Fairness-Aware Data Offloading in Wireless Body Area Networks with QoS Constraint

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***Abstract*—In recent years, the rapid development of Wireless Body Area Networks (WBANs) has provided efficient healthcare services to emergent medical patients. Nevertheless, the WBANs provide efficient healthcare services; however, the mobility and interference in WBANs inherently affect the quality of links between sensors and coordinators. Therefore, with poor link qualities, selecting the optimal coordinators among sensor nodes is necessary to minimize the network's heavy energy consumption rate and traffic load. Additionally, in mobile architecture, it is necessary to offload the medical data efficiently from sensor nodes to selected optimal coordinators to manage the Quality-of-Service (QoS) of sensor nodes. Thus, unlike most existing works in this paper, we propose a fairness-aware data offloading scheme for inter-BAN communication to optimize the traffic load and QoS of WBANs. Extensive simulation results show that FARE improves section rate, data offloading price, and throughput over other existing solutions.**

***Index Terms*—Wireless body area networks, coordinator selection, optimal QoS-constraint, data offloading.**

I. Introduction

Wireless Body Area Network (WBAN) [1] yields efficient and real-time services to patients equipped with medical sensors reliably. Hence, the evolution of WBAN provides significant improvement in electronic healthcare systems over traditional healthcare systems. The placed medical sensors are heterogeneous and have different data rates varying within the range of 10 Kbps – 10 Mbps, when each sensor node has different QoS requirements. However, due to human mobility and body movements, each medical sensor's power consumption rate and QoS decrease inherently. Not only does the mobility degrades the network's performance, but mutual and cross-radio interference between WBANs and additional wireless technologies decreases the resource availability of medical sensors. Consequently, the power consumption rate of medical sensors increases, which decreases the lifetime of medical sensors. In addition to this, on the other hand, selecting an optimal coordinator in a medical emergency is very important, as selecting an inappropriate coordinator inherently increases the mean service delay and power consumption of medical sensors. Additionally, offloading medical data from sensor nodes to optimal coordinators is crucial to optimize the data offloading delay and network throughput. To overcome these limitations, we propose a fairness-aware data offloading for WBANs. The principal *contributions* are summarized as:

- We propose an optimal coordinator selection scheme for sensor nodes to minimize the losing packets and transmission delay of medical data processing at the sensor nodes.
- We propose a fairness-aware data offloading scheme between sensor nodes and LPUs to improve network performance.
- Simulation results show that our scheme effectively offloads the traffic from sensor nodes to coordinators.

II. Related Work

The dynamics of coordinator placement in WBANs play a significant role in improving the overall network performance. However, a few works in the literature have addressed the problem of coordinator placement and its impact on the performance of WBANs. Sipal *et al.* [2] examined the effect of the coordinator in the channel prorogation properties for different positions of the coordinator like foot, head, and waist. Samanta *et al.* [3] proposed a quality-driven and energy-efficient big data aggregation mechanism in WBANs. Similarly, Cut *et al.* [4] designed a joint optimization problem with power and coordinator placement algorithm to improve the QoS requirements of WBANs. However, they failed to provide the optimal QoS to WBANs in the presence of mobility and temporal link-quality variation. Zhou *et al.* [5] proposed an energy-efficient optimization problem based on the TDMA strategy to improve the power consumption rate and the lifetime of medical sensors. Nevertheless, they did not consider the heterogeneous traffic designations for sensor nodes. Habib *et al.* [6] designed an adaptive data gathering algorithm to optimize the data transmission and provided a data fusion model for WBANs using the fuzzy set theory. However, this technique is only restricted to beyond-BAN communication units in WBANs. Bortolotti *et al.* [7] analyzed a trade-off between the reconstruction quality and energy efficiency for compressed sensing-based WBANs. This work is not adaptive to mobility and link-failure situations in WBANs.

These works only focus on the data transmission technique and the efficient routing protocol for WBANs. These works are not sufficient to optimize performance in the presence of a heavy traffic regime. Therefore, there is necessary to provide a coordinator selection and data offloading algorithm for WBANs in the company of topological disconnections while accounting for the priority of medical packets.

