Energy-Efficient and Distributed Network Management Cost Minimization in Opportunistic Wireless Body Area Networks

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Abstract—Mobility induced by limb/body movements in Wireless Body Area Networks (WBANs) significantly affects the link-quality of intra-BAN and inter-BAN communication units, which, in turn, affects the Quality-of-Service (QoS) of each WBAN in terms of reliability, efficient data transmission and network throughput guarantees. Further, the variation in link-quality between WBANs and Access Points (APs) makes the WBAN-equipped patients more resource-constrained in nature, which also increases the data dissemination delay. Therefore, to minimize the data dissemination delay of the network, WBANs send patients' physiological data to local servers using the proposed opportunistic transient connectivity establishment algorithm. Additionally, limb/body movements induce dynamic changes to the on-body network topology, which, in turn, increases the network management cost and decreases the life-time of the sensor nodes periodically. Also, the mutual and cross technology interference among coexisting WBANs and other radio technologies increase the energy consumption rate of the sensor nodes and also the energy management cost. To address the problem of increased network management cost and data dissemination delay, we propose a network management cost minimization framework to optimize the network throughput and QoS of each WBAN. The proposed framework tries to minimize the dynamic connectivity, interference management, and data dissemination costs for opportunistic WBAN. The performance of the proposed framework is analyzed based on different performance metrics — *Network throughput*, *Energy consumption*, *Network Management cost*, and *Data dissemination delay*. We also, theoretically, analyzed the performance of the proposed framework to provide reliable data transmission in opportunistic WBANs. Simulation results show significant improvement in the network performance compared to the existing solutions.

Index Terms—Wireless Body Area Networks, QoS, Fairness, Energy Efficient, Network Management Cost, Cost Minimization.

1 INTRODUCTION

A WBAN provides real-time electronic healthcare services to medically emergent patients in a cost effective manner. In a WBAN, several body sensor nodes are implanted on/in the human body to sense the physiological signals of patients. After sensing the physiological signals, the sensor nodes send the sensed data to the Local processing Unit (LPU). Subsequently, the LPU transmits the aggregated data to the local access points (APs), which, in turn, send them the medical servers [1], [2]. The WBAN architecture consists of three communication units — *intra-BAN*, *inter-BAN*, and *beyond-BAN* [3]. In intra-BAN communication, the sensor nodes typically use the IEEE 802.15.6/802.15.4 radio technology to send physiological signals to the LPU. For *inter-BAN* communication, the LPU sends the aggregated data to APs using WiFi and WiMax. Lastly, APs usually send data to medical servers using the Internet in *beyond-BAN* communication.

The body sensor nodes transmit the medical data to LPUs at wide range of data rates from 1kb/s to 1Mb/s [4]. Also, the energy consumption rate of sensor nodes are restricted to certain limits, as the battery power of these nodes is limited. To minimize energy consumption, the sensor nodes use a one-hop star topology to send their medical data [5]. However, mobility, body postures, and environmental obstacles increase the dynamism in WBANs, which frequently changes the network topology, which, in turn, decreases the network QoS. Additionally, the link-quality between nodes in WBANs varies as a function of time due to various body movements, which also affects the inter-node connectivity [6].

1.1 Motivation

Due to body movements and mobility of WBANs [7], the link qualities of intra-BAN and inter-BAN communication units degrade significantly, which increases the packet loss rate and decreases the life-time of the body sensor nodes. Further, the above also disrupts data dissemination. We analyze each of these conditions in detail below:

1) **Dynamic on-body topology**: Irregular mobility and body/limb movements is very common in WBANs, as patients move from one location to another to get appropriate medical services. Therefore, in the presence of body movements, links between sensor nodes and LPUs, and again between LPUs and APs are vulnerable to disruptions over time, which dynamically change the topology of WBANs. Therefore, instant data dissemination is not possible through a single path, which constantly increases the data dissemination cost.

2) **Propagation delay**: In the presence of dynamic topological disconnections, the propagation delay of the network increases, which, further increases the packet

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re-transmission cost, which is not desirable for delay-sensitive medical data.

3) Network management cost: Network management cost depends on the dynamic connectivity establishment, data dissemination, QoS-assurance, and interference management costs. However, due to dynamic topological disconnections and mutual and cross technology interference among WBANs, the overall network management cost increases.

4) Packet delivery ratio: Packet delivery distribution may be non-uniform due to irregular movements of heterogeneous WBANs and the corresponding patients' medical requirements. Therefore, data dissemination is not guaranteed from a source to the destination. Thus, improvement in packet delivery ratio is very important for opportunistic WBANs.

Therefore, we need a network management cost minimization framework to provide reliable and cost effective service to WBANs.

1.2 Contributions

The on-body sensor nodes are energy- and resource-constrained in nature. Therefore, mobility of WBANs constantly decreases the resource pool of the body sensor nodes, as the variation in the link-qualities between LPUs and APs are temporal in nature. Hence, the limitation in resource pool of body sensor nodes affects the data transmission rate of WBANs and also deceases their life-time. Additionally, body/limb movements dynamically change the on-body topologies of intra-BAN communication units, which increases the network management cost of WBANs. Therefore, to optimize the network management cost and energy-efficiency of WBANs, we proposed a novel framework to increase the overall network performance. The specific contributions of this work are presented as follows:

- This work proposes a novel network management cost minimization framework for dynamic connectivity and data dissemination in the intra-BAN and inter-BAN communication units of WBANs to optimize the network throughput and effective network management cost.
- We consider the effects of irregular body movements for WBANs in different positions such as walking, running, sleeping, and sitting.
- We study the behavior of WBANs for data transmission in intra-BAN and inter-BAN communication units. Also, we implement an algorithm to minimize the network management cost for data dissemination in opportunistic WBANs.
- The numerical results of this study demonstrate that the proposed algorithm can converge to the optimum and remarkably reduced the data dissemination delay and total energy consumption, compared to the algorithm without concurrent opportunistic data gathering and power control.
- We present theoretical analysis and extensive simulation results to verify the convergence of the proposed algorithm and demonstrate that the proposed algorithm can achieve lower network management cost compared to the opportunistic data dissemination process.

We considered the above as contributions of this work, as there is no similar holistic framework which exhibits the features of the study mentioned above.

1.3 Paper Organization

The manuscript is organized as follows. In Section II, we discuss the existing works on opportunistic WBANs and the corresponding energy consumption techniques. Section III describes the problem statement and system model. In Section IV, we formulate opportunistic data dissemination using a price-based approach. Section V presents the optimization of network management cost. Section VI presents the results of simulation. Section VII concludes the work.

2 RELATED WORK

Energy efficiency and network management cost minimization are two issues of primary concern in opportunistic WBANs, which are required to provide reliable and cost-effective healthcare services to the critical patients. Therefore, several research works targeted to address these issues. We review some of the relevant existing works, which motivate us to specifically address these issues.

2.1 Opportunistic Communication in WBANs

Due to unpredictable RF attenuation and human postural changes, the on-body topology of WBANs change significantly, thereby decreasing the overall performance of the network. To maintain the on-body topology of WBANs, Quwaider *et al.* [8] proposed a store-and-forward packet routing algorithm, which uses stochastic link cost formulation for capturing multi-scale topological localities of WBANs. Consequently, Sipal *et al.* [9] investigate the propagation properties of WBANs for three different locations of LPUs — head, foot, and waist. The existing channels between the LPUs and sensor nodes are evaluated for frequencies 5 and 7 GHz, as the location of the LPU has impact on the link-quality of the intra-BAN and inter-BAN communication units. In a link failure situation, interference and inefficient routing can make a WBAN unreliable, which is a major concern in WBANs. Therefore, Abbasi *et al.* [10] proposed an opportunistic routing protocol to overcome the reliability problem. Additionally, Abbasi *et al.* [11] proposed an opportunistic routing protocol to improve the reliability of WBANs using multi-hop opportunistic relay nodes in the presence of body shadowing, environmental interference, and other communicating factors. To investigate the reliability of WBANs, two different path models — Log-normal-path loss model and IEEE 802.15.6 Channel Model used by the authors, in which opportunistic routing with IEEE 802.15.6 provides more reliability to WBANs. Consequently, Dong *et al.* [12] proposed a two-hop communication scheme with opportunistic relaying in WBANs to mitigate interference from coexisting WBANs.

Abbasi *et al.* [13] proposed a cross-layer opportunistic MAC/routing (COMR) protocol, by using a timer-based approach to increase the reliability of WBANs. The value of this timer depends on RSSI and residual energy of sensor nodes. The relay node is selected with highest residual energy and minimal distance. Consequently, Hong *et al.* [14], proposed a scheme for joint sleep and opportunistic transmission in WBANs to minimize the power consumption of sensor nodes. The authors developed an energy-efficient scheduling scheme to prolong the life-time of sensor nodes in a WBAN. Similarly, Samanta *et al.* [15], [16] proposed a link-quality-aware resource allocation cum load balancing scheme for node in WBANs. In this method, the authors has used two sub problems — *link-quality measurement* and *dynamic resource allocation* in WBANs. WBANs offer a prominent role to improve the Quality of Life (QoI) of patients. Therefore, to provide QoI to each WBAN, Elias *at al.* [17] proposed an energy-aware optimal design of energy efficient and cost-effective WBANs. Though this approach has proposed a cost-effective model, the authors did not consider the effect of dynamic connectivity and opportunistic data dissemination in WBANs.

2.2 Energy Consumption Techniques

Yi *et al.* proposed an incentive-compatible system for delay-sensitive data packet scheduling for beyond-BAN communication in WBANs [18]. Similarly, Kim *et al.* proposed an adaptive load control algorithm for ZigBee-based WBAN [19]. Ullah *at al.* proposed a MAC protocol for RFID-enabled WBANs [20]. Additionally, Javaid *et al.* proposed a reliable and power-efficient routing protocol capable of yielding high throughput [21]. On the other hand, Sandhu *et al.* proposed a mobility model for the movement of WBANs based on different posture postures such as standing, sitting, and laying [22]. Also, Ahmed *et al.* proposed Link-Aware and Energy Efficient (LAEEBA) and Cooperative Link-Aware and Energy Efficient (CoLAEEBA) routing protocols for WBANs [23].

