Priority-Aware Cooperative Data Uploading in Body-to-body Networks for Healthcare IoT

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Abstract

The body-to-body network (BBN), which enables a group of wireless body area network (WBAN) users to collaborate and share their individual network resources, has emerged as a promised technology for the Internet of things (IoT)-based healthcare system. In BBN, WBAN users with good Internet connectivity act as gateway users and help their nearby WBAN users with poor Internet connectivity to upload their physiological data in exchange for incentives. The WBAN users are heterogeneous in terms of their data priority which depends on the criticality of medical data and require varying uplink transmission rates for uploading. Designing an incentive mechanism for such a scenario is very challenging because the data priority is a private information to the WBAN user. In this work, we propose an incentive scheme based on contract theory, to model the economic interaction between the gateway and requesting WBAN users and ensure priority-aware data uploading in BBN. First, the requesting WBAN users are categorized into different types based on their data priority. Thereafter, we formulate a contract design problem to maximize the payoff of gateway WBAN user while satisfying the requirements of requesting users. The gateway WBAN user offers a contract to requesting users and each requesting user selects it based on its type. Finally, the simulation results demonstrate that the proposed mechanism improves the payoffs of both the gateway and requesting WBAN users.

Index Terms

Healthcare IoT, Body-to-body networks, Data uploading, Resource allocation, Pricing, Incentive mechanism

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I. INTRODUCTION

The recent advances of the Internet of things in the healthcare domain has given rise to a new paradigm known as healthcare IoT (HIoT) [1], [2]. Wireless body area network (WBAN) is one of the core components of the HIoT architecture, which is useful for real-time remote monitoring of individual patients [3] and enabling m-health applications [4], [5]. The recent pandemic situation has created several new challenges for the existing healthcare systems worldwide and at the same time showing the importance of group-based healthcare monitoring from the existing individual patient-centric health monitoring [6]. Prominent examples include monitoring of patients quarantined in a room, healthworkers diagnosing group of critical patients admitted in the intensive care unit (ICU), and monitoring group of workers working heavy industry. In such scenarios, a group of WBAN users coexist in a geographical location and try to upload their physiological data to the Internet. One of the main challenges in group-based healthcare monitoring is to assure the desired quality-of-experience (QoE) to each individual WBAN user in the group [7]. This is because different WBAN users have different QoE requirements, such as uplink rate and uploading delay, based on their health conditions. To resolve this issue, researchers have proposed a *body-to-body network* (BBN) system that enables co-located WBAN users to form a cooperative group and share their network resources among each other for effective physiological data uploading [8]–[11]. The cooperative framework of BBN reduces the packet collision rate and retransmissions, minimizes the effect of interference due to coexistence and enhances the network reliability and overall throughput of the BBN [12]. Indeed, BBN is going to be one of the main components of the next generation HIoT systems and it is expected to be deployed for health monitoring in critical situations, such as in battle field for soldiers, inside deep mines, and fire-fighter monitoring.

In recent years, several works have emphasized on the importance of collaborative inter-WBAN data sharing. In [13], Keally et al. shown that inter-WBAN sensing data sharing not only reduces overall energy consumption, but also improves the accuracy of activity recognition of WBAN user. Further, modern healthcare applications allow users to share their diet, nutrition and fitness data with friends, healthcare experts [14]. Along with the data sharing, the BBN system accumulates multiple WBAN users' network resources (uplink bandwidth, battery energy) to satisfy the uploading demands of all participating WBAN users. A typical BBN is as a wireless mesh network that enables WBAN users to form a cooperative group and help each

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other in collaborative data uploading [15]. More specifically, the main aim of BBN is to enable WBAN users to exploit their neighboring WBAN users' resources for data uploading. In a BBN framework, each user can upload its own data and at the same time can help neighboring users to upload their data. Each WBAN user in BBN can act either as a requesting WBAN user, i.e. asking neighboring users for help, or gateway WBAN user, i.e. helping others to upload their data. Clearly, the success of BBN system depends on the willingness of the gateway WBAN users to help their neighboring requesting users [12]. Since the WBAN users are heterogeneous in terms of their healthcare severity, data privacy, uplink bandwidth, and energy sensitivity, there arises several novel techno-economic challenges for the BBN system.

A. *Motivation*

In a typical WBAN communication system, the medical data packets are categorized to priority level. Priority of a medical packet signifies the importance of the data and the value associated with it. For example, the priority of ECG data is higher higher than the body temperature data. According to the IEEE standard 802.15.6-2012 [16], which is specially designed to support WBAN communication, priority level of the medical packets are divided into eight levels. Based on the priority level, the uplink data rate requirement of the data is also different [17]. In this work, we focus on collaborative data uploading in BBN while considering the priority of each WBAN user. More specifically, to maintain QoE of the requesting WBAN users, the gateway users must have to consider the priority of the requesting WBAN users. However, there exists some challenges that should be addressed for priority-aware data uploading in BBN. First, the gateway WBAN users incur additional cost, such as energy cost and Internet access cost, when they agree to upload requesting WBAN user's data. Therefore, without proper incentives they will never agree to cooperate [18]. Thus, there is a need of proper *incentive mechanism* to enable collaborative data upload in BBN. Second, the priority of the medical data is a private information and the requesting WBAN users will be reluctant to disclose it. Since there is no central entity in BBN, the gateway WBAN users might not be aware of this private information of gateway users [19]. Therefore, it causes a scenario of *information asymmetry* between the gateway and requesting WBAN users. Further, the requesting WBAN users may behave strategically and misreport their priority to gateway WBAN users for benefiting themselves.

