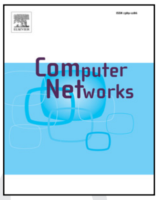
Computer Networks xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet



Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks

Q1 Changyan Yi[a], Zhen Zhao[a], Jun Cai[a,*], Ricardo Lobato de Faria[b], Gong (Michael) Zhang[b,c]

[a] *Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB R3T 5V6, Canada*
[b] *Seven Oaks General Hospital, Winnipeg, MB R2V 3M3, Canada*
[c] *Rizhao Hospital of Traditional Chinese Medicine, Rizhao, China*

ARTICLE INFO

Article history:
Received 1 June 2015
Revised 7 January 2016
Accepted 14 January 2016
Available online xxx

Keywords:
Transmission scheduling
Quality of service
Network pricing
Beyond-WBAN

ABSTRACT

In this paper, a radio resource allocation scheme for wireless body area networks (WBANs) is proposed. Unlike existing works in the literature, we focus on the communications in beyond-WBANs, and study the transmission scheduling under a scenario that there are a large number of gateways associating with one base station of medical centers. Motivated by the distinctions and requirements of beyond-WBAN communications, we introduce a priority-aware pricing-based capacity sharing scheme by taking into account the quality of service (QoS) requirements for different gateways. In the designed scheme, each gateway is intelligent to select transmission priorities and data rates according to its signal importance, and is charged by a price with regard to its transmission request. The capacity allocation is proceeded with guarantee of the absolute priority rule. In order to maximize the individual utility, gateways will compete with each other by choosing the optimal transmission strategies. Such decision process is formulated as a non-atomic game. Theoretical analyses show that our proposed pricing-based scheme can lead to an efficient Wardrop equilibrium. Through numerical results, we examine the convergence of strategy decisions, and demonstrate the effectiveness of our proposed mechanism in improving the utilities of gateways.

1. Introduction

With the growth of aging population [1] and the increasing demand for high quality of healthcare, exiting medical systems and hospital facilities have been confronting a burden of overload. To overcome this issue, electronic health (eHealth) [2] has been proposed as a promising paradigm, which adopts advanced information processing and communication technologies to enhance efficiency and flexibility of traditional medical services [3]. Wireless body area networks (WBANs) are key components in eHealth systems for pervasive and remote health monitoring. A WBAN generally consists of a few wearable, implantable, or portable biosensors, which are deployed on a patient for continuously sensing physiological signals, such as eletroencepalograph (EEG), Electrocardiograph (ECG) and Electromyography (EMG) data. The sensed signals are then aggregated at a gateway and forwarded to a remote medical center for interpretation and detection of abnormal health conditions. The gateway can be a patient's smart phone or any other smart device, and ordinarily has less stringent constraint on processing and power

---

[*] Corresponding author. Tel.: +12024746419.
E-mail addresses: changyan.yi@umanitoba.ca (C. Yi), zhaoz348@myumanitoba.ca (Z. Zhao), jun.cai@umanitoba.ca (J. Cai), rlobatodefaria@sogh.mb.ca (R. Lobato de Faria), gzhang@wrha.mb.ca (G. (Michael) Zhang).

http://dx.doi.org/10.1016/j.comnet.2016.01.010
1389-1286/© 2016 Elsevier B.V. All rights reserved.

capabilities compared to sensors [4]. Besides eHealth, WBANs have also been widely applied in sports, entertainments and military [5–7]. In this paper, we will focus our discussions on medical applications only.

Although the WBAN-based wireless technology can provide advantages over the conventional healthcare systems, the specifications of medical signal transmissions also introduce new challenges in designing eHealth networks. In the literature, most of existing works [8–10] in this area focused on intra-WBAN communications, i.e., the transmissions of medical signals from body sensors to the gateway. However, the technical issues related to beyond-WBAN communications, i.e., the data transmissions between gateways and the remote medical center, have not been well addressed. The main reason is that most researches are based on a common assumption that the beyond-WBAN communications can be achieved via existing network technologies, such as 3G/4G/WiFi [11]. However, in fact, medical data transmissions are different compared with traditional wireless communications. For instance, unlike conventional wireless networks that are mainly designed for throughput maximization, medical signals have relatively low data rates so that transmission capacity is not the primary concern for medical networks [12]. In contrast, medical data should be reported to the medical center promptly and with low packet loss. Unfortunately, existing wireless technologies cannot meet these requirements for beyond-WBAN communications because they cannot guarantee “anytime” and “anywhere” connections due to their limited radio resources and a large population of other subscribed wireless users.

Moreover, since the health conditions of patients are unpredictable, wireless networking may become a potential hazard for medical applications if some severe signals cannot be successfully transmitted in a timely manner [13]. For example, in the beyond-WBANs, it is possible that multiple gateways may transmit medical data simultaneously. In this case, it is necessary to provide priorities to emergent health information over those with regular importance, called “medical-grade priority”. Otherwise, transmissions with critical healthcare information may suffer high chances of packet loss, which may further lead to serious consequences.

Thus, in order to address the aforementioned challenges, it is important to achieve appropriate radio resource allocation among multiple gateways [14]. Note that different from the intra-WBAN communications where the appropriate medium access protocols are ordinarily contention-based [15,16], gateways are able to adopt more advanced and complicated resource allocation algorithms. Furthermore, since the availability of radio resource is commonly limited due to the large number of gateways, and medical signal transmissions require exclusive resource usages rather than opportunistic access due to their requirements for stable wireless connections, introducing network economics [17,18] for solving the resource allocation problem in beyond-WBAN communications is an intuitive and feasible approach.

In this paper, we propose a pricing-based radio resource sharing scheme for eHealth networks with the consideration of the medical-grade priority. We limit our discussion in the scenario that there are multiple gateways communicating with a single base station (which is further connected with single/multiple medical centers through internet). In our network architecture, there is a regulator who determines the allocation of the transmission capacity among gateways in each time frame. We consider a static pricing scheme where the prices associated with different transmission priorities are pre-determined, and will not change with the variation of network traffic. During each time frame, gateways are intelligent to strategically select transmission priorities and rates (in kbps) according to their own medical signal severities. Based on the requirement for the medical-grade QoS, we design a mechanism which guarantees the absolute priority to each category of traffic (i.e., traffic in a lower priority level will be served only if all traffic with higher priority has been completely served). As a selfish buyer, each gateway may select a higher transmission priority and demand a higher transmission rate so as to obtain a better service and more benefits. However, choosing a higher transmission priority and transmitting in a higher rate will also be charged by a higher price. Therefore, gateways will compete with each other to make the optimal strategies. Considering that one base station is subscribed with a large number of gateways, we formulate such a decision process as a non-atomic pricing game [19], and analyze the equilibrium accordingly.

To the best of our knowledge, this work is the first that introduces the concept of network economics in the resource allocation for beyond-WBAN communications with the consideration of medical-grade priority. The main contributions of this paper are summarized as follows:

- A pricing-based capacity sharing scheme is proposed for the communications between multiple gateways and the base station of medical centers.
- Each gateway is allowed to determine its transmission priority based on its medical signal severity, so that the medical-grade priority is considered in the transmission scheduling.
- The strategy decision process is formulated as a non-atomic pricing game, and the corresponding Wardrop equilibrium is derived.
- Simulation results demonstrate the superiority of our proposed allocation scheme in improving the utilities of gateways under medical emergencies.

The rest of the paper is organized as follows: Section 2 presents a brief literature review of related works. Section 3 describes the proposed communication architecture and provides the justifications for the model we studied. A non-atomic pricing game is then formulated in Section 4 to investigate the decision process of gateways. The analysis of the Wardrop equilibrium is given in Section 5. Section 6 illustrates some simulation results, and Section 7 concludes the paper.

2. Related work

As an emerging medical service system, eHealth becomes increasingly popular in both scientific and industrial fields. For instance, the authors in [3] proposed an eHealth

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

Table 1
Comparison of existing related works.

Related works	Aimed networks	Medical priority	User intelligence
Torabi et al. [4]	Intra-WBANs	✗	✗
Reusens et al. [8]	Intra-WBANs	✗	✗
Kim et al. [9]	Intra-WBANs	✗	✗
Shi et al. [10]	Intra-WBANs	✗	✗
Lee et al. [13]	Intra-WBANs	√	✗
Meharouech et al. [21]	Inter-WBANs	✗	√
Ali et al. [22]	Intra-WBANs	√	✗
Rezvani et al. [23]	Intra-WBANs	√	✗
Misra et al. [24]	Beyond-WBANs	√	✗
Xue et al. [25]	Ad Hoc Networks	✗	√
Yi et al. [26]	Cognitive Radio	✗	√

monitoring system with minimum service latency and privacy preservation by using geo-distributed clouds. Kilic et al. in [20] designed a scalable superpeer-based peer-to-peer architecture to achieve inter-operability among healthcare communities. Moreover, as the basic element of eHealth networks, WBAN has been attracting a lot of research interests recently. For example, Torabi et al. in [4] studied an interference-aware and topology-aware cross-layer communication framework where the reliability and delay requirements of WBANs were jointly considered. In [8], the authors characterized the path loss of transmissions between sensors on different parts of the human body. The authors in [9] discussed a novel transmission power control protocol to extend the lifetime of sensor nodes and to increase the link reliability in WBANs. In [10], a novel node authentication scheme for WBANs was investigated with the exploitation of physical layer characteristics. Meharouech et al. in [21] introduced a game theoretical approach for interference-aware channel allocations in inter-WBANs with different access technologies, where the impact of co-channel and mutual interferences were taken into account. However, all these works were limited to either intra-WBAN or inter-WBAN communications only.

