Collaborative and Efficient Body-to-Body Networks for IoT-Based Healthcare Systems

Pradyumna Kumar Bishoyi, *Student Member, IEEE,*
Sudip Misra, *Senior Member, IEEE,* and Neeraj Kumar, *Senior Member, IEEE*

Abstract

The recent advances in Internet-of-Things (IoT)-based healthcare systems pave the path for the development of body-to-body network (BBN), wherein a group of wireless body area network (WBAN) users collaborate and share their individual resources. Since these WBAN users have individual decision-making capabilities and are self-centric in nature, they always aim to maximize their own performance while expecting benefits through resource sharing. In this paper, we analyze the interaction among participating WBANs in BBN and develop joint data uploading and relaying strategy. In BBN, each WBAN not only utilizes its resources (uplink capacity and battery energy) to upload physiological data but also trades resources with other participating WBANs. Specifically, WBAN users with unused resources trade with other users deprived of Internet connection and low battery for mutual gain. Therefore, we model this interaction as a N-person bargaining game and design an efficient incentive mechanism to facilitate user cooperation. The proposed mechanism ensures efficient resource sharing and fair division of mutual benefit among the participating WBAN users. Also, we propose a distributed algorithm for the practical implementation of the proposed mechanism in decentralized BBN. The simulation results demonstrate that the proposed mechanism always improves WBAN user's individual performance together with overall BBN performance. Further, the overall performance increases with an increase in participating WBAN users' resource heterogeneity.

P. K. Bishoyi is with the Advanced Technology Development Center, Indian Institute of Technology Kharagpur, India. (e-mail: pradyumna.bishoyi@iitkgp.ac.in).

S. Misra is with the Department of Computer Science and Engineering, Indian Institute of Technology Kharagpur, India (e-mail: smisra@cse.iitkgp.ac.in).

N. Kumar is with the Department of Computer Science and Engineering, Thapar Institute of Engineering and Technology (Demmed to be University), Patiala (Punjab), India. He is also with School of Computer Science, University of Petroleum and Energy Studies, Dehradun, Uttarakhand and Department of Computer Science and Information Engineering, Asia University, Taiwan (e-mail: neeraj.kumar@thapar.edu).

Index Terms

IoT, healthcare, WBAN, body-to-body networks, Nash bargaining solution, distributed optimization

I. Introduction

With the rapid increase in the number of chronics disease patients and aging popularity, the usage of wireless body area network (WBAN) for remote patient monitoring has increased unprecedentedly [1]–[3]. This surging growth in the number of co-located WBAN users originates the issue of co-existence [4], and inter-network interference and has paved the path to the design and development of the body-to-body network (BBN) [5]–[7]. With the recent advancement in Internet-of-Things (IoT) BBN emerged as a paradigm shift in the healthcare sector by allowing a group of WBAN users to interact and collaborate with each other with an aim to achieve technological, social, and economic advantages [8], [9]. In particular, BBN enables WBAN users to cooperatively share their resources (such as Internet access and battery energy) among each other to provide ubiquitous healthcare facilities. For example, BBN facilitates remote monitoring of a WBAN user with no Internet access to avail the Internet connection of other participating user(s) while prolonging end-to-end connectivity [10], [11].

Typically, BBN can be conceived as a wireless mesh network in which WBAN user may act as a transmitting node, a relay node, or gateway node [5]. Each participating user can upload data through different gateway nodes having different Internet connections (either cellular or Wi-Fi) over multi-hop paths and can act as a relay for other users [12]. Indeed, the BBN leverages the Internet connection of gateway WBAN users to serve all participant users' data upload needs through appropriate network resource assignment. Some of the potential application areas of BBN are in-home elderly monitoring, ambient assisted living (AAL) [2], [13], athletes fitness tracking [8], tracking rescue team in the disaster area, epidemic control in mass gathering areas [10], and so on.

A. Motivation

Clearly, the performance of the BBN network is dependent on the willingness of WBAN users to collaborate and contribute their resources to the network. Since each WBAN user is an independent entity driven by its self-interest, therefore will only cooperate if the collaboration guarantees additional benefits [7]. For example, a WBAN user with Internet access and low battery energy will show reluctance to cooperate without proper incentive. The incentive mechanism should encourage users to collaborate and share their resources for either relaying or uploading other WBAN users' data. The efficiency of BBN is characterized in terms of total aggregate uploaded data which can be maximized by assigning gateway role to WBAN users having Internet connections and properly routing other participating WBAN users data [9], [11]. Another important factor that encourages user participation is fairness, which includes appropriate sharing of benefit among participants [14]. Failing these leads to no participation of WBAN users which affects the overall network performance substantially.

Designing an efficient and fair resource sharing scheme and incentive mechanism for BBN is very challenging due to the following reasons: i) since there is no central coordinator in BBN and each participating WBAN user only has information about its own resources and demands, therefore the resource sharing mechanism has to be distributed; ii) the participating users may charge different costs for sharing their resources which may originate unfairness in the system; iii) decision coupling, i.e., each user's decision to contribute resources are tightly coupled with other users and the overall BBN performance depends on every WBAN user's decision.

B. Contribution

To address these issues, first, we envisage BBN as a multi-hop mesh network in which participating WBAN users can upload or relay their own data along with other users' data. Each user has its own utility and cost function which takes into account its individual resources and demands which differs for other users. To obtain a collective decision of users we design a N-user bargaining game and to maintain both efficiency and fairness of the system we use the Nash bargaining solution (NBS) to solve the bargaining problem. Thereafter, we design a distributed algorithm that decomposes the coupled objective function and coupling constraint set of bargaining problems and solves iteratively. The main *contributions* of the work are as follows:

- We conceptualize a BBN network-based collaborative healthcare service model that comprises WBAN users' uplink data rate, Internet access cost, and energy consumption cost, which influence users' decision for cooperation in the network.

- We design a joint resource allocation and incentive mechanism scheme for BBN network based on the NBS. The proposed mechanism ensures fair resource allocation in the network and is Pareto-efficient.
- We propose a distributed algorithm for the computation of NBS based on decomposition theory, which facilitates the implementation of resource sharing mechanism in decentralized manner in BBN network.
- We also analytically show that the proposed decentralized algorithm converges to NBS. Further, the simulation results demonstrate that proposed mechanism always improves individual performance and BBN performance .

In Section II, the existing works related to BBN are discussed. In Section III, we discuss the system model and explained the optimization problem. The proposed Nash bargaining method is presented in Section IV and the distributed algorithm is proposed in Section V. Further, the performance evaluation is presented in Section VI. Finally, Section VII concludes the paper.

II. Related Works

In recent past few works have been reported pertaining to the modeling and performance analysis of BBN. A detailed review on design consideration of BBN is presented in [5]. The authors focused on major communication challenges and discussed suitable protocols suitable for BBN. In [8] Arbia *et al.* analyzed the communication performance of BBN in presence of different network parameters, such as, inter-WBAN interference, user mobility, and routing schemes. In [10] cluster and distributed data dissemination approaches for BBN is proposed. Mu *et al.* in [15] proposed self-organizing dynamic clustering (SDC) and reliable next hop relay selection scheme for multiple coexisting WBANs with an aim to mitigate co-channel interference among users and maintain heterogeneous QoS. In all the above schemes the cluster head is selected based on the WBAN having sufficient resources and acts as gateway for other users. However in case of BBN, each user may act as gateway or relay node based on its available resource.