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III. System Overview and Model

In this Section, we define the problem and communication architecture for the considered problem. We presume there are N WBANs denoted by, $\mathcal{B} = \{B_1, B_2, \cdots, B_N\}$, existing in order to receive efficient healthcare services (Figure 1). In one WBAN, n is the number of medical sensors denoted by $B = \{b_1, b_2, \cdots, b_n\}$, located on the patients to supervise the vital medical signals. After collecting the sensed medical data, the medical sensors dispatch the aggregated data to $\mathcal{G} = \{G_1, G_2, \cdots, G_m\}$ LPUs[1] and LPUs forward the data to APs denoted by, $A = \{A_1, A_2, \cdots, A_M\}$. Each WBAN is equipped with only one LPU, so the number of WBANs is equivalent to the number of LPUs $N = m$. In this scheme, the data packets arrive at the coordinator by the Poisson process, and the transmission of data packets is coordinated according to their data packets priority [8]. Each WBAN follows the IEEE 802.15.6 standard [9], and each of the sensor nodes has some predefined traffic designation according to the standard.

IV. Optimal Coordinator Selection

As discussed previously, we now design an optimal coordinator selection algorithm to minimize the loss rate and average delay. The uplink data communication link between the body sensor node b_i and LPU L_j is represented as:

$$H_{ij}^{ul}(t) = H_0^{ul}\left(\frac{h_{ij}(t)^{ul}}{h_{ij}(t)^{ul} + h_{ij}(t)^{dl}}\right), \quad (1)$$

where H_0^{ul} denotes the weighted average of previous uplinks, $h_{ij}(t)^{ul}$ and $h_{ij}(t)^{dl}$ are the communication links for uplink and downlink data offloading, respectively. The unit communication links for uplink and downlink are defined within the $(0, 1)$ range. The downlink data communication link between the LPU L_j and body sensor node b_i is defined as:

$$H_{ij}^{dl}(t) = H_0^{dl}\left(\frac{h_{ij}(t)^{dl}}{h_{ij}(t)^{ul} + h_{ij}(t)^{dl}}\right), \quad (2)$$

where H_0^{dl} denotes the weighted average of previous downlinks. The QoS factor is dependent on the count of packets from successful data transmissions of medical nodes and the average data offloading delay. We have:

$$\mathcal{Q}_i^{con}(t) = \frac{E[e] \times P_i^{ul+dl}(t)}{\sum\limits_{i \in n} \sum\limits_{t \in T} \left(D_q^i(t) + D_{tran}^i(t) + D_{prop}^i(t)\right)}, \quad (3)$$

where $E[e]$ is the size of the data packet payload, $P_i^{ul+dl}(t)$ is the count of transmitted packets from medical sensor b_i for both uplink and downlink, and $D_q^i(t)$, $D_{tran}^i(t)$, and $D_{prop}^i(t)$ are the queueing, transmission, and propagation delays. The resource availability $\mathcal{S}_i^t$ for a sensor node b_i is the total resource available for data processing and transmission at time t. Mathematically,

$$\mathcal{S}_i^t = V_i^t + \mathcal{R}_i^t \frac{R_i^{avil}(t)}{\sum\limits_{i \in n} \sum\limits_{t \in T} R_i^{avil}(t)}, \quad (4)$$

[1]The terms coordinators and LPUs are used alternatively in this paper.

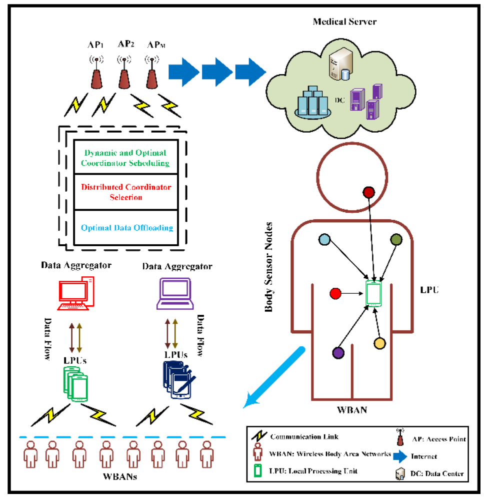


Figure 1: Data Offloading Architecture for WBANs

where V_i^t denotes the minimum resource provides to sensor node b_i to process their data packets, $\mathcal{R}_i^t$ denotes the resource scaling factor, and $R_i^{avil}(t)$ denotes the available resource for the sensor nodes to transmit their data packets.

