Enabling Collaborative Data Uploading in Body-to-Body Networks

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***Abstract*—In body-to-body networks (BBNs), a group of closely located wireless body area network (WBAN) users aggregates their network resources to improve the overall physiological data uploading performances. This enables users with the poor Internet connection, i.e., requesting users, to upload their data through their nearby WBAN users with a good Internet connection, i.e., gateway users. In this letter, we investigate the data uploading problem for BBN, where the requesting users incentivize the gateway users for data uploading. However, since the gateway users incur an additional cost (energy and Internet access cost) for uploading data, and they are heterogeneous in terms of their cost, it is more challenging to design the incentive scheme for them. To address this, we formulate a Stackelberg game, where the requesting users as leaders propose the prices, and the gateway users as followers decide the amount of requesting users' data they would upload. We prove the existence of Stackelberg equilibrium (SE) of the game using backward induction. Finally, the numerical results validate the effectiveness of the proposed incentive mechanism.**

***Index Terms*—Body-to-body networks, WBAN, Non-cooperative game, Equilibrium, cost-efficient**

I. Introduction

In recent years there is an unprecedented growth in the usage of wireless body area networks (WBANs), which is expected to reach 9 billion by 2022 [1], [2]. In a dense WBAN environment, where multiple WBAN users are located close to each other, coexistence will be a major issue while causing overall network throughput degradation [3], [4]. In this context, body-to-body network (BBN) appears as one of the most attractive solutions which enables cooperation and resource sharing among WBAN users to overcome the throughput degradation [5]. More specifically, BBN is a mesh network consisting of a group of WBAN users, where each WBAN user may act as a requesting node, a relay node, and gateway node (uploading data to the Internet). Each requesting WBAN user can simultaneously transmit its data to multiple gateway WBAN users over multi-hop paths and can serve as relay for other users [6]. Further, BBN provides a cost-effective solution for remote WBAN users monitoring in crowded indoor/outdoor environments and adverse environments (e.g. battlefield, mining, and disaster area) by allowing one WBAN user to transmit to nearby WBAN users and so on until reaching nearby WiFi or cellular access point without any external coordination [7].

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BBN is a type of cooperative network where participating users collaborate and contribute their network resources (such as Internet connectivity, battery energy, and so on) to relay data for other users to extend end-to-end network connectivity [5]. Some of the recent studies have been done to develop a prototype of BBN and analyze the technical benefits of it [6]–[9]. Arbia et al. in [6] analyzed the communication performance of BBN in the presence of different network parameters, such as, inter-WBAN interference, user mobility, and routing schemes. A smart phone-based collaborative system is proposed in [8] which enables sharing of sensed data among neighboring users by taking energy saving and classification accuracy into account. Shimly et al. [7] proposed two cross-layer optimization-based routing protocols fro BBN to ensure energy-efficiency and system reliability.

All the above works mainly discussed the technical aspect of BBN without considering the economic incentives of users to participate in BBN. The incentive design for BBN is of paramount importance, since the WBAN users participating in the BBN are rational, self-interested, and are expected to be reluctant to upload other users' data without proper incentives. Therefore, in this letter, we consider a BBN network consists of multiple requesting and gateway WBAN users and focus on the economic interaction between them. Specifically, we consider a scenario, where requesting users try to upload their data through their neighboring gateway users. We emphasize on the incentives that requesting users need to provide to gateway users in order to facilitate cooperative data uploading. The key questions we try to address is: *how much volume of data should each gateway user upload for the requesting user? and what is the corresponding reimbursement for each gateway user?*

In this work, we address the fundamental problem of resource sharing for BBN, to provide improved uplink throughput to all participating WBAN users. In particular, we model the problem as Stackelberg game, in order to obtain optimal uploading data volume and corresponding reimbursement. In the proposed game, the requesting users act as the game leaders specifying the payment to gateway users first, and then the gateway users act as followers determining the amount of requester users' data they are willing to upload. The main contributions of our work are: i) To the best of our knowledge, this is the first work that considers the economic aspect of BBN and analyzes the incentive design issue in BBN. ii) We study and analyze the economic interaction between requesting user and gateway users based on the Stackelberg game, iii) We theoretically analyzed the Stackelberg equilibrium (SE) of the game, and iv) finally, we propose an iterative algorithm to reach to the SE.

