EReM: Energy-Efficient Resource Management in Body Area Networks with Fault Tolerance

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***Abstract*—Wireless Body Area Networks (WBANs) are inherently resource-constrained in nature and each WBAN has different kind of Quality-of-Service (QoS) requirements. Therefore, in the presence of interference and poor link-quality, the resource pool of WBANs depletes significantly, which inherently increases the data transmission delay and decreases the QoS requirements of WBANs in terms of resource availability. In order to minimize the data transmission delay and to provide fair resources to WBANs in a link-failure condition, first we propose a fault tolerant mechanism for WBANs. Thereafter, we propose an energy-efficient resource management process to provide fair amount of resources to WBANs and minimize the energy consumption rate. We formulate the designed scheme mathematically and analyze it through a series of extensive simulations. Simulation results show that the designed scheme provides noteworthy refinement in terms of delay, fairness and network throughput.**

***Keywords*—Wireless Body Area Networks, E-Health, Energy Efficient, Resource Management, Performance Evaluation.**

I. INTRODUCTION

Due to recent advancement in healthcare services, WBANs provide a real-time patient monitoring system in a price-effective way. Each WBAN consists of several heterogeneous body sensor nodes. They are positioned on or in body to monitor the medical parameters of the patients. The placed on-body sensor nodes send the sensed and aggregated data to Local Processing Units (LPUs). Thereafter, LPUs transmit the medical data to Access Points (APs). Apart from healthcare monitoring, WBANs has different applications in online gaming, disaster management, and military operations [1]–[3]. The data rate of body sensor node varies from 10 Kbps to 10 Mbps. Also, the QoS requirements of body sensor nodes are heterogeneous for different applications [4]. Therefore, it is important to provide fair resources to fulfill the QoS requirements of body sensors.

Motivation: Due to mobility and body/limb movements of WBANs, the link-qualities of intra-BAN and inter-BAN communication units decrease over time. As the body sensor nodes and LPUs are naturally resource-constrained, therefore in the absence of strong link-qualities, the available resource-pool of body sensor nodes and LPUs decreases significantly. Additionally, the presence of mutual and cross technology interference in WBANs also increases the resource requirement of sensor nodes and LPUs. Therefore, in a critical energy situation, it is very important to provide reliable communication by providing fair amount of resources to sensor nodes and LPUs. Consequently, due to variation in link-qualities, the rate of energy consumption of sensor nodes and LPUs increases periodically, which is not desirable for low-power devices with limited battery resources. However, in a link-failure condition, it is also important to provide a fault-tolerant mechanism to deal with the connectivity problem between LPUs and APs to minimize the data dissemination delay in WBANs.

A. Contribution

As discussed earlier, it is very important to provide the fair amount of resources to sensor nodes and LPUs in a link-failure condition. Therefore, we propose an energy efficient resource management in WBANs with fault tolerance. The contributions of this work are elaborated as follows: 1) *This work provides a fault tolerant mechanism for WBANs to deal with the transient connectivity among LPUs and APs*, described in Section III. 2) *This work proposes an energy efficient resource management approach to provide fair amount of resources to WBANs in the existence of limb manoeuvres*, described in Section IV. 3) *To model the resource management process in WBANs, the criticality index of sensor is considered to optimize the QoS requirements of heterogeneous body sensor nodes*, described in Section IV.

II. RELATED WORK

Resource allocation problem in the absence of strong link-quality is an important topic for WBANs, where each body senor node demands different QoS requirements. Therefore, in this domain, He *et al.* proposed an effective resource allocation scheme to minimize the power consumption and the transmission rate at LPU to manage QoSs for WBANs [5]. Similarly, Rezvani *et al.* proposed a channel-based resource allocation scheme for WBANs, while considering the context-aware property of WBAN-users [6]. Additionally, Samanta *et al.* proposed a resource allocation and load balancing scheme in link-failure condition in WBANs [7], [8]. In this work, authors proposed a load balancing scheme to optimize the energy consumption rate of WBANs in link-failure condition. However, this work fails to provide the efficient fault tolerant mechanism for WBANs to optimize the data transmission delay and fair amount of resources to WBANs. Cui *et al.* proposed a joint power allocation and coordinator placement mechanism for WBANs to optimize the energy consumption rate [9]. Similarly, Xiaoli *et al.* proposed a energy efficient resource allocation scheme to minimize the energy consumption rate of sensor nodes [10]. Similarly, Liu *et al.* proposed energy-harvesting resource allocation scheme to WBANs [11]. The energy-harvesting scheme is analyzed though Markov chain analysis process to optimize the energy consumption rate. Consequently, Ren *et al.* proposed a throughput assurance mechanism for WBANs in the presence of multiple WBANs in an area [12].

