' \text{ and } \forall \ell, \ell' \in \mathcal{L}, \tag{5.58}$$

Proof. This is directly indicated by the adopted queueing discipline $\boldsymbol{\zeta}$. □

Theorem 5.2 (Individual rationality)**.** *With the implementation of TMDC, the expected utility for transmitting any data packet that has been reported truthfully with its actual priority will always be non-negative, i.e,*

$$\mathbb{E}[U(\ell|\ell)] = v_\ell(1 - Q(\ell)) - \pi(\ell) \geq 0,\ \forall \ell \in \mathcal{L}. \tag{5.59}$$

Proof. Substituting the formulated pricing function (5.57) into the expression of $\mathbb{E}[U(\ell|\ell)], \forall \ell \in \mathcal{L}$, we have

$$\mathbb{E}[U(\ell|\ell)] = v_\ell(1 - Q(\ell)) - \pi(\ell) = \sum_{h=0}^{\ell}(1 - Q(h))\delta \geq (1 - Q(0))\delta \geq 0, \tag{5.60}$$

where the above inequalities hold because $Q(0) \geq Q(h), \forall h \in \mathcal{L}$, and $Q(0)$ (which stands for a packet loss probability) must be less than or equal to 1. □

Theorem 5.3 (Truthfulness). *By implementing TMDC, gateways in the beyond-WBAN will always behave truthfully by reporting the actual priorities of their packets, because doing so can maximize the utility of each packet transmission, i.e.,*

$$\mathbb{E}[U(\ell|\ell)] \geq \mathbb{E}[U(\ell'|\ell)], \quad \forall \ell, \ell' \in \mathcal{L}. \tag{5.61}$$

Proof. With the pricing function (5.57), $\mathbb{E}[U(\ell'|\ell)]$ can be expressed as

$$\begin{aligned}\mathbb{E}[U(\ell'|\ell)] &= v_\ell(1 - Q(\ell')) - \pi(\ell') \\ &= v_\ell(1 - Q(\ell')) - v_{\ell'}(1 - Q(\ell')) + \sum_{h=0}^{\ell'}(1 - Q(h))\delta \\ &= (v_\ell - v_{\ell'})(1 - Q(\ell')) + \sum_{h=0}^{\ell'}(1 - Q(h))\delta, \quad \forall \ell \in \mathcal{L}.\end{aligned} \tag{5.62}$$

Besides, as illustrated in (5.60), $\mathbb{E}[U(\ell|\ell)] = \sum_{h=0}^{\ell}(1 - Q(h))\delta$. Hence, we have

$$\mathbb{E}[U(\ell|\ell)] - \mathbb{E}[U(\ell'|\ell)] = \sum_{h=0}^{\ell}(1-Q(h))\delta - \sum_{h=0}^{\ell'}(1-Q(h))\delta - (v_\ell - v_{\ell'})(1-Q(\ell')). \tag{5.63}$$

Next, let us consider three different cases.

i) If $\ell' = \ell$: It is obvious that

$$\mathbb{E}[U(\ell|\ell)] - \mathbb{E}[U(\ell'|\ell)] = 0. \tag{5.64}$$

ii) If $\ell' < \ell$: According to (5.2), we have $v_{\ell'} < v_\ell$, and thus (5.63) can be further rewritten as

$$\begin{aligned}&\mathbb{E}[U(\ell|\ell)] - \mathbb{E}[U(\ell'|\ell)]\\ =&\sum\nolimits_{h=\ell'+1}^{\ell}(1-Q(h))\delta - (v_\ell - v_{\ell'})(1-Q(\ell'))\\ \geq&\sum\nolimits_{h=\ell'+1}^{\ell}(1-Q(\ell'))\delta - \sum\nolimits_{h=\ell'+1}^{\ell}(1-Q(\ell'))\delta = 0,\end{aligned} \tag{5.65}$$

where the above inequality holds because $\boldsymbol{\zeta}$ leads to $Q(\ell') \geq Q(h), \forall h \in \{\ell'+1, \ldots, \ell\}$, and $v_\ell - v_{\ell'} = \sum_{h=\ell'+1}^{\ell} \delta$ by definition.

iii) If $\ell' > \ell$: In this case, we have $v_{\ell'} > v_\ell$, and thus (5.63) becomes

$$\begin{aligned}&\mathbb{E}[U(\ell|\ell)] - \mathbb{E}[U(\ell'|\ell)]\\ =&-\sum\nolimits_{h=\ell+1}^{\ell'}(1-Q(h))\delta + (v_{\ell'} - v_\ell)(1-Q(\ell'))\\ \geq&-\sum\nolimits_{h=\ell+1}^{\ell'}(1-Q(\ell'))\delta + \sum\nolimits_{h=\ell+1}^{\ell'}(1-Q(\ell'))\delta = 0,\end{aligned} \tag{5.66}$$

where the above inequality is true because $Q(\ell') \leq Q(h), \forall h \in \{\ell+1, \ldots, \ell'\}$, and $v_{\ell'} - v_\ell = \sum_{h=\ell+1}^{\ell'} \delta$.

In summary, we always have

$$\mathbb{E}[U(\ell|\ell)] - \mathbb{E}[U(\ell'|\ell)] \geq 0, \quad \forall \ell, \ell' \in \mathcal{L}, \tag{5.67}$$

which proves this theorem. □

To prove the optimality of TMDC on maximizing the BS's expected revenue $\mathcal{R}$, let us denote $P(\ell)$ as the probability that data packets in the beyond-WBAN are in priority level $\ell, \forall \ell \in \mathcal{L}$, such that $P(\ell) = \Lambda_\ell / \Lambda, \forall \ell \in \mathcal{L}$, where $\Lambda = \sum_{h=0}^{L} \Lambda_h$. Then, by substituting the pricing function (5.57) into the expression of $\mathcal{R}$ in (5.8), and after doing some mathematical manipulations, we have

$$\begin{aligned}\mathcal{R} &= \Lambda \sum_{\ell=0}^{L} P(\ell)\pi(\ell) \\ &= \Lambda \sum_{\ell=0}^{L} P(\ell) \left(v_\ell (1 - Q(\ell)) - \sum_{h=0}^{\ell} (1 - Q(h))\delta \right) \\ &= \Lambda \sum_{\ell=0}^{L} P(\ell)(1 - Q(\ell)) \left(v_\ell - \frac{\sum_{h=\ell}^{L} P(h)}{P(\ell)} \delta \right).\end{aligned} \tag{5.68}$$

Let $\psi(\ell) = \frac{\sum_{h=\ell}^{L} P(h)}{P(\ell)}$, so that (5.68) can be rewritten as

$$\mathcal{R} = \Lambda \sum_{\ell=0}^{L} P(\ell)(1 - Q(\ell)) \left(v_\ell - \psi(\ell)\delta \right). \tag{5.69}$$

Theorem 5.4 (Optimality)**.** *The proposed TMDC can maximize the BS's expected revenue $\mathcal{R}$, if the distribution of $P(\ell), \forall \ell \in \mathcal{L}$, satisfies a mild condition that $\psi(\ell)$ monotonically decreases with the increase of priority level ℓ.*

Proof. Consider data packets in any two different priority levels ℓ_i and ℓ_j, such that $0 \le \ell_i < \ell_j \le L$. According to the scheduling discipline $\boldsymbol{\zeta}$, we have $Q(\ell_i) > Q(\ell_j)$. Besides, if $\psi(\ell)$ monotonically decreases with the increase of priority level ℓ, we must have $\psi(\ell_i) > \psi(\ell_j)$. Clearly, if we modify the mechanism by exchanging the transmission orders of packets in priority levels ℓ_i and ℓ_j, their packet loss probabilities will also be exchanged. Denote $\mathcal{R}^{TMDC}$ and $\mathcal{R}^{M}$ as revenues of the BS under the proposed TMDC and the modified mechanism, respectively. Then the change of $\mathcal{R}$ due to such modification can be calculated as

$$\begin{aligned}\Delta &= \mathcal{R}^{TMDC} - \mathcal{R}^{M} \\ &= (1 - Q(\ell_i))(v_{\ell_i} - \psi(\ell_i)\delta) + (1 - Q(\ell_j))(v_{\ell_j} - \psi(\ell_j)\delta) \\ &\quad - (1 - Q(\ell_j))(v_{\ell_i} - \psi(\ell_i)\delta) + (1 - Q(\ell_i))(v_{\ell_j} - \psi(\ell_j)\delta) \\ &= (Q(\ell_i) - Q(\ell_j)) \left((v_{\ell_j} - v_{\ell_i}) + (\psi(\ell_i) - \psi(\ell_j))\delta \right) > 0.\end{aligned} \tag{5.70}$$