II. System Model

We consider a BBN consists of set of requesting users $\mathcal{M} \triangleq \{1, 2, \cdots M\}$ surrounded by gateway users of set $\mathcal{N} \triangleq \{1, 2, \cdots N\}$. The requesting users do not have their own Internet connection and hence, request neighboring gateway users to upload their data. On the contrary, the gateway users are connected to the Internet either through WiFi or cellular connection. The inter-WBAN communication between the requesting user and the gateway user is through WiFi Direct or Bluetooth connection. Further, for gateway users there is no restriction on usage of two different interface simultaneously. Therefore, the gateway user can receive and upload requesting users' data simultaneously. Our focus in this paper is per-time slot basis, and we assume a quasi-static network scenario, therefore, the uploading demand of requesting users remains unchanged during the time slot duration. Let r_{mn} is the amount of data requesting user m requests to gateway user n and z_{mn} is the corresponding payment from requesting user m to gateway user n. Then, $\mathbf{R} \triangleq (r_{mn})_{m\in\mathcal{M},n\in\mathcal{N}}$ be the data uploading matrix and $\mathbf{Z} \triangleq (z_{mn})_{m\in\mathcal{M},n\in\mathcal{N}}$ be the payment matrix.

A. Requesting user's payoff

Since there is no Internet connection available for the requesting user, it requests to nearby neighboring gateway users for scheduling its data. If no gateways users agree to upload its data, then the requesting user drops its data packets and bears certain cost due to the packet drop [3].

However, the requesting user may reduce its packet drop cost by properly incentivizing the nearby gateway users to upload its data. Let r_{mn} be the amount of data that gateway user $n \in \mathcal{N}$ agrees to offload for requesting user m and z_{mn} is the corresponding payment from requesting user m to gateway user n. We consider a linear payment mechanism, i.e., the payment z_{mn} is a linear function of data amount r_{mn} and denoted by $z_{mn} = p_{mn}r_{mn}$, where p_{mn} is the pricing parameter of gateway user n for unit data upload. Therefore, the total payoff, i.e. cost reduction, of requesting user after gateway user participation is,

$$S_m(\mathbf{r}_m, \mathbf{p}_m) = \eta_m \log\left(1 + \sum_{n\in\mathcal{N}} r_{mn}\right) - \sum_{n\in\mathcal{N}} p_{mn}r_{mn} \quad (1)$$

where $\mathbf{r}_m \triangleq (r_{mn})_{n\in\mathcal{N}}$ and $\mathbf{p}_m \triangleq (p_{mn})_{n\in\mathcal{N}}$ denote the upload request vector and payment vector of requesting user m, i.e., m^{th} row of $\mathbf{R}$ and $\mathbf{Z}$ matrix, respectively. The first term signifies the utility (satisfaction) obtained by the requesting user m when r_{mn} of its data is uploaded by gateway user n. We have taken logarithmic function to capture the principle of diminishing marginal returns. Here $\eta_m \in [0, 1]$ is the severity index of requesting user m. The severity of a requesting user is defined as $\eta_m = \left|\frac{(\Phi_m^u - \Phi_m)^2 - (\Phi_m - \Phi_m^l)^2}{(|\Phi_m^u| + |\Phi_m^l|)^2}\right|$,where Φ_m is the measured value of particular physiological parameter of WBAN user m. Φ_m^l and Φ_m^u are the lower and upper bounds of the that physiological parameter, respectively [3]. Clearly, the severity index represents the deviation of patient's physiological parameter from its normal value. Higher the value of η_m corresponds to more severe data and incurs more cost if it dropped. For example, in healthcare the importance of ECG data is higher than the temperature data.

B. Gateway user's payoff

Each gateway user is connected to the network infrastructure through WiFi or cellular connection. We denote the uplink capacity of gateway user n as $C_n \geq 0$, i.e. the maximum amount of data (in bytes) that gateway user can upload to the Internet. Further, each gateway user incurs energy for uploading data to the Internet. Clearly, the energy consumption depends on the volume of data uploaded. In our case, we assume a quadratic energy cost function. Additionally, the impact of Internet access cost on gateway user's decision to cooperate is very crucial. For example, the gateway user with LTE connectivity will show more reluctance to share its Internet connectivity than the gateway user with 3G connectivity, since the Internet access cost of LTE connection is more costly than 3G.