Furthermore, different from conventional wireless networks, the communications in eHealth systems impose some distinctions because of the unique characteristics of medical data. One major challenge is the consideration of medical-grade priority. In [13], the authors aimed to construct a wireless local area network for healthcare facilities, where signals were prioritized according to their medical severities. Ali et al. in [22] proposed an urgency-based medium access control protocol, in which sensors reporting urgent health information were given higher priority with the increase of channel access probability. The authors in [23] studied a context aware resource allocation in WBANs with traffic prioritization based on medical situations of users and channel conditions. Even though all these works realized the medical-grade priority for transmissions in the eHealth system, they were all designed for the intra-WBAN communications. Misra et al. in [24] investigated a priority-based time-slot allocation in medical emergencies, where the impact of medical-grade priority on beyond-WBAN communications was first mentioned. However, [24] mainly focused on the measurement of priorities, while the potentially heterogeneous requirements of gateways were not considered.

Generally, the beyond-WBAN communication refers to the physiological signal transmissions between on-body gateways and the remote medical center. Due to the intelligence and selfishness of each individual, the radio resource allocation (or transmission scheduling) among gateways has to be carefully studied. As a prospective approach, pricing-based sharing algorithms have been widely applied in various kinds of wireless networks to depict the behaviors of self-serving users [25–28]. For example, Xue et al. in [25] proposed a pricing-based resource allocation framework in wireless ad hoc networks to achieve optimal overall utilization and fairness among competing end-to-end flows. In [26], the authors analyzed the spectrum sharing issue in recall-based cognitive radio networks with combinatorial auction and Stackelberg pricing game. However, how to integrate the network economics in medical signal communications is still a novel and virgin area in research.

Table 1 summarizes all aforementioned works, and shows a clear gap in the literature regarding intelligent resource allocation for medical signal transmissions in beyond-WBANs. Our work tries to fill this gap by proposing a pricing-based capacity sharing scheme with medical-grade priority for beyond-WBAN communications.

3. Communication architecture

In this section, we illustrate our network design, and justify its feasibility and practicability. The system model under consideration is also described in details.

3.1. Network design

As the key component of the eHealth system, a WBAN consists of a gateway and a number of heterogeneous sensors worn on different parts of the body. Each sensor monitors one specific medical information, and transmits its sensed signal to the gateway. Such intra-WBAN communications have been defined in some existing standards, such as IEEE 802.15.4 [29] and IEEE 802.15.6 [30]. As a hub, the gateway collects all medical information from sensors, temporarily stores all data in its buffer (i.e., data storage), and then sends out the information to the remote medical center. Each gateway can identify the medical severities of its received signals, and determine the order of

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

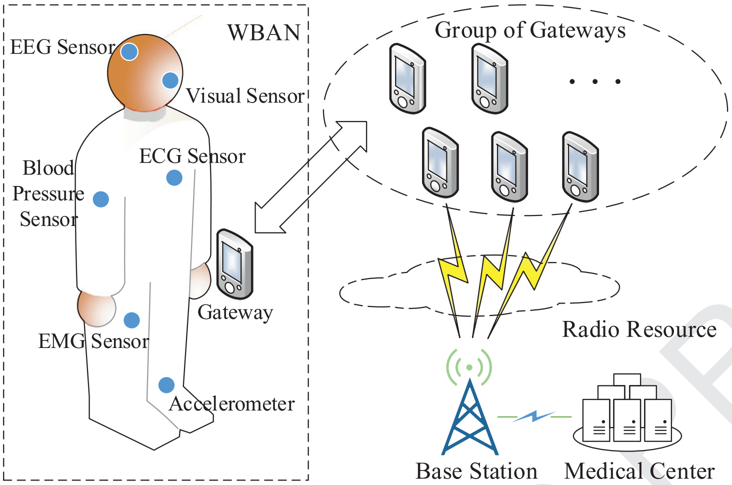


Fig. 1. An Illustration of the Network Architecture.

transmission. For explanation purpose, in this paper, we ignore the details of intra-WBAN communications and the local data processing by gateways, while focusing on the beyond-WBAN communications between gateways and the base station of medical centers.

The considered network architecture is illustrated in Fig. 1, where the base station of medical centers is subscribed with a large number of gateways. Gateways associated with the same base station form a group. Obviously, each gateway stands for one WBAN and all gateways in the same group will share the common radio resource to transmit their medical signals to the base station. Assume that there is a network regulator (e.g., the base station itself, or a third-party resource owner) who is responsible for determining the allocation of a fixed transmission capacity among gateways during each time frame. Each gateway decides its strategy based on its utility function, which is determined by the importance of its medical signal and the payment for transmission, and competes with other gateways for maximizing its own profit.

In addition, it is reasonable and applicable to charge gateways for medical data transmissions. In fact, we have paid for watching stream videos, downloading files, or sending emails with our smart devices through cellular networks. However, different from these existing wireless applications, gateways have to pay for not only the throughput they have experienced, but also the priorities they obtained. In beyond-WBAN communications, there are two kinds of priorities. One is the packet priority and the other is the transmission priority. They are not necessarily the same. Packet priority is determined by the severity of the sensed medical data (e.g., following the classification in IEEE 802.15.6 standard), while the transmission priority is selected by gateways strategically. For example, consider a gateway which wants to report an emergent medical signal to the base station. According to IEEE 802.15.6 standard, this information has the highest packet priority. However, the gateway may not select the highest transmission priority if the traffic from all other gateways has considerably low packet priorities (e.g., medical routine). In this case, the gateway may strategically choose a transmission priority just one level higher than the other traffic, so as to lower its transmission cost (which depends on the transmission priority) while still guaranteeing its medical-grade QoS. We further assume that all gateways are risk-neutral and individual rational, so that no gateway will make a strategy arbitrarily and without the consideration of its overall utility. In our proposed pricing mechanism, gateways will compete for selecting their transmission priorities exactly based on their packet priorities. Hence, medical-grade priority can be guaranteed in the transmission scheduling.

Note that for explanation purpose, we limit our radio resource allocation problem to capacity sharing only. However, this problem can be easily extended to bandwidth allocation given that signal-to-noise ratio (SNR) is fixed within one time frame. In this scenario, transmission capacity becomes a concave function (i.e., Shannon formula) of the bandwidth, and thus the proposed algorithm is still applicable except that the bandwidth should be transformed to the capacity through Shannon formula before calculating the utility for each gateway.

3.2. System model

Consider a network with a regulator who owns available transmission capacity C in one time frame. There is a set of gateways, $\mathcal{K} = \{1, 2, \dots, K\}$, associated with a base station of medical centers. During each time frame, each gateway is required to transmit one type of medical signals, while the medical signals transmitted by different gateways can be heterogeneous. Note that although each gateway may collect multiple types of medical data, it can store the data in the buffer and determine the order of transmission by itself.

At the beginning of the time frame, each gateway decides its transmission rate and priority according to its medical signal severity. Assume that the transmission priorities are selected from a discrete set $\mathcal{I} = \{1, 2, \dots, I\}$, where $j > i, \forall i, j \in \mathcal{I}$, if j indicates a higher transmission

Table 2
Important notations in this paper.

Symbol	Meaning
C	Total transmission capacity
$\mathcal{K}$	Set of gateways
$\mathcal{I}$	Set of transmission priorities
p_i	Unit payment for traffic with priority i
$\boldsymbol{x}_k$	Strategy decision vector of each gateway k
r_k	Transmission rate of each gateway k
ℓ_k	Transmission priority of each gateway k
$r(i)$	Aggregate traffic in each priority level i
$\theta(i, \boldsymbol{r})$	QoS for traffic in each priority i given $\boldsymbol{r}$
$\mathcal{G}_k(\cdot)$	Benefit of the achieved rate for each gateway k
c_k	cCoefficient of the penalty for each gateway k
$\mathcal{U}_k$	Utility of each gateway k

priority over i. Furthermore, there is a pre-determined unit payment $p_i > 0$ for capacity demand in each priority $i \in \mathcal{I}$. Intuitively, the demand with a higher priority should be charged more (because the traffic in a higher priority level can be granted with a better QoS). Thus, we have

$$p_j > p_i, \quad \text{if } j > i, \ \forall i, j \in \mathcal{I}. \tag{1}$$

Besides, similar to [31] and [32], we define that the price for each gateway is charged based on its original demand, i.e., demanded transmission rate and priority. Such pricing pattern can not only simplify the implementation, but also reduce the traffic congestion in medical networks. Obviously, if the payment is made according to the demand rather than the gain, no gateway will take the risk to send medical signals which are very trivial to the network (since they will be charged no matter whether they can be served or not).

For convenience, Table 2 lists some important notations used in this paper.

4. Pricing game formulation

In this section, the utility function of each gateway is first investigated. In order to guarantee the absolute priority in eHealth networks, we introduce a mechanism to determine the QoS for traffic in different priority levels. The decision process of gateways is then formulated as a non-atomic pricing game, and its corresponding Wardrop equilibrium is analyzed.

4.1. Utility functions of gateways

Let the decision strategy of each gateway $k \in \mathcal{K}$ be a vector denoted as $\boldsymbol{x}_k = (r_k, \ell_k)$, where $r_k \in [0, \infty)$ is its demanded transmission rate, and $\ell_k = 1, 2, \ldots, I$, indicates its selected transmission priority. Then, the aggregate traffic in each transmission priority $i \in \mathcal{I}$ from all gateways can be represented as

$$r(i) = \sum_{k \in \mathcal{K}, \ell_k = i} r_k, \quad \forall i \in \mathcal{I}. \tag{2}$$

We can further let $\boldsymbol{r} = (r(1), r(2), \ldots, r(I))$ be the aggregate traffic vector of the network.

Table 3
QoS requirements for some medical signals.

Medical applications	Required data rate
EEG	86.4 kbps
ECG	192 kbps
EMG	1.536 Mbps
Accelerometer	35 kbps
Pulse oximeter	16 bps
Glucose level monitor	1 kbps

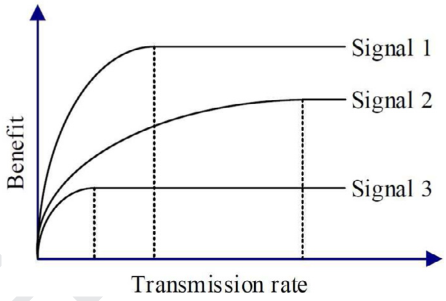


Fig. 2. Examples of *benefit* functions.