Few literature are reported on the cooperative resource sharing and routing scheme for multiple co-located WBANs. In [16] authors proposed a a novel hybrid medium access mechanism (MAC) and resource scheduling scheme for data sharing among neighboring WBAN nodes. Similarly, in [17] a smart phone-based activity recognition system is proposed which allows sharing of sensed data among neighboring users by taking energy saving and classification accuracy into account. In [18] authors presented the performance of cooperative WBAN communication and analyzed the role of WBAN relay between non-cooperating WBANs. To maximize the overall throughput of coexisting WBANs, authors in [19] first formulated a scheduling problem and address the complexity of original non-linear optimization problem by introducing recursive decomposition algorithm. In [6], two cross layer optimization-based routing protocol such as shortest path and cooperative multi-path routing (CMR) protocol for BBN is proposed to guarantee energy efficiency and reliability of overall network. Consequently, in [20] authors have proposed TDMA based MAC protocol with low duty cycle for BBN to enable interference free and energy efficient communication. Authors in [21] studied the outage probability and energy efficiency in case of Internet-of-things (IoT)-based healthcare system and proposed a cooperative communication protocol between two heterogeneous WBANs.

None of the above works considered the individual users relaying capacity and energy sensitivity into account which incurs different cost for different users and is essential in taking decision whether to relay or not. Similarly, most of the works have assumed either assumed WLAN or cellular connection for WBAN data uploading but not both. However, in case of BBN the participating WBAN users may have different Internet connectivity which allows to exploit the benefit of using best available connectivity (in terms of Internet access cost and network congestion) on demand basis. Therefore, there is a need of efficient and fair resource allocation and corresponding incentive mechanism for BBN taking individual participating WBAN users willingness and satisfaction into account.

III. System Model and Problem Formulation

We consider a set of heterogeneous WBAN users $\mathcal{N} = \{1, 2, \cdots, N\}$ which form a BBN and provide collaborative healthcare service to each other. The participating WBAN users may have Internet connection to cellular (3G/4G) base stations (BSs) or Wi-Fi access points (APs) for Internet access. For example, as shown in Fig. 1, user 1 and 2 are connected to cellular BS, user 3 and 4 have Wi-Fi connectivity, and user 5 and 6 have no Internet connection. The participating users communicate with neighbors through Bluetooth, Zigbee, Wi-Fi Direct. In BBN the WBAN users are connected with each other forming a mesh network topology which is represented by a connected graph $\mathbb{G} = (\mathcal{N}, \mathcal{E})$, where $\mathcal{E}$ represents the set of wireless link between WBAN users.

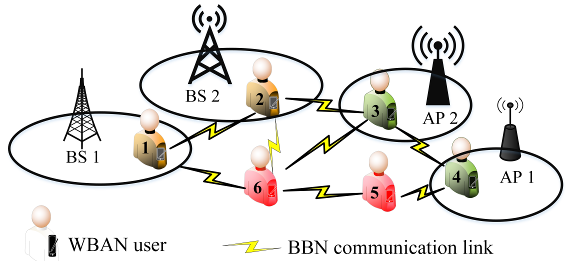


Figure 1: Illustration of BBN comprising of heterogeneous WBAN users

Since, it is a connected graph, any two WBAN users can communication with each other through one-hop/multi-hop over the communication links. We define the upstream one-hop neighbor of WBAN user i as $\mathcal{N}_i^+ = (j : (j,i) \in \mathcal{E})$ and downstream neighbor as $\mathcal{N}_i^- = (j : (i,j) \in \mathcal{E})$.

We divide the total time period $\mathcal{T}$ is divided into slots $t = 1, 2, \cdots T$, each of unit length. At the beginning of each time slot, each WBAN user $i \in \mathcal{N}$ decides its role for the current, i.e., whether to transmit its own to neighbor node, or act as relay for neighboring node, or upload the data.

Let S_{ij} be the capacity of the intra-WBAN wireless link between node i and j during the current slot. Similarly, let $S_{0i} \geq 0$ be the beyond-WBAN upload channel capacity of WBAN user i, i.e., the amount of data (in bytes) that a WBAN node $i \in \mathcal{N}$ uploads as a gateway to the Internet. Each and every WBAN users cooperatively communicate with each other and share the Internet access among each other to upload the data to nearest AP/BS. Let $u_i^k \geq 0$ be the amount of data that a WBAN user i uploads for user $k \in \mathcal{N}$. The total amount of upload data is upper bounded by the channel capacity between user $i \in \mathcal{N}$ and nearest AP/BS, i.e.,

$$\sum_{k \in N} u_i^k \leq S_{0i}, \quad \forall i \in \mathcal{N} \tag{1}$$

The total amount of upload data by all N WBAN users is defined as *uploading matrix* of BBN network, $\mathbf{u} = (u_i^k \geq 0 : i \in \mathcal{N}, k \in \mathcal{N})$. The uploading matrix includes both own data and the other WBAN users data uploaded by WBAN user i.

Let $r_{0i}^i \geq 0$ be the amount of user i's own data (in bytes) and $r_{ij}^k \geq 0$ be the amount of data (in bytes) of user k relayed by user i to its downstream neighbor user j. Clearly, the total amount of data transmitted is bounded by the maximum link capacity S_{ij}, i.e.,

$$\sum_{k\in N} r_{ij}^{k} \leq S_{ij}, \quad \forall (i,j) \in \mathcal{E} \tag{2}$$

We define the overall relaying data of all N users by all users as *relaying matrix* of BBN network, $\mathbf{r} = (r_{ij}^{k} \geq 0 : \forall (i,j) \in \mathcal{E}, k \in \mathcal{N})$. Both the relaying and routing matrix render the total amount of data of all WBAN users inside the BBN network relayed and/or uploaded to the nearest AP/BS by each WBAN user over the inter-WBAN and beyond-WBAN link [22]. The relaying and routing decision of each user $i \in \mathcal{N}$ should satisfy flow balance equation, i.e.,

$$\sum_{j\in \mathcal{N}_i^{-}} r_{ij}^{k} + u_i^{k} = \sum_{j\in \mathcal{N}_i^{+}} r_{ji}^{k} + r_{0i}^{i}, \quad \forall i,k \in \mathcal{N}, i \neq k \tag{3}$$

This signifies that the total amount of data relayed by the WBAN user $i \in \mathcal{N}$ to its downstream neighbor WBAN users plus the data the user uploads should be equal to the aggregate sum of its own generated data and the data it receives by from its upstream neighbor WBAN users. In case of no Internet connection the user transmits the total data to its downstream neighbor nodes.