Synthesis: However, the existing resource allocation and energy efficient mechanisms in the literature only considered the static behavior of link-qualities. They did not observe the temporal behavior of link-qualities, hence there is a requirement to design a fault tolerant mechanism, which provides dynamic connectivity with least mean square error in the presence of poor link-quality. Additionally, we propose a distributed resource management scheme to provide fair amount of resources to WBANs with fault tolerance.

III. SYSTEM MODEL

Suppose, N number of WBANs, $\mathcal{B} = \{B_1, B_2, \cdots, B_N\}$, are present in an area. Each WBAN consists of n number of body sensor nodes, $B = \{b_1, b_2, \cdots, b_n\}$, which are placed on-body to monitor the medical parameters of patients. After monitoring the medical parameters, the body sensor nodes transmit the aggregated data to LPU and LPUs transmit the data to APs in an area. Here, we consider M number of APs $A = \{A_1, A_2, \cdots, A_M\}$ in an area to transmit the medical data to medical servers. Each of the WBAN B_i has a requested BW^t_{avail} and available BW^t_{req} bandwidth at time t to provide the medical services. Here, the criticality index of i^{th} WBAN is considered to be $\bigtriangledown_i$ in order to provide the priority to critical WBANs. In the absence of strong link-quality, the resource pool of body sensor nodes and LPUs decreases inherently, which increases the energy consumption rate and data transmission delay of the network. Therefore, to optimize the energy consumption rate and data transmission delay, we propose a fault-tolerant energy efficient resource management scheme for WBANs.

Fault Tolerance Mechanism for WBANs*:* To provide the fault tolerant connectivity among WBANs and APs in the absence of strong link-quality, we introduce a fault tolerant graph model to consider the fault tolerant ties among WBANs and APs [13]. Fault tolerant tie denotes the strong communion links between WBANs and APs. Therefore, with the maximum usage of these fault tolerant ties, the resource availability of WBANs increases, which inherently decreases data dissemination delay and increases QoS of WBANs. Hence, by proving fault tolerant connectivity to WBANs, the resource availability of WBANs increases. The fault tolerant graph model is mathematically expressed as:

$$G_f = \{\mathcal{N}, \mathcal{E}\}, \mathcal{N} \in N \text{ and } \mathcal{E} = \{(N, M) : e_{N,M} = 1\} \quad (1)$$

where $\mathcal{N}$ and $\mathcal{E}$ denotes the vertexes and edges of fault tolerant graph. The fault tolerant edge between WBANs and APs is mathematically expressed as:

$$e_{N,M} = \begin{cases} 1, & \text{if } N \text{ and } M \text{ are connected} \\ 0, & \text{Otherwise} \end{cases} \quad (2)$$

1) Formation of Fault Tolerant Utility: After forming the fault tolerant graph among WBANs and APs, we formulated a fault tolerant utility to provide fault tolerant connectivity among WBANs and APs. To maximize the fault tolerant utility each WBAN has its own strategy in order to get seamless connectivity and fair amount of QoS.

Definition 1. The fault tolerant strategy profile for WBANs in a link-failure condition is defined as:

$$\mathcal{S} = \{S_1, S_2, \cdots, S_N\} \in \prod_{i=1}^{N} \mathbb{S}_i \quad (3)$$

It represents the strategy of each WBAN in order to establish a fault tolerant connectivity in a link-failure condition.

For the given strategy profile $\mathcal{S}$, the fault tolerant utility of each WBAN is denoted as $\mathcal{U}_i(S)$, which represents the payoff of utility of a WBAN B_i, accounting to establish a fault tolerant connectivity with APs. Therefore, the fault tolerant utility of a WBAN, B_i, with strategy, $\mathcal{S}$, is defined as:

$$\sum_{i=1}^{N} \mathcal{U}_i(S) = \sum_{i=1}^{N} \mathcal{Q}_i + \sum_{i=1}^{N} \mathcal{F}_i \quad (4)$$

where $\mathcal{Q}_i$ and $\mathcal{F}_i$ denote the QoS requirement of each WBAN and fault tolerant connectivity establishment factor, respectively. The QoS (in bytes per second) requirement, $\mathcal{Q}_i$, of WBAN, B_i is mathematically expressed as:

$$\sum_{i=1}^{N} \mathcal{Q}_i = \frac{\sum_{i=1}^{N} p_i \mathbb{P}}{\sum_{t=1}^{\mathcal{T}} \mathcal{D}_t + \sum_{i=1}^{N} \mathcal{Z}_i} \quad (5)$$

where p_i denotes the number of packets transmitted, $\mathbb{P}$ denotes packet size, and $\mathcal{D}_t$ denotes the packet transmission delay. $\mathcal{Z}_i$ denotes the delay-sensitive medical data transmission cost. It denotes the incurred data transmission cost in the presence of delay in the network, which is defined as:

$$\sum_{i=1}^{N} \mathcal{Z}_i = \sum_{t=1}^{\mathcal{T}} \left(\frac{\sum_{i=1}^{N} \sum_{j=1}^{M} d(i,j) \times C_t}{\mathcal{D}_t d_{max}} \right) \quad (6)$$

where $d(i,j)$ and d_{max} denotes the Euclidean distance and maximum Euclidean distance between WBANs and APs, respectively. C_t denotes unit cost of medical data transmission. The fault tolerant connectivity establishment factor is depends on different parameters — *residual energy factor*, *packet loss rate*, *normalized received signal strength*, and *channel link capacity*, which are discussed as follows:

- *Residual Energy Factor (REF)*: The residual energy factor, $\mathcal{X}_i$, of WBAN, B_i [8], is mathematically expressed as:

$$\sum_{i=1}^{N} \mathcal{X}_i = \Psi \sum_{i=1}^{N} \frac{E^i_{pre}}{E^i_{ini}} \quad (7)$$

where Ψ denotes the scaling energy factor of WBANs, E^i_{pre} and E^i_{ini} denote the present residual energy and initial energy of WBAN B_i, respectively.

- *Packet Loss Rate (PLR)*: In the absence of strong link-quality, the packet loss rate of WBANs is defined as:

$$\sum_{i=1}^{N} \sigma_i = \sum_{i=1}^{N} \sum_{t=1}^{\mathcal{T}} \left[\mathcal{P}^t_{loss,i} - \left(\frac{\mathcal{P}^t_{tran,i} - \mathcal{P}^t_{rec,i}}{\mathcal{P}^t_{tran,i}} \right) \right] \quad (8)$$

  where $\mathcal{P}^t_{loss,i}$ denotes the packet loss due to presence of interference and mobility of WBAN B_i. $\mathcal{P}^t_{tran,i}$ and $\mathcal{P}^t_{rec,i}$ denote the number of packet transmitted and received at time t of WBAN B_i, respectively.

- *Normalized Received Signal Strength (NRSS)*: Let RSSS value of a particular AP is γ, then the normalized RSSS value is denoted as $\gamma_{nor,i}$ [14], which is defined as:

$$\sum_{i=1}^{N} \gamma_{nor,i} = \sum_{i=1}^{N} \sum_{j=1}^{M} \left| \frac{(\gamma_{ij} - \gamma_{max}) \times 100}{(\gamma_{max} - \gamma_{min})} \right| \quad (9)$$

  where $\gamma_{nor,i}$ is the normalized RSSS value, γ_{ij} is the RSSS value from AP A_j to WBAN B_i. γ_{min} and γ_{max} are the minimum and maximum RSSS values of an AP, A_j.

- *Channel Link Capacity (CLC)*: The channel link capacity between WBANs and APs is mathematically expressed as:

$$\sum_{i=1}^{N} \mathcal{Y}_i = \sum_{t=1}^{\mathcal{T}} \sum_{i=1}^{N} \sum_{j=1}^{M} \left(L^t_{i,j} - l \frac{P^t_{receive}}{P^t_{noise}} \right) \quad (10)$$

  where $L^t_{i,j}$ denotes the link capacity of channel between i and j, and l denotes the link capacity factor (i.e., $l = \frac{L^t_{i,j}}{L^t_{max}}$). $\frac{P^t_{receive}}{P^t_{noise}}$ denotes the variation in the link capacity at time t. However, $P^t_{receive}$ and P^t_{noise} denotes the received signal power from AP and received noise signal power at time t, respectively.