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B. Contribution

To address these above mentioned issues, in this work, we propose an efficient incentive mechanism for BBN system that encourages the gateway users to cooperate with the requesting WBAN users for data uploading under the information asymmetry scenario. In particular, we leverage the principles of contract theory [20] and proposed an incentive mechanism to deal with the information asymmetry. Contract theory is a well-known economic theory which is used to model the interaction between an employer who tries to offer proper contracts to employees whose skill set are unknown a priori [21]. In our BBN scenario, the requesting WBAN users are classified into different types based on their priority level. The gateway WBAN users design and offer contract to each requesting WBAN user. Each contract includes the amount of resource the gateway user willing to share and the corresponding payment. The requesting WBAN users accept the contract which is best for them. By designing the proper contract the actual type of requesting WBAN user will be revealed, and the information asymmetry between the gateway and the requesting WBAN user can be mitigated. The main *contributions* of the work are as follows:

- First, we develop the cooperative framework for data uploading in BBN system and systematically analyze the interactions between the gateway WBAN user and the requesting WBAN users. In the considered scenario, the priority level is requesting WBAN user's private information.
- Thereafter, we propose a contract-based incentive mechanism to motivate the gateway WBAN users to share their network resources to requesting WBAN users for data uploading under information asymmetry scenario.
- Further, we derive an optimal contract, i.e. the optimal resource sharing amount and the corresponding payment, that maximizes the profit of gateway WBAN user while satisfying economic properties, such as incentive compatibility and individual rationality, of the requesting WBAN user.
- Finally, through extensive numerical results we show the effectiveness of the proposed incentive mechanism in terms of maximizing the overall performances of the BBN system.

II. RELATED WORKS

Recently, BBN-based group healthcare monitoring is attracting growing interest. In BBN, different WBAN users can upload their medical data to Internet simultaneously through collab-

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orative resource sharing and encounter several unique techno-economic challenges. A complete overview on BBN architecture, application, and design considerations is presented in [8]. Arbia et al. in [11] discussed the communication challenges of BBN and focused on the interference management, signal propagation on on-body channel, data dissemination, and routing aspects in BBN. Further, the authors have evaluated the end-to-end delay for BBN communication on a real testbed. Hammod et al. in [15] analytically shown that BBN improves the overall outage probability and energy efficiency than the case where there is no cooperation among coexisting WBAN users. A BBN framework having Zigbee protocol for inter-WBAN communication was proposed in [22]. In [10], authors proposed a cross-layer optimized routing protocol for BBN. Apart from focusing on BBN routing protocols, in [23], Mu *et al.* proposed a self-organized clustering mechanism and spectrum allocation mechanism for BBN scenario to maintain the QoS of each WBAN user. Keally *et al.* [13] proposed a smartphone-based application, namely Remora, which enables physiological data sharing in BBN for activity recognition while minimizing energy dissipation of participants. All the participating WBAN users data are of same priority level.

All the above-mentioned works focus primarily on technical aspect of BBN. Different from that some of works focused on the economic issues of BBN. In [24], a game-theoretic approach is proposed to mitigate cross-technology interference in BBN and the work is further extended to two-stage game theoretic model in [25]. In [12], authors modeled the resource sharing problem in BBN using Stackelberg game. In the proposed game model, the requesting WBAN users first set the reimbursement amount and based on that the gateway WBAN users decide the uploading data amount. Further, in [9] the authors proposed an auction-based mechanism for cooperative data uploading in BBN.

Synthesis:None of the works considered the priority of the medical data. Since the priority of medical data is private information for a requesting WBAN user, it can misuse it for its own benefit. Therefore, the above-mentioned mechanisms are not directly applicable to BBN. Therefore, to address these issues we propose an incentive mechanism scheme for BBN to enable resource sharing among participating WBANs, while considering the priority of medical data.

III. SYSTEM MODEL

We consider a BBN system consisting of set of $\mathcal{N} = \{1, 2, \ldots, N\}$ WBAN users as shown in Figure 1. Among them there are G gateway WBAN users and R requesting WBAN users, where

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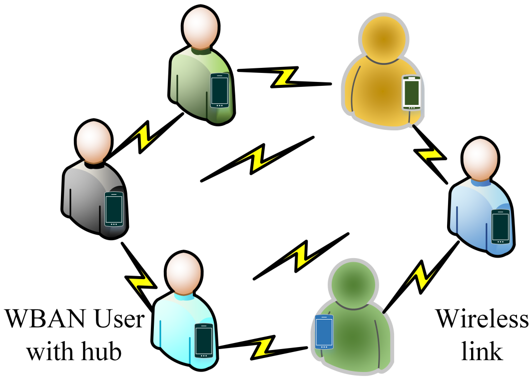

Figure 1: Illustration of BBN framework

$N = G + R$. We represent the set of gateway and requesting WBAN users as $\mathcal{G} \triangleq \{1, 2, \ldots, G\}$ and $\mathcal{R} \triangleq \{1, 2, \ldots, R\}$, respectively. We mainly focus on the uploading performance of BBN system, i.e., when the WBAN users upload their data to the Internet. The requesting WBAN users forward their data to the nearest gateway WBAN user for uploading. The communication link between a requesting WBAN user and gateway WBAN user is either through WiFi, Zigbee, or Bluetooth technology. We assume that each requesting WBAN user can be associated with at most one gateway WBAN user within its proximity. Let $\mathcal{R}_g \triangleq \{1, 2, \ldots, R_g\}$ denote the set of requesting WBAN user connected to the gateway user $g \in \mathcal{G}$ at any given time instant. In this paper, our main objective is to design an incentive mechanism to motivate gateway WBAN user to upload data of requesting users connected with it in exchange for reimbursement. We adopt a time-slot model in which the time horizon is divided into discrete time slots and our focus is on the BBN operations over a slot time duration.