Since $\Delta > 0$, it can be concluded that any modification on TMDC is not preferred. In other words, the expected revenue of the BS is maximized when TMDC is applied. Note that, it can be easily verified that most of common distributions (e.g., uniform, geometric and Poisson distributions) satisfy the mild condition that their resulted $\psi(\ell)$ is decreasing when ℓ increases. $\square$

5.3 Simulation Results

In this section, simulations are conducted by MATLAB to evaluate the performance of the proposed TMDC in managing delay-constrained multi-class priority-aware data packet transmissions in the beyond-WBAN.

5.3.1 Simulation Settings

Consider a beyond-WBAN with one BS which manages the beyond-WBAN data packet transmissions on $N = 10$ channels. Following the definition in IEEE std. 802.15.6 [10], all packets are categorized into $\mathcal{L} = \{0, 1, \ldots, 7\}$ priority classes, where 0 and 7 represent the lowest and the highest priority levels, respectively. Since the size of data packets in WBANs is around 100 Kb [27], and the average uplink transmission rate of 3G cellular networks is commonly 500 Kbps [70], it is reasonable to assume that the expected beyond-WBAN transmission time $1/\mu$ is 0.2 seconds. According to [105], the expected length of packets' delay constraints $1/\eta$ is set as 0.5 seconds. The aggregate arrival rate of all beyond-WBAN packet transmission requests, denoted by Λ, is chosen within the range of $[5, 45]$ packets per second. Similar settings have been employed in [28, 99, 106]. Besides, the probability $P(\ell), \forall \ell \in \{0, 1 \ldots, 7\}$, is

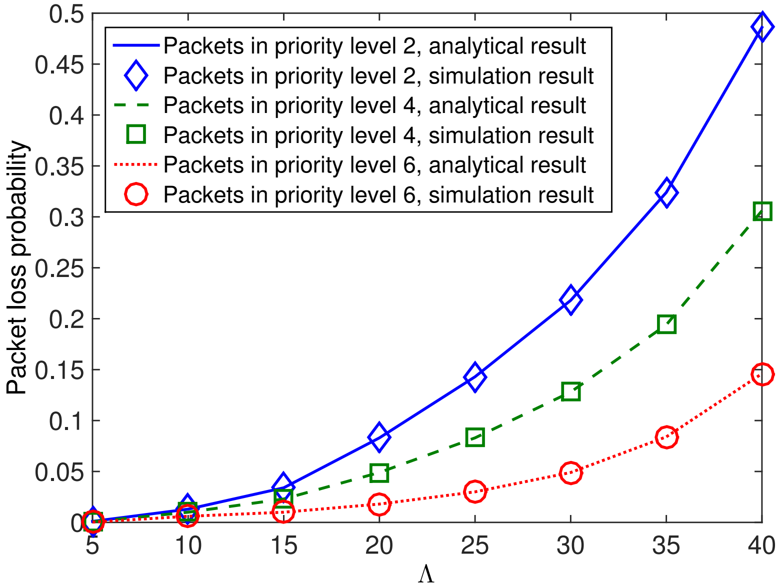

Figure 5.3: Packet loss probabilities of beyond-WBAN transmissions.

assumed to be $0.1, 0.1, 0.15, 0.15, 0.15, 0.15, 0.1, 0.1$, respectively, so that the monotone condition on $\psi(\ell)$ can be satisfied. Furthermore, define $v_0 = 2$ and $\delta = 1$. In the following, all results are obtained by taking averages over 100 runs.

5.3.2 Performance Evaluations

Fig. 5.3 shows the packet loss probabilities of beyond-WBAN data packet transmissions with different traffic arrival rates under the designed mechanism TMDC. From this figure, we can first observe that the curves produced by the analytical results well match those generated by simulations. This verifies the theoretical derivations presented in Section 5.2.2. Besides, this figure illustrates that the packet loss probability of data packets in a certain priority level increases with the aggregate traffic arrival rate Λ. Intuitively, a larger Λ implies a heavier traffic load caused by

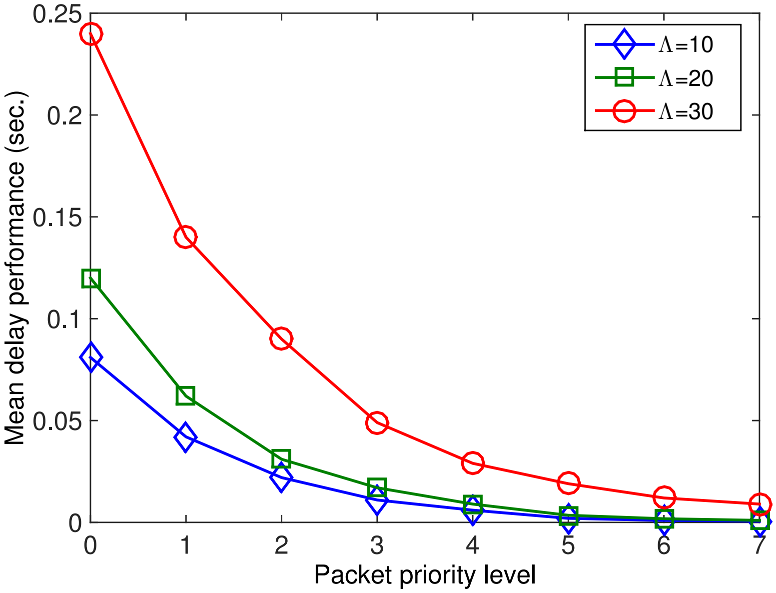

Figure 5.4: Delay performance of the delay-constrained scheduling system.

more beyond-WBAN packet transmission requests, and thus the scheduling system will become more congested, leading to a higher packet loss probability. In addition, by comparing the curves standing for packet loss probabilities of data packets in different priority levels (i.e., $\ell = 2, 4, 6$, respectively), we can see that, given a fixed Λ, the higher priority level the data packet has, the lower packet loss probability it obtains, which proves inequality (5.17) in a numerical way. The reasons for this fact are i) delay limits of all data packets' beyond-WBAN transmissions are set as a random variable D; and ii) the scheduling discipline $\boldsymbol{\zeta}$ guarantees that packets in a higher priority level are always transmitted prior to the others in a lower priority level.