1) Utility of WBAN user: The utility of each WBAN user $i \in \mathcal{N}$ depends on the amount of its own data uploaded or transmitted to downstream neighboring node. As the rate of data transfer increases, the service delay of WBAN user decreases, while overcoming the possibility of buffer overflow. Let d_i denotes the aggregate amount of data that user $i \in \mathcal{N}$ uploads and transfers to neighboring node (not including the relaying data of other users), i.e.,

$$d_i = u_i^{i} + \sum_{j\in \mathcal{N}_i^{-}} r_{ij}^{i} \forall i, \forall (i,j) \in \mathcal{E} \tag{4}$$

We define the utility function of a WBAN user $i \in \mathcal{N}$ as $\mathcal{S}_i(d_i)$, which is an increasing and strictly concave function of aggregated data rate d_i. The concavity of the function $\mathcal{S}_i(d_i)$ captures the satisfaction of WBAN user $i \in \mathcal{N}$ which increases with the transfer of aggregate data d_i. Note that, different WBAN users may have different utility functions.

2) Cost of Energy Consumption: Energy consumption of WBAN users in BBN network is a serious concern since the WBAN hub posses limited energy resource. Each WBAN user consumes energy while transmitting and receiving data to either neighboring node(s) or nearest

AP/BS. Let $e^t_{ij} > 0$ be the energy consumed by WBAN user i while transmitting one byte of data through link $(i,j) \in \mathcal{E}$. Conversely, let $e^r_{ij} > 0$ be the energy consumed by WBAN user j while receiving one byte of data from the user i. Lastly, let $e^u_{0i} > 0$ be the energy consumed by WBAN user $i \in \mathcal{N}$ while uploading to the Internet. The values of e^t_{ij}, e^r_{ij}, and e^u_{0i} depend on the communication interface of the WBAN user i. For example, the uploading energy e^u_{0i} of WBAN user having WiFi connection is different from WBAN user with cellular connection. Finally, the total energy consumed by WBAN user $i \in \mathcal{N}$ is,

$$e_i = e^u_{0i} \sum_{k\in\mathcal{N}} u^k_i + \sum_{j\in\mathcal{N}^-_i} e^t_{ij} \sum_{k\in N} r^k_{ij} + \sum_{j\in\mathcal{N}^+_i} e^r_{ij} \sum_{k\in\mathcal{N}} r^k_{ji} \tag{5}$$

The maximum energy budget of a WBAN user $i \in \mathcal{N}$ is $E_i \geq 0$. Clearly, for reliable BBN communication each node should consume energy within its maximum budget, i.e., $e_i \leq E_i$. However, in practical scenario, each user has different energy sensitivity and the cost of the same energy consumption perceived by different users vary dramatically [7], [9], [14]. For example, some WBAN users may want to deplete whole energy in current time slot for uploading or relaying data. On the other hand, one may decide to preserve energy. Therefore, to model this energy consumption preference phenomenon of a WBAN user $i \in \mathcal{N}$ we introduce an cost function $\mathcal{C}_i(e_i)$, which is an increasing and strictly convex function of energy consumption e_i. The convexity nature of $\mathcal{C}_i(e_i)$ function captures the dissatisfaction of WBAN user $i \in \mathcal{N}$ which increases with the depletion of energy. Note that, in BBN the total energy cost depends on the energy consumption due to the message exchange between WBAN for coordination, in addition to the energy consumption due to uploading and relaying. Formulating this message passing energy consumption cost is very complicated and beyond the scope of this work.

3) User's Payoff Function: Let $\mathcal{Q}(\cdot)$ be the payoff function of user $i \in \mathcal{N}$ which captures the utility, cost function of individual user in BBN network. Mathematically,

$$\mathcal{Q}(\mathbf{r_i}, \mathbf{r_{-i}}, \mathbf{u_i}) = \mathcal{S}_i(d_i) - \chi_i \sum_{k\in N} u^k_i - \mathcal{C}_i(e_i) \tag{6}$$

where $\mathbf{u_i} = (u^k_i : k \in \mathcal{N})$ denotes the uploading matrix. $\mathbf{r_i} = (r^k_{ij} : j \in \mathcal{N}^-_i, k \in \mathcal{N})$ denote the relaying matrix of user i and $\mathbf{r_{-i}} = (r^k_{ji} : j \in \mathcal{N}^+_i, k \in \mathcal{N})$ denote the routing decisions of its neighboring users (delivering data to i). Further, $\chi_i \geq 0$ denotes the price paid by the user i for uploading data (in bytes) to Internet. Gateway users having cellular connection for beyond-

WBAN communication pay according to the price charged by their respective cellular operators and on the other hand Wi-Fi users pay no charge for Internet access, i.e., $\chi_i = 0, \forall i \in \mathcal{N}$.

Clearly, as the uploading data u_i^i of WBAN user i increases, the payoff function increases along with the upload (monetary) cost and energy cost, which makes the payoff function $\mathcal{Q}(\cdot)$ non-increasing. However, the payoff function decreases the monotonically with amount of data it relay to its downstream neighbor user and uploads for other WBAN user $k \in \mathcal{N}, i \neq k$ because of increase in energy and upload (monetary) cost. Thus, the participating WBAN users are hesitant to cooperate without proper incentive.

4) Payment and Reward Function: In BBN network, reliability of overall network is mainly dependent on the cooperative nature of participating WBANs who either share their Internet access or share their bandwidth for relaying neighboring nodes data. Therefore, we assume that WBAN user pays for the service it receives and obtains reward for providing service. Since, the BBN network is a decentralized network and there is no central coordinator available to monitor the transaction between sender and gateway node, we assume that the transaction is done between two adjacent nodes of a link. Let $\mathbf{p_i} = (p_{ji}^k \geq 0 : j \in \mathcal{N}_i^+, k \in \mathcal{N})$ be the *payment matrix* of user $i \in \mathcal{N}$, where p_{ji}^k is the payment done by user i to its upstream neighbor user j for the data of user k, which is to be transmitted over the link $(j, i) \in \mathcal{E}$. Similarly, let $\mathbf{p_{-i}} = (p_{ij}^k \geq 0 : j \in \mathcal{N}_i^-, k \in \mathcal{N})$ be the *reward matrix* of user $i \in \mathcal{N}$, in which p_{ij}^k denotes the reward obtained by user i from its downstream neighbor user j for the data of user k.

Each WBAN user i has a budget $B_i \geq 0$ at the beginning of the time period. Along with that, each user is rewarded an amount $\varphi > 0$ for their involvement in cooperation in current time period, which is identical for all users. Therefore, the total budget of WBAN user $i \in \mathcal{N}$ is,

$$\mathcal{W}(\mathbf{p_i}, \mathbf{p_{-i}}) = \phi_i(B_i + \varphi + \sum_{k \in N} \sum_{j \in \mathcal{N}_i^-} p_{ij}^k - \sum_{k \in N} \sum_{j \in \mathcal{N}_i^+} p_{ji}^k) \tag{7}$$

where $\phi_i > 0$ is the discount rate of user $i \in \mathcal{N}$, which mainly captures the willingness of user i to cooperate in future time period. In case the user is not intend to participate in future time it may set the value of ϕ near to 0. Therefore, The total payoff of user i is

$$\mathcal{T}_i(\mathbf{r_i}, \mathbf{r_{-i}}, \mathbf{u_i}, \mathbf{p_i}, \mathbf{p_{-i}}) = \mathcal{Q}(\mathbf{r_i}, \mathbf{r_{-i}}, \mathbf{u_i}) + \mathcal{W}(\mathbf{p_i}, \mathbf{p_{-i}}) \tag{8}$$

The main objective is to design a joint resource allocation and incentive mechanism scheme for BBN network that determines the amount of resource the WBAN users contribute during participation in terms of upload bandwidth, battery, and relaying bandwidth, to maximize the total amount of upload data to nearest AP/BS within current time period.