Energy-efficient and reliable communication are important requirement of WBANs, as they carry sensitive medical data. Therefore, due to shadowing and fading effects in the networks, the energy consumption rate of sensor nodes increases, and also the reliability in data transmission decreases, periodically. Thus, to increase the energy efficiency and reliability in data transmission, Yousaf *et al.* proposed a new three-stage cooperative relaying scheme for WBANs [24]. Consequently, as body sensor nodes produce medical data at a variable rate, their corresponding traffic pattern is uncertain in nature. Therefore, Andreagiovanni *et al.* proposed a robust model for joint optimization of energy efficiency and data rate in WBANs under traffic uncertainty [25].

Shiwei *et al.* proposed a priority-aware scheduling scheme for used by a WBAN in the presence of multiple coexisting WBANs [26]. To maximize the network throughput of WBANs, a nonlinear optimization problem is formulated, while considering the priorities among WBANs. Energy harvesting is one of the promising ways to charge the body sensor nodes in WBANs. Ibarra *et al.* proposed a joint power and QoS control scheme to provide optimal use of energy and achieve the best possible QoS in WBANs [27]. Similarly, Seyedi *at al.* developed different energy efficient data transmission strategies for WBANs [28]. In order to provide energy-efficient data transmission, the tradeoff between energy consumption and packet error probability is embedded into the sensor nodes. Also, Seyedi *et al.* proposed a Markov-chain based analytical model for an energy harvesting node in WBANs [29], in which the probability of event loss is analyzed to identify the energy run-out situation of body sensor nodes. However, the proposed scheme provides significant improvement in terms of energy efficiency for energy harvesting nodes. On the other hand, Ren *et al.* proposed a framework which assures higher network throughput for coexisting WBANs [30].

Synthesis: None of the existing pieces of literature considers the effects of body movements and mobility of WBANs, to optimize the network management cost for dynamic connectivity and data dissemination in opportunistic WBANs. As link-quality affects the energy consumption of sensor nodes and the network management cost, we need a network management cost optimization technique for dynamic connectivity management and data dissemination in WBANs. This work contradicts from all preceding works by addressing the following specific requirements of electronic healthcare applications.

- The proposed architecture focuses on the energy-efficient network management cost optimization problem in the presence of dynamic topological disconnections, which occurs due to body/limb movements of WBANs in a critical emergency situation.
- The criticality index of WBANs is considered to model the network management cost optimization problem, while considering the QoS, in terms of packet transmission delay and bandwidth requirement.
- To quantify the quality-of-service of WBANs, a joint analysis of energy-efficiency and distributed optimal network management cost optimization technique is designed.

Table 1: Table of Notations

Parameters	**Values**
N	Total number of WBANs in an area
n	Number of sensor nodes in a WBAN
$\mathcal{T}$	Time slot of a MAC super-frame
$\mathcal{K}$	LPU in WBAN
$\xi^t_{decision}$	Decision metric at time instant t
$\mathcal{C}^t_{opp}$	Dynamic opportunistic connectivity cost at time instant t
$\mathcal{D}^t_{prop}$	Propagation delay between LPUs and APs at time instant t
$\mathcal{F}_{opp}(t)$	Opportunistic data flow constraint at time instant t
$\mathcal{F}^t_{ec}$	Opportunistic energy constraint at time instant t
$f_p(c)$	Waiting cost each data packet
γ	Signal-to-noise ratio (SINR)
γ_{th}	Threshold SINR value
BW^t_{avail}	Bandwidth available at time t
BW^t_{req}	Bandwidth requirement at time t
$\mathcal{H}(p)$	Network cost function
$\mathbb{P}$	Profit of each WBAN
$\mathcal{G}_{\mathbb{P}}$	Profit matrix of WBANs
E_p	Opportunistic energy consumption rate
$\mathcal{C}^t_{DC_{tot}}$	Data dissemination cost at time instant t
$\mathcal{C}^t_{inff_{tot}}$	Interference management cost at time instant t
$\mathcal{C}^t_{qos_{tot}}$	QoS ensuring cost at time instant t
$\mathcal{C}^t_{DT_{tot}}$	Dynamic topology management cost at time instant t
$\mathcal{C}^t_{tot}$	total network management cost at time instant t
$FI_{\mathcal{C}}$	Fairness index
$\mathcal{U}$	Network throughput

To the best of our knowledge, in WBANs, this work is one of the preliminary efforts to address the problem of network management cost minimization for dynamic connectivity and data dissemination in WBANs. There exists some works on network management, however they are mostly implemented for Cellular Networks (CN) and

Wireless Sensor Networks (WSNs) [31], [32], which are not staidly usable for the monitoring of physiological signals of WBAN-equipped patients, as in a WBAN, the aggregated medical information of patients need to be send without introducing much delay in process of data transmission for the early detection of diseases. In the recent past, though some of works focused on opportunistic data transmission in WBANs, but the existing works did not consider the problem of network management cost in the presence of dynamic topological disconnections and opportunistic data dissemination.

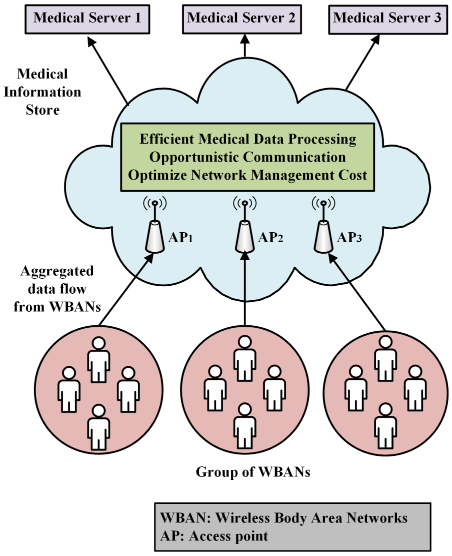


Figure 1: Opportunistic communication in WBANs

3 SYSTEM MODEL

In a hospital environment, N number of WBANs, $\mathcal{B} = \{B_1, B_2, \cdots, B_N\}$, are present in an area in order to get medical services in a medical emergency situation, as shown in Figure 1. Each WBAN consists of n number of body sensor nodes, $B = \{b_1, b_2, \cdots, b_n\}$, which are placed on-body to sense the physiological parameters of patients. The basic elements of the proposed architecture are shown as follows:

- $\mathcal{B} = \{B_1, B_2, \cdots, B_N\}$, denotes a set of WBANs present in an area.
- $A = \{A_1, A_2, \cdots, A_M\}$, denotes a set of APs present in an area to transmit the medical data to the medical servers.
- $E^i_{res} = 0.5$ J is the residual energy of i^{th} WBAN.
- BW_{req} and BW_{avail} denote the required and available bandwidth of WBANs .
- $\mathcal{C}^t_{tot}$ denotes the total network management cost of WBANs at time t.
- $\mathcal{C}_{intra}$ and $\mathcal{C}_{inter}$ are the intra-BAN and inter-BAN network cost of WBANs.

The formulated network management cost minimization problem, initially designs to report, first, where and how the sensor nodes communicate with LPU, and, then, how LPUs communicate with APs in the presence dynamic topological disconnections and coexisting interference among themselves. To solve the problem, we used a pricing-based approach [31] to optimize the network management cost for opportunistic WBANs. Concurrently, we have also taken into consideration, the behaviors of WBANs (i.e., critical and normal condition) to provide reliable services.

4 OPPORTUNISTIC DATA DISSEMINATION: A PRICE-BASED APPROACH

In this Section, first, we theoretically establish the requirement of opportunistic data dissemination in WBANs. We, then, discuss the data dissemination technique of WBANs using the price-based approach [31]. To understand the proposed architecture, some definitions are described as follows:

Definition 1. *The intra-BAN link cost is defined as the communication cost for radio-link between the sensor nodes and LPUs, which is mathematically defined as:*

$$\mathcal{C}^{intra}_{x_{ij}} = \sum_{i \in n} \sum_{j \in \mathcal{K}} \mathcal{C}^t_{x_{ij}} x^{intra}_{ij}, \forall t \in \mathcal{T} \tag{1}$$

where $C^t_{x_{ij}}$ is the unit cost of intra-BAN link at time t and x_{ij} denotes the intra-BAN link, which is mathematically given as:

$$x^{intra}_{ij} = \begin{cases} 1, & b_i \text{ is connected to } L_j \\ 0, & \text{Otherwise} \end{cases} \tag{2}$$

Definition 2. *The inter-BAN link cost is defined as the communication cost for radio-link between the LPUs and APs, which is mathematically defined as:*

$$\mathcal{C}^{inter}_{\mathcal{X}_{ij}} = \sum_{i \in N} \sum_{j \in M} \mathcal{C}^t_{\mathcal{X}_{ij}} \mathcal{X}^{inter}_{ij}, \forall t \in \mathcal{T} \tag{3}$$

where $C^t_{\mathcal{X}_{ij}}$ is the unit cost of inter-BAN link at time t and $\mathcal{X}_{ij}$ denotes the inter-BAN link, which is mathematically expressed as:

$$\mathcal{X}^{inter}_{ij} = \begin{cases} 1, & L_i \text{ is connected to } A_j \\ 0, & \text{Otherwise} \end{cases} \tag{4}$$

Definition 3. *The effective distance between an LPU and an AP is mathematically expressed as:*

$$d_{ij} = \frac{|L(i) - A(j)|^2 + |L(i) - A(j)|^2}{\sqrt{\left(L(i) - A(j)\right)^2 + \left(L(i) - A(j)\right)^2}} \tag{5}$$

where $L(i,j)$ and $A(i,j)$ denote the coordination of LPUs and APs, respectively.