Fig. 5.4 further evaluates the queueing performance of the designed TMDC in the considered beyond-WBAN transmission scheduling system by investigating the mean waiting delays experienced by successful transmissions of data packets in different

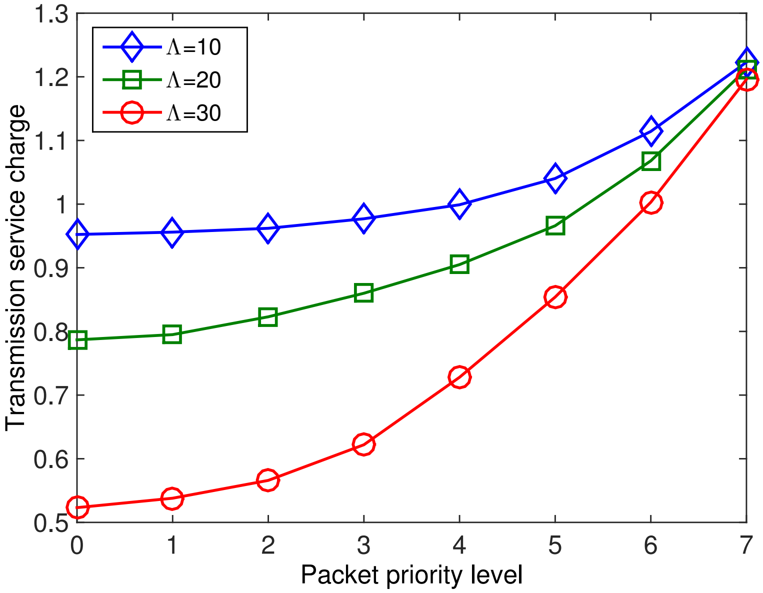

Figure 5.5: Beyond-WBAN transmission charge for different packets.

priority levels. Here, the packet delay is defined as the time duration between the instant when the data packet arrives and the instant when it is scheduled for beyond-WBAN transmission. From this figure, we can clearly see that the mean delay of data packets in beyond-WBAN transmissions decreases with the increase of the packet priority level. This is due to the employment of the absolutely prioritized queueing discipline $\boldsymbol{\zeta}$. Furthermore, the curves in this figure also indicate that a larger aggregate traffic arrival rate Λ results in a longer packets' mean waiting delay. The explanation for this follows the same as that for Fig. 5.3.

Fig. 5.5 reveals the relationship between the service charge for beyond-WBAN transmissions and the priority level of data packets under TMDC. It is shown in this figure that the transmission service charge increases with the packet priority level, which matches the observation obtained in Proposition 5.1 that the packet in a higher

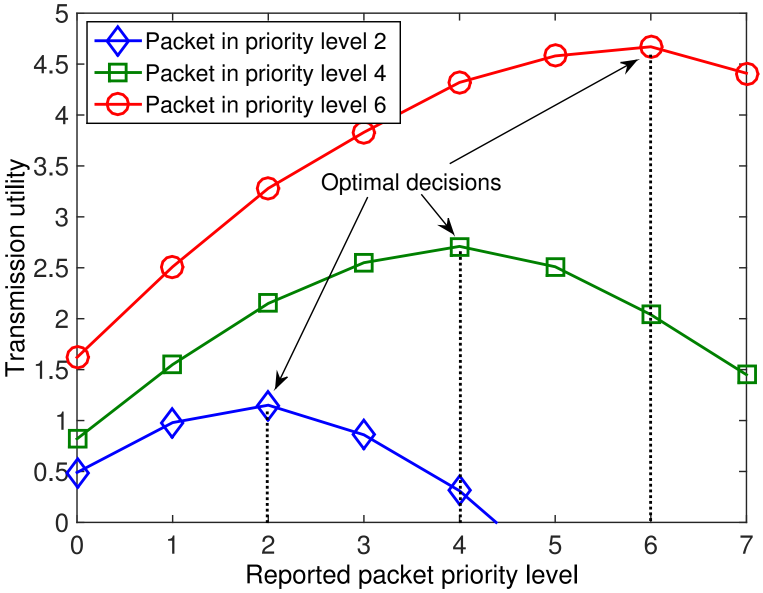

Figure 5.6: Truthfulness analysis of TMDC.

priority level so as to receive a better service (i.e., a lower packet loss probability) has to be charged by a higher price for its beyond-WBAN transmission. Besides, it is intuitive that a larger Λ leads to a lower beyond-WBAN transmission service charge for data packets in the same priority level, because a higher packet loss probability (or a worse transmission service) is produced in a more congested system as illustrated in Fig. 5.3. Notice that the curves in Fig. 5.5 almost merge when the highest packet priority level is reached. This is because the beyond-WBAN transmission of the most important packets (i.e., in priority level 7) is always protected so that the packet loss probability of these packets approaches zero regardless of the value of Λ.

Fig. 5.6 examines the truthfulness of TMDC by analyzing the transmission utility of a data packet with different reported packet priority levels. In the considered system, smart gateways can strategically report the packet priority level so as to maximize the transmission utility of each data packet. The trend of the curves in Fig. 5.6 shows that the transmission utility of a packet first increases with the reported priority level ℓ'. This is because reporting a larger ℓ' can result in a lower packet loss probability as demonstrated in Fig. 5.3, so that a higher utility may be obtained. However, after a certain point (i.e., the reported packet priority level ℓ' equals the actual one ℓ), the transmission service charge, which increases exponentially with the packet priority level as illustrated in Fig. 5.5, becomes dominant so that the utility decreases. Intuitively, the optimal decision (of smart gateways) is to report each data packet with its actual priority which can maximize its transmission utility, and thus Theorem 5.3 holds. Moreover, since it is defined in (5.2) that the value of a packet in a higher priority level is larger, then given the same packet loss probability, the transmission utility of a packet in a higher priority level is obviously higher.

5.3.3 Comparisons with Existing Mechanisms

For comparison purpose, two existing scheduling mechanisms, i.e., DTM-L mechanism [99] and non-priority mechanism [100], are simulated as benchmarks. DTM-L mechanism was designed for managing multi-class delay-sensitive data packet transmissions, where an extra delay control scheme was required for differentiating beyond-WBAN services among different packet priorities. While, the non-priority mechanism aimed to manage all beyond-WBAN packet transmissions based on a FCFS manner. Both of them ignored delay constraints for packet transmissions so that arbitrarily long delays may be introduced.

Fig. 5.7 depicts the beyond-WBAN transmission probabilities of data packets with

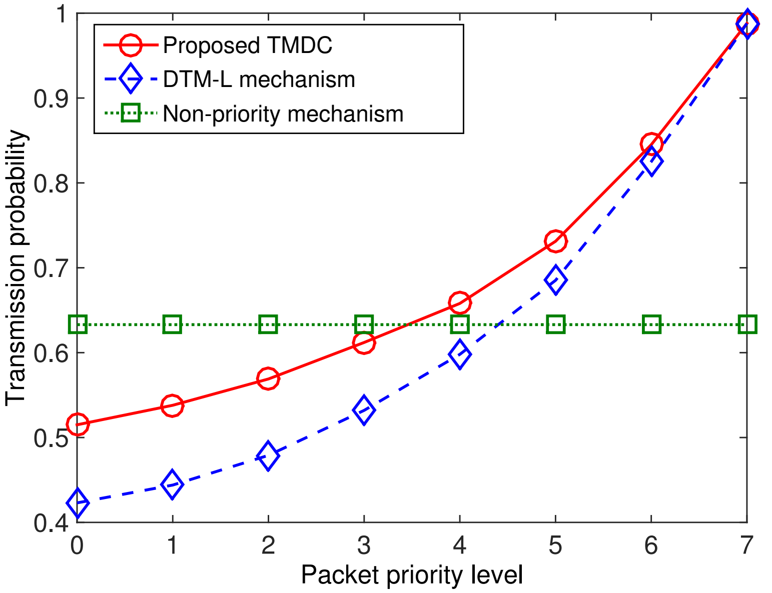

Figure 5.7: Comparison on the transmission probability.

different priorities in the delay-constrained network scenario. Here, the transmission probability is defined as the probability that a packet is transmitted in the beyond-WBAN within its required delay limit. From this figure, we can observe that when the proposed TMDC or DTM-L mechanism is employed, data packets in a higher priority level have a higher transmission probability. This is because both TMDC and DTM-L mechanisms are priority-aware, namely a better beyond-WBAN transmission service is always granted for packets with a higher priority. However, due to the extra delay control which introduces additional delays for packets in lower priority levels, the overall performance of DTM-L is worse than that of the proposed TMDC. Furthermore, the non-priority mechanism treats all transmission requests equally, so that the transmission probability remains unchanged for all data packets regardless of their priority levels.