IV. Proposed Mechanism

In BBN, the WBAN users which act as gateways or relays have to bear both energy cost and uploading data cost with increase in incoming neighboring data. Therefore, there is a need of proper incentive scheme to compensate these users and motivate them for cooperation. Hence, we design a N-user bargaining game, in which the WBAN users trade their resources (battery, relaying bandwidth, and Internet access) and get remunerated with proper reward value. Further, to maintain the efficiency and fairness of overall network we use Nash bargaining solution (NBS) to solve the proposed N-user bargaining game. The NBS captures the strategic interaction among conflicting users and provides a Pareto optimal and proportionally fair solution [23]. Since, maintaining both efficiency and fairness in case of BBN is up most important as it encourage users to join the network and cooperate with others.

Consider a bargaining game $\mathcal{G} = \langle \mathcal{N}, \mathbb{A}, g_{i i\in\mathcal{N}} \rangle$, where $\mathcal{N}$ represents the set of WBAN users. $\mathbb{A}$ denotes the strategy space, i.e., $\mathbb{A} = A_1 \times A_2 \times \cdots A_N$, where A_i represents the set of strategies available to user i. g_i represents the payoff of each user $i \in \mathcal{N}$. Let g_i^d be the disagreement of user $i \in \mathcal{N}$, i.e., the minimum payoff obtained without cooperation. Then the NBS of N-user bargaining game is defined as follows,

Definition 1. $\mathbf{a}^* = (a_1^*, a_2^*, \cdots a_I^*)$ is a NBS if it solves the optimization problem

$$\max_{\mathbf{a}\in\mathbb{A}, g_i(\mathbf{a}^*)\geq g_i^d} \prod_{i\in\mathcal{N}} (g_i(\mathbf{a}^*) - g_i^d)$$

Disagreement point of WBAN user: Since the participating WBAN users are rational, the users cooperate if and only if the payoff due to cooperation is higher than the pay off obtained due to independent or non-cooperative mode. In case of non-cooperative mode the WBAN user i uploads its own data and not responsible to relay or upload other users' data. Therefore, the optimal upload strategy (u_i^i) of user i in non-cooperative mode is obtained by solving the following problem termed as *non-cooperative mode problem*(NCP):

$$\mathcal{Q}_i^{ncp} = \arg\max_{0 \le u_i^i \le S_{0i}} \mathcal{S}_i(u_i^i) - \chi_i u_i^i - \mathcal{C}_i(u_i^i) \tag{9}$$

Clearly, the above NCP problem is concave optimization problem. Therefore, it has an unique solution named as $\mathcal{Q}_i^{ncp}$ which is the disagreement point of WBAN user i.

Since solving the above NBS problem is quite challenging we convert the product form of NBS problem into more tractable sum of logarithmic terms. Therefore, the optimization problem $\mathbf{P1}$ is

$$\max_{\mathbf{r},\mathbf{u},\mathbf{p}} \sum_{i \in \mathcal{N}} \log\left(\mathcal{T}_i(\mathbf{r_i}, \mathbf{r_{-i}}, \mathbf{u_i}, \mathbf{p_i}, \mathbf{p_{-i}}) - (\mathcal{Q}_i^{ncp} + \phi_i B_i)\right)$$

$$\text{s.t.} \quad (1), (2), (3)$$

$$\sum_{k \in N} \left(\sum_{j \in \mathcal{N}_i^-} p_{ij}^k - \sum_{j \in \mathcal{N}_i^+} p_{ji}^k \right) \ge B_i + \varphi, \forall i \in \mathcal{N} \tag{10}$$

$$\mathcal{T}_i(\mathbf{r_i}, \mathbf{r_{-i}}, \mathbf{u_i}, \mathbf{p_i}, \mathbf{p_{-i}}) \ge (\mathcal{Q}_i^{ncp} + \phi_i B_i), \forall i \in \mathcal{N} \tag{11}$$

$$r_{ij}^k \ge 0, u_i^k \ge 0, 0 \le p_{ij}^k \le \sum_{i \in \mathcal{N}} (B_i + \varphi), \forall i, j, k \in \mathcal{N} \tag{12}$$

The objective function contains both payoff function and disagreement point of user i. The sum of non-cooperative mode performance ($\mathcal{Q}_i^{ncp}$) as explained in Equation (9) and the initial budget of user ($\phi_i B_i$) defines the disagreement of user i. The constraint mentioned in Equation (10) illustrates that for relaying user the difference between payment done to downstream neighbor and the reward earned from upstream neighbor is upper bounded by its own budget. The constraint mentioned in Equation (11) signifies that users are individually-rational and only agree to cooperate if their payoff increases due to the cooperation.

The objective function of problem $\mathbf{P1}$ is concave in nature, as it is the sum of logarithm functions. Also, the constraint set defines a convex, compact feasible region. Note that, when WBAN user decides not to cooperate in BBN network can still operate in non-cooperative mode and has disagreement payoff. Therefore, the above problem is concave maximization problem and always posses a unique optimal solution $\mathbf{r}^*, \mathbf{u}^*, \mathbf{p}^*$, which can be solved by applying Karush-Kuhn-Tucker (KKT) conditions. The solution ensures efficient and fair uploading, relaying, and payment policy for participating WBAN users.

The optimal solution of above problem $\mathbf{P1}$ can be obtained by solving in a centralized fashion at the beginning of the time period and broadcast it to participating users to act accordingly. However, in case of BBN network there is no central controller present with decision taking abilities. Therefore, our main objective is design a distributed mechanism in such a way that, each WBAN user should take their own decision of whether to relay or upload and how much to charge or pay and eventually reaches to the optimal solution.

V. Distributed Algorithm for BBN

The design of distributed algorithm for problem $\mathbf{P1}$ is challenging due to two reasons. First, the objective function of each user $i \in \mathcal{N}$ is coupled, i.e., the payoff of the user is dependent not only on its own decision but also on the decision of its both upstream and downstream neighbor WBAN users. Second, the constraints of problem $\mathbf{P1}$ are also coupled, for example, the decision of routing of user i as shown in Equation (2) and (3) is dependent on its neighbors' capacity constraints and routing decision. Therefore, to decouple the utility function of user i from its neighbor nodes we introduce local auxiliary variables for each user i and then use additional equality constraints for each neighboring nodes which are known as *consistency constraints* [24]. This in turn transfers the problem to coupling in the constraints. The coupling constraint problem can be solved iteratively in a distributed fashion using primal-dual algorithm [25].