Definition 1. *The data flow $\mathcal{K}_{ij}^t$ between sensor node i to LPU j at time t is defined as:*

$$\mathcal{K}_{ij}^t = \begin{cases} \mathbb{D}_{ij}^{high} \mathcal{L}_{ij}^t, & \mathcal{L}_{ij}^t > 0.5, \\ \mathbb{D}_{ij}^{low} \mathcal{L}_{ij}^t, & \mathcal{L}_{ij}^t < 0.5, \end{cases} \quad (5)$$

where $\mathbb{D}_{ij}^{high}$ and $\mathbb{D}_{ij}^{low}$ denote the maximum and minimum data rate between sensor nodes and coordinators. Here, the data flow between the medical sensors and LPUs depends on the existing links $\mathcal{L}_{ij}^t$ between them. If the existing link $\mathcal{L}_{ij}^t$ is strong, then the data flow is higher; otherwise, the sensor nodes may face packet loss in the network.

Definition 2. *The flow priority is defined for each of the sensor nodes based on their traffic designations according to the IEEE 802.15.6 standard [9]. Mathematically,*

$$p_i > p_{i'}, \forall \mathcal{TD}_i > \mathcal{TD}'_i, \quad (6)$$

where p_i and $p_{i'}$ denote the flow priority of sensor node b_i and $b_{i'}$, respectively. Here, the traffic designation $\mathcal{TD}$ [9] of sensor node b_i is superior than the sensor node $b_{i'}$.

Definition 3. *The traffic load $\mathcal{TL}_i^t$ of a body sensor node b_i at time t is defined as the ratio of the actual and maximum traffic load of a sensor node. Mathematically,*

$$\mathcal{TL}_i^t = \frac{1}{\mathcal{K}_{ij}^t} \sum_{i \in n} \left(\frac{TF_{max,i}^t - TF_{act,i}^t}{TF_{max,i}^t}\right), \quad (7)$$

where $TF_{act,i}^t$ and $TF_{max,i}^t$ dotes the maximum and actual traffic load of a sensor node at time t, respectively.

Definition 4. *The changing rate $\mathcal{X}_i$ of data flows between the* *sensor node b_i and LPU L_j is mathematically expressed as:*

$$\mathcal{X}_i = \frac{\delta \mathcal{TL}_i^t}{\delta t} = \frac{\delta\Big(\frac{1}{\mathcal{K}_{ij}^t}\sum_{i\in n}\Big[\frac{TF_{max,i}^t - TF_{act,i}^t}{TF_{max,i}^t}\Big]\Big)}{\delta t}, \quad (8)$$

where $\delta\mathcal{TL}_i^t$ denotes the changing rate in traffic load of body sensor nodes concerning unit time δt.

A. Optimization Problem for Coordinator Selection

Using the Definitions IV–4, we formulate a coordinator selection metric $\mathcal{Z}_i^t$, which is expressed as:

$$\mathcal{Z}_i^t = \left(\mathcal{S}_i^t + l_1 \frac{\mathcal{Q}_i^{con}(t) + l_2 p_i \mathcal{X}_i \mathcal{TL}_i^t \mathcal{Q}_{th}^R(t)}{\mathcal{Q}_{th}^R(t)}\right), \quad (9)$$

where l_1 and l_2 denote the coefficient factors. $\mathcal{Q}_i^{con}(t)$ and $\mathcal{Q}_{th}^R(t)$ denote the estimated QoS factor and threshold QoS factor of WBANs. Having computed the coordinator selection metric of every sensor node, the node with the maximum coordinator selection metric emerges as the winner. We design an optimization problem:

$$\text{Maximize}\sum_{i\in N}\sum_{t\in T}\left(\mathbf{\mathcal{Z}_i^t = \mathcal{S}_i^t + \frac{l_1\mathcal{Q}_i^{con}(t)}{\mathcal{Q}_{th}^R(t)} + l_1 l_2 p_i \mathcal{X}_i \mathcal{TL}_i^t}\right), \quad (10)$$

$$\text{Subject to} \quad \gamma_{th} \le \gamma_i, i \in n, \quad (11)$$

$$\mathcal{TL}_i^t \ge \mathcal{TL}_{th}^t, i \in n, \quad (12)$$

$$\mathcal{S}_i^t \ge \mathcal{S}_{max}^t, i \in n, \quad (13)$$

We explain the optimization constraints in detail. (10) represents the objective formulation for optimal coordinator selection. (11) depicts that the sustained signal strength, γ_i, is to be greater than the threshold sustained signal strength, γ_{th}. The threshold data flow rate, $\mathcal{TL}_{th}^t$, should be lesser than the flow rate of the medical sensor, $\mathcal{TL}_i^t$, as shown in (12). (13) represents that the resource availability, $\mathcal{S}_i^t$, is to be greater than the threshold resource availability, $\mathcal{S}_{th}^t$. We apply the Lagrangian technique to solve the optimization. We solve the problem following the Lagrangian method.