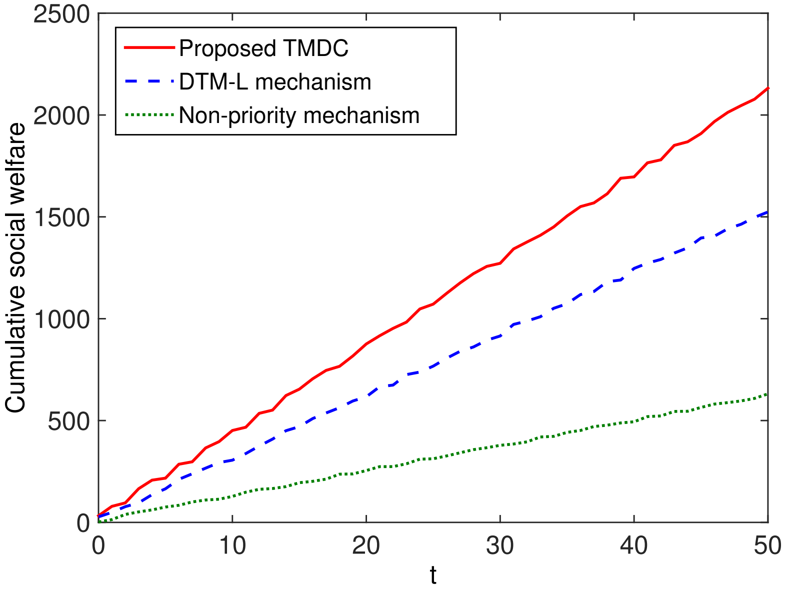

Figure 5.8: Comparison on the cumulative social welfare.

Fig. 5.8 compares the cumulative social welfare of all beyond-WBAN packet transmissions from 0 to 50 seconds achieved by the proposed TMDC, DTM-L and non-priority mechanisms. Here, the cumulative social welfare is defined as

$$\text{Welfare}(t) = \sum\nolimits_t \sum\nolimits_i v_{\ell_i}(1 - x(\ell_i)), \tag{5.71}$$

which calculates the total utility gain from all successful beyond-WBAN packet transmissions regardless of their service charges. It is intuitive that the cumulative social welfare must increase with the time. More importantly, it can be seen that the proposed TMDC has the best performance. This is because i) TMDC results in higher packet transmission probabilities than DTM-L mechanism, as illustrated in Fig. 5.7; and ii) TMDC can guarantee more desirable QoS for high-priority data packet transmissions than the non-priority mechanism.

Fig. 5.9 shows expected revenues of the BS when different mechanisms are im-

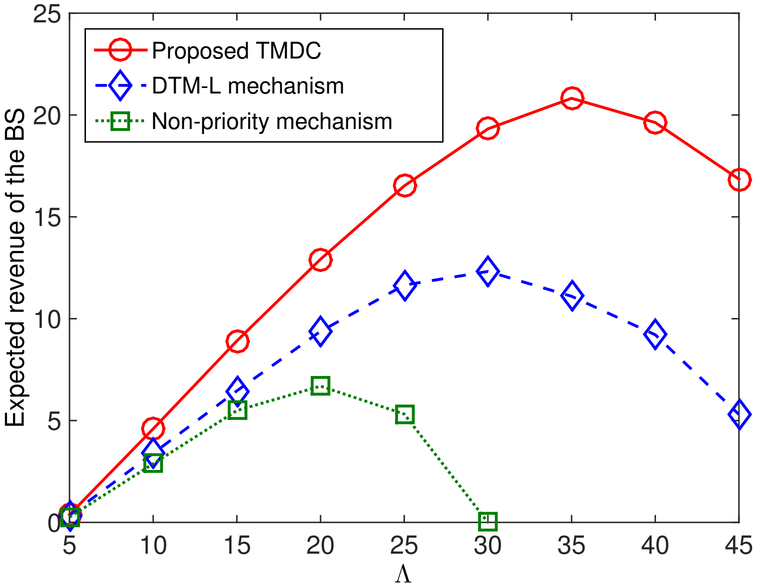

Figure 5.9: Comparison on the expected revenue of the BS.

plemented. It can be observed that the expected revenue first increases and then decreases with the aggregate traffic arrival rate Λ. Even though a larger Λ implies more beyond-WBAN packet transmission requests, the service charge for each individual packet transmission decreases with the increase of Λ due to the heavier system congestion, as examined in Fig. 5.5. Thus, when Λ increases over a certain value, reductions on packet transmission charges become dominant so that the revenue of the BS decreases. Moreover, this figure demonstrates that the proposed TMDC obviously outperforms both DTM-L and non-priority mechanisms, and explanations follow the same as that for Fig. 5.8.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

In this thesis, truthful mechanism design for transmission scheduling in beyond-WBANs with various QoS provisioning has been studied. In Chapter 1, the network architecture and research challenges of WBANs are discussed. Then, with a particular focus on the beyond-WBAN communications (which have not been well studied in the literature), the motivations and difficulties of designing truthful and efficient mechanisms for beyond-WBAN data packet transmission scheduling are illustrated. As the first step, in Chapter 2, we propose a truthful mechanism for delay-sensitive transmission scheduling with homogeneous packet transmission time in the beyond-WBAN. After that, by relaxing the assumption of homogeneous packet transmission time and defining a discretized priority classification fitting the existing IEEE standards for WBAN-applications, a novel truthful mechanism for supporting multi-class prioritized delay-sensitive beyond-WBAN transmission scheduling is designed in Chapter

3. With the further consideration of a more general transmission service process and the relaxation of the fixed priority requirement, Chapter 4 presents a truthful mechanism for managing delay-dependent dynamic prioritized transmission scheduling in the beyond-WBAN. In addition, for dealing with applications with stringent delay limits in the beyond-WBAN communication, in Chapter 5, we extend the previously employed delay-sensitive transmission scheduling framework to a delay-constrained one and develop a corresponding truthful mechanism for delay-constrained prioritized transmission scheduling. Specifically, the detailed conclusions for each chapter are summarized in the following.

In Chapter 2, the beyond-WBAN transmission scheduling of *delay-sensitive data packets with homogeneous packet transmission time* is investigated. To characterize the packet-level operation of the beyond-WBAN management framework, a prioritized $M/d/N$ queue is formulated (where M, d and N stand for Markovian/Poisson arrivals, deterministic service/transmission time and N servers/channels, respectively). Considering that the smart gateways in the beyond-WBAN may strategically misreport their packet delay sensitivities for maximizing their own transmission utilities, a truthful mechanism is designed, which can induce all gateways to behave truthfully by revealing the actual delay sensitivities of their packets when declaring their beyond-WBAN transmission requests. Theoretical analyses and numerical results examine the feasibility of the proposed mechanism, and show that it can also maximize the network revenue so as to incentivize the BS to run the beyond-WBAN management system, while always guaranteeing higher transmission priorities to more emergent data packets.

In Chapter 3, the dynamic management of *multi-class delay-sensitive data packet transmissions* in the beyond-WBAN is studied. The beyond-WBAN transmission scheduling system is modeled as a multi-class multi-server priority queue. To prevent smart gateways from misreporting the priority classes of their data packets, a truthful mechanism (i.e., DTM-2) for beyond-WBAN transmission scheduling with two-class prioritized data packets is first designed and analyzed. Then, the proposed DTM-2 is extended to a general form, namely DTM-L, which can support multi-class (i.e., more than two) prioritized data packet transmissions in the beyond-WBAN. Simulation results verify the desired properties of the proposed mechanism, and demonstrate its feasibility and superiority compared to the counterparts.

In Chapter 4, a novel management framework for *delay-dependent dynamic prioritized beyond-WBAN transmission scheduling* is formulated. Taking into account the dynamic nature and the QoS requirements of beyond-WBAN data packet transmissions, the packet-level operation of the scheduling system is modeled as a multi-class multi-server queue with a generally distributed service time (i.e., transmission time) and a delay-dependent dynamic priority discipline. With the objective of maximizing the network social welfare, a truthful mechanism, namely DPMT, is proposed, which is based on the equilibrium of a corresponding virtual queueing game. Theoretical analyses and simulation results show that the proposed mechanism can induce all gateways to truthfully report the transmission requests of their data packets with the actual class information, and can reduce the expected waiting costs of all data packet transmissions in the beyond-WBAN compared to the counterparts.