Let $\boldsymbol{\zeta_i} = (\zeta_{ji}^k : j \in \mathcal{N}_i^+, k \in \mathcal{N})$ and $\boldsymbol{\eta_i} = (\eta_{ij}^k : j \in \mathcal{N}_i^-, k \in \mathcal{N})$ are two auxiliary variable matrices of user $i \in \mathcal{N}$ and the respective equality constraints are, $\zeta_{ji}^k = r_{ji}^k, \forall i \in \mathcal{N}, j \in \mathcal{N}_i^+, k \in \mathcal{N}$ and $\eta_{ij}^k = p_{ij}^k, \forall i \in \mathcal{N}, j \in \mathcal{N}_i^-, k \in \mathcal{N}$. These two local auxiliary variables replace the decision variables $\mathbf{r_{-i}}$ and $\mathbf{p_{-i}}$ of neighbors (both upstream and downstream) of user i and allows to take optimal decision regarding the routing, uploading and payment independently. Furthermore, the auxiliary variables ensure that the decision of user takes into account its one-hop neighbors' decisions.

Now, we take a dual decomposition approach [25] to obtain the distributed algorithm. Let the Lagrangian multipliers of coupling constraints, i.e., (3), (10), ζ_{ji}^k and η_{ij}^k are $\boldsymbol{\mu} = (\mu_i^k : i, k \in \mathcal{N})$, $\boldsymbol{\lambda} = (\lambda_i \geq 0 : i \in \mathcal{N})$, $\boldsymbol{\upsilon} = (\upsilon_{ji}^k : i, k \in \mathcal{N}, j \in \mathcal{N}_i^+)$, and $\boldsymbol{\omega} = (\omega_{ij}^k : i, k \in \mathcal{N}, j \in \mathcal{N}_i^-)$, respectively. The Lagrangian function of the problem $\mathbf{P1}$ is

$$\mathcal{L} = \sum_{i\in\mathcal{N}} \Bigg[\log\big(\mathcal{T}_i(\mathbf{r_i},\mathbf{u_i},\mathbf{p_i}) - (\mathcal{Q}_i^{ncp}+\phi_i B_i)\big) + \sum_{k\in N}\sum_{j\in\mathcal{N}_i^+} \upsilon_{ji}^k\big(\zeta_{ji}^k - r_{ji}^k\big) + \sum_{k\in N}\sum_{j\in\mathcal{N}_i^-}\omega_{ij}^k\big(\eta_{ij}^k - p_{ij}^k\big)$$
$$- \lambda_i\Bigg(\sum_{k\in N}\sum_{j\in\mathcal{N}_i^+} p_{ji}^k - \sum_{k\in N}\sum_{j\in\mathcal{N}_i^-} p_{ij}^k - B_i - \varphi\Bigg) + \sum_{k\in\mathcal{N}} \mu_i^k\Bigg(\sum_{j\in\mathcal{N}_i^-} r_{ij}^k + u_i^k - \sum_{j\in\mathcal{N}_i^+} r_{ji}^k\Bigg)\Bigg] \quad (13)$$

where the Lagrangian multipliers υ_{ji}^k and ω_{ij}^k are also known as *consistency prices*. The Lagrangian $\mathcal{L}(.)$ can be subdivided into user specific Lagrangian $\mathcal{L}_i(.), i \in \mathcal{N}$ due to its decomposable structure is,

$$\mathcal{L}_i(\cdot) = \log\big(\mathcal{T}_i(\cdot) - (\mathcal{Q}_i^{ncp}+\phi_iB_i)\big) + \sum_{k\in N}\Bigg(\sum_{j\in\mathcal{N}_i^+}\big(\upsilon_{ji}^k\zeta_{ji}^k - \omega_{ji}^k p_{ji}^k\big) + \sum_{j\in\mathcal{N}_i^-}\big(\omega_{ij}^k\eta_{ij}^k - \upsilon_{ij}^k r_{ij}^k\big)\Bigg)$$
$$+ \sum_{k\in\mathcal{N}}\Bigg(\mu_i^k(u_i^k - r_{0i}^i) + \sum_{j\in\mathcal{N}_i^-} r_{ij}^k(\mu_j^k-\mu_i^k)\Bigg) - \lambda_i B_i + \sum_{j\in\mathcal{N}_i^+}\lambda_j\sum_{k\in N} p_{ij}^k - \sum_{k\in N}\sum_{j\in\mathcal{N}_i^+}\lambda_i p_{ji}^k \quad (14)$$

Therefore, the user-specific optimization problem $\mathbf{P2}$ is

$$\max_{\mathbf{r_i},\mathbf{u_i},\mathbf{p_i},\boldsymbol{\zeta_i},\boldsymbol{\eta_i}} \mathcal{L}_i(\mathbf{r_i},\mathbf{u_i},\mathbf{p_i},\boldsymbol{\zeta_i},\boldsymbol{\eta_i})$$
$$\text{s.t.} \quad (1),(2),(11),(12)$$
$$\zeta_{ji}^k,\eta_{ij}^k \geq 0, \forall i\in\mathcal{N}, j\in(\mathcal{N}_i^+\cup\mathcal{N}_i^-), k\in\mathcal{N} \quad (15)$$

The optimal value of problem $\mathbf{P2}$ is obtained for the given values of $\boldsymbol{\mu}$, $\boldsymbol{\lambda}$, $\boldsymbol{\upsilon}$, and $\boldsymbol{\omega}$. Let $g(.)$ be the dual function, i.e., $g(.) = \inf_{\lambda\geq 0}\mathcal{L}_i(\cdot)$. Then, the dual of the optimization problem is $\min_{\boldsymbol{\lambda}\geq 0}\big(\min_{\boldsymbol{\mu},\boldsymbol{\upsilon},\boldsymbol{\omega}} g(\boldsymbol{\mu},\boldsymbol{\lambda},\boldsymbol{\upsilon},\boldsymbol{\omega})\big)$. The dual problem can be solved by using gradient method [25] as follows, $\mu_i^{(k)(t+1)} = \mu_i^{(k)(t)} - \delta^t\Xi^{(k)(t)}$, $\lambda_i^{t+1} = [\lambda_i^t - \delta^t\Upsilon^t]^+$, $\upsilon_{ji}^{(k)(t+1)} = \upsilon_{ji}^{(k)(t)} - \delta^t\big(r_{ji}^{(k)(t)} - \zeta_{ji}^{(k)(t)}\big)$, and $\omega_{ij}^{(k)(t+1)} = \omega_{ij}^{(k)(t)} - \delta^t\big(p_{ij}^{(k)(t)} - \eta_{ij}^{(k)(t)}\big)$. Where $\Xi^{(k)(t)} = \sum_{j\in\mathcal{N}_i^+} r_{ji}^{(k)(t)} - u_i^{(k)(t)} - \sum_{j\in\mathcal{N}_i^-} r_{ij}^{(k)(t)}$, and $\Upsilon^t = B_i + \varphi - \sum_{k\in N}\sum_{j\in\mathcal{N}_i^-} p_{ij}^{(k)(t)} + \sum_{k\in N}\sum_{j\in\mathcal{N}_i^+} p_{ji}^{(k)(t)}$. Furthermore, $[.]^+$ ensures that the Lagrange multiplier attains non-negative value, i.e., $\lambda_i^{t+1}\geq 0$. $\delta^t > 0$ is the positive step size chosen during iteration t. We assume a diminishing step size $\delta^t = \frac{1+q}{t+q}$ for $q \geq 0$.

