Link Quality-Aware Resource Allocation with Load Balance in Wireless Body Area Networks

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***Abstract*—Due to interference from other coexisting wireless body area networks (WBANs), link quality between a particular WBAN and access points (APs) varies significantly. Consequently, performance of a WBAN varies with the changes in the link quality. Additionally, a WBAN unnecessarily tries to send its real-time data to the sink node, while the corresponding link quality drops below a predefined threshold value, to maintain adequate network performance. To address this situation, in this paper, we propose a link quality-aware resource allocation scheme in WBANs — an effort towards maximizing the overall network performance. The proposed scheme consists of two phases — *temporal link quality measurement* and *sub-channel allocation among the WBANs*. In the former, we predict correlations among different aspects of link quality. Based on the available correlated link qualities, the *sub-channel allocation* phase divides the available bandwidth into several sub-channels in order to maintain the quality of service (QoS) of the network. The performance of the proposed scheme is evaluated based on different performance metrics — path loss, throughput, number of dead nodes and fairness index of WBANs. The simulation results show that the performance of a WBAN increases significantly, if the link quality-aware resource allocation is made between a WBAN and available APs.**

***Index Terms*—Wireless Body Area Network, Energy-Efficiency, Sub-channel Allocation, Load Balance, Link Quality, Performance Evaluation**

I. INTRODUCTION

A WBAN is capable of providing real-time e-healthcare services to patients with emergency medical needs in a cost-effective and reliable manner. On the other hand, the growing concerns about real-time health monitoring using WBANs, requires that a patients physiological conditions be monitored in real-time. In a WBAN, each patient is equipped with several heterogeneous intelligent body sensors to monitor a patient's physiological condition. The physiological sensed information is forwarded to medical server through the local APs [1]. Based on the received information at the server, adequate decisions are taken by medical experts, and feedback is sent back to the relevant patient. Finally, the patient takes adequate treatments to recover his/her health conditions. Although WBANs provide valuable features in health monitoring, they also have some unavoidable constraints with respect to energy and reliability in data transmission between body sensor nodes. Additionally, battery replacement is also a major issue in a critical emergency situation in the WBAN environment.

A. Motivation

In many WBAN applications, a patient needs to move from one place to another to get his/her medical treatments, which necessitates adequate link quality to be maintained for real-time health monitoring [2]. Therefore, the connectivity links between a WBAN and the local APs get affected. On the other hand, as a WBAN consists of several heterogeneous body sensors, the communication and computational load of each body sensor differs from one another. Therefore, in the presence of heterogeneous sensor nodes in a mobile WBAN architecture, the link quality of intra-BAN and inter-BAN communication gets affected, which, in turn, degrades the network performance. Additionally, irregular link failure increases the communication and computational load on each body sensor. Hence, the intermittent connectivity between a WBAN and APs increases the energy consumption of the body sensors and degrades the overall network performance as well. Group-based mobility pattern of WBANs [3] abruptly affects the link quality between the AP and the WBAN, which significantly reduces the resources (such as energy and bandwidth) of the WBAN.

B. Contribution

To counter the above mentioned issues, in this paper, we propose a link quality-aware resource allocation scheme in order to maximize network performance of WBANs. To deal with this situation, we mathematically model a temporal link quality estimation approach to predict the correlation among different aspects of link quality. Therefore, the proposed approach consists of two phases — *temporal link quality measurement* and *sub-channel allocation*. In the *temporal link quality measurement* phase, correlations among different link quality parameters are predicted. To manage the resources among the WBANs based on the predicted link qualities, the available bandwidth is sub-divided into multiple sub-channels using the *sub-channel allocation* phase, in order to ensure quality of service (QoS) of the network. Finally, a load balancing scheme is proposed for link failure conditions, while preserving fairness among the WBANs. In brief, the *contributions* of this work are as follows:

- We propose a link quality-aware resource allocation scheme in order to maximize the network performance of wireless body area networks (WBANs).
- The proposed approach consists of two phases — *temporal link quality measurement* and *sub-channel allocation*. Temporal correlations among available link qualities are

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predicted with the *temporal link quality measurement* phase. On the other hand, the *sub-channel allocation* phase is used to divide the available bandwidth into several sub-channels to ensure QoS of the network.
- We propose a communication and computational load balancing scheme for individual WBANs in a link failure condition, while preserving fairness among them.