Given $\boldsymbol{r}$, we define a factor $\theta(i, \boldsymbol{r}) \in [0, 1]$ as the service satisfaction ratio for traffic with priority $i \in \mathcal{I}$. By considering the absolute priority rule, i.e., traffic with transmission priority i will be served only if all other traffic with priority $j > i$ has been served, we always have

$$\theta(j, \boldsymbol{r}) \geq \theta(i, \boldsymbol{r}), \quad \text{if } j > i, \ \forall i, j \in \mathcal{I}. \tag{3}$$

Note that $\theta(i, \boldsymbol{r})$ can directly reflect the QoS for traffic in each priority level i.

Given $\theta(i, \boldsymbol{r}), \forall i \in \mathcal{I}$, the transmission rate that each gateway $k \in \mathcal{K}$ will actually obtain can be calculated as $r_k \theta(\ell_k, \boldsymbol{r})$. Now, we can define the *benefit* for each type of medical signal as a function of its data transmission rate. Since each gateway can only transmit one type of signal in one time frame, the *benefit* can actually be defined as a function of the achieved rate by each gateway k, called $\mathcal{G}_k(\cdot)$. From the QoS requirements of some example medical signals as shown in Table 3 [11], we can expect that $\mathcal{G}_k(\cdot)$ will increase with the transmission rate, but the increasing trend will be reduced as the rate approaches the required value, till saturating at a certain bound. Obviously, such functions are non-decreasing, concave and bounded, as demonstrated in Fig. 2. Notice that, since *benefit* functions are related to the medical signals, they are heterogeneous among different gateways. Furthermore, due to the competition among gateways, we can also define a *penalty* for potential service degradation. Intuitively, if the demanded transmission rate cannot be completely satisfied, some packets will be dropped during the time frame. For explanation purpose, we consider the *penalty* as a linear function of the unsatisfied demanded rate with coefficient $c_k > 0$ for each gateway k so that the *penalty* can be mathematically expressed as $c_k r_k (1 - \theta(\ell_k, \boldsymbol{r}))$, where $1 - \theta(\ell_k, \boldsymbol{r})$ indicates the dissatisfaction ratio of the demanded rate.

With all above settings, we can formulate the utility function for each gateway $k \in \mathcal{K}$, called $\mathcal{U}_k$, which includes the *benefit* through its achievable transmission rate, the *penalty* for potential service dissatisfaction, and the

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

payment for demanded service. Namely,

$$\mathcal{U}_k = \mathcal{G}_k(r_k\theta(\ell_k, \mathbf{r})) - c_k r_k(1 - \theta(\ell_k, \mathbf{r})) - r_k p_{\ell_k}, \tag{4}$$

where the function $\mathcal{G}_k(\cdot)$ and the coefficient c_k are determined by the medical severity of the signal transmitted by each gateway. It is reasonable that $\mathcal{G}_k(\cdot)$ and c_k are only known to the gateway itself, and unknown to all other gateways and the network regulator.

From (4), each intelligent gateway may request a transmission in a higher priority level so as to gain more *benefit* and suffer less *penalty* with the increase of its service satisfaction ratio. However, doing so will also increase the payment since traffic with higher priority is more expensive. Thus, it is intuitive that each gateway will try to determine the best decision strategy to maximize its own utility.

Apparently, the decisions of gateways are not independent with each other because $\theta(i, \mathbf{r}), \forall i \in \mathcal{I}$ is related to the aggregate traffic allocation vector $\mathbf{r}$. Therefore, we have to first investigate the function of the QoS for traffic in different priorities with regard to the allocation strategies of all gateways. Given the total transmission capacity C, the allocation vector $\mathbf{r} = (r(1), r(2), \ldots, r(I))$, and the absolute priority rule in (3), all traffic in priority level i will be completely served if and only if the total traffic with priorities above i is less than or equal to the total available capacity, i.e.,

$$\sum_{j=i}^{I} r(j) \le C. \tag{5}$$

Thus, there is a threshold priority i_{th} such that (i) the traffic with priorities higher than it can be completely served, (ii) traffic with priority equal to i_{th} can only be partially served, and (iii) all other traffic with priorities lower than i_{th} will be completely dropped. Obviously, i_{th} satisfies the following conditions:

$$\sum_{j=i_{th}+1}^{I} r(j) \le C, \text{ and } \sum_{j=i_{th}}^{I} r(j) > C. \tag{6}$$

If the capacity for traffic in priority level i_{th}, i.e., $C - \sum_{j=i_{th}+1}^{I} r(j)$, is evenly distributed, the function of $\theta(i, \mathbf{r})$ for each priority $i \in \mathcal{I}$ can be defined as

$$\theta(i, \mathbf{r}) = \begin{cases} 1, & \text{if } \sum_{j=i}^{I} r(j) \le C, \\ \dfrac{C - \sum_{j=i+1}^{I} r(j)}{r(i)}, & \text{if } \sum_{j=i+1}^{I} r(j) \le C \\ & \text{and } \sum_{j=i}^{I} r(j) > C, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Let $\mathcal{R}(r_k\theta(\ell_k, \mathbf{r})) = \mathcal{G}_k(r_k\theta(\ell_k, \mathbf{r})) + c_k r_k \theta(\ell_k, \mathbf{r})$. Then, the utility function in (4) can be rewritten as

$$\mathcal{U}_k = \mathcal{R}(r_k\theta(\ell_k, \mathbf{r})) - (c_k + p_{\ell_k})r_k, \ \forall k \in \mathcal{K}. \tag{8}$$

Note that $\mathcal{R}_k(\cdot)$ is also non-decreasing and concave because the first term, $\mathcal{G}_k(\cdot)$, is a non-decreasing, concave function and the second term, $c_k r_k \theta(\ell_k, \mathbf{r})$, is a simple linear increasing function.

At the beginning of the time frame, each gateway declares a transmission rate which leads to the maximum utility if its service can be completely satisfied. In this case, the optimal value of r_k for each gateway k can be obtained by

$$\frac{\partial \mathcal{U}_k}{\partial r_k} = \mathcal{R}'_k(r_k) - (c_k + p_{\ell_k}) = 0, \text{ if } \theta(\ell_k, \mathbf{r}) = 1, \tag{9}$$

where $\mathcal{R}'_k(\cdot)$ represents the first-order derivative of $\mathcal{R}_k(\cdot)$ with respect to r_k.

Then, the optimal demanded rate of each gateway $k \in \mathcal{K}$ can be expressed as a function of the payment for its selected priority ℓ_k, i.e.,

$$r_k(p_{\ell_k}) = \begin{cases} \mathcal{R}'^{-1}_k(c_k + p_{\ell_k}), & \text{if } p_{\ell_k} \le \mathcal{R}'_k(0) - c_k, \\ 0, & \text{otherwise,} \end{cases} \tag{10}$$

where $\mathcal{R}'^{-1}(\cdot)$ is the inverse function of $\mathcal{R}'(\cdot)$. Eq. (10) meets the intuition that, if the payment, p_{ℓ_k}, is too high, the gateway k will not participate in the competition so that its demanded rate equals 0. From (9), we have $p_{\ell_k} = \mathcal{R}'_k(r_k) - c_k$. Moreover, since $\mathcal{R}_k(\cdot)$ is concave and $r_k > 0$, then $\mathcal{R}'_k(r_k) \le \mathcal{R}'_k(0)$. Thus, the condition for $r_k(p_{\ell_k}) \neq 0$ can be represented as $p_{\ell_k} \le \mathcal{R}'_k(0) - c_k$. Consequently, the decision of each gateway becomes $\mathbf{x}_k = (r_k(p_{\ell_k}), \ell_k), \forall k \in \mathcal{K}$. Considering that the payment for each priority level is pre-determined, $\mathbf{x}_k$ will only depend on ℓ_k.

4.2. Formulation of non-atomic game

With all settings in the previous subsection, gateways will compete with each other to maximize their utilities by strategically deciding their transmission priorities. Obviously, this results in a non-cooperative game.

By further considering the fact that in the eHealth system, one base station is normally associated with a large number of patients (gateways). Thus, the allocation decision of an individual gateway has little impact on the overall performance of the network. However, the aggregate effect of all gateways' decisions cannot be ignored, and may lead to significant changes on the QoS for traffic with different priorities. Naturally, gateways can observe the QoS for each priority level and change their decision strategies accordingly. In other words, the variations in $\theta(i, \mathbf{r}), \forall i \in \mathcal{I}$, will trigger the modifications on the strategy of each gateway, and the aggregate effect of strategy modifications will in turn change the determination of QoS for each priority level. Such back-and-forth interaction can be formulated as a non-atomic pricing game [33] and the corresponding Wardrop equilibrium is defined as follows.

Definition 4.1. Given that $\mathbf{x}_k^*$ is the strategy made by each gateway $k \in \mathcal{K}$, the strategy profile $(\mathbf{x}_1^*, \mathbf{x}_2^*, \ldots, \mathbf{x}_K^*)$ is an Wardrop equilibrium if for every gateway k, we have

$$\mathbf{x}_k^* = \arg\max_{\mathbf{x}_k} \{\mathcal{G}_k(r_k\theta(i, \mathbf{r}^*)) - c_k r_k(1 - \theta(i, \mathbf{r}^*)) - r_k p_i\},$$

where $\mathbf{r}^* = (r^*(1), r^*(2), \ldots, r^*(I))$ is the corresponding optimal aggregate allocation vector, i.e.,

$$r^*(i) = \sum_{k \in \mathcal{K}, \ell_k = i} r_k^*, \quad \forall i \in \mathcal{I}.$$

When this Wardrop equilibrium has been reached, no gateway will be willing to deviate its allocation decision.

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

5. Analysis of the equilibrium

In this section, we study the corresponding Wardrop equilibrium by first analyzing its properties, and then derive the necessary conditions for constructing a stable allocation.