Definition 4. *The propagation delay between an LPU, L_i, and an AP, A_j, for opportunistic connectivity is mathematically expressed as [32]:*

$$\mathcal{D}^t_{prop} = \left(\sum_{i \in N} \sum_{j \in M} \frac{\mathbb{P}^t_{ij}}{\delta C} + \frac{d_{ij}}{c} \right), \forall t \in \mathcal{T} \tag{6}$$

where C and δ denote the channel capacity and channel overhead, respectively. $\mathbb{P}^t_{ij}$ is the number of packets transmitted over channel (i, j) and c denotes the propagation speed of light.

Definition 5. *The decision metric is designed to identify the opportunistic connectivity for intra-BAN and inter-BAN com-*

munication units, depending on the link-quality and propagation delay at time t. It is mathematically expressed as:

$$\xi^t_{decision} = \left(\alpha \frac{\mathcal{D}^t_{prop}}{\mathcal{D}^{max}_{prop}} + \varsigma \frac{\mathcal{C}^{Intra}_{x_{ij}} + \mathcal{C}^{Inter}_{\mathcal{X}_{ij}}}{\mathcal{C}^{th}_{tot}} \right) \tag{7}$$

where α and ς are the scaling factors, and $\mathcal{C}^{th}_{tot}$ the total link cost of the intra-BAN and inter-BAN communication processes.

4.1 Requirements of Opportunistic Data Dissemination

In the presence of poor link-quality, a WBAN always attempts to send its critical data as fast as possible for early detection of diseases. Therefore, to send critical data in a link-failure situation, WBANs need to establish opportunistic connectivity with available APs and send the data opportunistically to the APs. However, in this Section, we mathematically establish the requirement of opportunistic connectivity between WBANs and APs.

Theorem 1. *If a WBAN moves from one place to another, then the decision metric becomes less than the threshold decision metric, which necessitates opportunistic connectivity between LPUs and APs. Mathematically,*

$$\xi^t_{decision_{\mathcal{L}_j}} < \xi^{th}_{decision} \tag{8}$$

Proof. Suppose a WBAN, B_i, moves from one place, $\mathcal{L}_{\S_i}$ to another, $\mathcal{L}_{\dagger_j}$, to get medical treatment. Then, the distance between a LPU and an AP increases, which significantly increases the propagation delay of the network and cost of communication between the LPU and the AP. Mathematically,

$$\begin{aligned} \mathcal{D}^t_{prop_{\mathcal{L}_{\dagger_j}}} >> \mathcal{D}^t_{prop_{\mathcal{L}_{\S_i}}}, \mathcal{C}^{intra}_{x_{ij_{\mathcal{L}_{\dagger_j}}}} >> \mathcal{C}^{intra}_{x_{ij_{\mathcal{L}_{\S_j}}}} \\ \mathcal{C}^{inter}_{\mathcal{X}_{ij_{\mathcal{L}_{\dagger_j}}}} >> \mathcal{C}^{inter}_{\mathcal{X}_{ij_{\mathcal{L}_{\S_i}}}} \end{aligned} \tag{9}$$

Also, intra-BAN communication cost also increases due to body movements. Now, the reformed decision metric is less than the threshold decision value $\xi^{th}_{decision}$. Mathematically,

$$\xi^t_{decision_{\mathcal{L}_{\dagger_j}}} = \left(\alpha \frac{\mathcal{D}^t_{prop_{\mathcal{L}_{\dagger_j}}}}{\mathcal{D}^{max}_{prop}} + \varsigma \frac{\mathcal{C}^{intra}_{x_{ij_{\mathcal{L}_{\dagger_j}}}} + \mathcal{C}^{inter}_{\mathcal{X}_{ij_{\mathcal{L}_{\dagger_j}}}}}{\mathcal{C}^{th}_{tot}} \right) << \xi^{th}_{decision} \tag{10}$$

The threshold decision is calculated, $\xi^{th}_{decision} = \frac{\xi^{max}_{decision} + \xi^{min}_{decision}}{2}$, where $\xi^{max}_{decision}$ and $\xi^{max}_{decision}$ are defined as the maximum and minimum decision values, respectively. Hence, the proof concludes. □

4.2 Opportunistic Connectivity for Data Dissemination

In this Subsection, we discuss the price-based approach [31] used for opportunistic data dissemination in WBANs. In a link-failure situation, WBANs need to find an appropriate opportunistic connection to minimize the data dissemination delay and deliver medical data as soon as possible. Now, the dynamic opportunistic connectivity cost is mathematically expressed as:

$$\mathcal{C}^t_{opp} = \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{C}^{opp^t}_{ij} \left(f_1 \frac{\gamma}{\gamma_{th}} + f_2 \frac{BW_{req}}{BW_{tot}} \right) \tag{11}$$

where $\mathcal{C}^{opp^t}_{ij}$ denotes the new opportunistic link establishment cost, BW_{req} and BW_{tot} denote the bandwidth requirement of WBANs and the total available bandwidth. Therefore, based on the value of $\mathcal{C}^t_{opp}$, each WBAN finds a dynamic opportunistic connection in the presence of link-quality variation and topological disconnections. WBANs always attempt to maximize their profit by finding an optimal connection. Therefore, an optimal opportunistic dynamic connection is established using the price-based approach [31]. Mathematically,

$$\mathcal{C}^t_{OC_{tot}} = \sum_{i=1}^{N} \sum_{j=1}^{M} \Gamma_{ij} \left[1 + \frac{\beta^t_{ij}}{\beta_{max}} (\mathcal{C}^t_{opp} - \mathcal{C}^t_{opp_{th}}) \right] \tag{12}$$

where Γ_{ij} denotes the scaling factor, and $\frac{\beta^t_{ij}}{\beta_{max}}$ the temporal link-quality factor between sensor nodes and LPUs. The optimization problem for optimal opportunistic connection establishment is defined as:

$$\begin{aligned} \text{Minimize} \sum_{t \in \mathcal{T}} \mathcal{C}^t_{OC} = \Bigg[\sum_{t \in \mathcal{T}} \sum_{i=1}^{N} \sum_{j=1}^{M} \delta_{ij} + \\ \sum_{t \in \mathcal{T}} \sum_{i=1}^{N} \sum_{j=1}^{M} \delta_{ij} \frac{\beta^t_N}{\beta_{max}} (\mathcal{C}^t_{opp} - \mathcal{C}^t_{opp_{th}}) \Bigg] \end{aligned} \tag{13}$$

$$\text{subject to} \quad \gamma_{th} \leq \gamma, \gamma = \frac{P_{tx}}{P_{tx} + P_{no} + \sum_{h \in N} P^k_{inf}} \tag{14}$$

$$\mathcal{C}^t_{OC} \geq \mathcal{C}^t_{OC_{th}}, t \in \{t_1, t_2, \cdots, t_t\} \tag{15}$$

$$\beta^t_{ij} \geq \beta_{max}, t \in \{t_1, t_2, \cdots, t_t\}, n \in N \tag{16}$$

$$\Gamma_{ij} \geq \Gamma^{th}, i \in N, j \in M \tag{17}$$

$$\sum_{t \in \mathcal{T}} \left(\sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{C}^t_{opp} \leq \mathcal{C}^t_{opp_{th}} \right) \tag{18}$$

$$\mathcal{D}^t_{prop_{\mathcal{L}_j}} \leq \mathcal{D}^{max}_{prop}, j \in M, t \in \mathcal{T} \tag{19}$$

4.3 Opportunistic Energy Constraint

Definition 6. *The opportunistic data flow constraint is defined as the total aggregated data for both ongoing and incoming opportunistic flows from a sensor for a specific time period $\mathcal{T}$.*

$$\mathcal{F}_{opp}(t) = \sum_{i=1}^{N} \sum_{j=1}^{M} f_{ij}(t) + R^a_{ij}(t) \tag{20}$$

where $f_{ij}(t)$ and $R^a_{ij}(t)$ denote the incoming traffic flow and data flow from sensor nodes, respectively.

Definition 7. *The opportunistic energy constraint is defined as the total aggregated energy consumption rate for both ongoing and incoming opportunistic data flow form a sensor for a specific time period $\mathcal{T}$.*

$$\mathcal{F}^t_{ec} = E_p \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{F}_{opp}(t) \tau(i,j) \tag{21}$$

where E_p denotes the opportunistic energy consumption rate and $\tau(i,j)$ denotes the total contact time of opportunistic connectivity between WABNs and LPUs.