Requesting WBAN users are highly heterogeneous in terms of their medical data priority and timeliness. Data priority is determined by the severity of the sensed physiological data [17]. The IEEE 802.15.6 standard which is especially designed for WBAN communication introduces eight different user priorities based on the traffic designation. Further, different priority of data require different uplink bandwidth for beyond-WBAN transmission. Data timeliness is considered as an another important aspect of medical data. The data timeliness is defined as the time interval for which the information carried by the medical packet is valid. For example, the electrocardiogram (ECG) data and respiratory data which are sensed continuously have shorter timelessness, i.e. more prone to become outdated. Clearly, the requesting user benefit when the gateway WBAN user agrees to upload its data. The benefit (utility) of requesting WBAN user is dependent on

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its data priority. The requesting WBAN user with high priority data gains more benefit than the user having lower priority of data. The gateway WBAN user charges to requesting WBAN user for this uploading service. The priority of the medical data is a private information and is only known to the requesting WBAN user. The requesting WBAN user may misreport their priority of medical data to gain some additional benefit from the gateway WBAN user. Therefore, there occurs information asymmetry between the gateway WBAN user and the requesting user. To overcome this challenge we use contract theory to investigate the interaction between gateway and requesting WBAN user and help the gateway WBAN user design a proper incentive mechanism for utility maximization. Table I provides a summary of notations used in the paper.

A. Contract Model

The gateway WBAN user $g \in \mathcal{G}$ offers contract consisting of priority type and corresponding price to the set of connected requested WBAN user $\mathcal{R}_g$. The gateway WBAN user provides different uplink rate for different data priority and charges different prices accordingly. The requesting WBAN user chooses the contract item which maximizes its utility given the payment. We classify the requesting WBAN users based on its data priority. Let there are I types of data priority, which are denoted by

$$\theta_1 < \theta_1 < \ldots < \theta_I \tag{1}$$

Based on the IEEE 802.15.6 standard [16], we consider eight types of priority, i.e. $I = 8$. A higher value of θ signifies that the requesting WBAN user posses high priority medical data. The gateway WBAN user is unaware of the exact type of requesting WBAN user. However, it can has the knowledge of the probability that the requesting WBAN user belongs to the type-θ_i. Let ζ_i denote the probability that a requesting WBAN user belongs to type-θ_i and $\sum_{i=1}^{I} \zeta_i = 1$.

The gateway WBAN user offers different contract to different requesting WBAN users according to its type. The contract designed by the gateway WBAN user for requesting user of type-θ_i is $(q_i(\theta_i), \pi_i(\theta_i))$, where $q_i(\theta_i)$ denote the uplink rate assigned for type-θ_i and $\pi_i(\theta_i)$ is the corresponding price charged. The requesting WBAN users are free to accept or decline the contract. If the requesting WBAN user declines to the contract, the value of contract is $(q_i, \pi_i) = (0, 0)$.

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Table I: Basic Notations

Symbol	**Physical Meaning**
N	Number of WBAN users
G, R	Number of gateway and requesting WBAN users
R_g	Number of requesting WBAN users connected to gateway user g
θ_i	Type of requesting WBAN user i
ζ_i	Probability distribution of type-θ_i
q_i	Uplink rate assigned for user i
π_i	Price charged to user i
V_i	Total data size of user i (in bytes)
D_i^{max}	Delay deadline
d_i^u	Uploading delay of user i
d_i^{tx}	Inter-BBN transmitting delay
β	Scaling parameter
ϱ_i	Severity index of WBAN user i
$C_i(\cdot)$	Cost of gateway WBAN user
$e_i^u(\cdot)$	Uploading energy cost of gateway user
$\chi_i^u(\cdot)$	Internet access cost of gateway WBAN user
$U_{GU}(\cdot)$	Payoff of gateway WBAN user
$U_{RU}(\cdot)$	Payoff of requesting WBAN user
$\Psi(\cdot)$	Social welfare function

B. *User model*

Now we first define the utility of gateway WBAN user when they offer service to the requesting WBAN users. Thereafter, we model the utility of requesting WBAN user when they choose the contract.

1) Gateway WBAN user payoff: The main objective of the gateway WBAN user is to maximize its payoff by offering contract, i.e. (q_i, π_i), to the requesting WBAN users. The payoff of the gateway WBAN user consists of two parts. First, the payment it receives from the requesting WBAN users for offering the service, i.e. π_i . Second is the cost in incurs for providing the uploading service. The cost of the gateway WBAN users includes the uploading energy cost and the Internet access cost. The total cost of the gateway WBAN user for uploading data of type-θ_i requesting WBAN user is

$$C_i(q_i) = e_i^u(q_i) + \chi_i^u(q_i) \tag{2}$$

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where $e_i^u(q_i)$ denote the uploading energy cost and $\chi_i^u(q_i)$ is the Internet access cost of gateway WBAN user for uploading data of type-θ_i. Note that, both $e_i^u(q_i)$ and $\chi_i^u(q_i)$ are increasing function of q_i and the overall cost of gateway WBAN users increases with q_i.