The paper is organized as follows. In Section II, we elaborate the existing works in two aspects — effects of transient link quality and resource allocation in WBAN. Section III describes the problem statement and mathematical model of the system. In Section IV, we analyze the problem of temporal link quality measurement in WBANs due to the transient link quality. Section V presents the sub-channel allocation to critical WBANs in order to improve network performance. In Section VI, we present the performance of the proposed scheme, while comparing with other existing schemes. Finally, Section VII concludes the paper while mentioning few future research directions.

II. RELATED WORK

Link quality management is an important issue in WBANs in order to maintain adequate network performance. The main idea is to manage temporal link quality-based resource allocation that satisfies different requirements such as admissible link rates, fairness, energy-efficiency, and network lifetime. To achieve some of these demands, researchers have studied the channel allocation and link scheduling problems over the years. Some of the existing works are discussed as follows.

Rango *et al.* [4] proposed a link-stability and energy-aware routing protocol (LAER), which guarantees the stability of link quality and minimization of energy consumption in static wireless networks. Several pieces of literature reveal that wireless links are dependent on each other, and the packet reception on the near-by wireless links are correlated to each other. Therefore, the assumption of link independence may cause serious estimation problems in the calculation of the fundamental metrics. Hence, Wang *et al.* proposed a link correlated opportunistic routing [5] model. The proposed solution improves the performance by taking into consideration of the correlated links with lower value.

On the other hand, Bodas *et al.* proposed a multi-channel scheduling algorithm for wireless down-link network [6]. The authors proposed an iterative longest queues first (iLQF) algorithm to minimize network delay. Similarly for wireless sensor networks (WSNs), Chowdhury *et al.* proposed the dynamic channel allocation (DCA) algorithm to maximize residual energy and to reduce message overhead [7]. The usage of multi-channel dramatically changes the energy constrained nature of the WSNs. The authors showed that network lifetime of a WSN can be maximized through multi-channel allocation.

Ahmed *et al.* [8] proposed a link-aware and energy-efficient routing protocol for WBANs (LAEEBA) — to analyze the performance in terms of path loss and energy efficiency. To select a relay node, the authors proposed a cost function based on the residual energy and the distance to the AP. Lee *et al.* proposed an efficient scheme to manage multiple channels by coordinating beacon-slot and data channel [9]. This channel aggregation makes the channel wide and suitable for different traffic types. On the other hand, Martelli *et al.* [10] proposed a link adaptation technique in WBANs to reduce packet loss. However, presence of fading in WBANs may change the channel condition, which may lead to a tremendous packet loss in the network. Therefore, in this situation, it is a challenging task to utilize channel efficiently, to prioritized different traffics, and to maintain reliability of the network.

However, the existing scheduling and resource allocation schemes in the literature only focused on the static behavior of the WBANs and did not consider the criticality of the patients. Therefore, there is a need to propose an distributed scheme, which allocates the channels by predicting the link quality and considering the criticality of the WBAN patient as well. In this paper, we propose a distributed resource allocation scheme in terms of channel allocation, while considering transient link quality due to the mobility of the WBANs.

III. SYSTEM MODEL

Let there be N number of WBANs, which are represented as a set $\mathcal{B} = \{B_1, B_2, \cdots, B_N\}$. In each WBAN, let there be h number of heterogeneous body sensors which are represented by the set $B = \{b_1, b_2, \cdots, b_h\}$. Additionally, let there be M number of access points (APs), denoted as a set $\mathcal{A} = \{A_1, A_2, \cdots, A_M\}$. Figure 1 shows an overview of a WBAN architecture consisting of body sensors, local processing units[1] (LPUs), access points (APs), and medical server. Therefore, the different components considered in this work are as follows:

- $E_{re,t} = \{E^1_{re,t}, E^2_{re,t}, \cdots, E^N_{re,t}\}$, denotes the set of residual energies of the WBANs at time t.
- $\mathcal{L} = \{L_1, L_2, \cdots, L_N\}$, denotes the set of communication and computational loads of the WBANs.
- $\mathcal{W} = \{W_1, W_2, \cdots, W_N\}$, denotes the set of available bandwidths to transmit data of the WBANs.
- $\rho_t = \{\rho^1_t, \rho^2_t, \cdots, \rho^N_t\}$ is the set of data transmission rates of the WBAN at time t.