In Chapter 5, extended from the scheduling framework for delay-sensitive beyond-

WBAN data packet transmissions discussed in previous chapters, the scheduling management of *multi-class delay-constrained packet transmissions* in the beyond-WBAN is investigated. A multi-class multi-server delay-constrained priority queueing system is formulated to describe the scheduling management of beyond-WBAN data packet transmissions. Extensive queueing analyses are conducted to evaluate the performance of the considered model. Based on the derived queueing outcome, a truthful mechanism, namely TMDC, for scheduling beyond-WBAN data packet transmissions with delay constraints is designed. Both theoretical and simulation results show that the proposed mechanism can guarantee the truthfulness from all smart gateways, and can outperform the counterparts in terms of the packet transmission probability, network social welfare and revenue.

6.2 Future Work

Some future research directions on truthful mechanism design for beyond-WBAN transmission scheduling and priority-aware dynamic radio resource management are outlined as follows.

- *Achieving various priority-aware QoS provisioning by one mechanism:* In this thesis, several different mechanisms have been designed for achieving different priority-aware QoS provisioning in the beyond-WBAN, including the absolutely prioritized delay-sensitive transmission scheduling discussed in Chapters 2 and 3, the delay-dependent dynamic prioritized transmission scheduling discussed in Chapter 4, and the delay-constrained prioritized transmission scheduling discussed in Chapter 5. These mechanisms are ordinarily proposed for different

WBAN application purposes with unique desired features, so that their designs are fundamentally different. However, in order to facilitate the wide implementation of WBAN-based medical/non-medical services, future WBANs should be able to simultaneously support a variety of applications, which may generate data information/packets with various QoS requirements in transmissions [2]. This necessitates the design of a mechanism for the beyond-WBAN transmission scheduling with heterogeneous priority-aware QoS provisioning. For example, one may consider to integrate features, such as the absolutely priority for emergency and the delay-dependent dynamic priority for non-emergency, the delay-sensitive scheduling for medical information delivery and the delay-constrained scheduling for non-medical information delivery, into a single beyond-WBAN framework and redesign a mechanism which can meet all these requirements. This will make the queueing analysis even more complicated because various queueing disciplines have to be integrated in one so as to guarantee heterogeneous QoS requirements. As a result, it will be much more difficult to explicitly analyze the relationship between the achieved QoS of the beyond-WBAN data packet transmissions and the scheduling mechanism. A potential solution for addressing this issue is to jointly model and analyze the transmission scheduling system and the strategic behaviors of smart gateways, and design efficient mechanisms without explicit expressions of the queueing performance.

- *Taking into account security and privacy:* In fact, WBAN-based applications may also raise various security and privacy concerns. Since physiological information (e.g., health conditions) collected by WBANs is relatively sensitive for users, any unintended disclosure may violate user privacy and even result in property loss [107]. Moreover, without the guarantee of security, malicious attackers may disrupt the desired priority-aware transmission scheduling in the WBAN, leading to serious consequences. In addition, the costs of security and privacy protections may vary with users' heterogeneous demands. For instance, complicated encryption techniques can offer users with more security guarantees but also bring higher computational overheads and longer latencies than lightweight ones. To satisfy users' diverse security requirements and balance the tradeoff between the performance and security protections, *quality of protection* has become a newly emerging concept that has to be considered in WBANs [108]. Although the design of security and privacy-preserving schemes is out of the scope of this thesis, integrating them with the proposed mechanisms for the beyond-WBAN transmission scheduling is of high importance and may be a very interesting and promising research direction in the future.

- *To be compatible with other existing wireless networks:* This thesis investigates a beyond-WBAN transmission scheduling framework built upon a cellular-like network architecture with dedicated spectrum resources. Such exclusive spectrum usage simplifies the analyses and the design of the beyond-WBAN transmission scheduling mechanism because of the independency between the beyond-WBAN and other network technologies. However, in practice, due to the inherently limited radio resources [29], the exclusive spectrum access manner may not be efficient. This prompts the need of considering the beyond-WBAN as a part of the heterogeneous network architecture [109] coexisting with other network technologies, such as WiFi, macro-cell and small-cell networks, on the same spectrum bands. In order to maintain the desired QoS for beyond-WBAN data packet transmissions, the following issues have to be well addressed: i) how to coordinate the interference among different wireless access technologies; ii) which transmission modes should be selected for different beyond-WBAN data packet transmissions in different circumstances; and iii) how to determine the data transmission priorities and as well as the network priorities. Clearly, by taking these into account, the overall scheduling management problem becomes much more complex and challenging due to the introductions of more decision variables/vectors and more system constraints. This motivates the future research efforts on cross-layer optimizations.

- *Extending mechanisms to a variety of network applications:* Technically speaking, in this thesis, truthful mechanism design integrating priority-aware queueing scheduling has been extensively studied. Even though this thesis limits the discussion on the beyond-WBAN transmission management, the proposed mechanisms may be extended and employed in other network applications for dealing with dynamic resource allocations and network optimization/scheduling. For example, following the similar ideas, an efficient mechanism may be designed for dynamically managing the joint computation offloading and transmission scheduling for delay-sensitive applications in mobile edge computing with intelligent and strategic multi-user interactions [110]. Other potential applications include traffic steering in IoT-based networks [111] and QoS-constrained multimedia communications [112].

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Appendix A

Appendices of Chapter 3

A.1 Proof of Proposition 3.2

Proof. Let us prove the equivalent statement that $\tilde{D}(0) = \tilde{D}(1)$, $\tilde{\pi}(0) = \tilde{\pi}(1)$ if and only if

$$\theta^r_{0,1} \geq \frac{\Lambda_1[\bar{F}_1(\pi^s_{0,1}) f_0(\pi^s_{0,1}) - \bar{F}_0(\pi^s_{0,1}) f_1(\pi^s_{0,1})]}{f_0(\pi^s_{0,1})[\Lambda_1 \bar{F}_1(\pi^s_{0,1}) + \Lambda_0 \bar{F}_0(\pi^s_{0,1})]}. \tag{A.1}$$

Since $\tilde{\pi}(0) = \tilde{\pi}(1)$ will automatically result in $\tilde{D}(0) = \tilde{D}(1)$, we only need to prove that (A.1) is both necessary and sufficient for $\tilde{\pi}(0) = \tilde{\pi}(1)$. By applying Proposition 3.1 and substituting $\theta^r_{0,1} = \theta_0/\theta_1$, $(\mathcal{P}2)$ can be rewritten as

$$\arg\max_{\pi(0),\pi(1)} \ \varphi_0 \pi(0) + \varphi_1 \pi(1) \tag{A.2}$$

$$s.t., \ \varphi_0 = \Lambda_0 \bar{F}_0\big(\theta^r_{0,1}\pi(1) + (1-\theta^r_{0,1})\pi(0)\big), \tag{A.3}$$

$$\varphi_1 = \Lambda_1 \bar{F}_1(\pi(1)), \tag{A.4}$$

$$\pi(1) \geq \pi(0), \tag{A.5}$$

$$\varphi_0 + \varphi_1 \leq N \cdot \mu. \tag{A.6}$$

By applying Karush-Kuhn-Tucker (KKT) conditions [113] and some mathematic manipulations, we have

a) if $\tilde{\pi}(1) = \tilde{\pi}(0) = \pi^s_{0,1}$,

$$(1-\theta^r_{0,1})\frac{f_0(\pi^s_{0,1})}{\bar{F}_0(\pi^s_{0,1})} \leq \frac{\Lambda_1 f_1(\pi^s_{0,1}) + \Lambda_0 f_0(\pi^s_{0,1})}{\Lambda_1 \bar{F}_1(\pi^s_{0,1}) + \Lambda_0 \bar{F}_0(\pi^s_{0,1})}; \tag{A.7}$$

b) if $\tilde{\pi}(1) > \tilde{\pi}(0)$,

$$\begin{aligned}\frac{f_1(\tilde{\pi}(1))}{\bar{F}_1(\tilde{\pi}(1))} < &\left[1 - \frac{\theta^r_{0,1}\Lambda_0\bar{F}_0\big(\theta^r_{0,1}\tilde{\pi}(1) + (1-\theta^r_{0,1})\tilde{\pi}(0)\big)}{(1-\theta^r_{0,1})\Lambda_1\bar{F}_1(\tilde{\pi}(1))}\right] \\ &\times(1-\theta^r_{0,1})\frac{f_0\big(\theta^r_{0,1}\tilde{\pi}(1) + (1-\theta^r_{0,1})\tilde{\pi}(0)\big)}{\bar{F}_0\big(\theta^r_{0,1}\tilde{\pi}(1) + (1-\theta^r_{0,1})\tilde{\pi}(0)\big)}.\end{aligned} \tag{A.8}$$