Let r_{nm} be the amount of data gateway user n agrees to upload for requesting user m, then, the payoff of gateway user n is,

$$Q_n(\mathbf{r}_n, \mathbf{p}_n) = \sum_{m=1}^{M} \left(p_{nm}r_{nm} - \zeta_n(e_n^u r_{nm})^2 - \chi_n r_{nm}\right) \quad (2)$$

where $\mathbf{r}_n \triangleq (r_{1n}, r_{2n}, \cdots r_{Mn})$ and $\mathbf{p}_n \triangleq (p_{1n}, p_{2n}, \cdots p_{Mn})$ be the data uploading vector and payment vector to gateway user n, i.e., n^{th} column of $\mathbf{R}$ and $\mathbf{Z}$ matrix, respectively. $p_{nm}r_{nm}$ is the payment received by gateway user n from the requesting user m for sharing its resource. ζ_n is the energy cost coefficient of gateway user n and $e_n^u > 0$ is the energy consumed by gateway user n for uploading one byte of data to the Internet. $\chi_i \geq 0$ denotes the Internet access cost (per byte) of gateway user n. Since each gateway user is rational and self-centric, it always tries to maximize its own payoff.

In BBN, there is no central controller and both the amount of uploading data and corresponding payment are decided freely by the requesting users and gateway users. Therefore, each requesting user always tries to minimize its cost function (Equation (1)) and each gateway user tries to maximize their own utility (Equation (2)). We formulate this interaction between requesting users and gateway users as two-stage Stackelberg game [10]. In the first stage, the requesting users (leaders) announce the pricing vector $\mathbf{p}_m \triangleq (p_{mn})_{n\in\mathcal{N}}$, where p_{mn} is the price that requesting user m announces for gateway n. In the second stage, each gateway user n responds with data uploading vector $\mathbf{r}_n \triangleq (r_{nm})_{m\in\mathcal{M}}$, based on the pricing vector $\mathbf{p}_m$. Where r_{nm} is the amount of data gateway user n agrees to upload for requesting user m.

III. Stackelberg Game Solution

In this section we analyze the Stackelberg game between requesting users and gateway users. We employ the backward induction method [11] to find the SE of the game.

1) Stage-II: First, we analyze the gateway user n's optimal decision variable r_{nm} in second stage, given the requesting user's announced price p_{mn}. The optimization problem for gateway user n is

$$\begin{aligned} &\max_{\mathbf{r}_n} \; Q_n(\mathbf{r}_n, \mathbf{p}_n) \\ &\text{s.t.} \; \sum_{m=1}^{M} r_{nm} \leq C_n \end{aligned} \tag{3}$$

Clearly, the optimization problem (3) is a convex optimization problem, thus there exists a unique optimal solution for the problem. Let λ_n is the Lagrangian multiplier, then the Lagrangian function of the problem (3) is $\mathcal{L} = \sum_{m=1}^{M} \big(p_{mn} r_{nm} - \zeta_n (e_n^u r_{nm})^2 - \chi_n r_{nm} - \lambda_n (\sum_{m=1}^{N} r_{nm} - C_n\big)$. The KKT conditions are

$$\frac{\partial \mathcal{L}}{\partial r_{nm}} = p_{nm} - 2\zeta_n e_n^u r_{nm} - \chi_n - \lambda_n = 0, \quad \forall m \in \mathcal{M} \tag{4}$$

$$\lambda_n \Big(\sum_{m=1}^{M} r_{nm} - C_n\Big) = 0, \quad \lambda_m \geq 0 \tag{5}$$

When $\lambda_n = 0$, from Equation (4) we have $r_{nm}^* = \frac{p_{nm} - \chi_n}{2\zeta_n e_n^u}$. When $\lambda_n > 0$, from Equation (4) the expression of r_{nm} is $r_{nm} = \frac{p_{nm} - \chi_n - \lambda_n}{2\zeta_n e_n^u}$. Substituting r_{nm} in Equation (5), we have $\lambda_n = \sum_{m=1}^{M} p_{nm} - \chi_n - 2\zeta_n e_n^u C_n$ and $r_{nm}^* = \frac{\sum_{i=1, l \neq m}^{M} p_{in} - \chi_n}{2\zeta_n e_n^u} - 1$. The optimal decision of gateway user n is

$$r_{mn}^* = \begin{cases} \frac{p_{mn} - \chi_n}{2\zeta_n e_n^u}, & \text{if } \sum_{m=1}^{M} r_{nm} < C_n, \\ \frac{\sum_{i=1, l \neq m}^{M} p_{in} - \chi_n}{2\zeta_n e_n^u} - 1, & \text{if } p_{mn} - \chi_n - 2\zeta_n e_n^u > 0, \\ 0 & \text{Otherwise .} \end{cases}$$