After calculating the energy constraints of WBANs for uploading and downloading the opportunistic medical data, we formulate a Lagrangian optimization problem to minimize the energy consumption rate of WBANs for opportunistic medical data uploading and downloading. The network management cost optimization problem for opportunistic WBANs is stated below:

$$\text{Minimize} \sum_{t=1}^{\mathcal{T}} \mathcal{F}_{ec}^{i} = \sum_{t=1}^{\mathcal{T}} E_p \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{F}_{opp}(t)\tau(i,j)$$

$$\text{Subject to} \quad \sum_{i=1}^{N} \mathcal{F}_{ec}^{i} \geq \mathcal{F}_{ec}^{th} \tag{22}$$

$$\mathcal{F}_{opp}(t) \geq \mathcal{F}_{opp}^{th}(t), t \in \mathcal{T} \tag{23}$$

$$R_{ij}^{a}(t) \geq R_{ij}^{th}(t), t \in \mathcal{T} \tag{24}$$

The problem is solved using the Lagrangian Optimization method. We have,

$$\mathcal{L}_{\mathcal{E}} = \sum_{i=1}^{N} \frac{\mathcal{P}_i}{\mathcal{F}_{ec}^{th}} \sum_{j=1}^{k} \mathcal{L}_j \left(E_p \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{F}_{opp}(t)\tau(i,j) \right)$$
$$-G_1 \left(\sum_{i=1}^{N} \mathcal{F}_{ec}^{i} - \mathcal{F}_{ec}^{th} \right) - G_2 \left(\sum_{i=1}^{N} \mathcal{F}_{opp}(t) - \mathcal{F}_{opp}^{th}(t) \right)$$
$$-G_3 \left(\sum_{i=1}^{N} R_{ij}^{a}(t) - R_{ij}^{th}(t) \right)$$

where G_1, G_2 and G_3 are the Lagrangian Multipliers constraints and $\mathcal{P}_i$ denotes the priority of WBANs based on the severity of medical condition. We aim to maximize $\mathcal{U}$ using the approach of Lagrange Multipliers. Thus,

$$\frac{\delta \mathcal{L}_{\mathcal{E}}}{\delta \mathcal{F}_{ec}^{i}} = \sum_{i=1}^{N} - \frac{\mathcal{P}_i \mathcal{L}_j \left(E_p \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{F}_{opp}(t)\tau(i,j) \right)}{{\mathcal{F}_{ec}^{th}}^{2}} \tag{25}$$

$$\frac{\delta \mathcal{L}_{\mathcal{E}}}{\delta \mathcal{F}_{opp}(t)} = \sum_{i=1}^{N} \frac{\mathcal{P}_i}{\mathcal{C}_{tot}^{th}} \sum_{j=1}^{M} \frac{\delta \mathcal{L}_j \left(E_p \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{F}_{opp}(t)\tau(i,j) \right)}{\delta \mathcal{F}_{opp}^{th}(t)} \tag{26}$$

$$\frac{\delta \mathcal{L}_{\mathcal{E}}}{\delta R_{ij}^{a}(t)} = \sum_{i=1}^{N} \frac{\mathcal{P}_i}{\mathcal{C}_{tot}^{th}} \sum_{j=1}^{M} \frac{\delta \mathcal{L}_j \left(E_p \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{F}_{opp}(t)\tau(i,j) \right)}{\delta R_{ij}^{th}(t)} \tag{27}$$

Using Equations, we can get the minimum value of $\mathcal{L}_{\mathcal{E}}$ to get the optimized energy constraint for the minimization of energy consumption in opportunistic WBANs. We proposed an algorithm for energy-efficient prioritized opportunistic communication in the presence of poor link-quality, which is shown in Subsection (4.4).

4.4 Algorithm for Energy-Efficient Prioritized Opportunistic Communication

Dynamic topological disconnections and variations in link-qualities increases the energy consumption rate of opportunistic WBANs. Therefore, we proposed energy-efficient prioritized opportunistic communication to optimize the energy consumption rate of WBANs. First, in the absence of strong link-quality, WBANs establish opportunistic connectivity with APs. Afterward, the WBANs calculate their own energy constraint for opportunistic connectivity. Then, to minimize the energy consumption of WBANs, the Lagrangian optimization technique is used to get the optimal energy consumption rate, based on the different medical priorities of WBANs.

Algorithm 1 Energy-Efficient Prioritized Opportunistic Communication

```
Inputs:
  • Number of WBANs, $B \in \mathcal{B}$.
  • Number of APs, $A \in \mathcal{A}$.
  • Number of sensor nodes, $b \in B$.
  • Total time period, $\mathcal{T}$.
Output: Optimal energy consumption rate ($\mathcal{F}_{ec}^{t^*}$).
Measure $x_{ij}^{Intra}$ and $\mathcal{X}_{ij}^{Inter}$ at time $t$.
Calculate $f_{ij}(t)$ and $R_{ij}^{a}(t)$ at time $t$.
if ($\xi_{decision}^{t} \geq \xi_{decision}^{th}$) then
    Establish an connectivity using Equation (11).
    Calculate $\mathcal{F}_{ec}^{t}$ at time $t$.
    if ($\mathcal{F}_{ec}^{t} \geq \mathcal{F}_{ec}^{th}$) then
        Formulate opportunistic energy constraint parameter.
        Formulate optimization problem using Equation 24.
    end if
    if ($\mathcal{P}_i \geq \mathcal{P}^{th}$) then
        Update waiting time $\mathcal{T}_{wait} = \mathcal{T}_{low}$.
        Optimal energy consumption rate ($\mathcal{F}_{ec}^{t^*}$).
    end if
end if
Update $\mathcal{T}_{wait}^{*} = (\mathcal{T}_{low} + 1)$.
Return when $\mathcal{T}^{*} = \mathcal{T}_{tot}$.
```

5 DISTRIBUTED OPTIMAL NETWORK MANAGEMENT COST MINIMIZATION FRAMEWORK

In this Section, we discuss the distributed network management cost minimization framework for WBANs in the presence of dynamic topological disconnections and link-failure situation. Before modeling the cost minimization framework, first we need to know the requirements of the network management cost minimization problem, which is shown in Theorem 2. Finally, we estimate the pricing function for network management cost and then model a distributed network management cost optimization problem for WBANs.

5.1 Requirements of the Network Management Cost Minimization Problem

Definition 8. *Waiting cost for each medical data packet depends on the delay function of each packet and its mean waiting time, which is mathematically expressed as:*

$$f_p(c) = \sum_{t=1}^{\mathcal{T}} \mathcal{Z}_t W(t) \tag{28}$$

where $\mathcal{Z}_t$ is the severity of each medical data packet in a particular time instant t, and $W(t)$ denotes the mean waiting time of each data packet.

Definition 9. *The network cost function for opportunistic connectivity in WBANs is defined as the delay-sensitive pricing function for network management cost, which is defined as:*

$$\mathcal{H}(p) = \mathcal{S} - \sum_{t=1}^{\mathcal{T}} \mathcal{Z}_t W(t) - P(c_t) \tag{29}$$

where $\mathcal{S}$ denotes the primary cost value for using the infrastructure, and $P(c_t)$ denotes the pricing function of network management cost for opportunistic WBANs.

Definition 10. *The profit of WBANs depends on the network cost management function and the data transmission rate of WBANs. It is mathematically expressed as:*

$$\begin{aligned}\mathbb{P} &= \int_{t=1}^{\mathcal{T}} \theta_t \mathcal{H}(p)\delta t \\ &= \int_{t=1}^{\mathcal{T}} \theta_t \Big(\mathcal{S} - \sum_{t=1}^{\mathcal{T}} \mathcal{Z}_t W(t) - P(c_t)\Big)\delta t \end{aligned} \tag{30}$$

where θ_t denotes the data transmission rate of body sensor nodes.

Theorem 2. *If the waiting cost of data packets increases in the presence of dynamic postural disconnections, then the profit of each WBAN decreases and the corresponding network management cost increases.*

$$\int_{t=1}^{\mathcal{T}} \theta_t \Big(\mathcal{S} - \sum_{t=1}^{\mathcal{T}} \mathcal{Z}_t W(t) - P(c_t)\Big)\delta t >> \\ \int_{t=1}^{\mathcal{T}+\Delta t} \theta_{t+\Delta t} \Big(\mathcal{S} - \sum_{t=1}^{\mathcal{T}+\Delta t} \mathcal{Z}_t W(t+\Delta t) - P(c_{t+\Delta t})\Big)\delta(t+\Delta t) \tag{31}$$

Proof. Suppose, at time t, a WBAN moves from one place to another. Then, the on-body topology of body sensor nodes get disconnected, which decreases the available link-quality between body sensor nodes and LPUs. Therefore, in the presence of topological disconnections, the WBANs not able to send its data which inherently increases the waiting cost the data packets, which is $f_p(c) = \sum_{t=1}^{\mathcal{T}} \mathcal{Z}_t W(t)$ and also the network management cost $\mathcal{H}(p)$ increases at time t. Therefore, the profit of WBANs decreases, which is defined as:

$$\mathbb{P}_t = \int_{t=1}^{\mathcal{T}} \theta_t \Big(\mathcal{S} - \sum_{t=1}^{\mathcal{T}} \mathcal{Z}_t W(t) - P(c_t)\Big)\delta t \tag{32}$$

However, after few instants of time $(t+\Delta t)$, the waiting cost of the data packets increases to $\sum_{t=1}^{\mathcal{T}+\Delta t} \mathcal{Z}_{t+\Delta t} W(t+\Delta t)$ and also the network management cost increases. We have, $\mathcal{H}(p) = \mathcal{S} - \sum_{t=1}^{\mathcal{T}+\Delta t} \mathcal{Z}_{t+\Delta t} W(t+\Delta t) - P(c_{t+\Delta t})$ at time $(t+\Delta t)$. Therefore, the the reformed profit of WBANs at time $(t+\Delta t)$ is defined as:

$$\begin{aligned}\mathbb{P}_{t+\Delta t} = \int_{t=1}^{\mathcal{T}+\Delta t} & \theta_{t+\Delta t} \Big(\mathcal{S} - \sum_{t=1}^{\mathcal{T}+\Delta t} \mathcal{Z}_t W(t+\Delta t) \\ & - P(c_{t+\Delta t})\Big)\delta(t+\Delta t) \end{aligned} \tag{33}$$

Therefore, we can observe that the profit and network management cost at time instant $t+\Delta t$ is greater than the profit and network management cost at time instant $t+\Delta t$. Mathematically,

$$\mathbb{P}_{t+\Delta t} >> \mathbb{P}_t \tag{34}$$

Hence, the proof concludes. ☐

Definition 11. *Profit matrix of WBANs is used to measure the total network management cost of WBANs in different time instants, which is mathematically expressed as:*

$$\mathcal{G}_{\mathbb{P}} = \begin{array}{c c} & \begin{array}{cccc} \mathcal{P}_1 & \mathcal{P}_2 & \dots & \mathcal{P}_M \end{array} \\ \begin{array}{c} R_1 \\ R_2 \\ \vdots \\ R_N \end{array} & \begin{pmatrix} C_{11} & C_{12} & \dots & C_{1M} \\ C_{21} & C_{22} & \dots & C_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \dots & C_{NM} \end{pmatrix} \end{array} \tag{35}$$

where $\mathcal{P} = \{\mathcal{P}_1, \mathcal{P}_2, \cdots, \mathcal{P}_M\}$ and $R = \{R_1, R_2, \cdots, R_N\}$ denotes the priority of WBANs, and the data generation rate of WBANs, respectively.