Since there are I types of requesting WBAN users with probability ζ_i, the expected payoff of gateway WBAN user is

$$U_{GU}(\mathbf{q}, \boldsymbol{\pi}) = \sum_{i=1}^{I} \zeta_i(\pi_i - C_i(q_i)) \tag{3}$$

where $\mathbf{q} = [q_1, q_2, \dots q_I]^T$ is the uplink rate assigned for requesting user of type-θ_i and $\boldsymbol{\pi} = [\pi_1, \pi_2, \dots \pi_I]^T$ is the corresponding payment.

2) Requesting WBAN user Payoff: The payoff of the requesting WBAN user is defined as the difference between the satisfaction it obtained due to the cooperation of gateway WBAN user and the price it for the service. The requesting WBAN user always desires to upload its data in a timely manner. This is because the medical data are highly time sensitive in nature and its medical value increases with the increase in delay [12]. Further, users having high priority data are more sensitive to the potential delays in data uploading. In our work, we define a satisfaction function for each requesting WBAN user which is based on its type, i.e θ_i and is a function of timeliness of the data. Let S_i denote the satisfaction function of requesting WBAN user of type-θ_i and is defined as

$$S_i(q_i) = \beta_i(D_i^{max} - d_i^u(q_i) - d_i^{tx}) \tag{4}$$

where D_i^{max} is the delay deadline of the medical data, i.e., the maximum tolerable delay limit. The second term d_i^u is the uploading delay, i.e. $d_i^u = V_i/q_i$, where V_i is the total data size transmitted by the requesting user to the gateway WBAN user. The third term d_i^{tx} is the inter-BBN propagation delay, i.e. the transmission delay of the communication link between the requesting user and the gateway WBAN user. Finally, β_i is a scaling parameter which captures the unit profit that requesting WBAN user obtains per delay saving. Clearly, with increase in uplink rate (q_i), the uploading delay decreases and thereby the satisfaction of the requesting WBAN user increases. From Equation (4), we observe that the satisfaction function, $S_i(q_i)$, is a non-decreasing and concave function of uplink rate q_i.

Further, each requesting WBAN user chooses its contract based on its type-θ_i. Based on the contract, the requesting WBAN user of the type-θ_i pays amount π_i to the gateway user. Thus,

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the total payoff of the type-θ_i requesting WBAN user is

$$U_{RU}^{i}(q_i, \pi_i) = \theta_i S_i(q_i) - \pi_i \tag{5}$$

3) Social Welfare: The social welfare is the summation of the payoffs of the gateway WBAN user and all the requesting users, i.e.

$$\begin{aligned}\Psi(\mathbf{q}) &= U_{GU}(\mathbf{q}, \boldsymbol{\pi}) + \sum_{i=1}^{I} U_{RU}^{i}(q_i, \pi_i) \\ &= \sum_{i=1}^{I} \theta_i S_i(q_i) - \sum_{i=1}^{R_g} \zeta_i C_i(q_i)\end{aligned} \tag{6}$$

Since the payment term is canceled each other, the social welfare is function of only q_i.

4) Contract Formulation: As discussed above, the type-θ is a private information for requesting WBAN user and may misreport it. The gateway WBAN user is unaware of the type and needs to design a contract that is suitable for the requesting WBAN user. According to contract theory [26], a feasible contract must satisfy two important economic properties — individual rationality (IR) and incentive compatibility (IC). The IR property ensures that the contract item that requesting user chooses ensures non-negative payoff, i.e., for type-θ_i requesting WBAN user

$$U_{RU}^{i}(q_i, \pi_i) = \theta_i S_i(q_i) - \pi_i \geq 0 \tag{7}$$

The IC property ensures that the requesting WBAN user can obtain maximum payoff if and only if it selects the contract designed specifically for its type, i.e.,

$$\theta_i S_i(q_i) - \pi_i \geq \theta_i S_j(q_j) - \pi_j, \quad i, j \in \mathcal{I}, i \neq j \tag{8}$$

Clearly, the IR constraint shows that the requesting WBAN user will not accept the contract which incurs negative payoff for itself. Along with that, the IC constraint guarantees incentive to requesting WBAN user to reveal its type truthfully by choosing the appropriate contract. Thus, these two economic properties should be satisfied for the formulation of a feasible contract [27].

The main objective of the gateway WBAN user to design a contract in such away that it

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maximize its own payoff while satisfying the above IR and IC economic constraints, i.e.,

$$\max_{\mathbf{q},\boldsymbol{\pi}} \quad U_{GU} = \sum_{i=1}^{I} \zeta_i(\pi_i - C_i(q_i)) \tag{9}$$
$$\text{Subject to}: (7), (8)$$

The above optimization problem is difficult to solve due to the presence of the complicated constraints. A thorough analysis on the solving of the optimal contract problem while satisfying both the IR and IC constraints of the requesting WBAN users is presented in the next section.

IV. OPTIMAL CONTRACT DESIGN

In this section, we solve the gateway WBAN user's optimal contract design problem. A contract is said to be *optimal* it maximizes the payoff of the gateway WBAN user [26]. However, the optimal contract is different for different information scenarios. In our case, we have considered two scenarios depending on whether the type of the requesting WBAN user is known to the gateway WBAN user. First is the *complete information scenario*, where the gateway WBAN user knows the priority type of the requesting WBAN user. Second is the *asymmetric information scenario*, where the gateway WBAN user is unaware of the type of the requesting WBAN user and only knows the probability with which the requesting WBAN user belongs to a certain type. A complete theoretical analysis on how to design optimal contract for both the scenarios is presented in this section.