To eliminate some trivial results, we make two basic assumptions:

- *Assumption 1:* The total traffic demand from all gateways selecting the lowest transmission priority is assumed to be always larger than the capacity limit, i.e.,

$$\sum_{k\in\mathcal{K}} r_k(p_1) > C.$$

Otherwise, the traffic demand from all gateways can be fully served even their declared transmission priorities are all at the lowest level. Obviously, there is a unique but trivial equilibrium for this case such that the optimal strategy for each gateway $k\in\mathcal{K}$ is $\boldsymbol{x}_k^* = (1, r_k(p_1))$.

- *Assumption 2:* When the unit payment for traffic with priority i is set as p_i, the demanded rate of each gateway k towards the payment p_i can be denoted as $r_k(p_i)$. Let $r(p_i) = \sum_{k\in\mathcal{K}} r_k(p_i)$. We assume that

$$r(p_i) > 0, \quad \forall i\in\mathcal{I}.$$

If this is not the case for some priorities, which means $r(p_i) = 0, \exists i\in\mathcal{I}$, then these priorities will not be selected by any gateway in the equilibrium. In other words, prices associated with these priorities are too high to all gateways. Without loss of generality, we ignore this trivial situation.

With the above two assumptions, we can expect that there is a transmission priority level i^* such that

$$\theta(i,\boldsymbol{r}^*)\begin{cases} =0, & \forall i<i^*,\\ >0, & \forall i\geq i^*,\end{cases} \tag{11}$$

which indicate that i^* is the threshold priority for the optimal allocation $\boldsymbol{r}^*$.

Now, assuming that the strategy decisions of all gateways are fixed except one gateway k, we can derive the following lemma.

Lemma 5.1. *For any gateway k, suppose that $\boldsymbol{x}_k^* = (r_k^*, \ell_k^*)$ is the optimal strategy for maximizing its utility, i.e.,*

$$\boldsymbol{x}_k^* = \arg\max_{\boldsymbol{x}_k=(r_k,\ell_k)} \{\mathcal{R}(r_k\theta(\ell_k,\boldsymbol{r}^*)) - (c_k+p_{\ell_k})r_k\}. \tag{12}$$

Then, we have

a) $r_k^*(p_{\ell_k}) = 0,\ \forall \ell_k\in\mathcal{I}\setminus\{i^*, i^*+1\}$.

b) $\theta(i^*,\boldsymbol{r}^*) \geq \dfrac{c_k+p_{i^*}}{c_k+p_{i^*+1}}$, *if* $r_k(p_{i^*}) > 0$.

c) $\theta(i^*,\boldsymbol{r}^*) \leq \dfrac{c_k+p_{i^*}}{c_k+p_{i^*+1}}$, *if* $r_k(p_{i^*+1}) > 0$.

Proof. As a non-atomic game, when the strategies of all other gateways are assumed to be fixed, the aggregate traffic allocation vector $\boldsymbol{r}^*$ will not be changed with $\boldsymbol{x}_k$. The utility function of gateway k can then be denoted as $\mathcal{U}_k(\boldsymbol{x}_k, \boldsymbol{r}^*)$. We can calculate the partial derivative of the utility with respect to r_k as

$$\mathcal{U}_k'(\boldsymbol{x}_k,\boldsymbol{r}^*) = \frac{\partial\mathcal{U}_k(\boldsymbol{x}_k,\boldsymbol{r}^*)}{\partial r_k} = \mathcal{R}_k'(r_k)\theta(\ell_k,\boldsymbol{r}^*) - (c_k+p_{\ell_k}),$$

where $\theta(\ell_k,\boldsymbol{r}^*)$ is only a function of ℓ_k.

If the best response of gateway k exists, we must have

$$\mathcal{U}_k'(\boldsymbol{x}_k,\boldsymbol{r}^*) \leq 0, \quad \forall \ell_k\in\mathcal{I}. \tag{13}$$

Given $\theta(i,\boldsymbol{r}^*) = 0, \forall i<i^*$ as stated in (11), we have

$$\mathcal{U}_k'(\boldsymbol{x}_k,\boldsymbol{r}^*) = -(c_k+p_{\ell_k}) < 0, \quad \forall \ell_k < i^*, \tag{14}$$

since both c_k and p_{ℓ_k} are positive. Furthermore, $\theta(i,\boldsymbol{r}^*) > 0, \forall i\geq i^*$ in (11) implies that $\theta(i,\boldsymbol{r}^*) = 1, \forall i\geq i^*+1$. Thus,

$$\mathcal{U}_k'(\boldsymbol{x}_k,\boldsymbol{r}^*) = \mathcal{R}_k'(r_k) - (c_k+p_{\ell_k}), \quad \forall \ell_k > i^*+1. \tag{15}$$

With the pricing rule in (1), we have $p_{\ell_k} > p_{i^*+1}, \forall \ell_k > i^*+1$, so that

$$\mathcal{R}_k'(r_k) - (c_k+p_{\ell_k}) < \mathcal{R}_k'(r_k) - (c_k+p_{i^*+1}). \tag{16}$$

This indicates that $\mathcal{U}_k'((\ell_k, r_k),\boldsymbol{r}^*) < \mathcal{U}_k'((i^*+1, r_k),\boldsymbol{r}^*)$. Since $\mathcal{U}_k'((i^*+1, r_k),\boldsymbol{r}^*) \leq 0$ according to the condition (13), we have

$$\mathcal{U}_k'((\ell_k, r_k),\boldsymbol{r}^*) < 0, \quad \forall \ell_k > i^*+1. \tag{17}$$

Based on (14) and (17), we can conclude that $\mathcal{U}_k'(\boldsymbol{x}_k,\boldsymbol{r}^*) < 0, \forall \ell_k\in\mathcal{I}\setminus\{i^*, i^*+1\}$, and thus the utility of gateway k is a decreasing function with r_k for all priority levels except i^* and i^*+1. As a result, we have $r_k^*(p_{\ell_k}) = 0, \forall \ell_k\in\mathcal{I}\setminus\{i^*, i^*+1\}$.

In addition, we may have $r_k^*(p_{\ell_k}) > 0$ for either $\ell_k = i^*$ or $\ell_k = i^*+1$. To satisfy the condition (13), when $r_k(p_{i^*}) > 0$, we have

$$\begin{aligned} \mathcal{U}_k'((i^*, r_k),\boldsymbol{r}^*) &= \mathcal{R}_k'(r_k)\theta(i^*,\boldsymbol{r}^*) - (c_k+p_{i^*}) = 0,\\ \mathcal{U}_k'((i^*+1, r_k),\boldsymbol{r}^*) &= \mathcal{R}_k'(r_k) - (c_k+p_{i^*+1}) \leq 0. \end{aligned}$$

From the above two equations, we can conclude that

$$\theta(i^*,\boldsymbol{r}^*) \geq \frac{c_k+p_{i^*}}{c_k+p_{i^*+1}}, \quad \text{if}\, r_k(p_{i^*}) > 0. \tag{18}$$

Similarly, when $r_k(p_{i^*+1}) > 0$, we have

$$\begin{aligned} \mathcal{U}_k'((i^*, r_k),\boldsymbol{r}^*) &= \mathcal{R}_k'(r_k)\theta(i^*,\boldsymbol{r}^*) - (c_k+p_{i^*}) \leq 0,\\ \mathcal{U}_k'((i^*+1, r_k),\boldsymbol{r}^*) &= \mathcal{R}_k'(r_k) - (c_k+p_{i^*+1}) = 0. \end{aligned}$$

Thus,

$$\theta(i^*,\boldsymbol{r}^*) \leq \frac{c_k+p_{i^*}}{c_k+p_{i^*+1}}, \quad \text{if}\, r_k(p_{i^*+1}) > 0. \tag{19}$$

In summary, Lemma 5.1 is proved. □

From Lemma 5.1, we can obtain some important properties (necessary conditions) of the Wardrop equilibrium, and can further prove its existence.

Proposition 5.1. *For all gateways in $\mathcal{K}$, if $(\boldsymbol{x}_1^*, \boldsymbol{x}_2^*, \ldots, \boldsymbol{x}_K^*)$ is an Wardrop equilibrium, then we have the following properties.*

i) $r_k^*(p_{\ell_k}) = 0,\ \forall \ell_k\in\mathcal{I}\setminus\{i^*, i^*+1\},\ \forall k\in\mathcal{K}$.

ii) $\min\left\{\dfrac{c_k+p_{i^*}}{c_k+p_{i^*+1}}\right\} \leq \theta(i^*,\boldsymbol{r}^*) \leq \max\left\{\dfrac{c_k+p_{i^*}}{c_k+p_{i^*+1}}\right\}$.

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

iii) $\sum_{k\in\mathcal{K}}\sum_{\ell_k\in\mathcal{I}} r_k^*(p_i)\theta(\ell_k, \boldsymbol{r}^*) = C.$

Proof. Property i) follows exactly the same argument as (a) in Lemma 5.1. Furthermore, since $\frac{c_k+p_{i^*}}{c_k+p_{i^*+1}}$ can be easily proved as an increasing function of c_k, property ii) can be directly observed from (b) and (c) in Lemma 5.1.

Now, according to property (i), we know that only priority level i^* and i^*+1 will be potentially used. Thus,

$$\sum_{k\in\mathcal{K}}\sum_{\ell_k\in\mathcal{I}} r_k^*(p_i)\theta(\ell_k, \boldsymbol{r}^*) = \sum_{k\in\mathcal{K}} r_k^*(p_{i^*})\theta(i^*, \boldsymbol{r}^*) + \sum_{k\in\mathcal{K}} r_k^*(p_{i^*+1}). \tag{20}$$

Moreover, with the function of QoS in (7), we have

$$\theta(i^*, \boldsymbol{r}^*) = \frac{C - \sum_{k\in\mathcal{K}} r_k^*(p_{i^*+1})}{\sum_{k\in\mathcal{K}} r_k^*(p_{i^*})}. \tag{21}$$

By substituting (21) into (20), property (iii) can be proved. □

From property (i) of Proposition 5.1, we can observe that only two priority levels, i.e., i^* and i^*+1, are potentially used by all gateways when the equilibrium is reached. The reason is actually intuitive. Remember that since all traffic submitted to the network will be charged, then no gateway is willing to declare a transmission priority less than i^* which will definitely result in a complete service dissatisfaction. In other words, no gateway wants to pay for 100% failure. On the other hand, declaring a transmission priority higher than i^*+1 will not produce a better service since priority i^*+1 can already guarantee 100% satisfaction. Thus, there is no incentive for a gateway to pay more money for the same service. Besides, property (ii) identifies the bound for the QoS of traffic in priority level i^*, and property (iii) shows the efficiency of the allocation, where all available capacity is fully utilized.