Now, the fault tolerant connectivity establishment factor is mathematically expressed as:

$$\mathcal{F}_i = \left(f_{\mathcal{X}} \frac{\mathcal{X}_i}{\mathcal{X}_{max}} + f_\sigma \frac{\sigma_i}{\sigma_{max}} + f_\gamma \frac{\gamma_i}{\gamma_{max}} + f_{\mathcal{Y}} \frac{\mathcal{Y}_i}{\mathcal{Y}_{max}} \right) \quad (11)$$

where $f_{\mathcal{X}}$, f_σ, f_γ, and $f_{\mathcal{Y}}$ denotes the normalized factor for REF, PLR, NRSS, and CLC, respectively.

2) A Fault Tolerant Utility Maximization Framework: To provide fault tolerant connectivity to WBANs, we need to maximize the Fault Tolerant Utility (FTU), which is mathematically expressed as:

$$\sum_{i=1}^{N} \mathcal{U}_i(S) = \frac{\sum_{i=1}^{N} p_i \mathbb{P}}{\sum_{t=1}^{\mathcal{T}} \mathcal{D}_t + \sum_{i=1}^{N} \mathcal{Z}_i} + \sum_{i=1}^{N} \left(f_{\mathcal{X}} \frac{\mathcal{X}_i}{\mathcal{X}_{max}} + f_\sigma \frac{\sigma_i}{\sigma_{max}} + f_\gamma \frac{\gamma_i}{\gamma_{max}} + f_{\mathcal{Y}} \frac{\mathcal{Y}_i}{\mathcal{Y}_{max}} \right) \quad (12)$$

Therefore. the optimization problem for optimal fault tolerant connectivity is mathematically expressed as:

$$\text{Maximize} \sum_{i=1}^{N} \mathcal{U}_i(S) = \frac{\sum_{i=1}^{N} p_i \mathbb{P}}{\sum_{t=1}^{\mathcal{T}} \mathcal{D}_t + \sum_{i=1}^{N} \mathcal{Z}_i} + \sum_{i=1}^{N} \left(\frac{f_{\mathcal{X}} \mathcal{X}_i}{\mathcal{X}_{max}} + \frac{f_\sigma \sigma_i}{\sigma_{max}} + f_\gamma \frac{\gamma_i}{\gamma_{max}} + \frac{f_{\mathcal{Y}} \mathcal{Y}_i}{\mathcal{Y}_{max}} \right)$$

$$\text{Subject to} \quad \gamma_{th} \le \gamma_i, \gamma_i = \frac{P_{tx}}{P_{tx} + P_{no} + \sum_{h \in N} P^k_{inf}} \quad (13)$$

$$L^t_{i,j} \ge L^{th}_{i,j}, t \in \{t_1, t_2, \cdots, t_t\} \quad (14)$$

$$\mathcal{Q}_i \ge \mathcal{Q}^{th}, \mathcal{F}_i \ge \mathcal{F}^{th}, i \in N, j \in M \quad (15)$$

Detailed illustration of the scheme is discussed. Equation (12) shows the main optimization problem. Equation (13) describes that the NRSS, γ_i, is to be greater than the threshold NRSS, γ_{th}. The bandwidth capacity of a link, $L^t_{i,j}$, is to be greater than the threshold bandwidth capacity, $L^{th}_{i,j}$, as present in Equation (14). Equation (15) shows that the QoS requirements, $\mathcal{Q}_i$, is to be greater than the threshold QoS requirements of WBANs, $\mathcal{Q}^{th}$ and the fault tolerant connectivity factor, $\mathcal{F}_i$, is to be greater than threshold fault tolerant connectivity factor, $\mathcal{F}^{th}$.

IV. EREM: ENERGY-EFFICIENT RESOURCE MANAGEMENT

In the presence of link-failure condition, the availability of fair amount of resources to sensor nodes and LPUs is very important to provide reliable communication. Therefore, to model the energy efficient resource management scheme, we present some definitions for the easier understanding of the proposed mathematical model. They are described as follows:

Definition 2. The weight of each link represents the communication cost for data transmission in WBANs [15], which is:

$$\mathcal{W}^t_{ij} = \begin{cases} C^t_{com,ij}, & \text{if } i \ne j \\ \mathbb{S} + C^t_{com,ij}, & \text{Otherwise} \end{cases} \quad (16)$$

where $C^t_{com,ij}$ denotes the unit communication cost of data transmission between WBAN B_i and AP A_j at time t and $\mathbb{S}$ denotes the initial network management cost.