A. Complete Information Scenario

In this subsection, we derive the optimal contract for the scenario where the gateway WBAN user knows precisely the priority type of the requesting WBAN user beforehand. However, in practical scenario, this assumption may not be valid, since the requesting WBAN user may not reveal its private information to the gateway WBAN user [28]. The maximum payoff obtained by the gateway WBAN user in this scenario is considered as a benchmark to compare the performance in asymmetry information scenario.

As the gateway WBAN user is aware of the type of the requesting WBAN user, it offers contract (q_i, π_i) to the type-θ_i requesting WBAN user. This ensures that the IC property is satisfied. Since the requesting WBAN user is rational, it accepts the contract only when it obtains

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non-negative payoff. Thus, the optimal contract design problem will have only IR constraint. The optimal contract problem in complete information scenario is,

$$\max_{\mathbf{q},\boldsymbol{\pi}} \quad U_{GU} = \sum_{i=1}^{I} \pi_i - C_i(q_i) \tag{10}$$
$$\text{Subject to} : \theta_i S_i(q_i) - \pi_i \geq 0$$

The above constrained optimization can easily be transformed to an unconstrained optimization problem. For that, first we transform the inequality constraint to equality constraint using the method proposed in [26]. Let the type-θ_i requesting WBAN user chooses a contract which results $\theta_i S_i(q_i) - \pi_i > 0$. In that case the gateway WBAN user maximizes its payoff by increasing π_i till the payoff of requesting WBAN user equal to zero, i.e. $\theta_i S_i(q_i) - \pi_i = 0$. In that case the IR constraint is still satisfied. Now, substituting this equality constraint in the objective function of the optimization problem (10), the unconstrained optimization problem is

$$\max_{\mathbf{q}} \quad U_{GU} = \sum_{i=1}^{I} \theta_i S_i(q_i) - C_i(q_i) \tag{11}$$

Now taking first-order derivative of the objective function (U_{GU}) with respect to q_i, we get

$$\frac{dU_{GU}}{dq_i} = \frac{\theta_i \beta_i V_i}{q_i^2} - C_i^{'}(q_i) \tag{12}$$

We can find the optimal solution of the problem by taking the first order derivative to 0. The optimal solutions are:

$$q_i^* = \sqrt{\frac{\theta_i \beta V_i}{C_i^{'}(q_i)}}, \quad \pi_i^* = \theta_i \beta \big(D_i^{max} - \sqrt{\frac{V_i C_i^{'}(q_i)}{\theta_i \beta_i}} - d_i^{tx}\big) \tag{13}$$

B. Asymmetric Information Scenario

In this subsection, we focus on optimal contract design where the gateway WBAN user is not aware of the type of the requesting WBAN user and only aware of the probability (ζ_i) with which the requesting WBAN user belongs to type-θ_i. We solve the optimization problem described in (9) with IR and IC constraint. There are total I IR constraints and $I(I-1)$ IC constraints in the optimization problem (9). As a result, solving the optimization problem directly is difficult. For that, we reduce these constraints in order to transform the problem into more tractable form.

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First, from the IR and IC constraints, we derive set of sufficient conditions for the feasibility of the contract.

Lemma 1. *For any feasible contract* (q_i, π_i)*,* $q_i > q_j$ *if and only if* $\theta_i > \theta_j$*.*

Proof. We proof this lemma in two parts. First, we prove that if $\theta_i > \theta_j$ then $q_i > q_j$. According to the IC constraint in Equation (8), we have

$$\theta_i S_i(q_i) - \pi_i \geq \theta_i S_j(q_j) - \pi_j \tag{14}$$

$$\theta_j S_j(q_j) - \pi_j \geq \theta_j S_i(q_i) - \pi_i \tag{15}$$

Combining Equations (14) and (15), we have

$$\theta_i S_i(q_i) - \theta_j S_i(q_i) \geq \theta_i S_j(q_j) - \theta_j S_j(q_j) \tag{16}$$

Furthermore, by rearranging the terms, we get

$$S_i(q_i)(\theta_i - \theta_j) \geq S_j(q_j)(\theta_i - \theta_j) \tag{17}$$

As $\theta_i - \theta_j > 0$, we have $S_i(q_i) - S_j(q_j) > 0$. Since $S_i(q_i)$ is increasing function with respect to q_i, we conclude that $q_i > q_j$.

Thereafter, we prove that if $q_i > q_j$ then $\theta_i > \theta_j$. Rearranging the terms in Equation (16), we have

$$\theta_i S_i(q_i) - \theta_i S_j(q_j) \geq \theta_j S_i(q_i) - \theta_j S_j(q_j) \tag{18}$$

Simplifying further we obtain

$$\theta_i (S_i(q_i) - S_j(q_j)) \geq \theta_j (S_i(q_i) - S_j(q_j)) \tag{19}$$

Given $q_i > q_j$ and according to the monotonicity property [29] of $S_i(\cdot)$ function, we have $S_i(q_i) - S_j(q_j) > 0$. Thus, we conclude that $\theta_i > \theta_j$. This concludes the proof. ☐

Lemma 2. *For a requesting WBAN user* i *of type-*θ_i*, a feasible contract* (q_i, π_i) *satisfies* $\pi_i > \pi_j$ *if and only if* $q_i > q_j$ *and* $\pi_i = \pi_j$ *if and only if* $q_i = q_j$*.*

Proof. Similar to Lemma 1 we proof this lemma in two parts. First, we prove if $\pi_i > \pi_j$ then

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$q_i > q_j$. Based on the IC constraint in Equation (8), we have

$$\theta_i(S_i(q_i) - S_j(q_j)) \geq \pi_i - \pi_j$$

Given $\pi_i - \pi_j > 0$, $S_i(q_i) - S_j(q_j) > 0$ and $S_i(q_i)$ is increasing function with respect to q_i. Hence we conclude that $q_i > q_j$.