In each iteration, each WBAN user $i\in\mathcal{N}$ first solves their individual optimization problem $\mathbf{P2}$ and calculates their primal variables, i.e., $\mathbf{r_i},\mathbf{u_i},\mathbf{p_i},\boldsymbol{\zeta_i},\boldsymbol{\eta_i}$. After that, it uses these primal variables to calculate its dual variables. Finally, it broadcasts its dual variables to one-hop neighbor WBAN users. Similarly, Neighboring users update their dual variables using both their own primal variables and received dual variable, and broadcast the updated value. The iteration continues till the difference between the values of dual variables in two consecutive iteration is sufficiently small. We use convergence index $\epsilon > 0$ for that. The complete algorithm is given in Algorithm 1.

Proposition 1. *The proposed distributed algorithm converges to the optimal solution of problem* $\mathbf{P1}$*, i.e.,* $(\mathbf{r}^*, \mathbf{u}^*, \mathbf{p}^*)$.

Proof: The convergence of Algorithm 1 is proved if it satisfy two conditions. First, the gradient used for dual updates should be bounded. Second, the step size δ^t should be chosen properly. Clearly, from Equations (1), (2), (11), and (12) the primal variables $\mathbf{r_i}, \mathbf{u_i}, \mathbf{p_i}$ are bounded, and the auxiliary variables $\boldsymbol{\zeta_i}, \boldsymbol{\eta_i}$ are bounded as per Equations (15). Therefore, the dual variables which are updated using primal variables are bounded. Along with that, the step size is diminishing with each iteration, therefore, the Algorithm 1 converges to the optimal solution. ∎

Algorithm 1: Distributed Algorithm for BBN

Inputs : δ, ϵ
Outputs: $\mathbf{r}^*, \mathbf{u}^*, \mathbf{p}^*$
Set $\mathbf{r}^{(0)}, \mathbf{u}^{(0)}, \mathbf{p}^{(0)}, \boldsymbol{\mu}^{(0)}, \boldsymbol{\zeta}^{(0)}, \boldsymbol{\eta}^{(0)}, \boldsymbol{\lambda}^{(0)}, \boldsymbol{\upsilon}^{(0)}, \boldsymbol{\omega}^{(0)}$
$converge = 0, t = 0$
while *converge = 0* **do**
  $t \leftarrow t + 1$
  for $i = 1 : \mathcal{N}$ **do**
    Compute $\mathbf{r_i}^t, \mathbf{u_i}^t, \mathbf{p_i}^t, \boldsymbol{\zeta_i}^t, \boldsymbol{\eta_i}^t$ by solving optimization problem $\mathbf{P2}$
    Send $p_{ji}^{(k)(t)}, \forall k \in \mathcal{N} \setminus i$ to $j \in \mathcal{N}_i^+$
    Send $r_{ij}^{(k)(t)}, \forall k \in \mathcal{N} \setminus i$ to $j \in \mathcal{N}_i^-$
    Compute dual variables $\mu_i^{(k)(t+1)}$, λ_i^{t+1}, $\upsilon_{ji}^{(k)(t+1)}$, and $\omega_{ij}^{(k)(t+1)}$
    Send $\mu_i^{(k)(t+1)}, \upsilon_{ji}^{(k)(t+1)} \forall k \in \mathcal{N} \setminus i$ to $j \in \mathcal{N}_i^+$
    Send $\lambda_i^{t+1}, \omega_{ij}^{(k)(t+1)} \forall k \in \mathcal{N} \setminus i$ to $j \in \mathcal{N}_i^-$
  if $|\mu_i^{(k)(t+1)} - \mu_i^{(k)(t)}|$, $|\lambda_i^{t+1} - \lambda_i^t|$, $|\upsilon_{ji}^{(k)(t+1)} - \upsilon_{ji}^{(k)(t)}|$, $|\omega_{ij}^{(k)(t+1)} - \omega_{ij}^{(k)(t)}| < \epsilon$ **then**
    $converge \leftarrow 1$

VI. Performance Evaluation

In this section we demonstrate the effectiveness of collaboration among heterogeneous WBAN users in different scenarios. First, we show the improvement of individual user performance in BBN due to cooperation than its independent mode. Thereafter, we show the impact of diversity of the WBAN user's resources (battery, Internet access cost) on overall BBN performance.

We consider a BBN comprises of 6 heterogeneous WBAN users uniformly located in a geographical area of $100 \times 100m^2$. We consider utility for user $i \in \mathcal{N}$ is a logarithmic function, i.e., $\mathcal{S}_i(d_i) = \rho_i log(1+d_i)$, to capture the principle of diminishing marginal return. The parameter $\rho \in (0,1]$ captures the communication need of the WBAN user based on its severity (criticality). For example a WBAN user with high severity condition has ρ value near to 1. We model the energy cost function using exponential function, i.e., $\mathcal{C}_i(e_i) = \gamma_i \exp(e_i)$. The parameter $\gamma_i \in (0,1]$ captures the energy sensitivity of WBAN user. Similarly, the value of discount rate $\phi_i, \forall i \in \mathcal{N}$ (in Equation (7)) is uniformly distributed in $(0,1)$. Further, we assume that the Internet access cost of gateway user with cellular connection is $0.2/Mbits$ [22] and the value is 0 for the user connecting to WiFi access point.

To show the effectiveness of our proposed NBS-based approach we consider two different schemes as benchmarks. i) *Non-cooperation (NCP)*: In this scheme there is no provision of cooperating (relaying) and users upload their data independently. Each user obtains their solution by solving Equation (9). ii) *Social welfare (SW) maximization*: This scheme maximizes the sum of utilities all participating users, i.e., $\max \sum_{i \in \mathcal{N}} \mathcal{T}_i$.

Fig. 2 illustrates the individual payoff of participating users in BBN for different schemes. We observe that the proposed NBS-based scheme improves the total payoff of all users than the NCP scheme. This indicates that the outcome of each user in cooperation always outperforms the outcome in independent mode. Therefore, the proposed NBS-based scheme motivates WBAN users to join the BBN and improve their payoff. However, the SW maximization scheme leads to lower payoff in some users than NCP (independent) scheme. For example, the total payoff of user 2 and 5 worsen in SW maximization scheme-based cooperation compared to NCP scheme. This indicates the fairness in resource allocation in case of NBS-based scheme.