Definition 3. The data transmission rate of each link between LPUs and APs at time t is defined as:

$$\sum_{i=1}^{N} \sum_{j=1}^{M} \Theta^t_{ij} = \sum_{i=1}^{N} \sum_{j=1}^{M} p^t_{ij} \mathbb{P} \times \mathcal{T} \quad (17)$$

where p^t_{ij} denotes the number of packets transmitted from WBAN B_i to AP A_j, $\mathbb{P}$ denotes the size of the data packets, and $\mathcal{T}$ denotes the total packet transmission period.

Definition 4. The resource requirement of data transmission over a link between i and j is mathematically expressed as:

$$\mathcal{H}_t = R + \sum_{i=1}^{N} \sum_{j=1}^{M} \beta \left(\frac{\Theta^t_{ij}}{\Theta_{max}} \right) G_{ij} \quad (18)$$

where $\frac{\Theta_{ij}^t}{\Theta_{max}}$ denotes the data transmission factor, Θ_{max} denotes the maximum data transmission rate, β denotes the channel overhead, R denotes the initial resource requirement of data processing, and G_{ij} denotes the bandwidth capacity of existing link.

A. Necessity of Cooperative Resource Management

In this section, we mathematically prove the necessity of cooperative resource management in Theorem 1.

Theorem 1. *If in the absence of strong link-quality, the rate change of resource requirement of WBANs increases over time, then the resource availability decreases.*

$$\mathcal{H}_t >> \mathcal{H}_{t+1} \tag{19}$$

Proof. The rate of change of resource requirement, $r(t)$, of WBANs at time, t, for the time period, T_t to T_{t-1} [15], is defined as:

$$r(t) = \frac{\sum_{t=1}^{\mathcal{T}} |\mathcal{H}_t - \mathcal{H}_{t-1}|}{\sum_{t=1}^{\mathcal{T}} T_t - T_{t-1}} \tag{20}$$

Now, in the presence of poor link-quality, the rate of change of resource requirements of WBANs at time $t+1$ increases over the period, T_{t+1} to T_t, which is mathematically expressed as:

$$r(t+1) = \frac{\sum_{t=1}^{\mathcal{T}} |\mathcal{H}_{t+1} - \mathcal{H}_t|}{\sum_{t=1}^{\mathcal{T}} T_{t+1} - T_t} \tag{21}$$

However, as in the presence of poor link-quality, the value of Θ_{ij}^t decreases therefore the resource availability, $\mathcal{Z}_{t+1}$, of WBANs at time $t+1$ increases. Therefore, we get, $r(t+1) << r(t)$. Hence, the proof concludes. □

B. Resource Management using Cost-based Approach

After establishment of fault tolerant connectivity among WBANs and APs, it is important to provide fair amount of resources to WBANs. Therefore, in the presence of link-failure condition, the availability of fair amount of resources to sensor nodes and LPUs depletes over time. However, we model an energy efficient resource management scheme using price-based approach to provide reliable connection to WBANs in a link-failure condition. The price-based approach for resource management in WBANs is mainly categorized into two cost functions — *energy-consumption cost* and *monetary cost for data transmission*. These two cost function are described as:

- The first cost function, $\mathbb{E}(c)$, represents the total energy consumption in WBANs due to presence of mutual and cross technology interference, and for data transmission and reception process. It is defined as:

$$\mathbb{E}(c) = \sum_{t=1}^{\mathcal{T}}\sum_{i=1}^{N}\sum_{j=1}^{M} E_{d_t,B_i}\phi_{ij}^t + \sum_{t=1}^{\mathcal{T}}\sum_{i=1}^{N}\sum_{j=1}^{M} E_{d_t,b_i}(1-\phi_{ij}^t) \tag{22}$$

where E_{d_t,B_i} and E_{d_t,b_i} denotes the unit energy-consumption cost in WBANs for intra-BAN and inter-BAN communication. ϕ_{ij}^t and $(1-\phi_{ij}^t)$ denotes the probability of data transmission in intra-BAN and inter-BAN communication units, respectively.