Secondly, we prove that if $q_i > q_j$ then $\pi_i > \pi_j$. By rearranging the terms in Equation (16), we get

$$\theta_j(S_j(q_j) - S_i(q_i)) > \pi_j - \pi_i$$

Since $q_i > q_j$, according to the monotonicity property of $S_i(q_i)$, it holds $S_j(q_j) - S_i(q_i) < 0$. Then, from above equation we obtain

$$\pi_j - \pi_i < \theta_j(S_j(q_j) - S_i(q_i)) < 0$$

Hence, we conclude that $\pi_j < \pi_i$.

Following a above similar argumentation, we can easily prove that if $\pi_i = \pi_j$ then $q_i = q_j$ and vice-versa. This concludes the proof. □

Remarks: Lemma 1 shows that the requesting WBAN user with high priority will pay higher price for availing the service. From Lemma 2, we infer that the gateway WBAN user charges more price when the uplink data rate is higher. Further, for same uplink rate the price charged for the service is same.

Now based on the above Lemmas, we focus on the reduction of IR and IC constraints, i,e, Equation (7) and (8).

Lemma 3. *If the type-θ_1 requesting WBAN user's IR constraint is satisfied, then the IR constraints of all other types of users are automatically satisfied.*

Proof. We proof the above using the IC constraint, i.e. Equation (8). By iteratively employing the IC constraint, we get

$$\theta_i S_i(q_i) - \pi_i \geq \theta_i S_1(q_1) - \pi_1 \geq \theta_1 S_1(q_1) - \pi_1 \geq 0 \tag{20}$$

The last inequality shows that once the IR constraint of type-θ_1 requesting WBAN user is satisfied, the other user's IR constraint will automatically satisfied. Therefore, the original IR

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constraint is in Equation (7) can be reduced to $\theta_1 S_1(q_1) - \pi_1 \geq 0$. This concludes the proof. $\square$

We reduce the original IC constraints to two different parts. First, the IC constraint between type-θ_i and type-θ_{i-1} users is called local downward IC constraint (LDIC). Second, the IC constraint between type-θ_i and type-θ_{i+1} users is called local upward IC constraint (LDUC) [26].

Lemma 4. *The IC constraint can be reduced to LDIC, i.e.*

$$\theta_i S_i(q_i) - \pi_i \geq \theta_i S_{i-1}(q_{i-1}) - \pi_{i-1}, \forall i \in \{2, 3, \ldots, I\} \tag{21}$$

and LUIC, i.e.

$$\theta_i S_i(q_i) - \pi_i \geq \theta_i S_{i+1}(q_{i+1}) - \pi_{i+1}, \forall i \in \{1, 2, \ldots, I-1\} \tag{22}$$

Proof. Here we consider three types of requesting WBAN users, i.e. $\theta_{i+1} < \theta_i < \theta_{i-1}$. According to the IC constraints the LDIC constraints for these three types of users are

$$\theta_{i+1} S_{i+1}(q_{i+1}) - \pi_{i+1} \geq \theta_{i+1} S_i(q_i) - \pi_i, \tag{23}$$

$$\theta_i S_i(q_i) - \pi_i \geq \theta_i S_{i-1}(q_{i-1}) - \pi_{i-1} \tag{24}$$

According to Lemmas 1 and 2, $q_i > q_j$ and $\pi_i > \pi_j$ when $\theta_i > \theta_j$. Using this, the inequality in Equation (24) becomes

$$\theta_{i+1}[S_i(q_i) - S_{i-1}(q_{i-1})] \geq \theta_i[S_i(q_i) - S_{i-1}(q_{i-1})] \geq \pi_i - \pi_{i-1} \tag{25}$$

Combining Equation (23) and (25), we have

$$\theta_{i+1} S_{i+1}(q_{i+1}) - \pi_{i+1} \geq \theta_{i+1} S_i(q_i) - \pi_i \geq \theta_{i+1} S_{i-1}(q_{i-1}) - \pi_{i-1} \tag{26}$$

Thus, we have

$$\theta_{i+1} S_{i+1}(q_{i+1}) - \pi_{i+1} \geq \theta_{i+1} S_{i-1}(q_{i-1}) - \pi_{i-1} \tag{27}$$

The inequality in Equation (27) can be used iteratively to prove the LDIC for all the users. The prove of LDUC is similar to the proof of LDIC. So we omit here. The analysis show that the IC constraint can be reduced to LDIC and LDUC constraints. $\square$

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Based on the above analysis, we can transform the original contract design optimization problem in (9) to a reduced constraint optimization problem. The simplified optimization problem is

$$\max_{\mathbf{q},\boldsymbol{\pi}} \quad U_{GU} = \sum_{i=1}^{I} \zeta_i(\pi_i - C_i(q_i)) \tag{28}$$

$$\text{s.t}: \theta_1 S_1(q_1) - \pi_1 = 0, \quad \forall i \in 2, \ldots, N \tag{29}$$

$$\theta_i S_i(q_i) - \pi_i = \theta_i S_{i-1}(q_{i-1}) - \pi_{i-1} \tag{30}$$

$$0 < \pi_1 < \pi_2 < \ldots < \pi_I \tag{31}$$

The reduced optimization problem is equivalent to the original optimization problem in (9). Now we solve the aforementioned problem to obtain the optimal contract. For that, we first solve the relaxed problem without the constraint (31) and then verify that the solution guarantees the constraint. Iterating the constraints (29) and (30), we have

$$\begin{aligned} \pi_i &= \theta_1 S_1(q_1) + \sum_{i=2}^{I} \theta_i [S_i(q_i) - S_{i-1}(q_{i-1})] \\ &= \theta_i S_i(q_i) + \sum_{i=2}^{I} [\theta_{i-1} - \theta_i] S_{i-1}(q_{i-1}) \end{aligned} \tag{32}$$