Next in Fig. 3, we illustrate the effectiveness of bargaining scheme on BBN networks. We assume that two among six users (users 1 and 2) are connected to cellular (4G) network, other

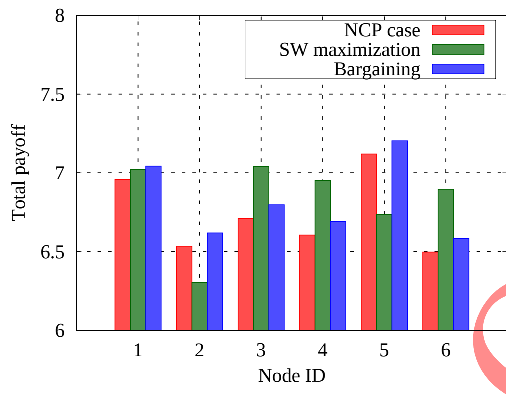
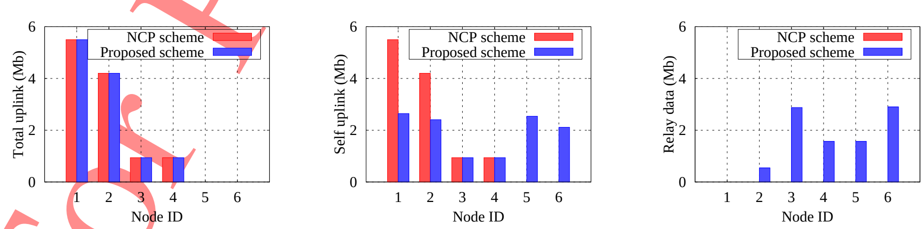


Figure 2: Comparison of individual payoff

two users (users 3 and 4) avail Wi-Fi connectivity, and remaining two users have no Internet connectivity. The average uplink rate for LTE is 5.64 Mbps and 0.96Mbps for WiFi [11], [22]. In particular, we show the total uplink data, self uplink data, and relaying data amount of all participating users for both NCP and proposed scheme. We observe in Fig. 3(a) that, the amount of total uplink data is the same for all users in both the schemes. This is because as the amount of uplink data increases the user's payoff increases as shown in Equation (6). The self uplink data amount in proposed scheme is less for some users than the NCP scheme, since they relay and upload other users' data based on their payoff function. This decision of cooperation (relay and/or upload) depends on individual user's Internet access cost, uplink capacity, energy consumption cost, and reward received from other users. Note that, for user 6 the total uplink data amount is zero in NCP scheme due to unavailability of Internet connection. However, the proposed NBS-based approach enables user 5 and 6 to upload its data through relaying it to other users having Internet connection with fair amount of payment transfer.



(a) Total uplink data (b) Self uplink data (c) Relay data

Figure 3: Effectiveness of bargaining scheme on BBN networks

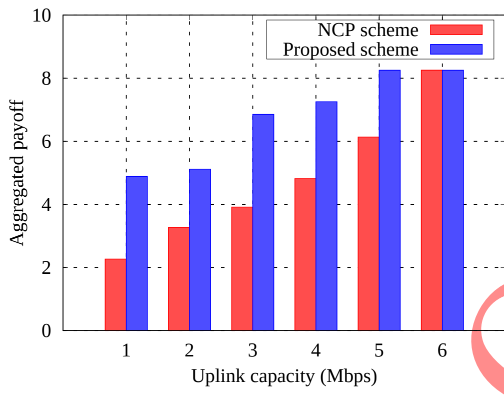
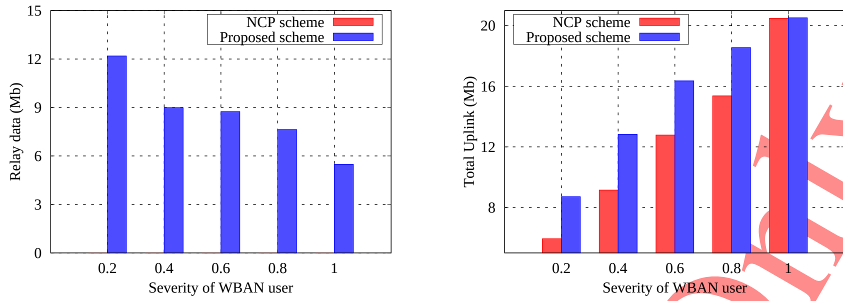


Figure 4: Effect of diverse uplink capacity on BBN performance

We investigate the effect of user diversities on the performance of BBN. In our case, user diversity is characterized by three parameters — i) uplink capacity, ii) WBAN user severity (ρ), and iii) energy sensitivity or battery energy cost (γ). Typical WBAN users avail cellular service and WiFi services for beyond-WBAN communication. Therefore, the uplink capacity of a WBAN user accessing Internet is dependent on the service it use. To observe the BBN performance in presence of different users having different Internet uplink access capacity, we consider a BBN with two WBAN users having high speed Internet uplink capacity (10 Mbps) and remaining users having identical but low uplink capacity and increases gradually from 1 to 6 Mbps. We compare the total uplink data (in Mbps) in case of NBS scheme with NCP scheme in Fig. 4. We observe that as the uplink capacity of users increases, the difference of total uplink data for proposed NBS scheme and NCP scheme decreases. In other words, as the users become less diverse in terms of Internet uplink capacity, all users upload their data through their own connection. In summery, the benefit of cooperation is insignificant when the diversity among users is low.

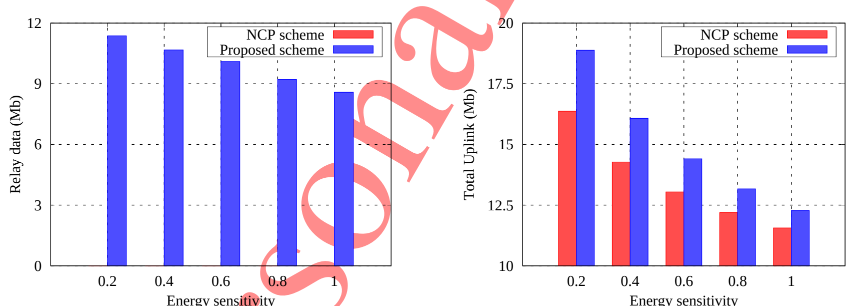
Fig. 5 illustrates the impact of user diversity with regards to severity parameter (ρ) on data relaying amount (in Mbps) and total uplink data of BBN. We assume that among six users two users are highly server, i.e., $\rho = 1$ and for remaining four users the severity value is initially low ($\rho = 0.1$) and gradually increases to 1. In Fig. 5(a), we observe that as the severity of WBAN users increases the relaying amount decreases in proposed scheme. This is because each user tries to upload its data using its own Internet connection. We compare the total uplink data amount using our proposed scheme with NCP scheme in Fig. 5(b). We observe that as the severity of



(a) Relay data (b) Total uplink data

Figure 5: Effect of WBAN user severity on BBN performance

users increase the uplink data amount also increases for both the scheme. Further, with increase in severity, the benefit of NBS approach decreases from 32.3% to 0%. With increase severity of each user, diversity diminishes and each user tries to upload its own data rather than depending on neighboring gateway WBAN users. Consequently, this diminishes the benefits of cooperation.