With this proposition, the following theorem can be proved by construction, which then indicates the existence of the equilibrium.

Theorem 5.1. *The formulated non-atomic game has at least one Wardrop equilibrium.*

Proof. The proof is provided in Appendix A. □

Recall the utility function of each gateway in (8), and consider the second term $(c_k + p_{\ell_k})r_k$ as the cost of each gateway $k\in\mathcal{K}$. Then, physically, we can imagine that a gateway will select transmission priority level i^*+1 if its penalty dominates the cost, which means that the gateway does not want to have any degradation on the satisfaction ratio (because its medical information is critical). On the other hand, if the cost is dominated by the payment, priority level i^* will be chosen, which indicates that the gateway is willing to suffer some QoS degradation rather than paying more money for a better service (because its medical information is not emergent). Even though the equilibrium point of this game may not have a closed-form expression, it can be found by applying the dynamic adaption algorithm [34]. The details of this algorithm will be presented in Section 6.1, and its convergence is analytically proved in Appendix B and numerically demonstrated in Section 6.2.

6. Simulation results

In this section, simulations are conducted to evaluate the performance of the proposed pricing-based capacity sharing scheme for beyond-WBAN communications. The convergence of the individual strategy making is first illustrated. Then, the impacts of the penalty and the payment on strategy decisions are investigated. Finally, the superiority of the proposed scheme under medical emergencies is demonstrated.

6.1. Simulation settings

Consider an eHealth system with $K = 30$ gateways sharing a capacity $C = 1000$ kbps (the average uplink transmission rate of 3G cellular networks [35]) in one time frame. In simulations, there are totally 10 priority levels, i.e., $\mathcal{I} = \{1, 2, \ldots, 10\}$, and the associated unit payment for each level is $0.1i + \Delta p, \forall i\in\mathcal{I}$, without loss of generality, where Δp is a uniform base payment which varies from 0.1 to 0.5. For each gateway k, its *benefit* from the achieved rate y is set as a non-decreasing, concave and bounded function $\mathcal{G}_k(y) = \alpha_k(1-\exp(-\beta_k y))$, where $\beta_k = 1/16$ for all gateways, and α_k is selected randomly in [50, 100], which indicates the upper bound of the *benefit* for each individual. Notice that, $\mathcal{G}_k(y)$ meets the required properties of WBAN applications since it increases with the transmission rate, but such increasing trend becomes flatter as the rate approaches to a certain limit. Similar observations can also be obtained by applying any other functions following same properties. In addition, the penalty coefficient c_k of each gateway is randomly chosen in [0, 3]. According to the adaption algorithm [34], each gateway starts with an arbitrarily initial strategy and then updates its decision at discrete time instances (i.e., iterations) to maximize its utility. Suppose that the adaptive variables are the gateways' estimations on the service satisfaction ratios of each priority level. At iteration τ, each gateway k will calculate its estimate $\hat{\theta}_k^{\tau}(i)$ for priority level $i\in\mathcal{I}$ as

$$\hat{\theta}_k^{\tau}(i) = \hat{\theta}_k^{\tau-1}(i) + \epsilon(\theta^{\tau-1}(i) - \hat{\theta}_k^{\tau-1}(i)), \ \forall k\in\mathcal{K}, \tag{22}$$

where ϵ is the adaption rate which is set to be 0.05. $\theta^{\tau-1}(i)$ represents the actual satisfaction ratio for priority level i in the previous iteration, and is a common knowledge in the current iteration. Thus, each gateway k updates its decision in iteration τ based on its estimated vector $(\hat{\theta}_k^{\tau}(1), \hat{\theta}_k^{\tau}(2), \ldots, \hat{\theta}_k^{\tau}(10))$. Without loss of generality, we let $\hat{\theta}_k^{0}(i) = 1, \forall i\in\mathcal{I}, k\in\mathcal{K}$, so that all gateways will start from the lowest priority level (since it is cheapest). The technical proof for the convergence of this adaption algorithm can be found in Appendix B.

In the following, numerical results are shown based on an average over 20 runs. Note that some parameters may vary according to evaluation scenarios.

6.2. Convergence of strategy decisions

Fig. 3 illustrates the convergence of gateways' decisions on transmission priorities. For clarity, we only plot

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

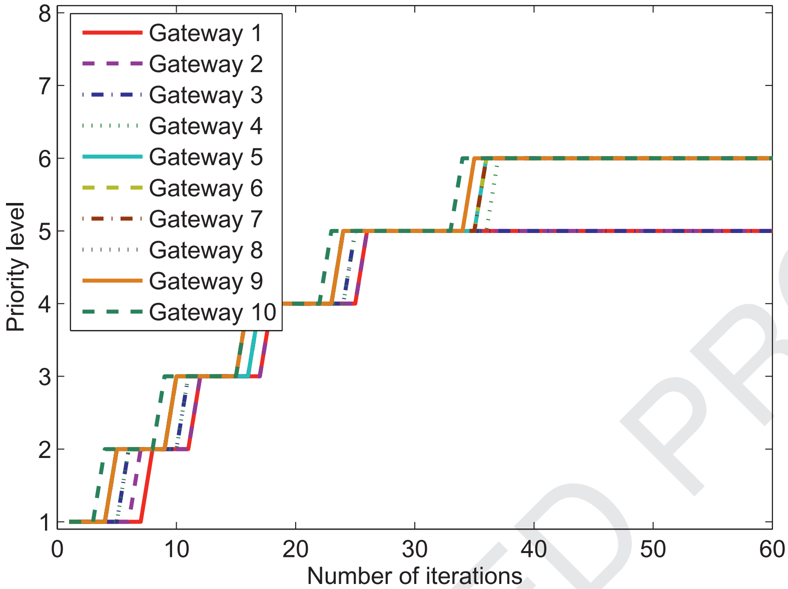


Fig. 3. The convergence of gateways' decisions on transmission priorities.

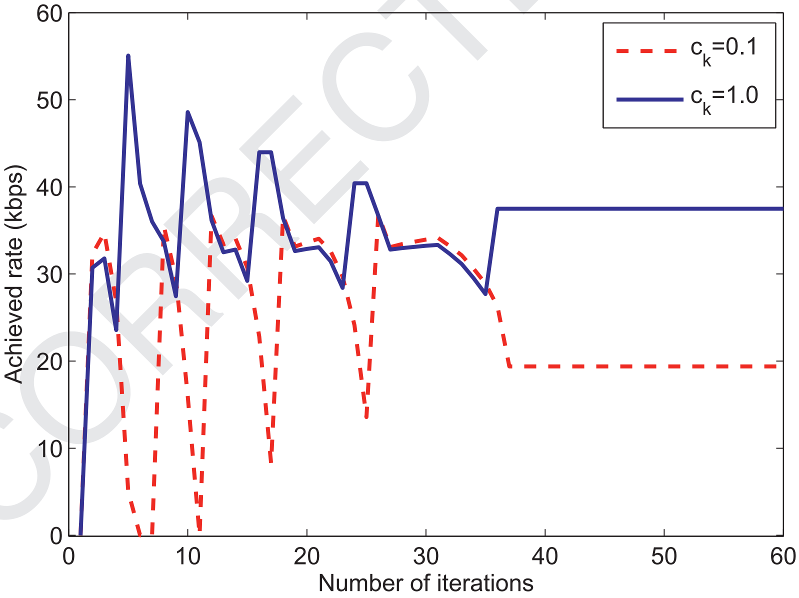


Fig. 4. The achieved rates of gateways with different penalty coefficients.

the variations of decisions made by 10 randomly selected gateways. In this figure, it is shown that all gateways initially start at the lowest transmission priority (i.e., priority level 1), update their decisions by increasing the priorities, and eventually converge to either priority level 5 or 6. Obviously, this trend satisfies the Proposition 5.1 that only two adjacent priority levels will be used when the system is stable. Moreover, we can also observe that the curves in Fig. 3 are stepwise. This is because the gateways with larger penalty coefficients will always adjust their decisions first, and then temporally stay at their chosen levels until the gateways with lower penalties update their decisions to the same level. When the equilibrium is reached, gateways with less important medical information will stop increasing their priorities from 5 to 6 (since a higher priority results in a larger payment), and the gateways with critical information will remain at priority level 6 (since there is no need to do any further increment).

Fig. 4 shows the convergence of the achieved data rates by two gateways with the same *benefit* function (i.e., the same α_k) but different penalty coefficients. In accordance with Fig. 3, both curves are converged after 37 iterations. In addition, before the system becomes stable, the achieved rates of gateways are highly fluctuating. The

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

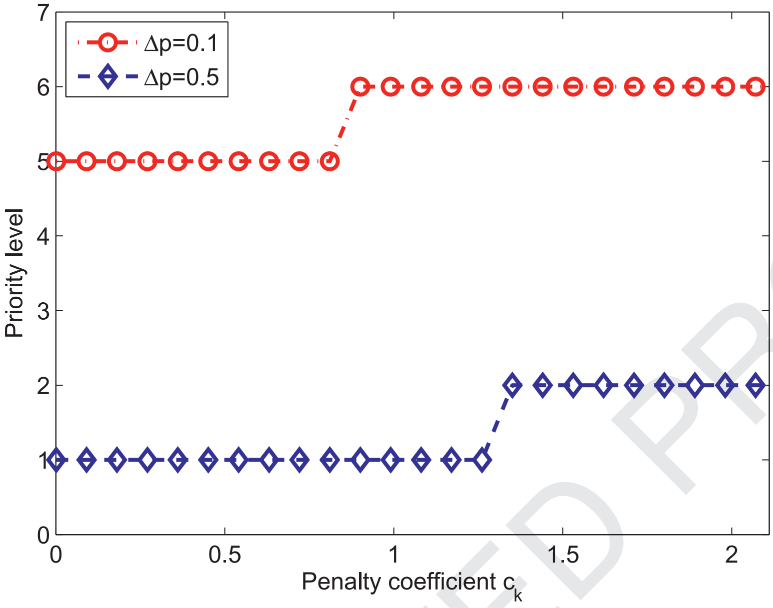


Fig. 5. The strategy decision of gateway k with different value of c_k.