Substituting the expression of π_i in objective function (28) we get

$$\max_{\mathbf{q}} \sum_{i=1}^{I} \zeta_i \left(\theta_i S_i(q_i) + \sum_{i=2}^{I} [\theta_{i-1} - \theta_i] S_{i-1}(q_{i-1}) - C_i(q_i) \right) \tag{33}$$

By solving the problem in (33), we obtain the optimal value $\mathbf{q}^*$. Thereafter, we substitute the value of $\mathbf{q}^*$ in the Equation (32) and obtain the optimal value π_i^*.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed contract-based incentive mechanism using MATLAB platform. We consider a $100\text{m} \times 100\text{m}$ geographical area, where 20 WBAN users are randomly located. Among them 5 are gateway WBAN users and the rest are requesting WBAN users. The gateway WBAN users may have either cellular (LTE-A) or WiFi connection for Internet access. Based on the data priority level, the requesting WBAN users are divided into eight user types, i.e. $\theta_1 < \theta_2 < \ldots < \theta_8$. The packet size of WBAN user is 512 Bytes and the maximum transmit power is 6 mW [10]. The delay deadline of requesting WBAN user D_i^{max} is

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assumed to be uniformly distributed between $[50-100]$ ms and the value of β is chosen as a integer between $[1-10]$.

To show the effectiveness of the proposed contract-based incentive (CBI) scheme, we compare with it three other incentive schemes. First is complete information (CI) case, as discussed in Section-IV(A), where the gateway WBAN user is aware of the user type. The second is Stackelberg game based incentive (SG) scheme [12], where the gateway WBAN user as leader sets the price and based on that the requesting WBAN users as followers request the uplink rate for them. The third one is Evolutionary game-based incentive scheme, namely PATS, proposed by Misra et al. [17], where the interaction between WBAN users is modeled using *hawk-dove game* and uplink rate of user is decided based on its data priority. We consider four metrics for performance evaluation: i) payoff of gateway user, ii) payoff of requesting WBAN users, iii) average uploading delay and iv) social welfare.

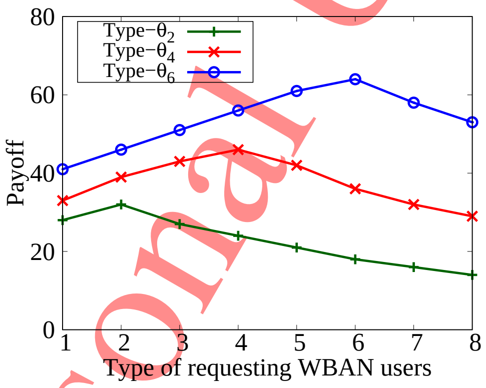

Figure 2: Requesting user's payoff versus types

In Figure 2, we evaluate the feasibility of the proposed CBI scheme by verifying the IR and IC constraints of the requesting WBAN users. For that, in Figure 2, we show the payoff of type-θ_2, type-θ_4, and type-θ_6 requesting WBAN users when selecting all contract types offered by the gateway WBAN user. We observe that each requesting user obtains maximum payoff when it chooses contract of its type. For example, the payoff of type-θ_4 is maximum for type-4 contract, i.e. (q_4, π_4) and reduces for all other contract types. Thus, the IC constraint is satisfied. The non-linearity of user payoff is due to the concavity property of user payoff function, as defined in Equation (4). Further, from Figure 2, we observe that all the users receive non-negative payoff for their chosen contract which verifies the IR constraint. This verifies the feasibility of the proposed contract.

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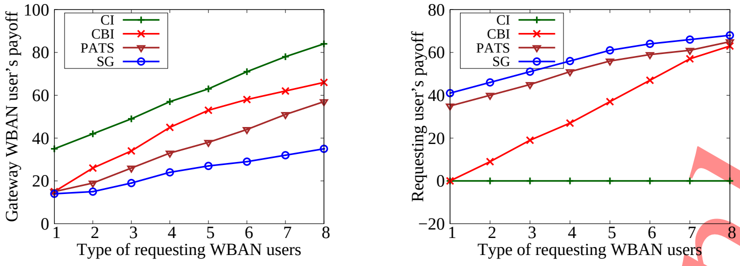

(a) Gateway WBAN user's payoff (b) Requesting WBAN user's payoff

Figure 3: Impact of user types on payoffs

In Figure 3, we show the impact of different user types on the payoffs of gateway and requesting WBAN users. We compare the payoffs among all the three schemes. Figure 3(a) shows that the payoff of gateway WBAN user is highest for CI scheme. Since the gateway user has complete knowledge of the type of the requesting WBAN user, it offers contract which maximizes its own payoff. The proposed CBI scheme outperforms the SG scheme in terms of the payoff obtained by the gateway WBAN user. Further, we observe that payoff difference between CBI and CI scheme is less, which shows the performance of the proposed scheme is close to ideal no information asymmetry case. Figure 3(b) illustrates the payoff of requesting WBAN users. In case of CI scheme the payoff is zero. As discussed in Section IV(B), in CI scheme, the gateway WBAN users already know the type of requesting WBAN user and thus, tries to maximizes its own payoff by leaving payoff of requesting WBAN user to zero. In case of proposed CBI scheme, the payoff of requesting WBAN user is high for higher user type and payoff of type-θ_1 is zero, as explained in Equation (29). Further, comparing all the schemes, we observe that the payoff of requesting WBAN user is better in SG and PATS schemes than the proposed CBI scheme. This is because in contract scheme, the gateway WBAN user tries to maximize its own payoff while satisfying the IR and IC constraints of the requested WBAN user. Thus, the gateway WBAN user extracts more benefit and leaves less surplus for the requesting WBAN user. However, in SG scheme, each requesting WBAN user tries to maximize its own payoff and obtains more surplus. This same reason holds for PATS scheme. Thus, in SG and PATS scheme the payoff of gateway WBAN user is worst than contract approach.