(a) Relay data (b) Total uplink data

Figure 6: Effect of energy sensitivity on BBN performance

Finally, we analyze the impact of energy sensitivity diversity on the performance of BBN in Fig. 6. We fixed the energy sensitivity parameter value ($\gamma = 1$) for two users and for remaining four users the γ value increases gradually from $[0.1 - 1]$, while keeping all other network parameters fixed. In Fig. 6(a) we observe that, in proposed scheme, as the γ value decreases the sharing amount decreases. This is because the energy sensitive WBAN users are reluctant to act as relay. Moreover, we compare the total uplink data amount using our proposed scheme with NCP scheme in Fig. 6(b). We observe that as the severity of users increase the uplink data amount decreases for both the scheme. Further, the difference between the uplink data amount for both the schemes decreases as the energy sensitivity of users increases.

VII. Conclusion

In this paper, we proposed a BBN framework and analyzed the resource sharing problem among heterogeneous WBAN users. First, we modeled the payoff function of the WBAN user by taking into account their individual uplink data rate, Internet access cost for uploading data, and energy consumption cost due to both relaying and uploading. Thereafter, we designed a N-person bargaining game that captures the interaction among payoff maximizing WBAN users and solved it using NBS. The proposed mechanism ensures efficient resource sharing and fair division of mutual benefit among participants. Further, we proposed a distributed algorithm to obtain the NBS and shown its convergence analytically. Numerical simulation results demonstrated the efficacy of our proposed scheme in improving both individual WBAN user's payoff and overall BBN performance.

In future, we plan to extend our work while considering the effects of mobility, message overhead, and time varying uplink capacity of WBAN users in BBN. Further, we also plan to focus on the incentive design where the participating users are strategic in nature.

References

[1] S. Deep, X. Zheng, C. Karmakar, D. Yu, L. Hamey, and J. Jin, "A Survey on Anomalous Behaviour Detection for Elderly Care using Dense-sensing Networks," *IEEE Commun. Surv. Tut.*, pp. 1–1, 2019.

[2] S. M. R. Islam, D. Kwak, M. H. Kabir, M. Hossain, and K. Kwak, "The Internet of Things for Health Care: A Comprehensive Survey," *IEEE Access*, vol. 3, pp. 678–708, 2015.

[3] P. K. Bishoyi and S. Misra, "Enabling Green Mobile-Edge Computing for 5G-Based Healthcare Applications," *IEEE Trans. Green Communi. Netw.*, vol. 5, no. 3, pp. 1623–1631, 2021.

[4] P. K. Bishoyi and S. Misra, "Coexistence Throughput Analysis of Cyber-Physical WBAN System in Presence of WLAN," in *Proc. IEEE GLOBECOM Workshops*, 2018, pp. 1–6.

[5] A. Meharouech, J. Elias, and A. Mehaoua, "Future body-to-body networks for ubiquitous healthcare: a survey, taxonomy and challenges," in *Proc. IEEE Ubi-HealthTech*, May 2015, pp. 1–6.

[6] S. M. Shimly, D. B. Smith, and S. Movassaghi, "Experimental Analysis of Cross-Layer Optimization for Distributed Wireless Body-to-Body Networks," *IEEE Sensors J.*, vol. 19, no. 24, pp. 12 494–12 509, Dec 2019.

[7] P. K. Bishoyi and S. Misra, "Distributed Resource Allocation for Collaborative Data Uploading in Body-to-Body Networks," *IEEE Trans. Commun.*, pp. 1–10, 2021.

[8] D. B. Arbia, M. M. Alam, Y. L. Moullec, and E. B. Hamida, "Communication Challenges in on-Body and Body-to-Body Wearable Wireless Networks—A Connectivity Perspective," *Techn.*, vol. 5, no. 3, 2017.

[9] P. K. Bishoyi and S. Misra, "Enabling Collaborative Data Uploading in Body-to-Body Networks," *IEEE Commun. Lett.*, vol. 25, no. 2, pp. 538–541, 2021.

[10] D. Ben Arbia, M. M. Alam, R. Attia, and E. Ben Hamida, "Data dissemination strategies for emerging wireless body-to-body networks based internet of humans," in *Proc. IEEE WiMob*, Oct 2015, pp. 1–8.

[11] G. Iosifidis, L. Gao, J. Huang, and L. Tassiulas, "Enabling crowd-sourced mobile internet access," in *Proc. IEEE INFOCOM*, April 2014, pp. 451–459.

[12] P. K. Bishoyi and S. Misra, "Priority-Aware Cooperative Data Uploading in Body-to-body Networks for Healthcare IoT," *IEEE Internet Things J.*, pp. 1–8, 2021.

[13] S. Misra, P. K. Bishoyi, and S. Sarkar, "i-MAC: In-Body Sensor MAC in Wireless Body Area Networks for Healthcare IoT," *IEEE Syst J*, vol. 15, no. 3, pp. 4413–4420, 2021.

[14] S. Kumar and S. Misra, "Joint Content Sharing and Incentive Mechanism for Cache-Enabled Device-to-Device Networks," *IEEE Trans. Veh. Techn.*, vol. 70, no. 5, pp. 4993–5002, 2021.

[15] J. Mu, R. Stewart, L. Han, and D. Crawford, "A Self-Organized Dynamic Clustering Method and Its Multiple Access Mechanism for Multiple WBANs," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 6042–6051, Aug 2019.

[16] Z. Ren, X. Qi, G. Zhou, H. Wang, and D. T. Nguyen, "Throughput assurance for multiple body sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 27, no. 2, pp. 546–557, Feb 2016.

[17] M. Keally, G. Zhou, G. Xing, and J. Wu, "Remora: Sensing resource sharing among smartphone-based body sensor networks," in *Proc. IEEE IWQoS*, June 2013, pp. 1–10.

[18] J. Dong and D. Smith, "Cooperative body-area-communications: Enhancing coexistence without coordination between networks," in *Proc. IEEE PIMRC*, Sep. 2012, pp. 2269–2274.

[19] S. Huang and J. Cai, "Priority-aware scheduling for coexisting wireless body area networks (invited paper)," in *Proc. IEEE WCSP*, Oct 2015, pp. 1–5.

[20] S. Shimly, D. B. Smith, and S. Movassaghi, "Cross-layer optimized routing with low duty cycle TDMA across multiple wireless body area networks," in *Proc. IEEE ICC*, May 2017, pp. 1–6.

[21] D. Abdulmohsin Hammood, H. A. Rahim, A. Alkhayyat, and R. B. Ahmad, "Body-to-Body Cooperation in Internet of Medical Things: Toward Energy Efficiency Improvement," *Future Internet*, vol. 11, no. 11, 2019.

[22] J. Huang, F. Qian, A. Gerber, Z. M. Mao, S. Sen, and O. Spatscheck, "A Close Examination of Performance and Power Characteristics of 4G LTE Networks," in *Proc. ACM MobiSys*, 2012, pp. 225–238.

[23] D. Fudenberg and J. Tirole, *Game Theory*. MIT press, 1991.

[24] D. P. Palomar and Mung Chiang, "A tutorial on decomposition methods for network utility maximization," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 8, pp. 1439–1451, Aug 2006.

[25] S. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge university press, 2004.