2) Stage-I: The requesting users set their optimal price $\mathbf{p}_m$ in first stage, based on the prediction of best response of each gateway user's optimal decision r_{mn}^* in second stage. Substituting the value of r_{nm}^* into requesting user's cost function (in Equation (1)), we obtain $S_m = \eta_m \log\big(1 + \sum_{n \in \mathcal{N}} r_{nm}^*\big) - \sum_{n \in \mathcal{N}} p_{mn} r_{nm}^*$. Now, the cost minimization problem of requesting user is

$$\max_{\mathbf{p}_m} \quad S_m(\mathbf{r}_m, \mathbf{p}_m) \tag{6}$$

As the uploading amount of gateway users are motivated by the pricing scheme, the requesting users compete among each other for optimal price determination. The competition among requesting users at Stage-I can be modeled as a non-cooperative game.

Proposition 1. *The non-cooperative game between the requesting users at Stage-I has a unique NE.*

Proof. The feasible region of p_{mn} of optimization problem in Equation 6 is nonempty, closed and convex. Further, by taking the second derivative of $S_m(\cdot)$ with respect to p_{mn}, we observe that, $\frac{\partial^2 Q}{\partial p_{mn}^2} \leq 0$ also $\frac{\partial^2 Q}{\partial P_{mn} P_{ln}} \leq 0$ (the derivation is omitted due to space constraint). Thus, $S_m(\cdot)$ is concave in $\mathbf{p}_m$. This property holds for all requesting users and the game between the requesting users is a concave multi-player game. Therefore, according to the Debreu-Glicksberg-Fan theorem [12] there exists a unique NE between requesting users at Stage-I. □

A. Stackelberg equilibrium

In this subsection, we find out the SE of the game defined above and propose an algorithm to achieve it.

Definition 1: Let $\mathbf{r}_n^*$ and $\mathbf{p}_m^*$ denote the optimal data uploading amount of all the gateway users and optimal pricing vector, respectively. Then $(\mathbf{r}_n^*, \mathbf{p}_m^*)$ is the SE point if it satisfies both the following conditions

$$\begin{aligned} S_m(\mathbf{r}_n^*, \mathbf{p}_m^*) &\geq S_m(\mathbf{r}_n^*, \mathbf{p}_m) \\ Q_n(\mathbf{r}_n^*, \mathbf{p}_m^*) &\geq Q_n(\mathbf{r}_n, \mathbf{p}_m^*) \end{aligned} \tag{7}$$

According to the Proposition (1), there exists a unique NE for all requesting users at Stage-I. Further, all the requesting users obtain their unique optimal decision points once the pricing is declared by the requesting users (refer to Section III). Therefore, we can conclude that both requesting users and gateway users agree on the $(\mathbf{r}^*, \mathbf{p}^*)$, and hence, attains a unique SE.

Further, we propose a gradient-based iterative algorithm to obtain the SE. In each iteration, first the requesting users update their price p_{mn} based on the gradient direction. Thereafter, the gateway users update data amount r_{mn}. The step size of requesting user and gateway user are δ and ω, respectively. The iteration continues till the difference between the values in two consecutive iteration is sufficiently small [11]. We use convergence index $\epsilon_0 > 0$ and $\epsilon_1 > 0$ for that. The complete algorithm is given in Algorithm 1.

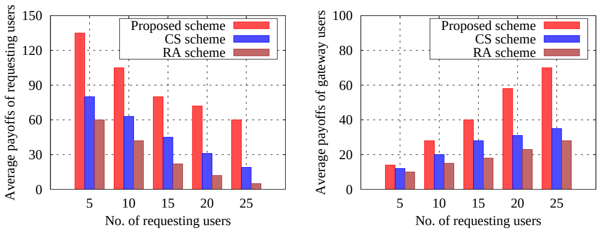
Algorithm 1: Iterative Algorithm for SE

```
Inputs  : δ, ω ε_0, ε_1
Outputs: p*_mn, r*_mn
Set Select initial input p_m = [p_mn]_{n∈N}
converge = 0, t = 0, τ = 0
while converge = 0 do
    t ← t + 1
    Update each requesting user n price as
    p_mn(t + 1) = p_mn(t + 1) + δ ∂Q/∂p_mn
    while |r_mn(t + 1) − r_mn(t)| < ε_1 do
        τ ← τ + 1
        Update each gateway user m as
        r_mn(τ + 1) = r_mn(τ + 1) + ω ∂Q/∂r_mn
    if |p_mn(t + 1) − p_mn(t)| < ε_0 then
        converge ← 1
```