V. Distributed Data Offloading Scheme

After the selection of the optimal coordinator, the coordinator is scheduled to each sensor node to offload their data with minimum offloading delay and price. Hence, we discuss a distributed and fairness-aware data offloading scheme for body sensor nodes. The offloading scheme is divided into two main modules – *estimation of offloading delay* and *approximation of offloading utility*. In the first module, we estimate the delay incurred by the sensor nodes while offloading the medical data to coordinators. Later, we formulate an optimal utility for medical sensors in order to provide them fairness in terms of offloading price and network throughput.

A. Estimation of Offloading Delay

As the sensor nodes deal with the sensitive medical packets, hence it is important to offload those packets with minimum offloading delay. Hence, first, we estimate the necessary offloading delay for sensor nodes. After that, we present a mathematical framework for the data offloading model in sensor nodes.

Definition 5. ***Offloading Delay****: The offloading delay $\mathcal{D}_{off,i}^t$ is directly proportional to the average offloading workload and total offloading time of sensor node b_i. Mathematically,*

$$\mathcal{D}_{off,i}^t = \sum_{i\in n}\big(\sigma_i F_{ij} d_{ij} + \mathbb{T}_i\big), \quad (14)$$

where F_{ij} denotes the decision variable for medical data offloading, d_{ij} denotes the actual data transmission delay between WBAN b_i and coordinator L_j, and $\mathbb{T}_i$ is the offloading time of medical sensor b_i. σ_i is the average offloading rate of senor node b_i for a service request.

B. Data Offloading Model

Here, the sensor node manages some real-time medical applications, where the sensor nodes offload critical medical data to the optimal coordinator. The medical data that need to be offloaded is denoted by a set $\mathbb{W} = \{w_1, w_2, \cdots, w_n\}$, where $w_i =< \mathbb{S}_i, \mathbb{T}_i >$, in which, $\mathbb{S}_i$ and $\mathbb{T}_i$ denote the offloading medical data size and offloading time of sensor node b_i, respectively. For simplification, we consider that the offloading data sizes are classified according to the offloading time in ascending order, which is $t_1 \le t_2 \le \cdots \le t_n$.

Offloading Utility Approximation. Now, we discuss the approximation of offloading utility for sensor nodes. The offloading utility is comprised of different metrics – *profit level*, *data loss rate*, and *offloading price*. Hence, the metrics are discussed in detail as follows:

Definition 6. ***Profit Level****. The profit level $\mathbb{P}_i$ of sensor nodes b_i is dependent on the critical data obtained from medical sensors $\mathcal{H}$ and data offloading reward $\mathcal{R}$. We have,*

$$\mathbb{P}(J_i, \mathbb{R}) = \begin{cases} 0, & \mathbb{R} < J_i, \\ \mathcal{H} - \mathbb{R}, & \mathbb{R} \ge J_i, \end{cases} \quad (15)$$

where J_i denotes the unit offloading cost of sensor node b_i. Following the distribution of J_i, it is dependent on the value of H and the reward factor $\mathbb{R}$ [10], the profit can be expressed as:

$$\mathbb{P}_i = \int_0^\infty \mathbb{P}(J_i, \mathbb{R}) f(J_i) dJ_i = \int_0^{\mathbb{R}} (\mathcal{H} - \mathbb{R}) f(J_i) dJ_i = F(\mathbb{R})(\mathcal{H} - \mathbb{R}). \quad (16)$$

Definition 7. ***Data Loss Rate****. The data loss rate denoted by $\mathbb{S}_i^{loss}$, of sensor node b_i is dependent on the total data size to be transmitted and successfully transmitted data size. Mathematically,*

$$\mathbb{S}_i^{loss} = \mathbb{S}_i^{tot} - \mathbb{S}_i^{succ}, \quad (17)$$

where $\mathbb{S}_i^{tot}$ and $\mathbb{S}_i^{succ}$ are the total medical data to be transmitted and successfully transmitted from medical sensor b_i, *respectively.*

Definition 8. ***Probability of Successful Data Offloading***. *The probability $\mathcal{Z}_i$ of successful data offloading for sensor node b_i is dependent on the historical data offloading transactions. It is defined as:*

$$\mathbb{Z}_i = 1 - \prod_{h=1}^{n-1}(1 - p_h), h \in n, h \neq i, \tag{18}$$

where p_h denotes the corresponding frequency of historical data offloading transactions.