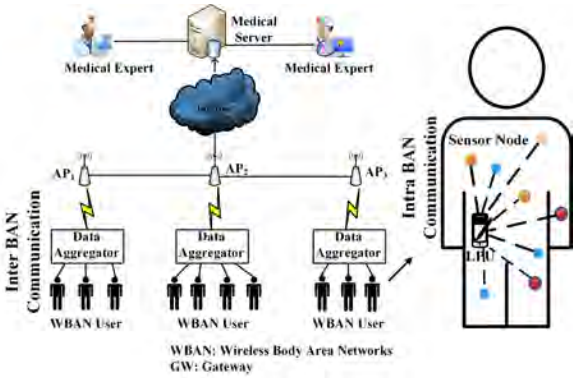

Figure 1: A schematic view of a WBAN architecture

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[1] The LPUs serve the purpose of data aggregator units (DAUs), i.e., the LPUs aggregate received data from individual sensor nodes. Therefore, in this work, the LPUs and the DAUs are considered to be the same.

- $L_t = \{l_t^1, l_t^2, \cdots, l_t^N\}$, denotes the set of links between a WBAN and the local APs at time t.
- $d_t = \sqrt{(X_{i,t} - X_{j,t})^2 + (Y_{i,t} - Y_{j,t})^2}$ is the Euclidean distance between a LPU with coordinate $(X_{i,t}, Y_{i,t})$ and a local AP with coordinate $(X_{j,t}, Y_{j,t})$ at time t.
- $\Phi_t = \{\phi_t^1, \phi_t^2, \cdots, \phi_t^N\}$, denotes the set of criticality indexes of the WBANs at time t.

A. *Energy Model of WBAN*

In this Section, we calculate energy consumption of a WBAN due to data transmission and reception, interference, and link failure conditions.

1) Energy Consumption for Data Transmission and Reception: Each WBAN has residual energy E_{re}. According to the radio model in [11], the required energy of a WBAN to transmit data is mathematically expressed as follows:

$$E_{tran} = K(E_{elec} + E_{amp}d^2) \tag{1}$$

where E_{elec} is the energy consumed by the electric circuit of the body sensor, K is the message size, E_{amp} is the energy required by the amplifier, and d is the distance between the body sensors and corresponding LPU. On the other hand, the required energy for receiving data is calculated as follows:

$$E_{rec} = KE_{elec} \tag{2}$$

2) Energy Consumption due to Interference and Link Failure: In the presence of interference from coexisting WBANs and link failures between WBANs and APs, a WBAN unnecessarily tries to communicate with the AP, which, in turn, causes the energy loss, E_{loss}. We calculate energy consumption of a WBAN due to interference and link failure as follows:

$$E_{loss} = n\gamma E_{inf} + \beta E_{link} \tag{3}$$

where n denotes the number of other coexisting WBANs. γE_{inf} and βE_{link} denote the rate of energy consumption due to interference and link failures, respectively. Therefore, the reformed energy profile of the WBAN is expressed as:

$$E_{re} = E_{tot} - (E_{tran} + E_{rec} + E_{loss}) \tag{4}$$

Thus, we formulate an objective function for a WBAN in order to minimize energy consumption as follows:

$$\text{Maximize} \sum_{i=1}^{N} E_{re}^{i}$$

$$\text{subject to} \quad E_{re} \leq E_{tot} \tag{5}$$

$$E_{tran} \geq 0, E_{rec} \geq 0, \text{ and } E_{loss} \geq 0 \tag{6}$$

where Equation (5) denotes that the residual energy is always less than or equal to the total energy of WBAN. Equation (6) denotes the required energy for transmission and reception, and due to interference and link failure is always positive.

B. *Effective Load Calculation*

Each WBAN consists of several heterogeneous body sensors. Therefore, each body sensor has different communication and computational loads. The load of each body sensor, b_i, is a combination of the computational load and the communication load, which is also termed as the Intra-BAN communication load. Mathematically,

$$\mathcal{L}_{intra}^{b_i} = \sum_{t=1}^{T} \left(P_t^{(b_i \to G)} + \mathcal{H}_{i_t}^{(b_i \to G)} \right) \tag{7}$$

where $P_t^{(b_i \to G)}$ is the communication cost, which is calculated based on message size, to a body sensor b_i at time t. $\mathcal{H}_{i_t}^{(b_i \to G)}$ is the computational processing cost, and it is expressed as:

$$\mathcal{H}_{i_t} = \frac{P_{rec}^{G}}{P_{max}^{G}} \tag{8}$$

where P_{rec}^{G} and P_{max}^{G} denote the received signal power and the maximum signal power from the LPU, G, respectively.