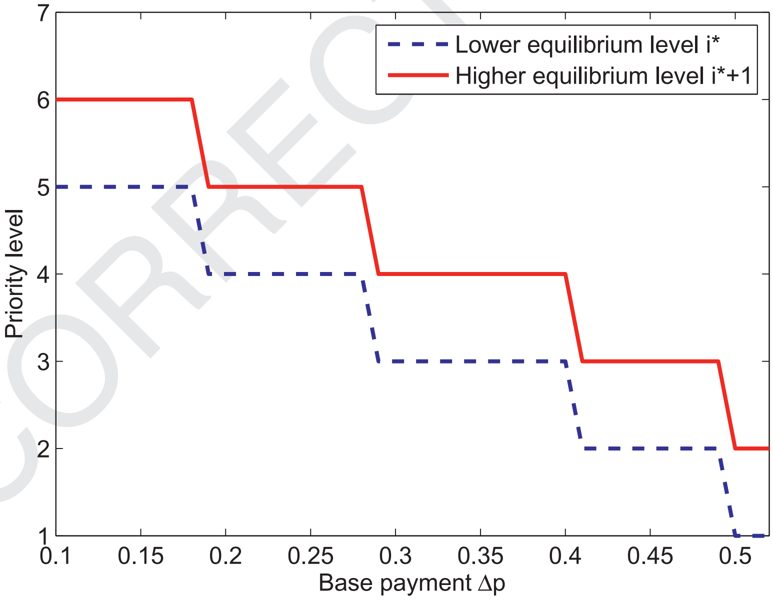


Fig. 6. The strategy decision of gateway k with different value of Δp.

reason is that the achieved rate is in fact determined by the product of the demanded rate and the received satisfaction ratio. When gateways select relatively low priority levels, they will demand high transmission rates according to (10). However, with the increasing number of gateways choosing the same priority level, the satisfaction ratio decreases so that the achieved rates will also decrease. In order to receive better services, gateways will then choose higher transmission priorities till they reach the equilibrium. Furthermore, Fig. 4 also shows that the gateway with more important information (i.e., a larger c_k) will finally achieve a higher transmission rate.

6.3. Impacts of penalty and payment settings

Fig. 5 examines the impact of the penalty coefficient c_k on the strategy decision of gateway k. Obviously, the transmission priority decided by gateway k has a sudden change from a lower level to the higher one when c_k increases. The explanation is as follows: when c_k is small (which means that the medical information is not emergent), the payment dominates the cost so that gateway k is willing to suffer more QoS degradation by choosing a cheaper priority level. However, after c_k increases over a threshold, the penalty will then dominate the cost so that

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

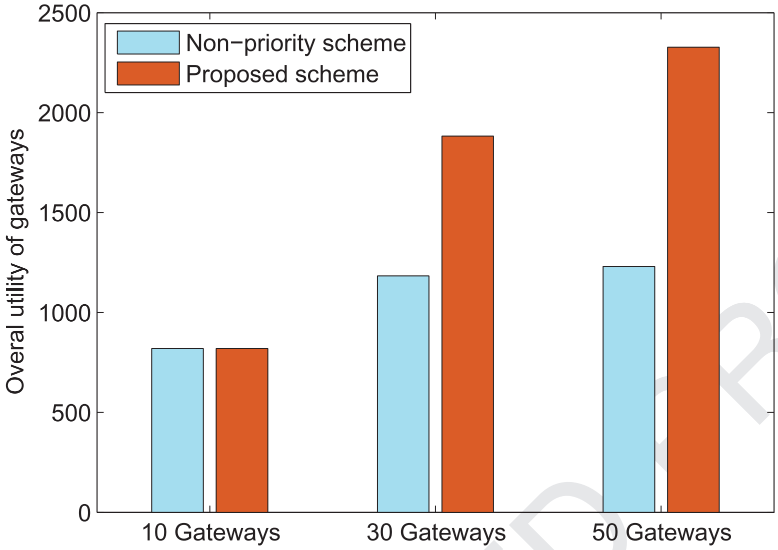


Fig. 7. The overall performance of the total utility with different amount of gateways.

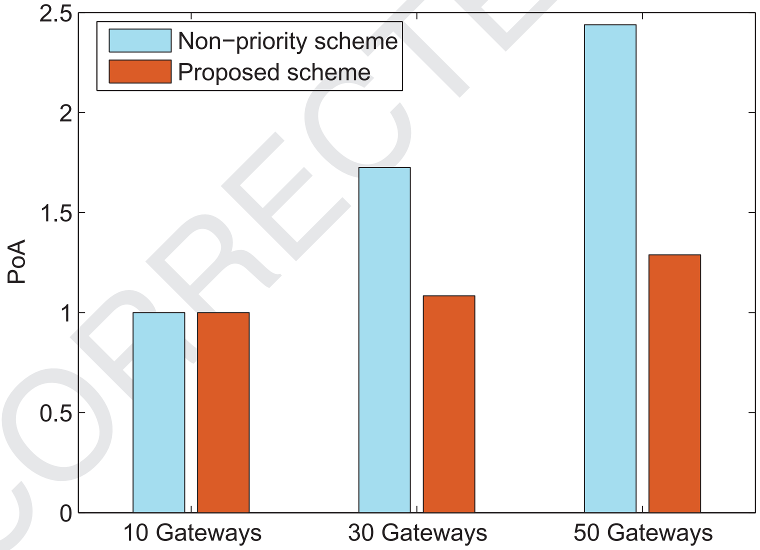


Fig. 8. The performance on PoA of different schemes.

gateway k changes its decision to the higher priority level in order to guarantee the service for critical data transmission. Besides, it is intuitive that the higher payment (i.e., larger Δp) leads to a later change of strategy decision. Furthermore, this figure also demonstrates that the equilibrium will be in lower priority levels when payments increase.

In Fig. 6, the relationship between the payment and the decision of an individual gateway is investigated. It is shown that the level of transmission priority selected by gateway k will decrease with the increase of Δp, which exactly matches the results in Fig. 5. This is because when gateways cannot afford the high payments, their decisions will automatically converge to lower priority levels. Note that such decreasing trend is not continuous but rather stepwise. It is intuitive since the gateway will not change its priority level when the variation of the payment is marginal.

6.4. Performance improvement of the proposed scheme

For comparison purpose, two existing allocation schemes, i.e., non-priority scheme [36] and priority-based proportional tuning [37], are simulated as benchmarks. Different from our proposed scheme, the non-priority scheme fairly distributes the capacity among gateways only based on their different demands, and the priority-based proportional tuning allocates capacity for each gateway proportionally according to the medical emergency of its packets.

Fig. 7 reveals the total utility with different amount of gateways in the system. When the system is underloaded

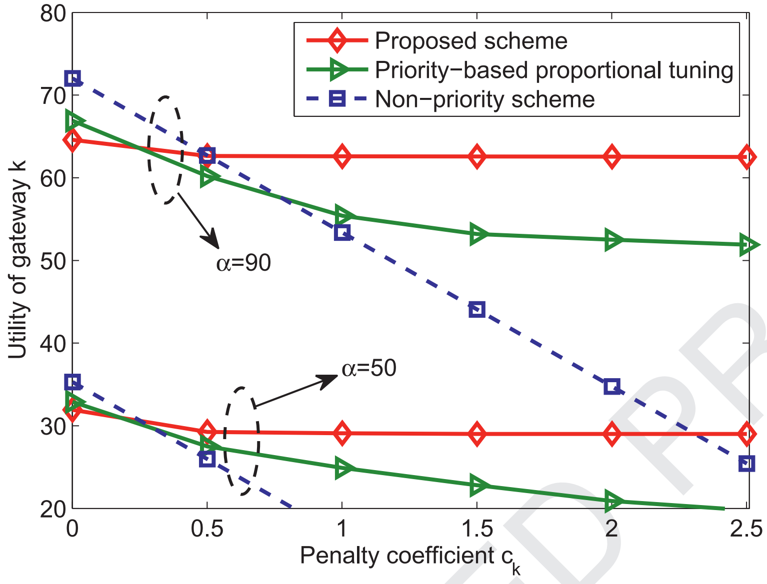


Fig. 9. The comparison of gateway *k*'s utility with different schemes.

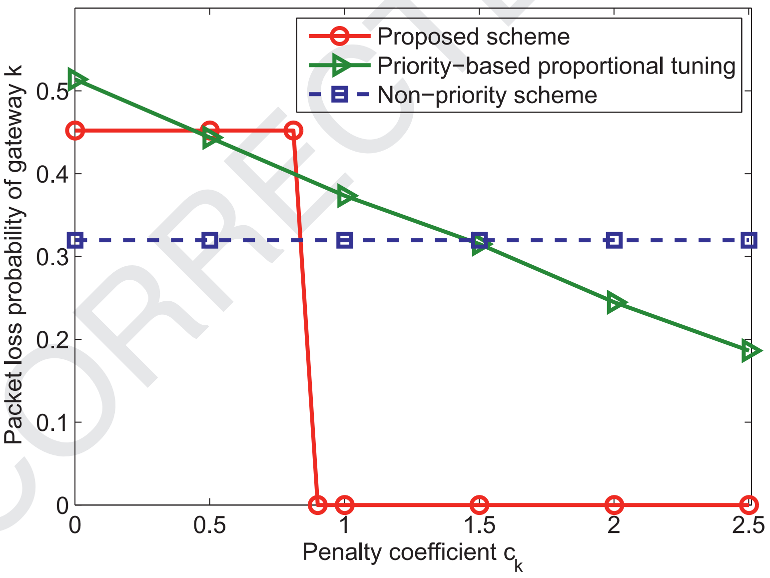


Fig. 10. The comparison of gateway *k*'s packet loss probability with different schemes.