Figure 4 illustrates the impact of number of requesting WBAN users on the payoff values. We have considered that the requesting WBAN users are of type-θ_5. We observe from Figure 4 that the payoff of gateway WBAN user is highest in CI scheme and worst in case of SG scheme. The

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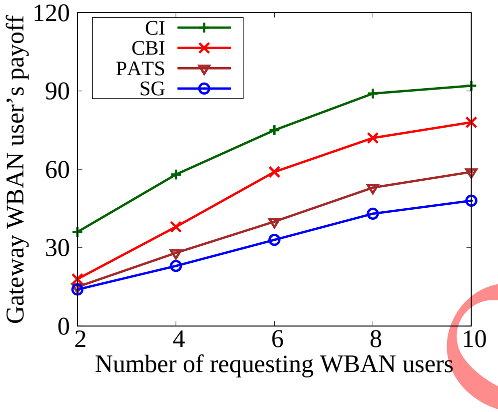

Figure 4: Gateway WBAN user's payoff versus number of requesting users

proposed CBI scheme provides better payoff than SG and PATS schemes, and less than the CI scheme. The advantage of CI scheme occurs due to no information asymmetry. From Figure 3 and 4 we infer that the gateway WBAN user obtains higher payoff when there is no information asymmetry and at the same time requesting WBAN users obtain benefit due to this asymmetry.

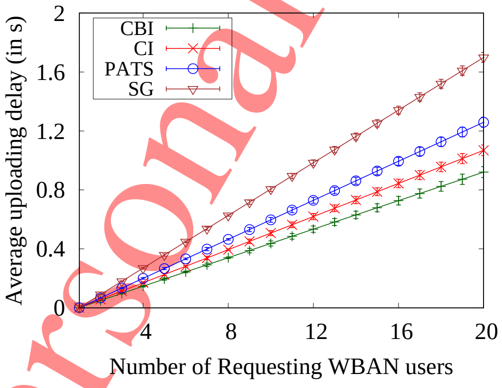

Figure 5: Effect of number of requesting users on social welfare

Figure 5 illustrates the effect of variation in the number of requesting WBAN users on average uploading delay for different schemes. The requesting WBAN users are varied between 0 to 20 and all the users are of type-θ_5. All results are taken with 95% confidence. We observe that as the number of requesting WBAN user increases, the average uploading delay increases linearly for all schemes. Clearly, uploading large amount of requesting WBAN users' data incurs additional delay at the gateway user end. Further, we observe that the average uploading delay in case of proposed CBI scheme is lesser than other schemes. This is because, in contract theory approach with larger number of requesting WBAN users, the gateway user receives more payoff and offers

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more resources than the other schemes.

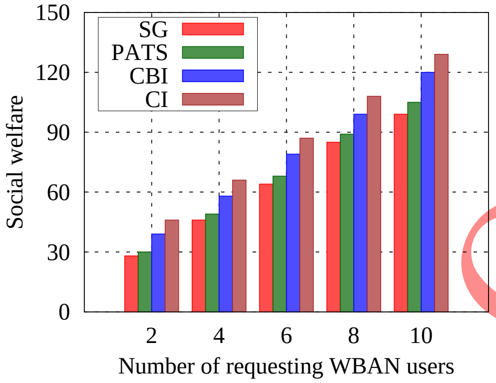

Figure 6: Effect of number of requesting users on social welfare

Figure 6 depicts the comparison of social welfare among all the three schemes. In Figure 6, we vary the number of requesting WBAN users and analyze its impact on the social welfare value. We observe that for all the schemes the value of social welfare increases with increase in the number of the requesting WBAN users. This comes as a straightforward observation, as the number of requesting WBAN users increases the gateway WBAN user obtains more profit by serving them. Thus, as the number of users increases, the social welfare increases. This also can be verified theoretically from social welfare expression defined in Equation (6). Similar to Figure 3 and 4, the social welfare is highest for CI scheme due to no information asymmetry. The proposed CBI scheme outperforms the SG and PATS schemes in terms of social welfare.

VI. CONCLUSION

In this paper, we proposed an incentive mechanism for priority-aware data uploading in BBN. Since the priority of medical data is private information for requesting WBAN user, it creates issue of information asymmetry. Therefore, we have proposed a contract theory-based incentive scheme to model the economic interaction between the gateway user and the requesting WBAN users. Specifically, we have formulated a contract design problem which maximizes the payoff of gateway WBAN users while satisfying the IR and IC properties of requesting WBAN users. Further, we derived the optimal contract for two scenarios, i.e. complete information and information asymmetry. Finally, numerical results showed the effectiveness of the proposed contract-based incentive scheme than other benchmark schemes. In future work, we would like to consider a scenario consisting of both information asymmetry and competition among requesting

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users and in that scenario, we will focus on the economic interaction between the participating users.

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