Definition 9. ***Offloading Price***. *The price for data offloading between the sensor nodes and LPUs is denoted by $\mathcal{P}^t_{off,i}$. It is basically comprised of different pricing factors — data processing price, data flow management price, fixed data offloading price, and dynamic data offloading price, which are discussed individually in the subsequent paragraph.*

Definition 10. ***Offloading Bandwidth Factor***. *The bandwidth required to offload the medical data efficiently from sensor nodes to the coordinator is defined as the ratio of the total bandwidth required to offload the data and the maximum bandwidth available to the coordinator. Mathematically,*

$$\mathcal{BW}^t_i = \frac{BW^t_{req,i}}{BW^t_{max}}, \forall BW^t_{min} < BW^<_{req,i} BW^t_{max}, \tag{19}$$

where $BW^t_{req,i}$, BW^t_{min} and BW^t_{max} denote the total bandwidth required for sensor node b_i, minimum bandwidth limit and maximum bandwidth limit at time t, respectively.

Definition 11. ***Offloading Utility***. *The offloading utility $\mathcal{U}_i$ of a sensor node b_i, $\forall i = \{1, 2, \cdots, n\}$, at time instant t, is a function of offloading delay, profit level, probability of successful data offloading and offloading price.*

$$\mathbb{U}^t_i = \left[\frac{1}{\mathbb{Q}_1}\left(\frac{\mathbb{P}_i\mathbb{Z}_i}{\mathbb{S}^{loss}_i} + \frac{\mathcal{BW}^t_i}{\mathcal{BW}^t_{th}}\right) - \frac{1}{\mathbb{Q}_2}\left(\frac{\mathcal{D}^t_{off,i}}{\mathcal{D}^t_{off,th}} + \frac{\mathcal{P}^t_{off,i}}{\mathcal{P}^t_{off,th}}\right)\right], \tag{20}$$

where $\mathbb{Q}_1$ and $\mathbb{Q}_2$ are the offloading utility coefficients. $\mathcal{D}^t_{off,th}$, $\mathcal{BW}^t_{th}$ and $\mathcal{P}^t_{off,th}$ denote the threshold offloading delay, bandwidth factor, and offloading price, respectively.

Offloading Price Estimation. The offloading price between the sensor nodes and LPUs is dependent on several pricing factors – *data processing*, *data flow management*, *fixed data offloading* and *dynamic data offloading* prices. Each of the pricing factors is discussed in detail below.

- ***Data Processing Price***: In order to process the data packets, the sensor nodes use their available bandwidth and battery power. Thus, they charge an incentive in terms of data processing charges to make some profit. Mathematically,

$$\mathcal{P}^t_{dp,i} = \sum_{i\in n}\sum_{j\in m}\sum_{l\in\mathcal{L}}\sum_{t\in\mathcal{T}}\left[\mathcal{O}^{ul}_{ij}(t)x^t_{ul} + \mathcal{O}^{dl}_{ji}(t)y^t_{dl}\right], \tag{21}$$

where x^t_{ul} and y^t_{dl} are the medical data processing prices for uplink and downlink at time t, respectively. $\mathcal{O}^{ul}_{ij}(t)$ and $\mathcal{O}^{dl}_{ij}$ is the total count of medical packets that need to be processed for uplink and downlink, respectively. $l = \{ul, dl\}$, $\forall l \in \mathcal{L}$, here $\mathcal{L}$ represents the uplink and downlink sets.

- ***Flow Management Price***: The flow management price $\mathcal{P}^t_{fm,i}$ is dependent on the unit data traffic management cost for both uplinks and downlinks. It is depicted as:

$$\mathcal{P}^t_{fm,i} = \sum_{i\in n}\sum_{j\in m}\sum_{l\in\mathcal{L}}\sum_{t\in\mathcal{T}}\left[\psi\mathcal{J}^{ul}_{ij}(t)x^t_{ul} + \zeta\mathcal{J}^{dl}_{ji}(t)y^t_{dl}\right], \tag{22}$$

here ψ and ζ are the data flow price coefficients for uplink and downlink, respectively. $\mathcal{J}^{ul}_{ij}(t)$ and $\mathcal{J}^{dl}_{ji}(t)$ are the uplink and downlink medical flow rates for medical sensor b_i at time t, respectively.