(i.e., the case with 10 gateways) which means that the total traffic demand from all gateways is less than the available capacity, there is no difference between the non-priority allocation scheme and the proposed scheme since the demands of all gateways will be completely satisfied. However, when the system becomes overloaded (i.e., the cases with 30 and 50 gateways), the proposed scheme achieves a much higher utility than the non-priority scheme, and such superiority becomes more obvious when the number of gateways increases. This is because the non-priority scheme cannot guarantee the service satisfaction for critical data transmission under traffic congestions, which results in a large penalty. However, our proposed scheme can effectively balance the utility gain and the penalty by differentiating the transmission priorities of gateways according to their heterogeneous medical severities. The performance improvement of the proposed scheme can also be verified by comparing the Price of Anarchy (PoA) of different schemes as shown in Fig. 8, where the PoA is defined as the ratio between the total utility achieved by the optimal "centralized" solution and the one obtained by the equilibrium of the game, i.e., $(\sum_{k\in\mathcal{K}}\mathcal{U}_k)^{OPT}/(\sum_{k\in\mathcal{K}}\mathcal{U}_k(\boldsymbol{x}_k^*))^{Equilibrium}$. From this figure, we can see that the PoA of the proposed scheme is always smaller than that of the non-priority scheme, and its values are close to 1. This further demonstrates the superiority of our proposed scheme.

Fig. 9 compares the different allocation schemes in terms of the utility of an individual gateway. It can be seen from the figure that the curve of the non-priority scheme

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

declines significantly with the increase of the penalty coefficient c_k. While, the curve of the priority-based proportional tuning has a much slower decreasing trend because it employs the idea of relative priority [13] (which is proportional to the medical emergency). Note that the curve of the proposed scheme only decreases slightly and keeps stable for most range of c_k. This is because in the proposed scheme, the gateway's transmission will always be completely served if its medical information is considerably important (i.e., c_k is sufficiently large), and thus does not experience any penalty. However, when c_k is small, the non-priority scheme produces the highest utility since it ignores the medical-grade priority and grants the gateway a good service even though it is not important. In summary, we can conclude that our proposed scheme outperforms the other two schemes on gateways' utilities under medical emergencies. In addition, Fig. 9 also indicates that the higher bound (i.e., α_k) of *benefit* the gateway has, the more utility it can obtain.

Fig. 10 shows the packet loss probability of a selected gateway with the change of its packets' penalty coefficient c_k. For the non-priority scheme, since the service satisfaction ratio is the same for all transmissions, the packet loss probability remains unchanged for packets with different medical severities. Though the priority-based proportional tuning differentiates the transmission services for packets based on their criticality, the important medical packets still suffer a chance of packet loss. On the contrary, the proposed scheme guarantees zero packet loss probabilities for emergent medical signal transmissions (with larger penalty coefficients) because of the achievement of the absolute priority rule.

7. Conclusion

In this paper, a pricing-based resource allocation scheme for eHealth systems has been proposed. To characterize the feature of medical-grade priority in beyond-WBAN communications, we introduce the concept of network economics in the capacity sharing among multiple on-body gateways. The utility functions of gateways are formulated, and the strategy decision process is built up as a non-atomic pricing game. Theoretical and simulation results show that our proposed allocation scheme will produce an efficient Wardrop equilibrium, and can improve the utilities of gateways under medical emergencies.

In our future works, we will consider to extend the pricing scheme to a more complex scenario where the unit prices for traffics in different transmission priorities are strategic decisions of the base station. In addition, in order to prevent the untruthful behaviors from smart gateways (i.e., misreporting their packet severities), the design of incentive-compatible mechanisms for medical packet transmissions will also be discussed.

Acknowledgment

The authors would like to thank Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant and Engage Grant.

Appendix A. Proof of Theorem 5.1

Proof. According to our assumption that $r(p_1) > C$, and $r(p_0) = 0$ for p_0 which exceeds the acceptance ranges of all gateways, we are able to find a priority level i_0 such that $r(p_{i_0+1}) \leq C < r(p_{i_0})$. Again, let priority i^* satisfy the condition that $\theta(i, \boldsymbol{r}^*) = 0, \forall i < i^*$ and $\theta(i, \boldsymbol{r}^*) > 0, \forall i \geq i^*$. From the definition, we can clearly observe that i_0 and i^* are equivalent.

For notation simplicity, we define $\theta_k = \theta(\ell_k, \boldsymbol{r})$ as the service satisfaction ratio for all gateways $k \in \mathcal{K}$ which selects transmission priority ℓ_k. In this case, r_k can be considered as a function of θ_k as $r_k(\theta_k)$. With properties i) and ii) in Proposition 5.1, we can derive the expression of $r_k(\theta_k)$ as

$$r_k(\theta_k) = \mathcal{R}_k'^{-1}\left(\frac{p_{i^*} + c_k}{\theta_k}\right), \forall \theta_k \geq \min\left\{\frac{c_k + p_{i^*}}{c_k + p_{i^*+1}}\right\}.$$

Since $p_{i^*+1} > p_{i^*}$ and $c_k > 0$, we have

$$\frac{p_{i^*}}{p_{i^*+1}} < \min\left\{\frac{c_k + p_{i^*}}{c_k + p_{i^*+1}}, \forall k \in \mathcal{K}\right\}.$$

Thus, $r_k(\theta_k)$ is continuous on $\theta_k \in (p_{i^*}/p_{i^*+1}, 1)$. According to the function of θ_k in (7),

$$f(\theta_k) = \frac{C - \sum_{k\in\mathcal{K}} r_k(i^* + 1, \theta_k)}{\sum_{k\in\mathcal{K}} r_k(i^*, \theta_k)}, \quad \forall k \in \mathcal{K},$$

is also continuous on $(p_{i^*}/p_{i^*+1}, 1)$. We must be able to find $\theta_k^*, \forall k \in \mathcal{K}$, such that

$$f(\theta_k^*) = \frac{C - \sum_{k\in\mathcal{K}} r_k(i^* + 1, \theta_k^*)}{\sum_{k\in\mathcal{K}} r_k(i^*, \theta_k^*)} = \theta_k^*.$$

It is not difficult to prove that $(r_1(\theta_1^*), r_2(\theta_1^*), \ldots, r_K(\theta_1^*))$ satisfies all properties in Proposition 5.1. Therefore, the game has at least one equilibrium. □

Appendix B. Proof of convergence

Proof. The employed dynamic adaption algorithm (22) actually follows the *tâtonnement process* [38] for adjusting the estimated service satisfaction ratio to obtain the equilibrium. The corresponding decision of each gateway k will be updated, depending on whether its utility can be further increased or not, until the equilibrium priority level has been reached. Let $\hat{\theta}_k^s(i)$ denote the stable estimation for any gateway k at the equilibrium.

With the iteration τ increasing, the estimated $\hat{\theta}_k^\tau(i)$ changes accordingly. Suppose that the rate of such variation can be expressed as

$$\frac{\partial \hat{\theta}_k^\tau(i)}{\partial \tau} = g(\theta^{\tau-1}(i) - \hat{\theta}_k^{\tau-1}(i)) = g(\delta(\hat{\theta}_k^\tau(i))),$$

where $g' \geq 0$ and $\delta(\hat{\theta}_k^\tau(i)) = \theta^{\tau-1}(i) - \hat{\theta}_k^{\tau-1}(i)$. Intuitively, if such *tâtonnement process* is successful, we should have

$$\lim_{\tau\to\infty} \hat{\theta}_k^\tau(i) = \hat{\theta}_k^s(i),$$

which indicates that the adaption will converge to the equilibrium. To prove this, we can first expand the function $g(\delta(\hat{\theta}_k(i)))$ by Taylor series as

$$g(\delta(\hat{\theta}_k^\tau(i))) = g(\delta(\hat{\theta}_k^s(i))) + g'\delta'(\hat{\theta}_k^s(i))(\hat{\theta}_k^\tau(i) - \hat{\theta}_k^s(i)) + \cdots$$

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

where the higher orders are negligible.

Since $\delta(\hat{\theta}_k^s(i)) = 0$ by the definition of the adaption process, the above series can be rewritten as

$$g(\delta(\hat{\theta}_k^\tau(i))) = g'\delta'(\hat{\theta}_k^\tau(i) - \hat{\theta}_k^s(i)).$$

The solution of the above equation can be then derived as

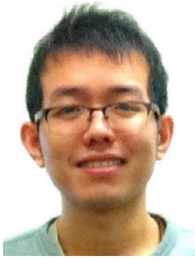
$$\hat{\theta}_k^\tau(i) = \hat{\theta}_k^s(i) + (\hat{\theta}_k^0(i) - \hat{\theta}_k^s(i))e^{(g'\delta')\tau},$$

where $\hat{\theta}_k^0(i)$ is the initial estimation.