Obviously, (A.7) can be easily transformed to (A.1) so that it can be concluded that (A.1) is necessary for $\tilde{\pi}(1) = \tilde{\pi}(0)$. Besides, (A.8) reveals that if $\tilde{\pi}(1) = \tilde{\pi}(0) = \pi^s_{0,1}$, we have

$$\frac{f_1(\pi^s_{0,1})}{\bar{F}_1(\pi^s_{0,1})} \geq \left[1 - \frac{\theta^r_{0,1}}{1-\theta^r_{0,1}}\frac{\Lambda_0\bar{F}_0(\pi^s_{0,1})}{\Lambda_1\bar{F}_1(\pi^s_{0,1})}\right](1-\theta^r_{0,1})\frac{f_0(\pi^s_{0,1})}{\bar{F}_0(\pi^s_{0,1})}, \tag{A.9}$$

which is equivalent to (A.1) after some manipulations. Thus, (A.1) is also sufficient for $\tilde{\pi}(1) = \tilde{\pi}(0)$. □

A.2 Proof of Theorem 3.1

Proof. i) Because of the preemptive-resume priority queueing discipline, the transmissions of emergent data packets cannot be affected by any normal packet transmissions. Thus, $\mathbb{E}[W^\nu(1)]$ depends on the admission rate of emergent packets φ^ν_1 only. On the other hand, $\mathbb{E}[W^\nu(0)]$ is not only related to the admission rate of normal packets φ^ν_0, but also φ^ν_1 (due to the potential preemptions). With a slight abuse of notations, let us denote $\mathbb{E}[W^\nu(1)]$ and $\mathbb{E}[W^\nu(0)]$ as functions $\mathbb{E}[W^\nu_1(\varphi^\nu_1)]$ and $\mathbb{E}[W^\nu_0(\varphi^\nu_0, \varphi^\nu_1)]$, respectively. Clearly, $\mathbb{E}[W^\nu_1(\varphi^\nu_1)]$ is monotone increasing with φ^ν_1, and $\mathbb{E}[W^\nu_0(\varphi^\nu_0, \varphi^\nu_1)]$ is monotone increasing with both φ^ν_0 and φ^ν_1.

The admission rate of data packets with truthful priorities can also be expressed as functions of their overall delays $\mathbb{E}[D^\nu(\ell)]$, i.e., $\varphi^\nu_\ell\big(\mathbb{E}[D^\nu(\ell)]\big) = \Lambda^\nu_\ell\bar{F}_\ell\big(\tilde{\pi}(\ell) + \theta_\ell\mathbb{E}[D^\nu(\ell)]\big)$. Note that $\varphi^\nu_\ell\big(\mathbb{E}[D^\nu(\ell)]\big)$ is monotone non-increasing with $\mathbb{E}[D^\nu(\ell)]$. Naturally, the queueing system is stable if and only its expected waiting delay $(\mathbb{E}[D^\nu(0)], \mathbb{E}[D^\nu(1)])$ can jointly satisfy

$$\varphi^\nu_\ell\big(\mathbb{E}[D^\nu(0)]\big) + \varphi^\nu_\ell\big(\mathbb{E}[D^\nu(1)]\big) < N^\nu\mu, \tag{A.10}$$

$$\mathbb{E}[D^\nu(0)] = \mathbb{E}[W^\nu_0(\varphi^\nu_0(\mathbb{E}[W^\nu(0)] + \delta), \varphi^\nu_\ell(\mathbb{E}[W^\nu(1)]))] + \delta, \tag{A.11}$$

$$\mathbb{E}[D^\nu(1)] = \mathbb{E}[W^\nu(1)] = \mathbb{E}\left[W_1^\nu\big(\varphi_\ell^\nu(\mathbb{E}[W^\nu(1)])\big)\right]. \tag{A.12}$$

Since the normal packets can be ignored in the scheduling of emergent packet transmissions, we will first prove (A.12), and then show that (A.11) holds given (A.12) and subject to (A.10).

Define $g_1(x) = x - \mathbb{E}\left[W_1^\nu\big(\varphi_\ell^\nu(x)\big)\right]$. Observe that $g_1(x)$ is continuous with x and $g_1(0) < 0$, $g_1(\infty) > 0$, since $\varphi_1^\nu(\infty) = 0$ and $\varphi_1^\nu(0) = \Lambda_1^\nu \bar{F}_1(\tilde{\pi}(1)) < N^\nu \mu$. Moreover, $g_1(x)$ is monotone increasing, since $\mathbb{E}\left[W_1^\nu\big(\varphi_\ell^\nu(x)\big)\right]$ is monotone non-increasing with x. Therefore, there exists a unique $\mathbb{E}[W^\nu(1)]$ such that $g_1\big(\mathbb{E}[W^\nu(1)]\big) = 0$, which proves (A.12).

Now, fix $\varphi_1^\nu = \Lambda_1^\nu \bar{F}_1\big(\tilde{\pi}(1) + \theta_\ell \mathbb{E}[W^\nu(1)]\big)$ and further define $g_0(x) = x - \delta - \mathbb{E}\left[W_0^\nu\big(\varphi_0^\nu(x+\delta), \varphi_1^\nu\big)\right]$. $g_0(x)$ is also continuous and $g_0(\infty) > 0$, since $\varphi_0^\nu(\delta + \infty) = 0$. Moreover, $g_0(x)$ is monotone increasing with x, since $\mathbb{E}\left[W_0^\nu\big(\varphi_0^\nu(x+\delta), \varphi_1^\nu\big)\right]$ is monotone non-increasing with x. If $g_0(\underline{x}) < 0$ for some $\underline{x} \geq 0$, and $\varphi_0^\nu(\delta + \mathbb{E}[W^\nu(0)]) < N^\nu\mu - \varphi_1^\nu$ for $\mathbb{E}[W^\nu(0)] \geq \underline{x}$, there must be a unique $\mathbb{E}[D^\nu(0)] = \mathbb{E}[W^\nu(0)] + \delta$ such that $g_0(\mathbb{E}[W^\nu(0)]) = 0$, which proves (A.11). Hence, we have to explore the existence of $\underline{x}$. For the incapacitated system ($\xi_0 + \xi_1 < 1,\ \delta = \tilde{D}(0)$), we can choose $\underline{x} = 0$ because $\varphi_0^\nu(\tilde{D}(0)) = \Lambda_0^\nu \bar{F}_0\big(\tilde{\pi}(0) + \theta_0 \tilde{D}(0)\big) > 0$ and $\varphi_0^\nu(\tilde{D}(0)) + \varphi_1^\nu < N^\nu\mu$. For the capacitated system ($\xi_0 + \xi_1 = 1,\ \delta = 0$), we can set $\underline{x}$ as the value such that $\varphi_0^\nu(\underline{x}) + \varphi_1^\nu = N^\nu\mu$. Then, as $x \to \underline{x}$, $\mathbb{E}[W_0^\nu(\varphi_0^\nu(x), \varphi_1^\nu)] \to \infty$, and for some $\epsilon > 0$, we must have $g_0(\underline{x} + \epsilon) < 0$ and $\varphi_0^\nu(\underline{x} + \epsilon) + \varphi_1^\nu < N^\nu\mu$.