- ***Fixed Data Offloading Price***: The fixed data offloading price $\mathcal{P}^t_{fo,i}$ is dependent on the total data packets that need to be offloaded to a coordinator for both inflow and outflow traffics. It is called fixed, as the traffic load and demand of the flows are static in nature. Mathematically,

$$\mathcal{P}^t_{fo,i} = \sum_{i\in n}\sum_{j\in m}\sum_{l\in\mathcal{L}}\sum_{t\in\mathcal{T}}\left[\Gamma\in^{in}_{ij}(t)x^t_{ul} + \Xi\in^{out}_{ji}(t)y^t_{dl}\right], \tag{23}$$

where Γ is the price for medical inflow traffic and Ξ is the price for medical outflow traffic. $\in^{ij}_{in}(t)$ the raw inflow traffic and $\in^{out}_{ji}(t)$ is the outflow traffic in WBANs.

- ***Dynamic Data Offloading Price***: The dynamic data offloading price is dependent on the unit price for offloading the count of medical data packets to the coordinator for uplink and downlink. Mathematically,

$$\mathcal{P}^t_{do,i} = \sum_{i\in n}\sum_{j\in m}\sum_{l\in\mathcal{L}}\sum_{t\in\mathcal{T}}\Big[\mathbb{E}(t) + \mathcal{W}^{ul}_{ij}(t)\mathcal{V}^{ul}_{ij}(t)x^t_{ul} + \big(1 - \mathcal{W}^{ul}_{ji}(t)\big)\mathcal{V}^{dl}_{ji}(t)y^t_{dl}\Big], \tag{24}$$

where $\mathcal{W}^{ul}_{ij}(t)$ and $\mathcal{W}^{dl}_{ji}(t)$ denote the demand response rate for uplink and downlink offloading data at time t, respectively. Here, $\mathcal{W}^{ul}_{ij}(t) + \mathcal{W}^{dl}_{ji}(t) = 1$. $\mathbb{E}(t)$ denotes the unit price for queue management. $\mathcal{V}^{ul}_{ij}(t)$ and $\mathcal{V}^{dl}_{ji}(t)$ denote the unit price for offloading the total number of data packets to a coordinator for uplink and downlink at time t, respectively.

By combining the Equations (21) – (24), we calculated the total offloading price. It is expressed in Equation (25). Thus, the offloading utility factor for sensor nodes is defined as:

$$\sum_{i\in N}\sum_{t\in T}\left(\mathcal{I}^t_i = \frac{\mathbb{U}^t_i}{\mathbb{U}^t_{th}} = \frac{1}{\mathbb{U}^t_{th}}\left[\frac{1}{\mathbb{Q}_1}\left(\frac{\mathbb{P}_i\mathbb{Z}_i}{\mathbb{S}^{loss}_i} + \frac{\mathcal{BW}^t_i}{\mathcal{BW}^t_{th}}\right) - \frac{1}{\mathbb{Q}_2}\left(\frac{\mathcal{D}^t_{off,i}}{\mathcal{D}^t_{off,th}} + \frac{\mathcal{P}^t_{off,i}}{\mathcal{P}^t_{off,th}}\right)\right]\right).$$

$$\mathcal{P}^t_{off,i} = f(\mathcal{P}_{dp}, \mathcal{P}_{fm}, \mathcal{P}_{fo}, \mathcal{P}_{do}) = \sum_{i\in n}\sum_{j\in m}\sum_{l\in\mathcal{L}}\sum_{t\in\mathcal{T}} \Bigg[\Big(\mathcal{O}^{ul}_{ij}(t)x^t_{ul} + \mathcal{O}^{dl}_{ji}(t)y^t_{dl}\Big) + \Big(\psi\mathcal{J}^{ul}_{ij}(t)x^t_{ul} + \zeta\mathcal{J}^{dl}_{ji}(t)y^t_{dl}\Big)$$
$$+ \Big(\Gamma\in^{ij}_{ij}(t)x^t_{ul} + \Xi\in^{out}_{ji}(t)y^t_{dl}\Big) + \Big(\mathbb{E}(t) + \mathcal{W}^{ul}_{ij}(t)\mathcal{V}^{ul}_{ij}(t)x^t_{ul} + \big(1-\mathcal{W}^{dl}_{ji}(t)\big)\mathcal{V}^{dl}_{ji}(t)y^t_{dl}\Big)\Bigg]. \quad (25)$$

where $\mathbb{U}^t_{th}$ denotes the threshold offloading utility at time t. The WBAN utility vector is depicted as: $\mathbb{U} = \{\mathbb{U}^t_1, \mathbb{U}^t_2, \cdots, \mathbb{U}^t_N\}$.