5.2 Estimation of Total Network Management Cost

The total management cost of an opportunistic WBAN not only depends on the opportunistic connection establishment cost, but also on the opportunistic data dissemination cost, interference management cost, and the cost for ensuring QoS. The mathematical formulations of these different costs are given below:

- ***Computation of Data Dissemination Cost***: After opportunistic connectivity establishment, the WBANs disseminate their data to the AP. Therefore, the data dissemination cost for opportunistic connection in WBANs is mathematically expressed as:

$$C^t_{DC_{tot}} = \sum_{i=1}^{N}\sum_{j=1}^{M} \xi_i \frac{C^t_P}{N} \tag{36}$$

  where $\xi_i = \frac{\mathcal{E}_P^{com}}{\mathcal{E}_{tot}^{com}}$ denotes energy consumption per packet, and C^t_P, the data dissemination cost at time t.
- ***Computation of Interference Management Cost***: In the presence of coexisting WBANs, WBANs strongly face mutual and cross technology interference. Therefore, the interference management cost for opportunistic connectivity is mathematically expressed as:

$$C^t_{inff_{tot}} = \sum_{i=1}^{N}\sum_{j=1}^{M} C^{t_{inff}}_{ij} \frac{(\gamma_1 + \gamma_2 + \cdots + \gamma_K)P_{eff}}{\sum_{i=1}^{k} P^i_{eff}} \tag{37}$$

  where $\sum_{i=1}^{k} P^i_{eff}$ denotes effective power from k number of coexisting WBANs, γ denotes the SINR value in different time instants, and $C^{t_{inff}}_{ij}$, the unit cost for interference management.
- ***Computation of QoS Ensuring Cost***: As, each WBAN has different QoS requirement in different instants of time, the QoS ensuring profile of WBANs is defined as:

$$\mathcal{Q}^* = \{\mathcal{Q}_1, \mathcal{Q}_2, \cdots, \mathcal{Q}_N\} \tag{38}$$

Therefore, the QoS ensuring cost of WBANs for an opportunistic connection is defined as:

$$\mathcal{C}^t_{qos_{tot}} = \left(\prod_{k=1}^{H} \mathcal{Q}_i \sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{C}^t_{qos} \right), \forall t \in \mathcal{T} \tag{39}$$

where $\mathcal{C}^t_{qos}$ denotes the unit QoS-assurance cost for opportunistic data dissemination at time t.

- ***Computation of Energy Management Cost***: Due to the resource-constrained nature of these WBANs, we need to manage the energy consumption of senor nodes. Therefore, the energy management cost for opportunistic connectivity is given as:

$$\mathcal{C}^t_{E_{tot}} = \begin{cases} \mathcal{C}^t_{E_{max}} \frac{E^t_{ini}}{d_{ij}}, & d_{ij} << d_{th} \\ \mathcal{C}^t_{E_{min}} \frac{E^t_{th}}{d_{ij}}, & d_{ij} >> d_{th} \end{cases} \tag{40}$$

  where $\frac{E^t_{ini}}{d_{ij}}$ and $\frac{E^t_{th}}{d_{ij}}$ define the energy dissemination factor and threshold energy dissemination factor, respectively. $\mathcal{C}^t_{E_{max}}$ and $\mathcal{C}^t_{E_{min}}$ denote the maximum and minimum energy consumption management costs.
- ***Computation of Dynamic Topology Management Cost***: Dynamic topological disconnections in WBANs necessitate opportunistic connectivity in them. Therefore, the dynamic topology management cost is mathematically expressed as:

$$\mathcal{C}^t_{DT_{tot}} = \mathcal{C}^t_{DT} \left(\mathcal{H}_{ij} + \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{V}_{ij}}{\mathcal{V}_{th}} \right) \tag{41}$$

  where $\mathcal{H}_{ij}$ defines the initial topological deployment cost of sensor nodes, $\frac{\sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{V}_{ij}}{\mathcal{V}_{th}}$ the rate of change in the topological disconnections, and $\mathcal{C}^t_{DT}$ the topological disconnection management cost.

The total estimated network management cost for inter-BAN communication is calculated as:

$$\mathcal{C}^t_{tot} = \mathcal{C}^t_{OC_{tot}} + \mathcal{C}^t_{DC_{tot}} + \mathcal{C}^t_{inff_{tot}} + \mathcal{C}^t_{qos_{tot}} + \mathcal{C}^t_{E_{tot}} + \mathcal{C}^t_{DT_{tot}} \tag{42}$$

5.3 Formulation of the Lagrangian Optimization Problem

The network management cost optimization problem for opportunistic WBANs is mathematically expressed as:

$$\text{Minimize} \sum_{i=1}^{N} \mathcal{C}^t_{tot}$$

$$\text{Subject to} \quad \sum_{i=1}^{N} \mathcal{C}^t_{OC_{tot}} \geq \mathcal{C}^{th}_{OC} \tag{43}$$

$$\mathcal{C}^t_{qos_{tot}} \geq \mathcal{C}^{th}_{qos} \tag{44}$$

$$\mathcal{C}^t_{inff_{tot}} \geq \mathcal{C}^{th}_{inff} \tag{45}$$

Solving the optimization problem using the Lagrangian Optimization method, we have,

$$\mathcal{L}_{\mathcal{U}} = \sum_{i=1}^{N} \frac{\mathcal{P}_i}{\mathcal{C}^{th}_{tot}} \sum_{j=1}^{k} \mathcal{L}_j(\mathcal{C}^t_{OC_{tot}}, \mathcal{C}^t_{qos_{tot}}, \mathcal{C}^t_{inff_{tot}}) - F_1 \left(\sum_{i=1}^{N} \mathcal{C}^t_{OC_{tot}} - \mathcal{C}^{th}_{OC} \right) - F_2 \left(\sum_{i=1}^{N} \mathcal{C}^t_{qos_{tot}} - \mathcal{C}^{th}_{qos} \right) - F_3 \left(\sum_{i=1}^{N} \mathcal{C}^t_{inff_{tot}} - \mathcal{C}^{th}_{inff} \right)$$

where F_1, F_2 and F_3 are the Lagrangian Multipliers constraints, and $\mathcal{P}_i$ denotes the priority of WBANs, based on the medical conditions. We aim to maximize $\mathcal{U}$ using the approach of Lagrange Multipliers. Thus,

$$\frac{\delta \mathcal{L}_{\mathcal{U}}}{\delta \mathcal{C}^t_{tot}} = \sum_{i=1}^{N} - \frac{\mathcal{P}_i \mathcal{L}_j(\mathcal{C}^t_{OC_{tot}}, \mathcal{C}^t_{qos}, \mathcal{C}^t_{inff_{tot}})}{{\mathcal{C}^{th}_{tot}}^2} \tag{46}$$

$$\frac{\delta \mathcal{L}_{\mathcal{U}}}{\delta \mathcal{C}^t_{OC_{tot}}} = \sum_{i=1}^{N} \frac{\mathcal{P}_i}{\mathcal{C}^{th}_{tot}} \sum_{j=1}^{M} \frac{\delta \mathcal{L}_j(\mathcal{C}^t_{OC_{tot}}, \mathcal{C}^t_{qos_{tot}}, \mathcal{C}^t_{inff_{tot}})}{\delta \mathcal{C}^t_{OC_{tot}}} \tag{47}$$

$$\frac{\delta \mathcal{L}_{\mathcal{U}}}{\delta \mathcal{C}^t_{qos_{tot}}} = \sum_{i=1}^{N} \frac{\mathcal{P}_i s}{\mathcal{C}^{th}_{tot}} \sum_{j=1}^{M} \frac{\delta \mathcal{L}_j(\mathcal{C}^t_{OC_{tot}}, \mathcal{C}^t_{qos_{tot}}, \mathcal{C}^t_{inff_{tot}})}{\delta \mathcal{C}^t_{qos_{tot}}} \tag{48}$$

Using these Equations, we get the minimum value of $\mathcal{U}$ to get the optimized network management value for opportunistic WBANs. To analyze the overall performance, we propose the following algorithm — *Network Management Cost Minimization for Dynamic Connectivity and Data Dissemination* (*NCMD*) for opportunistic WBAN connection.

5.4 Optimal Network Management Cost Minimization Algorithm

To minimize the network management cost, we propose an optimal network management cost minimization algorithm. The network management cost minimization algorithm considers the data dissemination cost, interference management cost, energy management cost, and QoS-ensuring cost. In this algorithm, the body sensor nodes and LPUs measure the link-quality with LPUs and APs, respectively. Thereafter, based on the decision metric $\xi^t_{decision}$, the sensor nodes and LPUs try to establish opportunistic connectivity with LPUs and APs. As the mobility and body movements increases the network management cost, the WBANs calculate their network management cost, if the measured network management cost is higher than the threshold network management cost. Then, the Lagrangian optimization technique is implemented to minimize the total network management cost. The overall block diagram of the proposed framework is shown in Figure 2.

6 THEORETICAL ANALYSIS

In this Section, we theoretically analyze the performance of the proposed framework — NCMD — in terms of computational complexity, pricing limit of network management cost, and optimal limit of decision metric for opportunistic connectivity in WBANs.