- The second cost function, $\Phi(c)$, represents the total monetary cost [16] of providing fair resources to WBANs in the absence of strong link-quality, which is defined as:

$$\Phi(c) = \sum_{t=1}^{\mathcal{T}} \mathcal{C}_p^t + \mathcal{C}_{BW}^t \tag{23}$$

where $\mathcal{C}_p^t$ and $\mathcal{C}_{BW}^t$ denotes data processing cost and bandwidth allocation cost, respectively. The data processing cost, $\mathcal{C}_p^t$, for medical data transmission in WBANs after establishing a fault connectivity is expressed as:

$$\mathcal{C}_p^t = \sum_{i=1}^{N}\sum_{j=1}^{M}(\mu_h^t\mathcal{C}_c^{in} + \kappa_h^t\mathcal{C}_c^{out})\mathcal{W}_{ij}^t + \sum_{i=1}^{N}\sum_{j=1}^{M}\mathcal{C}_T\mathcal{J}_t\mathcal{W}_{ij}^t \tag{24}$$

where μ_h^t and κ_h^t denotes the amount of data generated and transmitted at time t, respectively. $\mathcal{C}_c^{in}$ and $\mathcal{C}_c^{out}$ denotes the unit cost of processing inbound and outbound traffic of WBANs. $\mathcal{C}_T$ denotes the monetary cost per unit time period of data transmission and $\mathcal{J}_t$ denotes required number of slots of unit time. $\mathcal{W}_{ij}^t$ denotes the probability of data transmission in WBANs after establishment of fault tolerant connectivity. However, the bandwidth allocation cost of WBANs, $\mathcal{C}_{BW}^t$, for fault tolerant connectivity is mathematically expressed as:

$$\mathcal{C}_{BW}^t = \lambda_{e,t}\mathcal{C}_{BW}^{e_t}U(t)BW_{alloc} \tag{25}$$

where BW_{alloc} denotes the amount of bandwidth resource allocated to one unit of data, $U(t)$ denotes the total data size, $\lambda_{e,t}$ denotes the fraction of total data size of $U(t)$ transmitted over edge e_{ij}, and $\mathcal{C}_{BW}^{e_t}$ denotes the cost of occupying one unit of bandwidth along link e_{ij} per time slot. The network cost optimization for energy-efficient resource management in WBANs is defined as:

$$\begin{aligned}&\text{Minimize } \sum_{t=1}^{\mathcal{T}} \mathcal{C}_{tot}^t = \mathbb{E}(c) + \Phi(c)\\ &\text{Subject to } \sum_{i=1}^{N} E_{d_t,B_i} \geq E_{d_t,B_i}^{th}, \mathcal{C}_p^t \geq \mathcal{C}_p^{th}, \mathcal{C}_{BW}^t \geq \mathcal{C}_{BW}^{th}\end{aligned} \tag{26}$$

Solving the optimization problem using Lagrangian Optimization problem is expressed as:

$$\begin{aligned}\mathcal{L}_{\mathcal{U}} = &\sum_{i=1}^{N}\frac{\triangledown_i}{\mathcal{C}_{tot}^{th}}\sum_{k=1}^{K}\mathcal{L}_k(E_{d_t,B_i},\mathcal{C}_p^t,\mathcal{C}_{BW}^t) - F_1\left(\sum_{t=1}^{\mathcal{T}}\mathcal{C}_p^t - \mathcal{C}_p^{th}\right)\\ &-F_2\left(\sum_{i=1}^{N}E_{d_t,B_i} - E_{d_t,B_i}^{th}\right) - F_3\left(\sum_{t=1}^{\mathcal{T}}\mathcal{C}_{BW}^t - \mathcal{C}_{BW}^{th}\right)\end{aligned}$$

where F_1, F_2 and F_3 are the constraints for Lagrangian Multipliers and $\triangledown_i$ represents criticality index of WBANs based on medical situations. Hence, we focus on to optimize $\mathcal{L}_{\mathcal{U}}$ using the Lagrange Multiplier. Thus,

$$\frac{\delta\mathcal{L}_{\mathcal{U}}}{\delta\mathcal{C}_{tot}^t} = \sum_{i=1}^{N}\sum_{k=1}^{K} -\frac{\triangledown_i\mathcal{L}_k(E_{d_t,B_i},\mathcal{C}_p^t,\mathcal{C}_{BW}^t)}{{\mathcal{C}_{tot}^{th}}^2} \tag{27}$$

$$\frac{\delta \mathcal{L}_{\mathcal{U}}}{\delta \mathcal{C}_p^t} = \sum_{i=1}^{N} \frac{\nabla_i}{\mathcal{C}_{tot}^{th}} \sum_{k=1}^{K} \frac{\delta \mathcal{L}_k(E_{d_t,B_i}, \mathcal{C}_p^t, \mathcal{C}_{BW}^t)}{\delta \mathcal{C}_p^t} \tag{28}$$

$$\frac{\delta \mathcal{L}_{\mathcal{U}}}{\delta \mathcal{C}_{BW}^t} = \sum_{i=1}^{N} \frac{\nabla_i}{\mathcal{C}_{tot}^{th}} \sum_{k=1}^{K} \frac{\delta \mathcal{L}_k(E_{d_t,B_i}, \mathcal{C}_p^t, \mathcal{C}_{BW}^t)}{\delta \mathcal{C}_{BW}^t} \tag{29}$$

Using the equations, we obtain the minimum value of $\mathcal{L}_{\mathcal{U}}$ to get the minimized resource management cost for WBANs. To analyze the overall performance, our proposed approach is named as — *E2R with fault tolerance* for WBANs.