C. Max-Min Fairness Approach

In WBANs, different sensor nodes tend to achieve lesser offloading prices. In some scenarios, a balanced service condition, namely, optimizing the minimum individual offloading price to attain the max-min fairness among sensor nodes, is more desirable, and it can guarantee to improve offloading delay as much as possible even in the presence of link failures and mobility. In such a case, the related data offloading problem with limited offloading price and delay is formulated. Hence, the offloading utility optimization problem for sensor nodes is mathematically expressed as:

$$\text{Max Min}\sum_{i\in N}\sum_{t\in T}\Bigg(\mathcal{I}^t_i = \frac{1}{\mathbb{U}^t_{th}}\Bigg[\frac{1}{\mathbb{Q}_1}\Big(\frac{\mathbb{P}_i\mathbb{Z}_i}{\mathbb{S}^{loss}_i} + \frac{\mathcal{BW}^t_i}{\mathcal{BW}^t_{th}}\Big) - \frac{1}{\mathbb{Q}_2}\Big(\frac{\mathcal{D}^t_{off,i}}{\mathcal{D}^t_{off,th}} + \frac{\mathcal{P}^t_{off,i}}{\mathcal{P}^t_{off,th}}\Big)\Bigg]\Bigg), \quad (26)$$

$$\text{Subject to} \quad \mathbb{S}^{loss}_i \geq \mathbb{S}^{loss}_{max}, \forall i \in n, \quad (27)$$
$$\mathcal{P}^t_{off,i} \geq \mathcal{P}^t_{off,th}, \forall i \in n, t \in T, \quad (28)$$
$$BW^t_{req,i} \geq BW^t_{req,th}, \forall i \in n, t \in T, \quad (29)$$
$$\mathbb{P}_i \geq \mathbb{P}_{th}, \forall i \in n, \quad (30)$$
$$\mathbb{Z}_i \leq \mathbb{Z}_{th}, \forall i \in n, \quad (31)$$
$$\mathcal{TL}^t_i \leq \mathcal{TL}^t_{th}, \forall i \in n, t \in T. \quad (32)$$

We explain the optimization constraints in detail. (26) represents the objective formulation for data offloading. (27) depicts that the data loss rate, $\mathbb{S}^{loss}_i$, should be greater than the maximum data loss rate, $\mathbb{S}^{loss}_{max}$. From (28), we see that the offloading price of sensor node b_i at time t, $\mathcal{P}^t_{off,i}$, is to be greater than the threshold offloading price, $\mathcal{P}^t_{off,th}$. (29) represents that the offloading bandwidth factor, $BW^t_{req,i}$, is to be greater than the threshold offloading bandwidth factor, $BW^t_{req,th}$. The profit level of sensor node b_i, $\mathbb{P}_i$, is to be greater than the threshold profit level, $\mathbb{P}_{th}$, as shown in (30). (31) represents that the probability of successful data offloading of sensor node b_i, $\mathbb{Z}_i$, is to be lesser than the threshold probability of successful data offloading, $\mathbb{Z}_{th}$. The traffic load of sensor node b_i at time t, $\mathcal{TL}^t_i$, is to be less than the threshold traffic load, $\mathcal{TL}^t_{th}$, as shown in (32). We solve the problem following the Lagrangian method.

VI. Performance Evaluation

We analyze the performance of FARE[2] and list the experimental values in Table I. Here, we consider $100 - 300$ WBANs placed arbitrarily within a zone of 5×5 Km. The WBAN consists of 8 medical sensors. To examine the mobility of WBANs following Group-based mobility [11]–[13]. We contemplated Raleigh fading for the transmission between the medical sensor and the coordinator within a path loss range of $2.5 - 3$. We also contemplated Log-normal fading for the transmission between coordinators and APs within a path loss range of $3.5-4$ [14]–[16]. We examine two baseline algorithms. JPCD [4] provides an optimization problem that jointly optimizes coordinator placement while minimizing the power consumption in WBANs. FEEL [17] provides an efficient routing protocol to route data in WBANs reliably.