IV. Numerical Results

In this section, we show the effectiveness of our proposed Stackelberg game-based approach in BBN scenario. In the simulation we consider a BBN of 8 WBAN users, among them 5 gateway WBAN users and 3 requesting users by default. The simulation parameters are adapted from [2], [3]. We evaluate the payoffs of both gateway and requesting users by varying different parameters. We compare our proposed scheme with two benchmark schemes — the cooperative scheduling scheme (CS) [3] and the random assignment scheme (RA). In CS approach, the critical WBANs choose their access point dynamically using dynamic connectivity assignment (DCE) algorithm, based on pricing-based approach. In RAS approach, the requesting users randomly set their prices and the gateway users randomly decide the upload data amount.

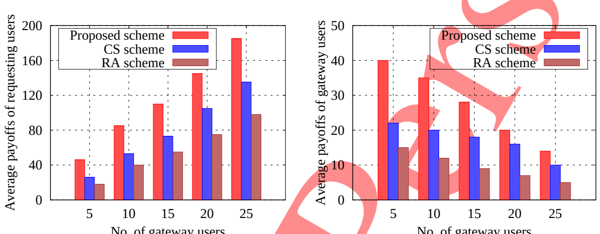
First, we show the variation of payoff of requesting and gateway users when varying the number of requesting users in Fig. 1. We vary the number of requesting users between 2 to 20. In Fig. 1(a), we observe that as the number of requesting users increases, the payoff of requesting WBAN users decreases. This is because the presence of more number of requesting users leads to competition among requesting users, and therefore, the requesting users need to pay more to gateway users. This results in decrement of their payoff values. However, in Fig. 1(b), we observe that the payoffs of gateway users increase as the number of requesting users increases. Further, the payoff obtained in proposed algorithm is always higher than the benchmark algorithm.



(a) Payoffs of requesting users (b) Payoffs of gateway users

Figure 1: Performance comparison when varying number of requesting users

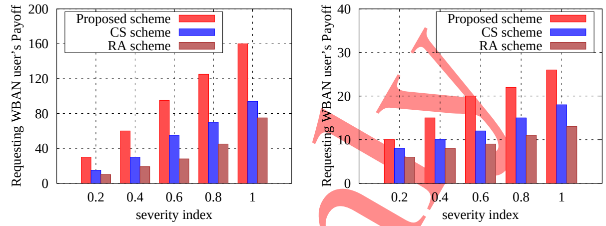
Fig. 2 illustrates the variation of respective payoffs of requesting users and gateway users against number of gateway users. We observe that with more number of gateway users, the payoff of requesting users increases, and the payoff of gateway users decreases as shown in Fig. 2(b). This is due to fact that the presence of more number of gateway users creates more option for requesting users to choose for their data uploading.



(a) Payoffs of requesting users (b) Payoffs of gateway users

Figure 2: Performance comparison when varying number of gateway users

The impact of severity index η_m on BBN performance is shown in Fig. 3. We vary the value of η_m between 0.1 to 1. In Fig. 3(a), we observe that the payoff of requesting users increases with increase in the value of η_m. This is because the requesting users receive larger payoffs when more severe data are uploaded. Fig. 3(b) illustrates that, the payoffs of gateway users increase with increase in the value of η_m. The reason behind this is with increase in severity index the requesting users will offer more price to gateway user to upload, and hence, the gateway users obtain higher payoff value.



(a) Payoffs of requesting users (b) Payoffs of gateway users

Figure 3: Effect of severity index

V. Conclusion

In this letter, we modeled and analyzed the interactions among the requesting and gateway users in BBN and designed a joint pricing and data uploading strategy for the BBN. A multi-leader and multi-follower Stackelberg game has been developed to jointly maximize the payoffs of the requesting users and gateway users. Thereafter, we proved the existence and uniqueness of SE. Extensive numerical simulations showed the effectiveness of proposed incentive mechanism compared to existing baseline algorithm. In future, we will extend this game model to two-sided information asymmetry scenario which is more suitable for BBN.

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