V. PERFORMANCE EVALUATION

We examine the performance of proposed scheme using MATLAB simulator and follow the simulation setup according to [15], [17] and Table I. We consider the area of 2.5 Km × 2.5 Km, where $50-300$ number of WBANs are present. The residual energy of each WBAN is considered to be 5 J and the sensing range of body sensors is $0.5-1.5$ m. The packet rate of sensor node is 4 packets/sec with the packet size of 512 Bytes. We consider the group-based mobility of WBANs, proposed by Nabi *et al.* [18]. However, the experimental setup follows the IEEE 802.15.6 standard [19] in order to evaluate the real-life performance the proposed approach. The data transmission between sensor nodes and coordinator, and coordinator to APs follows the single-hop star topology. The energy consumption rate of WBANs is mathematically expressed as [7]:

$$E_{re} = E_{tot} - (E_{tran} + E_{rec} + E_{loss}) \tag{30}$$

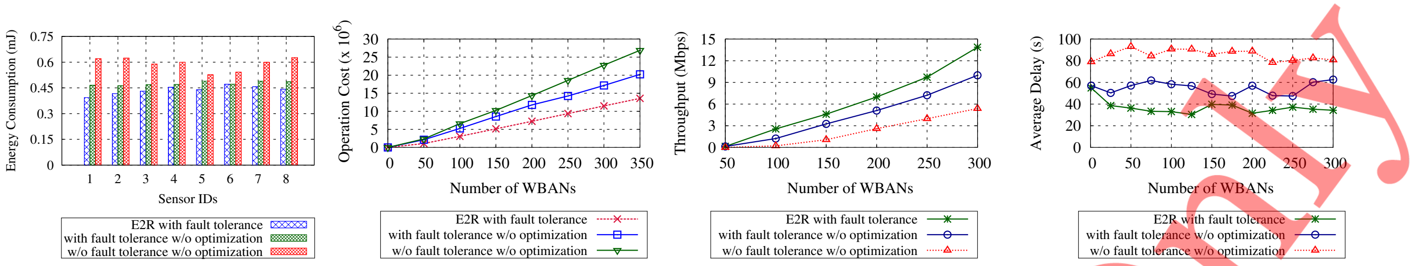
where E_{tot}, E_{tran}, E_{rec}, and E_{loss} denotes the initial residual energy of WBANs, energy consumption for data transmission, energy consumption for data packets reception, and energy consumption due to interference and link-failure condition in WBANs. The fairness of resource management among WBANs is mathematically expressed as, $\mathbb{F}_i = \frac{BW_{req}^t}{BW_{avail}^t}$. Here, the fairness is described by the fact that, how fairly the resources are being distributed among WBANs.

Table I: Simulation Parameters

Parameter	Value
Simulation area	2.5 Km × 2.5 Km
Simulation duration (Sec)	150
Number of WBANs	$50-300$
Number of body sensor within a WBAN	8
Number of LPUs per WBAN	1
Residual energy of each WBAN	0.5 J
Velocity of each WBAN	1.5 m/s
Energy consumption of Tx-circuit [15]	16.7 nJ
Energy consumption of Rx-circuit [15]	36.1 nJ
Energy consumption of Amplifier-circuit [15]	1.97 nJ