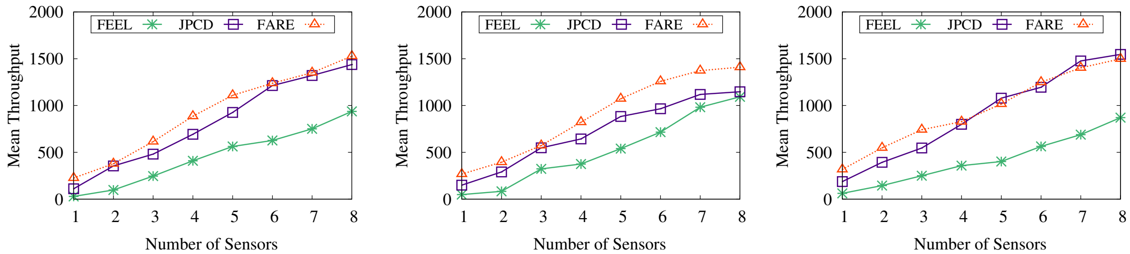
Table I: Simulation Parameters

Parameter	Value
Simulation time	500 s
Number of body sensors	8
Residual energy of a WBAN	0.5 J
Velocity of WBANs	1.5-2.5 m/s
Transmitter energy consumption	16.7 nJ
Receiver energy consumption	36.1 nJ
Amplifier energy consumption	1.97 nJ
Sensing range for body sensors	0.5-1.5 m
Data packet generation rate	4 packets/sec
Data packet size	512 Bytes [18]

We discuss the performance of FARE in terms of throughput, and offloading price. We analyze the mean throughput of the network with the variation in medical sensor data rates. In figure 2, we observe that the mean throughput of the network increases with the increase in data rates. As the data rate increases, the medical data transmission rate also increases; thus, the mean throughput of the network increases. Figure 2 depicts that the mean network throughput is higher in FARE than in JPCD and FEEL. FARE optimally selects the coordinator, which eventually decreases the packet loss rate in the network. Hence, the mean throughput increases. Subsequently, the proposed distributed offloading scheme offloads the medical data effectively to APs, which also increases the mean throughput of the network. The network throughput for FARE increases by 12% and 17% than JPCD and FEEL.

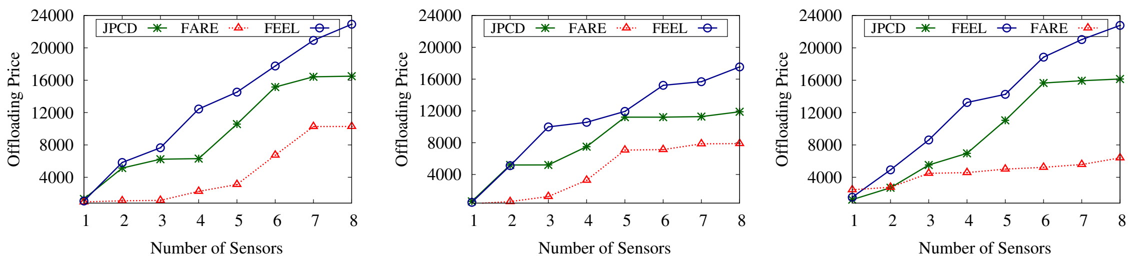
Figure 3 shows the offloading price with the variation in data rates. In figure 3, we depict that the offloading price increases if we increase the medical sensor data rates. As

[2] The combination of both the algorithms – *Optimal Coordinator Selection* and Fairness-Aware Data Offloading is called FARE.



(a) Data Rate = 1 Mbps (b) Data Rate = 800 Kbps (c) Data Rate = 600 Kbps

Figure 2: Analysis of mean throughput



(a) Data Rate = 1 Mbps (b) Data Rate = 800 Kbps (c) Data Rate = 600 Kbps

Figure 3: Analysis of data offloading price

the data rate increases, the successful data transmission rate and packet processing rate increase; thus, the offloading price increases. Figure 3 depicts that the offloading price is lesser in FARE than in JPCD and FEEL. FARE optimally offloaded the medical data to coordinators while minimizing the total offloading price. Therefore, it eventually decreases the offloading price in the network. On the other hand, the proposed optimal coordinator selection scheme minimizes the delay and optimizes the data transmission rate, which also decreases the data transmission price. Hence, the total price decreases, and FARE outperforms – JPCD and FEEL. The offloading price decreases by 13% and 24% than JPCD and FEEL, respectively.

VII. Conclusion

This paper proposed an optimal coordinator selection scheme for sensor nodes to optimize the packet-loss rate and average delay of medical data processing at the sensor nodes. Then, we proposed a fairness-aware data offloading scheme for inter-BAN communication in order to cope with the heavy traffic and QoS of WBANs. FARE presents notable advances with regard to network throughput and fairness in the resource augmentation process. In the future, we would like to develop a dynamic power consumption and scheduling algorithm for data offloading in WBANs. We also like to design an incentive and pricing scheme for data offloading in WBANs.

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