Algorithm 2 Optimal Network Management Cost Minimization Algorithm

```
Inputs:
  • Number of WBANs, $B \in \mathcal{B}$.
  • Number of APs, $A \in \mathcal{A}$.
  • Number of sensor nodes, $b \in B$.
  • Total time period, $\mathcal{T}$.
Output: Optimal Network Management Cost Management Matrix ($\mathcal{CM}^*_{i,j}$).
Measure $x^{Intra}_{ij}$ and $\mathcal{X}^{Inter}_{ij}$ at time $t$.
Calculate $\mathcal{C}^{Intra}_{x_{ij}}$ and $\mathcal{C}^{Inter}_{\mathcal{X}_{ij}}$ at time $t$.
if $\xi^t_{decision} \geq \xi^{th}_{decision}$ then
    Establish an opportunistic connectivity using Equation (11).
    Update waiting time $\mathcal{T}_{wait} = \mathcal{T}_{low}$.
    if $\mathcal{C}^t_{OC_{tot}} \geq \mathcal{C}^{th}_{OC}$ then
        Calculate $\mathcal{C}^t_{DC_{tot}}, \mathcal{C}^t_{inff_{tot}}$ using Equations 36 and 37.
        Calculate $\mathcal{C}^t_{qos_{tot}}, \mathcal{C}^t_{E_{tot}}$ using Equations 39 and 40.
    end if
    if $\mathcal{C}^t_{tot} \geq \mathcal{C}^{th}_{tot}$ then
        Optimize the network management cost using Equation 45.
        Optimal Network Management Cost Management Matrix ($\mathcal{CM}^*_{i,j}$).
    end if
end if
Update $\mathcal{T}^*_{wait} = (\mathcal{T}_{low} + 1)$.
Return when $\mathcal{T}^* = \mathcal{T}_{tot}$.
```

Lemma 1. *The theoretical pricing limit of dynamic opportunistic connectivity is mathematically expressed as:*

$$\mathcal{C}^t_{opp_{max}} = \sum_{i=1}^{N}\sum_{j=1}^{M} \mathcal{C}^{opp^t}_{ij} \frac{BW_{req}}{BW_{tot}}$$

$$\mathcal{C}^t_{opp_{min}} = \sum_{i=1}^{N}\sum_{j=1}^{M} \mathcal{C}^{opp^t}_{ij} f\left(\frac{\gamma}{0.5} + \frac{BW_{req}}{BW_{tot}}\right)$$

Proof. The selection function, $\mathcal{C}^t_{opp}$, is a linear function of variables γ, γ_{th}, BW_{req}, and BW_{tot} is a constant for choosing the opportunistic connectivity in WBANs. The selection function in Equation (11) gives the maximum value, when $\gamma = 0$ and $f_1 = 1$. Therefore, the maximum selection rate is expressed as:

$$\mathcal{C}^t_{opp_{max}} = \sum_{i=1}^{N}\sum_{j=1}^{M} \mathcal{C}^{opp^t}_{ij} f_2 \frac{BW_{req}}{BW_{tot}} \tag{49}$$

where $\mathcal{C}^{opp^t}_{ij}$ is the new opportunistic link establishment cost. We have, $f_2 = 1$ for the maximum value of $\mathcal{C}^t_{opp}$, as the values of f_1 and f_2 vary in the range $(0, 1)$. Therefore, the reformed maximum value $\mathcal{C}^t_{opp}$ is,

$$\mathcal{C}^t_{opp_{max}} = \sum_{i=1}^{N}\sum_{j=1}^{M} \mathcal{C}^{opp^t}_{ij} \frac{BW_{req}}{BW_{tot}} \tag{50}$$

The selection function is minimum, when $\gamma_{th} = 0.5$, and the selection rate $f_1 = f_2$. Therefore, the minimum value of the selection function is expressed as:

$$\mathcal{C}^t_{opp_{min}} = \sum_{i=1}^{N}\sum_{j=1}^{M} \mathcal{C}^{opp^t}_{ij} f\left(\frac{\gamma}{0.5} + \frac{BW_{req}}{BW_{tot}}\right) \tag{51}$$

Hence, the proof concludes. □

Theorem 3. *The worst case time complexity of the proposed algorithm is $O(G\mathcal{N}^2)$, where $\mathcal{N}$ is the number of WBANs.*

Proof. In the first algorithm, each WBAN tries to optimize its energy consumption rate using the energy-efficient prioritized opportunistic communication algorithm. To optimize the energy consumption rate, the worst case computation complexity using Algorithm (1) is $O(\mathcal{A}N)$. After the establishment of opportunistic connectivity, we need to minimize the network management cost. To minimize the network management cost, we propose the optimal network management cost minimization algorithm. Hence, the worst case complexity of network management cost algorithm is $O(\mathcal{Y}N)$.

$$T(n) = C_1\{\mathcal{A}T(N) + \mathcal{Y}T(N)\} + C_2T(1) \tag{52}$$

Now, the combined worst case complexity of the proposed framework — NCMD — is $O(GN^2)$, where $G = \mathcal{A} + \mathcal{Y}$. Hence, we observe that the total computational complexity of the proposed algorithm, in the worst case, is $O(GN^2)$, where N is the number of WBANs. This completes the proof. □

Theorem 4. *The maximum and minimum values of the dynamic topological management cost algorithm are:*

$$\mathcal{C}^t_{DT_{tot_{max}}} = \mathcal{C}^t_{DT}\left(\frac{1 - \sum_{i=1}^{k} S_i(t)}{S(t)} + \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\mathcal{V}_{ij}}{\mathcal{V}_{th}}\right)$$

$$\mathcal{C}^t_{DT_{tot_{min}}} = \mathcal{C}^t_{DT}\left(\frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\mathcal{V}_{ij}}{0.5}\right)$$

Proof. The initial topological deployment cost of sensor nodes $\mathcal{H}_{ij}$ is mathematically expressed as:

$$\mathcal{H}_{ij} = \begin{cases} 1, & S_i(t) < S(t)^{th} \\ \frac{1-\sum_{i=1}^{k} S_i(t)}{S(t)}, & S_i(t) > S(t)^{th} \\ 0, & \text{Otherwise} \end{cases} \tag{53}$$

where $S_i(t)$ denotes the unit cost for topological maintenance, and $S(t)^{th}$ denotes the threshold topological maintenance cost of sensor nodes in a particular time instant t. Therefore, we get the maximum value of $\mathcal{C}^t_{DT_{tot}}$, when $S_i(t) > S(t)^{th}$. Therefore, the maximum value of the dynamic topological management cost is expressed as:

$$\mathcal{C}^t_{DT_{tot_{max}}} = \mathcal{C}^t_{DT}\left(\frac{1 - \sum_{i=1}^{k} S_i(t)}{S(t)} + \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\mathcal{V}_{ij}}{\mathcal{V}_{th}}\right) \tag{54}$$

Also, we get the minimum value of $\mathcal{C}^t_{DT_{tot}}$, when $S_i(t) < S(t)^{th}$ and $\mathcal{V}_{th} = 0.5$. Therefore, the minimum value of the dynamic topological management cost is expressed as:

$$\mathcal{C}^t_{DT_{tot_{min}}} = \mathcal{C}^t_{DT}\left(\frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\mathcal{V}_{ij}}{0.5}\right) \tag{55}$$

Hence, the proof concludes. □

Proposition 1. *The proposed network management cost minimization framework satisfies the Potential Pareto criterion.*

Proof. As per the Pareto optimal criterion [33], the optimized network management cost for WBANs is always better than the network management cost for WBANs in the normal condition. Therefore, for optimized network management cost, we have,

$$\mathcal{C}^t_{tot_{max}} > \mathcal{C}^t_{tot_{th}} \tag{56}$$

Hence, the compensation of network management cost is expressed as $\mathcal{C}^t_{tot}$, and the benefit function is defined as $\mathcal{C}^t_{tot_{max}} - \sigma\mathcal{C}^t_{tot}$. Mathematically,

$$(\mathcal{C}^t_{OC_{tot_{max}}} + \mathcal{C}^t_{DC_{tot_{max}}} + \mathcal{C}^t_{inff_{tot_{max}}} + \mathcal{C}^t_{qos_{tot_{max}}} + \mathcal{C}^t_{E_{tot_{max}}} + \mathcal{C}^t_{DT_{tot_{max}}}) > \sigma(\mathcal{C}^t_{OC_{tot_{th}}} + \mathcal{C}^t_{DC_{tot_{th}}} + \mathcal{C}^t_{inff_{tot_{th}}} + \mathcal{C}^t_{qos_{tot_{th}}} + \mathcal{C}^t_{E_{tot_{th}}} + \mathcal{C}^t_{DT_{tot_{th}}}) \tag{57}$$

Therefore, $\mathcal{C}^t_{tot}$ compensates the normal network management cost framework, which incuring a positive benefit C_{pre}, thereby, satisfying the Potential Pareto criterion.

$$\mathcal{C}^t_{tot_{max}} = \mathcal{C}^t_{tot_{th}} + C_{pre} \tag{58}$$

Hence, the proof concludes. □

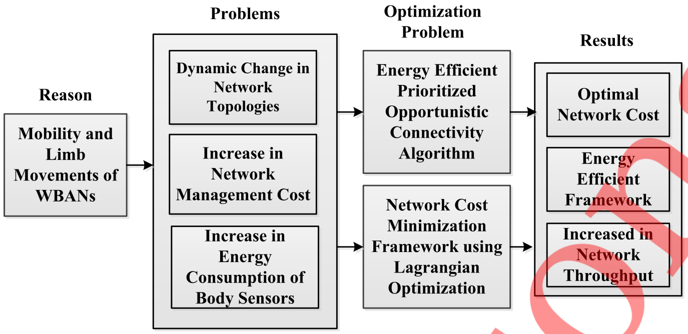


Figure 2: Block diagram for opportunistic WBANs

7 PERFORMANCE ANALYSIS

We analyze the performance of the proposed framework, NCMD, based on different performance the metrics. We use MATLAB simulator to simulate the proposed framework. The simulation parameters are presented in Table 2. To compare the proposed framework, NCMD, with the benchmark algorithm, JSOT, proposed by Hong *et al.* [14].

7.1 Performance Metrics

The performance metrics used for the evaluation of the proposed framework are discussed below.