In conclusion, there exists a unique stationary state which can be represented by $(\mathbb{E}[D^\nu(0)], \mathbb{E}[D^\nu(1)])$ or equivalently the load factor (η_0^ν, η_1^ν), where

$$\eta_\ell^\nu = \frac{\Lambda_\ell^\nu \bar{F}_\ell\big(\tilde{\pi}(\ell) + \theta_\ell \mathbb{E}[D^\nu(\ell)]\big)}{N^\nu \mu}, \ \forall \ell \in \{0, 1\}. \tag{A.13}$$

ii) For the incapacitated system ($\xi_0 + \xi_1 < 1,\ \delta = \tilde{D}(0)$), we can derive that

$$\eta_0^\nu + \eta_1^\nu \leq \xi_0 + \xi_1 < 1. \tag{A.14}$$

According to [114], in the queueing system with scale $\nu \to \infty$, $\eta_0^\nu + \eta_1^\nu < 1$ implies $\mathbb{E}[W^\nu(0)] \to 0$ and $\mathbb{E}[W^\nu(1)] \to 0$. Thus, we can conclude that $\mathbb{E}[D^\nu(0)] \to \delta = \tilde{D}(0)$ and $\mathbb{E}[D^\nu(1)] \to \tilde{D}(1) = 0$, as $\nu \to \infty$.

For the capacitated system ($\xi_0 + \xi_1 = 1, \ \delta = 0$), we have $\eta_1^\nu \leq \xi_1 < 1$ so that $\mathbb{E}[D^\nu(1)] = \mathbb{E}[W^\nu(1)] \to \tilde{D}(1) = 0$ and $\eta_1^\nu \to \xi_1$, as $\nu \to \infty$. In order to prove $\lim_{\nu\to\infty} \mathbb{E}[D^\nu(0)] \to \tilde{D}(0)$, we assume by the way of contradiction that a) $\lim_{\nu\to\infty} \mathbb{E}[D^\nu(0)] < \tilde{D}(0)$, or b) $\lim_{\nu\to\infty} \mathbb{E}[D^\nu(0)] > \tilde{D}(0)$.

If a) holds, there must exist $\epsilon > 0$ such that

$$\eta_0^\nu = \frac{\Lambda_0^\nu \bar{F}_0\big(\tilde{\pi}(0) + \theta_0 \mathbb{E}[W^\nu(0)]\big)}{N^\nu \mu} \geq \xi_0 + \epsilon, \text{ as } \nu \to \infty. \tag{A.15}$$

Since $\eta_1^\nu \to \xi_1$, we have $\eta_0 + \eta_1 > \xi_0 + \xi_1 = 1$, which implies that a) can never be met.

If b) holds, there must exist $\epsilon > 0$ such that

$$\eta_0^\nu = \frac{\Lambda_0^\nu \bar{F}_0\big(\tilde{\pi}(0) + \theta_0 \mathbb{E}[W^\nu(0)]\big)}{N^\nu \mu} \leq \xi_0 - \epsilon, \text{ as } \nu \to \infty. \tag{A.16}$$

Since $\eta_1^\nu \to \xi_1$, we have $\eta_0 + \eta_1 < 1$, which implies $\mathbb{E}[W^\nu(0)] \to 0$, and contradicts b).

In summary, as $\nu \to \infty$, we have $\mathbb{E}[D^\nu(\ell)] \to \tilde{D}(\ell)$ or equivalently $\eta_\ell^\nu \to \xi_\ell$. □

Appendix B

Appendices of Chapter 4

B.1 Proof of Lemma 4.1

Proof. In the queueing system for delay-dependent prioritized beyond-WBAN transmissions, the waiting delay for a non-emergent data packet with criticality coefficient β_ℓ consists of three parts, i.e., the remaining service time for packets that are currently under transmission, the total service time for future arrived packets that will overtake the considered packet in transmission, and the total service time for packets that are already waiting in the buffer and will be transmitted in prior to the considered packet. Thus, $\mathbb{E}[D(\beta_\ell, \hat{\boldsymbol{\beta}})]$ can be written as

$$\mathbb{E}[D(\beta_\ell, \hat{\boldsymbol{\beta}})] = \kappa + \mathbb{E}\left[\sum_{\ell'=0}^{L-1}\left(\sum_{j=1}^{Y_{\ell'}(\beta_\ell)} T_{\ell'}(j) + \sum_{j=1}^{Z_{\ell'}(\beta_\ell)} T_{\ell'}(j)\right)\right], \tag{B.1}$$

where κ denotes the expected remaining service time for packets in transmission, $T_{\ell'}(j)$ is the service time of the packet in class ℓ' with an index j, $Y_{\ell'}(\beta_\ell)$ represents the expected number of packets in class ℓ' that will arrive later but can be transmitted earlier, $Z_{\ell'}(\beta_\ell)$ indicates the expected number of packets in class ℓ' that arrived earlier and will also be transmitted earlier. Due to the independence between the service time of the system and the arrival of transmission requests, (B.1) can be rewritten as

$$\mathbb{E}[D(\beta_\ell, \hat{\boldsymbol{\beta}})] = \kappa + \sum_{\ell'=0}^{L-1} \mathbb{E}[T_{\ell'}](Y_{\ell'}(\beta_\ell) + Z_{\ell'}(\beta_\ell)). \tag{B.2}$$

To obtain $Y_{\ell'}(\beta_\ell)$, let us consider that the data packet with β_ℓ has arrived at time 0 and waited for w. Then, any other packets with $\beta > \beta_\ell$ that will arrive at time $t > 0$ such that $\beta(w - t) > \beta_\ell w$ can overtake the considered packet in delay-dependent prioritized beyond-WBAN transmissions. In other words, all new arrived packets within $(0, w(1 - \frac{\beta_\ell}{\beta}))$ will obtain higher transmission priorities than the considered packet if they have $\beta > \beta_\ell$. By the superposition and splitting property [115] of Poisson process and with some mathematical manipulations, we have

$$Y_{\ell'}(\beta_\ell) = \Lambda_{\ell'}\mathbb{E}[D(\beta_\ell, \hat{\boldsymbol{\beta}})] \int_{\beta_\ell}^{\infty} (1 - \frac{\beta_\ell}{\beta}) d(\hat{\beta}_{\ell'}(\beta)), \tag{B.3}$$

which calculates the expected number of packets in any class ℓ' with criticality coefficient larger than β_ℓ that arrive later than the considered packet.

We are now left with computing $Z_{\ell'}(\beta_\ell)$, i.e., the expected number of packets that are already waiting in the buffer and will not be overtaken by the considered packet with β_ℓ. Clearly, any buffered packet with $\beta \geq \beta_\ell$ will definitely be transmitted before the considered one, and the expected number of these packets can be calculated by

$$Z_{\ell'}(\beta_\ell)^{(1)} = \Lambda_{\ell'} \int_{\beta_\ell}^{\infty} \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] d(\hat{\beta}_{\ell'}(\beta)). \tag{B.4}$$

Besides, for any buffered packet with $\beta < \beta_\ell$ that arrived at $t - \tau$, the probability of not being overtaken by the packet with β_ℓ which arrived at t is equivalent to

$$\Pr.(\tau < \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] < \frac{\beta_\ell}{\beta_\ell - \beta}\tau). \tag{B.5}$$