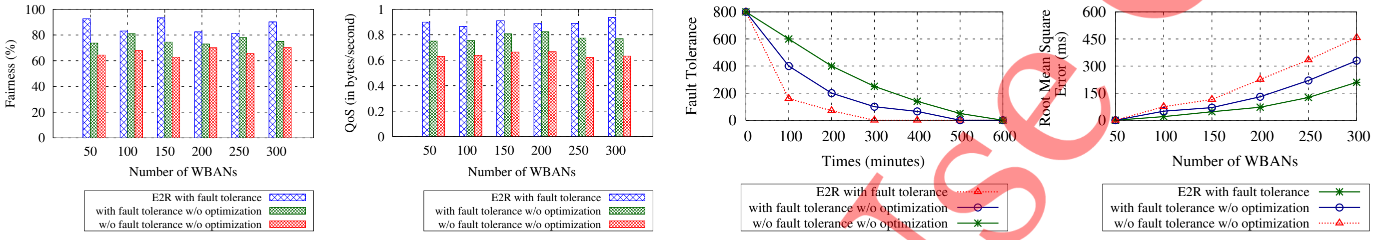
Results and Discussion: Figure 1(a) depicts the total energy consumption of different sensor nodes in the presence of fault tolerant connectivity between WBANs and APs. As in the absence of fair link-quality between WBANs and APs, the energy consumption rate of sensor nodes increases, therefore we proposed a fault tolerant mechanism to minimize the energy consumption rate of sensor nodes. From the figure, we observe that the energy consumption rate using proposed approach — *E2R with fault tolerance* decreases over time. We also compared our proposed scheme with *with fault tolerance w/o optimization* and *w/o fault tolerance w/o optimization*, where we observe that our scheme perform better in terms of energy consumption by 10% and 20%, respectively. Figure 1(b) presents the cost incurs for resource management process in WBANs. From the figure, we observe that the cumulative cost incurs due to resource management process for the increase number of WBANs. To optimize the resource management cost, we proposed a resource management cost optimization approach, through which we are able to minimize the resource management cost than the two approaches *with fault tolerance w/o optimization* and *w/o fault tolerance w/o optimization*. Therefore, our proposed approach — *E2R with fault tolerance* outperforms the other approaches by 8% and 10%, respectively. Figure 1(c) shows the normalized network throughput for varying number of WBANs. From the figure, we observe that the proposed approach — *E2R with fault tolerance* able to provide the optimal fault tolerant connectivity to WBANs for poor link-quality. Therefore the network throughput of WBANs increases, while the other approaches fails to provide maximum achievable throughput to WBANs. Figure 1(d) provides the average delay of the network for the varying number of WBANs. In the absence of strong link-quality, the data transmission delay of WBAN increases as WBANs are not able to transmit its packets instantly. Hence, to optimize the data transmission delay, we proposed a fault tolerant mechanism with fair resource management to WBANs, which inherently decreases the average delay of WBANs than the other approaches — *with fault tolerance w/o optimization* and *w/o fault tolerance w/o optimization*.

Figure 2(a) presents the fairness of WBANs in terms of resource availability in the absence of strong link-quality. From the figure, we observe that the availability of resources to WBANs using our proposed scheme — *E2R with fault tolerance* is more, therefore the fairness among WBANs increases using our scheme. We also compared our schemes with the other approaches, where our approach outperforms the existing approach by $5-8$%. Figure 2(b) shows the quality-of-service of WBANs for the proposed system model. From the figure, we see that the QoS increases for WBANs using our proposed scheme — *E2R with fault tolerance*, as we provide fault tolerant mechanism with fair resource distribution among WBANs. Figure 2(c) presents the fault tolerance activity of the proposed approach — *E2R with fault tolerance*. From the figure, we see that the proposed approach is more adaptive towards the poor link-quality than the other approaches — *with fault tolerance w/o optimization* and *w/o fault tolerance w/o optimization*. As the proposed approach provides a dynamic fault tolerant mechanism to WBANs, therefore the fault tolerance of the network increases for link-failure condition. Figure 2(d) shows the mean square error of the fault tolerant mechanism. We observe that the error rate using our proposed approach is lesser than the existing approaches. The proposed approach — *E2R with fault tolerance* out performs others by 12% and 15%.



(a) Energy consumption (b) Network cost (c) Network throughput (d) Average delay

Figure 1: Analysis of energy consumption, network cost, throughput, and average delay



(a) Fairness (b) Quality-of-Service (c) Fault tolerance (d) Mean square error

Figure 2: Analysis of fairness, QoS, fault tolerance, and mean square error

VI. CONCLUSION

In this work, we proposed a fault tolerant with fair resource allocation scheme for WBANs in the absence of strong link-quality between WBANs and APs. First, we proposed a fault tolerant mechanism to optimize the data transmission delay of WBANs. In which, we tries to provide a dynamic connectivity to WBANs using fault tolerant mechanism with lesser mean square error. Afterward, to manage the fair amount of resources to WBANs and to minimize the resource management cost, we proposed a resource management scheme to provide fair resources to WBANs in a link-failure condition.

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