- *Energy Consumption*: The energy consumption of sensor nodes in the two-hop extended star topology is [34]:

$$E_{M-Hop} = \eta K(E_{tx} + E_{amp})d^2 + K(\eta - 1)E_{rx} \tag{59}$$

  where η is total hop-count, $E_{tx} = 16.7$ nJ denotes the energy consumption of transmitted circuit, $E_{rx} = 36.1$ nJ denotes the energy consumption of receiver circuit, E_{amp} denotes energy consumption of amplifier circuit and K denotes the data rate of the sensor nodes.
- *Fairness Index*: To analyze the fairness of WBANs, we used Jain's fairness index [35] in terms of effective cost, which is expressed as follows:

$$FI_{\mathcal{C}} = \frac{\sum_{i=1}^{N} |\mathcal{C}^t_{tot}|^2}{N|\sum_{i=1}^{N} \mathcal{C}^t_{tot}|^2} \tag{60}$$

- *Data Dissemination Delay*: The data dissemination delay is defined as the total data transmission delay in the presence of transient connectivity between LPUs and APs. It is mathematically expressed as:

$$\mathcal{D}_d = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\{d^t_{u_{i,j}}\phi_u + d^t_{s_{i,j}}\sigma_s\}}{\sum_{t=1}^{T}\{d^t_u + d^t_s\}} \tag{61}$$

  where $d^t_{u_{i,j}}$ and $d^t_{s_{i,j}}$ denote the processing delay and transmission delay, respectively, and ϕ_u and σ_s denote the processing delay and transmission delay per byte.
- *Network Throughput*: Network throughput defines the total number of successfully received packets at the receiver end (i.e. AP). Mathematically,

$$\mathcal{U} = \sum_{t=1}^{T}\left(\sum_{i=1}^{N}\sum_{j=1}^{M} P^t_{tran_{ij}} - P^t_{loss_{ij}}\right) \tag{62}$$

  where $P^t_{tran_{ij}}$ and $P^t_{loss_{ij}}$ denote the number of packets transmitted and the number of packets lose from LPU i to AP j at time t, respectively.
- *Network Life-time*: Network life-time is defined in this work as total time until the group of sensor nodes in the network runs out of energy.

$$T_{lif} = \sum_{i=1}^{n} t^e_i + T_{ini} \tag{63}$$

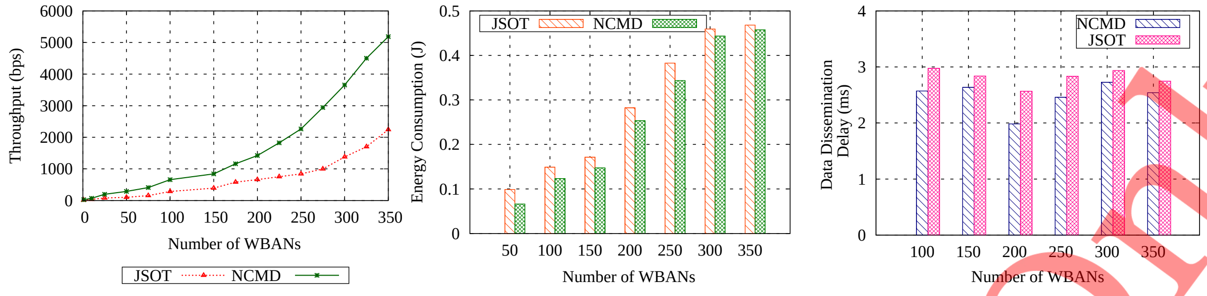
  where t^e_i denotes the total life-time of a sensor node, b_i, and T_{ini} denotes the deployment time of sensor nodes.
- *Packet Block Probability*: The packet blocking probability is defined in this work as the union of probability of packet drop and probability of packet error rate. It is mathematically expressed as:

$$\mathbb{B}_i = 1 - \prod_{i \in N}\Big(1 - q_i(w)\Big) \tag{64}$$

  where $q_i(w)$ denotes the probability of successful packet transmission. Therefore, the union of probability of packet drop and probability of packer error rate is $(1 - q_i(w))$.
- *Packet Delivery Ratio*: The ratio of packets that are successfully delivered to a receiver compared to the number of packets that are sent from the transmitter. It is defined as follows:

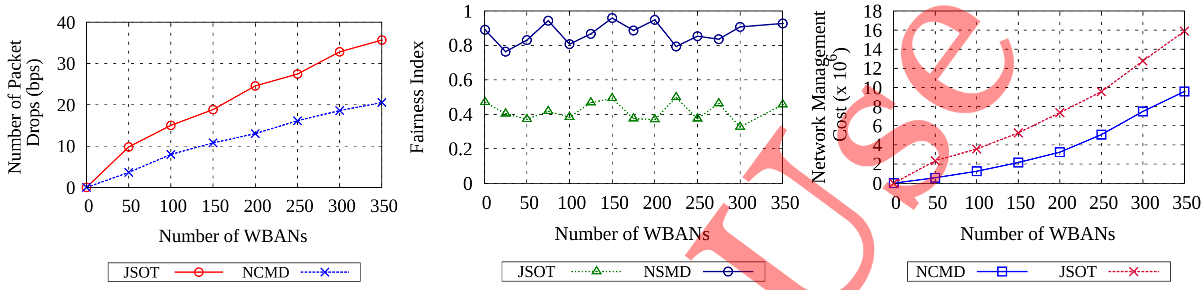
$$\mathbb{P} = \frac{P_{tot} - P_{loss}}{P_{tran}} \tag{65}$$

  where P_{tot}, P_{loss}, and P_{tran} denote the total number



(a) Network Throughput (b) Energy Consumption (c) Data Dissemination Delay

Figure 3: Analysis of energy consumption, data dissemination delay, and network throughput



(a) Number of packets drop (b) Fairness index (c) Network management cost

Figure 4: Analysis of packet drop rate, fairness index, and network management cost

of packets generated from body sensor nodes, the number of packets lose, and the number of packets transmitted from body sensor nodes.

- *Channel Utilization*: Channel utilization $\mathcal{Y}_{ch}$ is defined as the ratio of the amount of channel utilized in unit time to the maximum channel bandwidth $\mathcal{Y}_{ch}^{max}$ of the channel. It is expressed as:

$$\mathcal{Y}_{ch} = \frac{\sum_{q=1}^{q_{max}} P \times p_q}{\mathcal{Y}_{ch}^{max}} \times 100\% \tag{66}$$

7.2 Simulation Settings

To evaluate the performance of the proposed framework — NCMD — we considered group-based mobility of WBANs [36]. Also, we consider the multi-hop topology for data transmission in WBANs, where each WBAN consists of 8 body sensor nodes, which are placed on the body surface, as was also done in the study reported in [37]. In the presence of poor link-quality and mobility of WBANs, some of links between the body sensor nodes and the LPUs get disconnected. Therefore, in our experiment, we considered the link-failure situation for WBANs, where the maximum link-failure situation is considered to be as $\mathcal{A} = 4$ and the minimum link-failure situation is considered to be as $\mathcal{A} = 1$, where $\mathcal{A}$ denotes the number of link-failure between sensor nodes and LPUs ($Max(\mathcal{A}) = 8$) in the network. The cost function for network cost management is defined as $f(\mathcal{C}_{tot}) = \mathcal{C}_{tot}^{t}(x_{b_i}^{t})^2$, where $x_{b_i}^{t}$ defines data transmission rate of body sensor nodes.

Table 2: Simulation Parameters

Parameter	Value
Simulation area	$5\ Km \times 5\ Km$
Number of WBANs	300
Number of Sensor Nodes in a WBAN	8
Number of APs	10
Velocity of each WBAN	1.5 m/s
Residual energy of each WBAN	0.5 J
Energy consumption of Tx-circuit	16.7 nJ
Energy consumption of Rx-circuit	36.1 nJ
Energy consumption of Amplifier-circuit	1.97 nJ
Residual energy of each WBAN	0.5 J
SINR threshold	5-15 dB

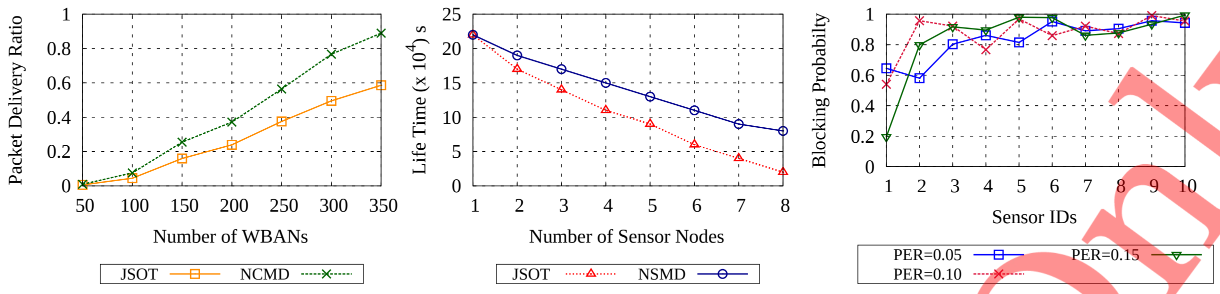
7.3 Results and Discussion

7.3.1 *Analysis of Network Throughput*

Figure 3(a) shows the network throughput of WBANs in the presence of body movement in WBANs. Throughput is defined as the successful reception of transmitted packets from sensor nodes, which is defined in Equation (62). The proposed framework, NCMD, not only minimizes the network management cost, but also establishes opportunistic connectivity with APs in the presence of poor link-quality and body movements. Therefore, as WBANs are able to establish opportunistic connectivity with APs, the network throughput of WBANs increases. Hence, the proposed framework NCMD provides higher throughput than the existing framework — JSOT, which is the benchmark considered in this work, as explained in Section II.