Again, by the superposition and splitting property, we have

$$\begin{aligned}
&Z_{\ell'}(\beta_\ell)^{(2)} \\
&= \Lambda_{\ell'} \int_0^{\beta_\ell} \left[\Pr.(\tau < \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] < \frac{\beta_\ell}{\beta_\ell - \beta}\tau)\right] d\tau d(\hat{\beta}_{\ell'}(\beta)) \\
&= \Lambda_{\ell'} \int_0^{\beta_\ell} \left[\mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] - (1 - \frac{\beta}{\beta_\ell})\mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})]\right] d(\hat{\beta}_{\ell'}(\beta)) \\
&= \Lambda_{\ell'} \int_0^{\beta_\ell} \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] \frac{\beta}{\beta_\ell} d(\hat{\beta}_{\ell'}(\beta)).
\end{aligned} \tag{B.6}$$

which calculates the expected number of packets with criticality coefficient smaller than β_ℓ but will not be overtaken by the considered packet due to the sufficiently long experienced delays. In summary,

$$Z_{\ell'}(\beta_\ell) = Z_{\ell'}(\beta_\ell)^{(1)} + Z_{\ell'}(\beta_\ell)^{(2)}. \tag{B.7}$$

Substituting (B.3) and (B.7) into (B.2) yields

$$\begin{aligned}\mathbb{E}[D(\beta_\ell, \hat{\boldsymbol{\beta}})] = \kappa + &\sum_{\ell'=1}^{L} \rho_{\ell'} \Bigg[\int_0^{\beta_\ell} \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] \frac{\beta}{\beta_\ell} d(\hat{\beta}_{\ell'}(\beta)) \\ &+ \int_{\beta_\ell}^{\infty} \big(\mathbb{E}[D(\beta_\ell, \hat{\boldsymbol{\beta}})](1 - \frac{\beta_\ell}{\beta}) + \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] \big) d(\hat{\beta}_{\ell'}(\beta)) \Bigg].\end{aligned} \tag{B.8}$$

According to [116], κ can be well approximated by $\sum_{\ell=0}^{L-1} \frac{\rho_\ell \mathbb{E}[Z_\ell^2]}{2\mathbb{E}[Z_\ell]}$. Based on the conservation law [117], we have

$$\begin{aligned}&\sum_{\ell'=0}^{L-1} \rho_{\ell'} \int_{\beta_\ell}^{\infty} \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] d(\hat{\beta}_{\ell'}(\beta)) \\ &\qquad = \frac{\kappa\rho}{1-\rho} - \sum_{\ell'=0}^{L-1} \int_0^{\beta_\ell} \mathbb{E}[D(\beta, \hat{\boldsymbol{\beta}})] d(\hat{\beta}_{\ell'}(\beta)).\end{aligned} \tag{B.9}$$

Finally, substituting (B.9) into (B.8) along with some mathematical manipulations, (4.39) can be derived. □

B.2 Proof of Lemma 4.2

Proof. Let

$$V_1(\beta_\ell) = \sum\nolimits_{\{\ell' | \beta_{\ell'} < \beta_\ell\}} \rho_{\ell'} (1 - \frac{\beta_{\ell'}}{\beta_\ell}) \mathbb{E}[D(\beta_{\ell'}, \boldsymbol{\beta}_{-\ell'})], \tag{B.10}$$

$$V_2(\beta_\ell) = \sum\nolimits_{\{\ell' | \beta_{\ell'} \geq \beta_\ell\}} \rho_{\ell'} (1 - \frac{\beta_\ell}{\beta_{\ell'}}). \tag{B.11}$$

Then, the expression of $\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]$ in (4.39) can be rewritten as

$$\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})] = \frac{\frac{\kappa}{1-\rho} - V_1(\beta_\ell)}{1 - V_2(\beta_\ell)}. \tag{B.12}$$

Clearly, $1 - V_2(\beta_\ell) > 0$ due to the queueing stability, and $\frac{\kappa}{1-\rho} - V_1(\beta_\ell) \geq 0$ for guaranteeing non-negativity of the expected waiting delay.

Taking the first order derivative of $\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]$ with respect to β_ℓ, we have

$$\frac{\partial \mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]}{\partial \beta_\ell} = \frac{-\frac{\partial V_1(\beta_\ell)}{\partial \beta_\ell}(1 - V_2(\beta_\ell)) + \frac{\partial V_2(\beta_\ell)}{\partial \beta_\ell}(\frac{\kappa}{1-\rho} - V_1(\beta_\ell))}{(1 - V_2(\beta_\ell))^2}. \tag{B.13}$$

Since $\frac{\partial V_1(\beta_\ell)}{\partial \beta_\ell} \geq 0$, $\frac{\partial V_2(\beta_\ell)}{\partial \beta_\ell} \leq 0$ (which can be easily verified from (B.10) and (B.11)), and $1 - V_2(\beta_\ell) > 0$, $\frac{\kappa}{1-\rho} - V_1(\beta_\ell) \geq 0$ (as explained previously), we can conclude that

$$\frac{\partial \mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]}{\partial \beta_\ell} \leq 0, \tag{B.14}$$

and thus $\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]$ is non-increasing with β_ℓ.

Moreover, by substituting (B.12) into (B.13), we have

$$\frac{\partial \mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]}{\partial \beta_\ell} = \frac{-\frac{\partial V_1(\beta_\ell)}{\partial \beta_\ell} + \frac{\partial V_2(\beta_\ell)}{\partial \beta_\ell}\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]}{1 - V_2(\beta_\ell)}. \tag{B.15}$$

Then, the second order derivative of $\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]$ with respect to β_ℓ can be derived as

$$\frac{\partial^2 \mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]}{\partial \beta_\ell^2} = \frac{\frac{\partial V_3(\beta_\ell)}{\partial \beta_\ell}(1 - V_2(\beta_\ell)) + \frac{\partial V_2(\beta_\ell)}{\partial \beta_\ell} V_3(\beta_\ell)}{(1 - V_2(\beta_\ell))^2}, \tag{B.16}$$

where

$$V_3(\beta_\ell) = -\frac{\partial V_1(\beta_\ell)}{\partial \beta_\ell} + \frac{\partial V_2(\beta_\ell)}{\partial \beta_\ell}\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]. \tag{B.17}$$

Since it is obvious that $V_3(\beta_\ell) \geq 0$ and $\frac{\partial V_3(\beta_\ell)}{\partial \beta_\ell} \geq 0$, we have

$$\frac{\partial^2 \mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]}{\partial \beta_\ell^2} \geq 0. \tag{B.18}$$

Namely, $\mathbb{E}[D(\beta_\ell, \boldsymbol{\beta}_{-\ell})]$ is a convex function of β_ℓ. □

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[1] **Changyan Yi** and Jun Cai, "Transmission Management of Delay-Sensitive Medical Packets in Beyond Wireless Body Area Networks: A Queueing Game Approach," accepted for publication in *IEEE Trans. Mobile Computing*, 2018.

[2] **Changyan Yi**, Shiwei Huang, and Jun Cai "An Incentive Mechanism Integrating Joint Power, Channel and Link Management for Social-Aware D2D Content Sharing and Proactive Caching," *IEEE Trans. Mobile Computing*, vol. 17, no. 4, pp. 789-802, Apr. 2018.

[3] **Changyan Yi** and Jun Cai, "Ascending-Price Progressive Spectrum Auction for Cognitive Radio Networks with Power-Constrained Multi-Radio Secondary Users," *IEEE Trans. Vehicular Technology*, vol. 67, no. 1, pp. 781-794, Jan. 2018.

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[14] **Changyan Yi** and Jun Cai, "A Truthful Mechanism for Scheduling Delay-Constrained Transmissions in IoT-Based Healthcare Networks," submitted to *IEEE Trans. Wireless Communications.*

[15] **Changyan Yi** and Jun Cai, "Delay-Dependent Prioritized Medical Packet Transmission Scheduling in E-Health Networks: A Mechanism Design Approach," submitted to *IEEE Trans. Vehicular Technology.*

[16] Jiefei Ding, Jun Cai and **Changyan Yi**, "An Improved Coalition Game Approach for MIMO-NOMA Clustering Integrating Beamforming and Power Allocation," submitted to *IEEE Trans. Vehicular Technology.*

[17] Shiwei Huang, Jun Cai and **Changyan Yi**, "Joint Admission Control and Resource Management for D2D-Assisted Mobile Edge Computing," submitted to *IEEE Trans. Mobile Computing.*

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