Apparently, the assertion of convergence requires that $e^{(g'\delta')\tau} \rightarrow 0$ as $\tau \rightarrow \infty$. Since $g' \geq 0$, our remaining job is to prove that $\delta' < 0$. Recall that the initial value of $\hat{\theta}_k^0(i)$ is set as 1, and the strategy decision is a hill climbing process [39]. Thus, δ is always decreasing with the increase of τ, i.e., $\delta' < 0$. Therefore, in conclusion, the system with this dynamic adaption algorithm will converge to a stable equilibrium. ☐

References

[1] K. Christensen, G. Doblhammer, R. Rau, J.W. Vaupel, Ageing populations: the challenges ahead, Lancet 374 (2009) 1196–1208.
[2] M.J. Ball, J. Lillis, E-health: transforming the physician/patient relationship, Int. J. Med. Inform. 61 (1) (2001) 1–10.
[3] Q. Shen, X. Liang, X. Shen, X. Lin, H. Luo, Exploiting geo-distributed clouds for a e-health monitoring system with minimum service delay and privacy preservation, IEEE J. Biomed. Health Inform. 18 (2) (2014) 430–439.
[4] N. Torabi, V. Leung, Cross-layer design for prompt and reliable transmissions over body area networks, IEEE J. Biomed. Health Inform. 18 (4) (2014) 1303–1316.
[5] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, V. Leung, Body area networks: a survey, Mobile Netw. Appl. 16 (2) (2011) 171–193.
[6] D. Tobon, T. Falk, M. Maier, Context awareness in WBANs: a survey on medical and non-medical applications, IEEE Wirel. Commun. 20 (4) (2013) 30–37.
[7] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, A. Jamalipour, Wireless body area networks: a survey, IEEE Commun. Surv. Tutor. 16 (3) (2014) 1658–1686.
[8] E. Reusens, W. Joseph, et al., Characterization of on-body communication channel and energy efficient topology design for wireless body area networks, IEEE Trans. Inf. Technol. Biomed. 13 (6) (2009) 933–945.
[9] S. Kim, D.-S. Eom, Link-state-estimation-based transmission power control in wireless body area networks, IEEE J. Biomed. Health Inform. 18 (4) (2014) 1294–1302.
[10] L. Shi, M. Li, S. Yu, J. Yuan, Bana: Body area network authentication exploiting channel characteristics, IEEE J. Sel. Areas Commun. 31 (9) (2013) 1803–1816.
[11] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, R. Verdone, A survey on wireless body area networks: technologies and design challenges, IEEE Commun. Surv. Tut. 16 (3) (2014) 1635–1657.
[12] N. Torabi, V. Leung, Realization of public m-health service in license-free spectrum, IEEE J. Biomed. Health Inform. 17 (1) (2013) 19–29.
[13] H. Lee, K.-J. Park, Y.-B. Ko, C.-H. Choi, Wireless LAN with medical-grade QoS for e-healthcare, J. Commun. and Netw. 13 (2) (2011) 149–159.
Q3 [14] C. Yi, A. Alfa, J. Cai, An incentive-compatible mechanism for transmission scheduling of delay-sensitive medical packets in e-health networks, IEEE Trans. Mobile Comput. PP (99) (2015), doi:10.1109/TMC.2015.2500241.1–1
[15] A. Boulis, D. Smith, D. Miniutti, L. Libman, Y. Tselishchev, Challenges in body area networks for healthcare: the MAC, IEEE Commun. Mag. 50 (5) (2012) 100–106.
[16] B. Liu, Z. Yan, C.W. Chen, MAC protocol in wireless body area networks for e-health: challenges and a context-aware design, IEEE Wirel. Commun. 20 (4) (2013) 64–72.
[17] C. Gizelis, D. Vergados, A survey of pricing schemes in wireless networks, IEEE Commun. Surv. Tut. 13 (1) (2011) 126–145.
[18] C. Yi, J. Cai, Multi-item spectrum auction for recall-based cognitive radio networks with multiple heterogeneous secondary users, IEEE Trans. Veh. Technol. 64 (2) (2015) 781–792.
[19] D. Schmeidler, Equilibrium points of nonatomic games, J. Stat. Phys. 7 (4) (1973) 295–300.
[20] O. Kilic, A. Dogac, M. Eichelberg, Providing interoperability of ehealth communities through peer-to-peer networks, IEEE Trans. Inf. Technol. Biomed. 14 (3) (2010) 846–853.
[21] A. Meharouech, J. Elias, S. Paris, A. Mehaoua, A game theoretical approach for interference mitigation in body-to-body networks, in: Proceedings of the IEEE International Conference Communications - Workshop on ICT-enabled services and technologies for eHealth and Ambient Assisted Living, 2015, pp. 259–264.
[22] K. Ali, J. Sarker, H. Mouftah, Urgency-based MAC protocol for wireless sensor body area networks, in: Proceedings of the IEEE International Conference on Communications, 2010, pp. 1–6.
[23] S. Rezvani, S. Ghorashi, Context aware and channel-based resource allocation for wireless body area networks, IET Wirel. Sensor Syst. 3 (1) (2013) 16–25.
[24] S. Misra, S. Sarkar, Priority-based time-slot allocation in wireless body area networks during medical emergency situations: an evolutionary game-theoretic perspective, IEEE J. Biomed. Health Inform. 19 (2) (2015) 541–548.
[25] Y. Xue, B. Li, K. Nahrstedt, Optimal resource allocation in wireless ad hoc networks: a price-based approach, IEEE Trans. Mobile Comput. 5 (4) (2006) 347–364.
[26] C. Yi, J. Cai, Two-stage spectrum sharing with combinatorial auction and stackelberg game in recall-based cognitive radio networks, IEEE Trans. Commun. 62 (11) (2014) 3740–3752.
[27] C. Yi, J. Cai, Combinatorial spectrum auction with multiple heterogeneous sellers in cognitive radio networks, in: Proceedings of the IEEE International Conference on Communications, 2014, pp. 1626–1631.
[28] C. Yi, J. Cai, G. Zhang, Online spectrum auction in cognitive radio networks with uncertain activities of primary users, in: Proceedings of the IEEE International Conference Communicatins, 2015, pp. 7576–7581.
[29] IEEE standard for local and metropolitan area networks - part 15.4: low-rate wireless personal area networks (lr-wpans) amendment 4: alternative physical layer extension to support medical body area network (mban) services operating in the 2360 mhz 2400 mhz band, IEEE Std 802.15.4j-2013 (2013) 1–24.
[30] IEEE standard for local and metropolitan area networks - part 15.6: wireless body area networks, IEEE Std 802.15.6-2012 (2012) 1–271.
[31] V. Gajic, J. Huang, B. Rimoldi, Competition of wireless providers for atomic users, IEEE/ACM Trans. Netw. 22 (2) (2014) 512–525.
[32] P. Marbach, Analysis of a static pricing scheme for priority services, IEEE/ACM Trans. Netw. 12 (2) (2004) 312–325.
[33] N. Bonneau, M. Debbah, E. Altman, A. Hjorungnes, Non-atomic games for multi-user systems, IEEE J. Sel. Areas Commun. 26 (7) (2008) 1047–1058.
[34] X. Wang, H. Schulzrinne, Incentive-compatible adaptation of internet real-time multimedia, IEEE J. Select. Areas Commun. 23 (2) (2005) 417–436.
[35] R. Gass, C. Diot, An experimental performance comparison of 3G and Wi-Fi, in: Passive and Active Measurement, Springer, 2010, pp. 71–80.
[36] A. Parekh, R. Gallager, A generalized processor sharing approach to flow control in integrated services networks: the single-node case, IEEE/ACM Trans. Netw. 1 (3) (1993) 344–357.
[37] S. Misra, S. Moulik, H.-C. Chao, A cooperative bargaining solution for priority-based data-rate tuning in a wireless body area network, IEEE Trans. Wirel. Commun. 14 (5) (2015) 2769–2777.
[38] H.R. Varian, Microeconomic Analysis, WW Norton, 1992.
[39] S.S. Skiena, The Algorithm Design Manual: Text, vol. 1, Springer Science & Business Media, 1998.



Changyan Yi is a Ph.D. candidate in the Department of Electrical and Computer Engineering, University of Manitoba. He received the B.Sc. degree from Guilin University of Electronic Technology, China, in 2012, and M.Sc. degree from University of Manitoba, Winnipeg, MB, Canada, in 2014. He was awarded Edward R. Toporeck Graduate Fellowship in Engineering in 2014 and 2015, and University of Manitoba Graduate Fellowship (UMGF) in 2015–2018. His research interests include algorithmic game, optimization and queueing theories for radio resource management, prioritized scheduling and network economics in wireless communications.

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010

Zhen Zhao is currently working toward the M.Sc. degree in the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, Canada. He received the B.Sc. degree in communication engineering from Guilin University of Electronic Technology, China, in 2013. His research interests include wireless communication and energy management in wireless network.

Jun Cai received the B.Sc. and M.Sc. degrees from Xi'an Jiaotong University, China, in 1996 and 1999, respectively, and the Ph.D. degree from the University of Waterloo, ON, Canada, in 2004, all in electrical engineering. From June 2004 to April 2006, he was with McMaster University, as a NSERC Postdoctoral Fellow. Since July 2006, he has been with the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, Canada, where he is currently an Associate Professor. His research interests include energy-efficient and green communications, dynamic spectrum management and radio resource management in wireless communications networks, and performance analysis.

Ricardo Lobato de Faria received MB. BCh. from University of Witwatersrand, South Africa, in 1987, and M.B.A. from Athabasca University, Alberta, Canada, in 2014. He is currently the Chief Medical Officer and Emergency Medical Director of the Seven Oaks Hospital, Winnipeg, MB, Canada. His main interest is on how data can be integrated with strategies to enhance patient experience and improve flow in systems currently seen to work at or beyond capacity.

Gong (Michael) Zhang is an adjunct professor of applied computer science of University of Winnipeg and research director of Seven Oaks General Hospital Wellness Institute. He is also a research scientist in Rizhao Hospital of Traditional Chinese Medicine, China. His research is focused on big medical data analysis and development of biosensors of point of care system. In 2008 and 2009, he received the top awards for pulse wave analysis for cardiovascular health and H1N1 biosensor from the biomedical commercialization of Canada. He is currently working on developing new wearable system for chronic disease monitoring.

Please cite this article as: C. Yi et al., Priority-aware pricing-based capacity sharing scheme for beyond-wireless body area networks, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.01.010