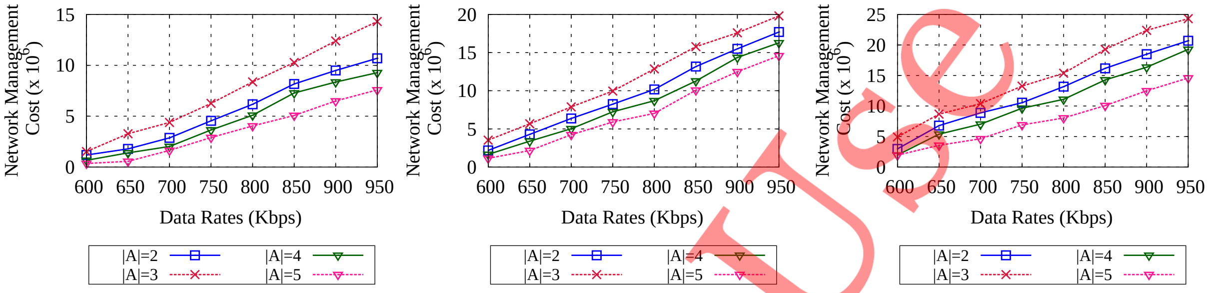
7.3.2 *Analysis of Energy Consumption*

Figure 3(b) depicts the energy consumption of sensor nodes for the proposed framework — NCMD. In the figure, we can



(a) Packet delivery ratio (b) Lifetime of sensor nodes (c) Packet blocking probability

Figure 5: Analysis of life-time, packet delivery ratio, and packet blocking probability



(a) Network management cost (b) Network management cost (c) Network management cost

Figure 6: Analysis of network management cost in the presence of 100, 200, and 300 WBANs

observe that with the increase in the number of WBANs, the energy consumption of sensors increases. In our proposed framework, WBANs optimally decrease the overall network management cost. Therefore, the sensor nodes consume less energy using NCMD than using JSOT. Also, we propose an energy-efficient prioritized opportunistic communication framework to minimize the energy consumption rate of sensor nodes in the presence of body movements and mobility of WBANs. Therefore, Figure 3(b) depicts that the energy consumption is lesser in NCDM than in JSOT.

7.3.3 Analysis of Data Dissemination Delay

Figure 3(c) depicts the data dissemination delay of WBANs for opportunistic communication. From this figure, we can see that using the proposed framework, WBANs incur reduced data dissemination delay than using the existing framework. In NCDM, we proposed opportunistic connectivity to WBANs in the presence of poor link-quality and mobility of WBANs. Therefore, opportunistic connectivity minimizes the data dissemination delay by optimizing the dynamism in WBANs, using the opportunistic connectivity algorithm. Hence, using NCDM, WBANs can send their data as immediately as possible. Therefore, we observe that the proposed framework, NCMD, outperforms JSOT in terms of data dissemination delay.

7.3.4 Analysis of Fairness Index

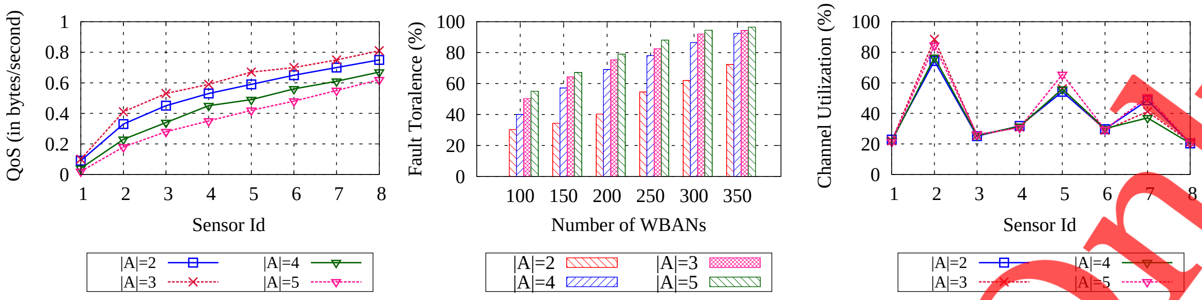
Figure 4(b) shows the measured fairness among WBANs for opportunistic communication. Due to interference and dynamic changes in the on-body typologies, the network management cost of WBANs increases significantly. Therefore, to provide fairness among WBANs, the optimization of network management cost is very important to increase the overall network performance. The fairness among WBANs is measured using Equation (60). However, the fairness among WBANs is improved using the proposed network management framework, NCMD, than using JSOT, as the former guarantees improved fairness among WBANs by optimizing the network management cost.

7.3.5 Analysis of Packet Drop

Figure 4(a) shows the total number of packets dropped in WBANs in opportunistic communication. In the presence of irregular body movements, large number of packets are dropped periodically from LPUs. However, the proposed framework, NCMD, significantly minimizes the number of packets dropped in the network, as the framework uses opportunistic connectivity establishment to minimize the packet drop rate. Therefore, the proposed framework, NCDM, outperforms the existing framework, JSOT, in terms of the packet drop rate.

7.3.6 Analysis of Packet Delivery Ratio

Figure 5(a) shows the packet delivery ratio of WBANs for both the frameworks — NCMD and JSOT. Packet delivery ratio is defined as the number of successfully received packets at the AP, and the ratio between the total number of packets transmitted from the LPU. In the proposed framework, in the presence of dynamic topological changes, WBANs manage the network management cost, which significantly increases the packet delivery ratio. In the other frameworks, WBANs are inefficient in withstanding the dynamic topological disconnections and interference from coexisting WBANs, which increases the packet delivery ratio.



(a) Analysis of QoS (b) Fault tolerance (c) Channel utilization

Figure 7: Analysis of QoS, fault tolerance, and channel utilization

7.3.7 Analysis of Network Management Cost

Figure 6 shows the network management cost for opportunistic communication with varying number of WBANs. The network management cost is analyzed for different link-failure situations. From Figure 6(a), we observe the the network management cost for 100 WBANs in different link-failure situations. When $\mathcal{A} = 4$, the network management cost is higher than in the case of other link-failure situations. Also, we analyze the network management cost for 200 and 300 WBANs, as shown in Figures 6(b) and 6(c). In Figures 6(a), 6(b), and 6(c), we observe that the network management cost increases with the increase in the number of WBANs in different link-failure situations. Also, our proposed framework, NCMD, minimizes the network management cost over the considered benchmark, JSOT, as shown in Figure 4(c).

7.3.8 Analysis of Channel Utilization

Figure 7(c) shows figures of channel utilization in WBANs for different link-failure situations — $\mathcal{A} = 4$, $\mathcal{A} = 3$, $\mathcal{A} = 2$, and $\mathcal{A} = 1$. Using the proposed framework, NCDM, the channel utilization is lesser when $\mathcal{A} = 1$, than the other link-failure situations. Therefore, improvement in the channel utilization increases the packet reception reception rate of sensor nodes, which inherently increases the network throughput and QoS of each WBAN.

7.3.9 Analysis of Lifetime

Figure 5(b) shows the network lifetime of the proposed framework. Network lifetime is defined as the time duration for which the total remaining energy of the network is above zero, i.e., the time duration for which the network remains alive. Figure 5(b) shows that the lifetime of sensor node is more using, NCDM, than using existing framework, JSOT. The increase in the lifetime of the sensor nodes also increases the fault tolerant property and also the QoS assurance rate of the proposed framework.

7.3.10 Analysis of Packet Blocking Probability

Figure 5(c) shows the packet blocking probability in WBANs Packet blocking probability defines the probability of blocking of packets in the presence of dynamic changes in body movements. Using the proposed framework – NCDM, the packet block probability is lesser in $\mathcal{A} = 1$, than the other link-failure situations — $\mathcal{A} = 4$, $\mathcal{A} = 3$, and $\mathcal{A} = 2$, as the occurrence of failure link-qualities is more in this case.

7.3.11 Analysis of QoS

Figure 7(a) depicts the QoS requirements of sensor nodes for opportunistic connectivity. From the figure, we observe the QoS assurance rate of sensor nodes for different link-failure situations — $\mathcal{A} = 1$, $\mathcal{A} = 2$, $\mathcal{A} = 3$, and $\mathcal{A} = 4$. The figure shows that the QoS assurance rate to WBANs for link-failures situation $\mathcal{A} = 4$ is lesser than when $\mathcal{A} = 3, 2, 1$, as for the $\mathcal{A} = 4$ situation, the poor link-quality between the sensor nodes and LPUs is 4. Therefore, using the proposed framework NCMD, it is possible to provide QoS to WBANs in link-failure situations.

7.3.12 Analysis of Fault Tolerance

Figure 7(b) shows a comparative study of fault tolerance in WBANs for different link-failure situations. Fault tolerance is one of the major concerns in WBANs due to the periodic change in the connectivity between sensor nodes and LPUs. Therefore, to decrease the fault tolerance rate in WBANs, we propose an opportunistic connectivity algorithm to optimize the fault tolerance rate to WBANs in link-failure situations. Using the proposed framework, NCDM, the fault tolerance rate is lesser when $\mathcal{A} = 1$, than when $\mathcal{A} = 4$, $\mathcal{A} = 3$, and $\mathcal{A} = 2$.

8 CONCLUSION

Body movements and mobility of WBANs periodically affect the on-body network topology significantly. Due to the periodic change in the on-body topology of body sensor nodes, the nodes get disconnected from the LPU, which inherently increases the topology management, data transmission, mobility management, and the QoS management costs. Therefore, to manage the increased network management cost, we proposed a network management cost minimization framework for opportunistic WBANs. Consequently, in the presence of dynamic postural disconnections, the link-quality of intra-BAN and inter-BAN communication units decreases, which, in turn, affects the network management cost and the life-time of the sensor nodes. Therefore, we proposed a joint energy-efficient and distributed network management cost minimization framework for dynamic connectivity and data dissemination in opportunistic WBANs.

In the future, we propose to model a pricing mechanism for opportunistic data dissemination in WBANs. Additionally, we propose to analyze the performance of the proposed framework in a real-life scenario.

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