Similarly, we calculate the load of each WBAN, B_j, as the combination of all sensors' load in a WBAN and computational load of the WBAN for communicating with an AP, which is also termed as Inter-BAN communication load. Therefore, the Inter-BAN communication load is mathematically expressed as:

$$\mathcal{L}_{inter}^{B_j} = \sum_{t=1}^{T} \left(P_t^{(G \to A_l)} + \mathcal{H}_{i,t}^{(G \to A_l)} \right) \tag{9}$$

where $P_t^{(G \to A_l)}$ is the communication cost calculated based on the message size of the WBAN. $\mathcal{H}_{i_t}^{(G \to A_l)}$ is the computational processing cost of a particular WBAN, B_j, and it is mathematically presented as:

$$\mathcal{H}_{i_t}^{(G \to A_l)} = \frac{P_{rec}^{A_l}}{P_{max}^{A_l}} \tag{10}$$

where $P_{rec}^{A_l}$ and $P_{max}^{A_l}$ denote the received signal power and the maximum signal power from the AP, A_l, respectively. Therefore, the total load of a WBAN, B_j, for intra-BAN and inter-BAN communication for a particular time period, $\mathcal{T}$, is calculated as:

$$\mathcal{L}_{\mathcal{T}}^{B_j} = \sum_{i=1}^{h} \mathcal{L}_{intra}^{b_i \subseteq B} + \sum_{j=1}^{m \subseteq \mathcal{A}} \mathcal{L}_{inter}^{B_j} \tag{11}$$

where $m \subseteq \mathcal{A}$ denotes that m number of APs are available to the WBAN from the total number of APs at the time period $\mathcal{T}$.

Thus, minimization of communication and computational cost for both the Intra-BAN and the Inter-BAN communication can be formulated as an optimization problem as follows:

$$\text{Minimize} \sum_{k=1}^{N} \mathcal{L}_{\mathcal{T}}^{k} = \sum_{k=1}^{N} \left(\sum_{i=1}^{h \subseteq B} \mathcal{L}_{intra}^{b_i} + \sum_{j=1}^{m \subseteq \mathcal{A}} \mathcal{L}_{inter}^{B_j} \right)$$

$$\text{subject to} \quad \mathcal{L}_{\mathcal{T}}^{k} \leq \mathcal{L}_{\mathcal{T}}^{th} \tag{12}$$

where $\mathcal{L}_{\mathcal{T}}^{th}$ is the maximum load capacity of a WBAN.

IV. TEMPORAL LINK QUALITY MEASUREMENT

In this section, we measure temporal link quality between LPUs and APs. Let, for a specific time period, t, an LPU, B_i, be connected to a particular access point, A_j. Due to the mobility of the WBANs, radio link quality and medical data transmission get affected. Therefore, we calculate the probability of existing a link between the LPU and the AP for data transmission as follows:

$$\mu_{ij} = \begin{cases} 1, & \text{if i and j are connected} \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

To measure the radio link quality, we follow a probabilistic approach, in which, the link quality is measured using Equation (13) between the LPU, G_i, and the access point, A_j. Therefore, the probabilistic link quality estimator is calculated as [2]:

$$\mathcal{I}_{ij}^{t} = \begin{cases} \mu_{ij} + \eta(1-\mu_{ij}), & \text{if i and j are connected} \\ \eta\mu_{ij}, & \text{otherwise} \end{cases} \tag{14}$$

where, η is the link failure rate, which is bounded within $[0, 1]$. Therefore, based on different link qualities according to Equation (14), the temporal link correlation factor is mathematically expressed as:

$$\mathcal{C} = \frac{\mathcal{I}_{ij}^{t} - \mathcal{I}_{ij}^{t-1}}{\mathcal{I}_{ij}^{t}} \tag{15}$$

where $\mathcal{I}_{ij}^{t-1}$ is the measured link quality at time instant $(t-1)$. After calculating the temporal correlation factor in (15), we calculate the temporal link quality based on the auto-regressive (AG) model, and, in which, the present link quality depends on the previous link qualities linearly [12]. Mathematically,

$$\mathcal{I}_{ij}^{t+1} = a + \mathcal{C}\sum_{i=1}^{T}\Omega_{ij}\mathcal{I}_{ij}^{i} + \chi_t \tag{16}$$

where a is the constant value, χ_t is the Gaussian white noise at time t, and Ω_{ij} is the received signal strength indicator (RSSI). Based on Equations (14) and (16), if there does not exist any constant connection for a specific time period, the WBAN, B_i, with transient connectivity, scans the RSSI value, Ω_{ij}, from the AP, A_j. Therefore, to supervise the transient link condition and the connectivity problem, an election parameter is formulated to preserve the constant connectivity (which provides fault tolerance feature) between the WBAN and the AP. It is mathematically expressed as:

$$Z = \left(\frac{E_{re}^{pre}}{E_{re}^{ini}} + \frac{\Omega_{ij}}{\Omega_{ij}^{max}} + \mathcal{C}\right) - \left(\frac{P(u,u')}{P_{max}}\right) \tag{17}$$

where E_{re}^{pre} and E_{re}^{ini} denote present residual energy and initial residual energy, respectively. Ω_{ij}^{max} denotes the maximum RSSI value in the network. P_{max} denotes the maximum communication cost. $P(u, u')$ is the communication cost after movement of WBAN from a reference point u to u', which is calculated as:

$$P(u,u') = \begin{cases} P(u,v), & \text{if i and j are connected} \\ P(u',v) + \vartheta, & \text{otherwise} \end{cases} \tag{18}$$

where ϑ is the relocation cost, and it depends on the group-based mobility model of the WBAN [3]. Based on the predicted link quality in Equation (16), a deciding factor, λ, is used in order to take decision whether to choose the present connection or newly available connections. Mathematically,

$$\lambda = \begin{cases} 1, & \text{if } \mathcal{I}_{i,j}^{t+1} > \mathcal{I}_{i,j}^{t} \\ 0, & \text{otherwise} \end{cases} \tag{19}$$

Based on the λ obtained from Equation (19), Equation (17) is represented as:

$$\mathcal{Z} = \lambda\left(\left(\frac{E_{re}^{pre}}{E_{re}^{ini}} + \frac{\Omega_{ij}}{\Omega_{ij}^{max}} + \mathcal{C}\right) - \left(\frac{P(u,u')}{P_{max}}\right)\right) \tag{20}$$

V. SUB-CHANNEL ALLOCATION IN WBAN

After predicting the link quality between the WBAN, B_i, and the AP, A_j, as discussed in Section IV, B_i tries to connect with the other available APs, $A_k \in \mathcal{A}$, $j \neq k$, according to Equation (20), while there is an inconsistent connectivity between B_i and A_j. Consequently, B_i is connected to a new AP, A_k, in order to improve network performance. However, the available bandwidth to the newly connected AP needs to be allocated through sub-channels to provide fairness among WBANs, while minimizing the communication and computational load. We discuss the requirement of sub-channel allocation strategy in the following subsection in an elaborated manner.

A. Requirement of Sub-Channel Allocation

Let, for a specific time period $T^2 = \{t_1, t_2, \cdots, t_n\}$, each body sensor generate a set of packets, $\mathcal{P} = \{p_{b_1}, p_{b_2}, \cdots, p_{b_h}\}$, which are stored in the transmission queue of the sensor node. Let us assume that before the distortion of the link quality, $\mathcal{P}_i = \{p_{b_1}, p_{b_2}, \cdots, p_{b_i}\}$ is the set of packets transmitted to the AP through the LPU. Therefore, due to the transient link quality, $(\mathcal{P} - \mathcal{P}_i)$ packets are left in the transmission queue of the LPU. Therefore, if the link quality gets distorted for a noticeable time period, the communication and computation load on the LPU increases, as depicted in Theorem 1. Therefore, we need to have a sub-channel allocation scheme in order to minimize the load on the LPU.

Theorem 1. *Transient link quality between LPU and AP increases the communication and computation load on the LPU of the WBAN for real-time services.*

Proof. The generated packets from each body sensor are stored in the transmission queue, Q, of the LPU. Based on the link quality, $\mathcal{I}_{ij}$, the number of packets stored in the queue at time, t, can be represented as follows:

$$Q_{\mathcal{I}_{ij}}^{t} = \sum_{i=1}^{h} p_{b_i}^{t} \tag{21}$$

If $\mathcal{P}_d^t$ is the number of packets transmitted from the queue at time, t, remaining queue size is as follows:

$$Q_{\mathcal{I}_{ij}}^{t+1} = Q_{\mathcal{I}_{ij}}^{0} + \sum_{i=1}^{h}\left(\mathcal{P}_g^t - \mathcal{P}_d^t\right) \tag{22}$$

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[2] A time period consists of n number of time instants.

where $Q^0_{\mathcal{I}_{ij}}$ denotes the number of packets present in the queue initially. $\mathcal{P}^t_g$ denotes the number of generated packets. Therefore, if there exists a transient connection for a specific time period, $T_{tran} < T$, no packet can be transmitted from the LPU to the AP. However, the sensor nodes generate packets continuously and transmit to the LPU. Consequently, the queue of the LPU is overloaded, while there is a transient connectivity between the LPU and the AP. □

B. Joint Optimization Problem for Sub-Channel Allocation

Due to the dynamic changes in the link quality, each WBAN waits for a random time, t_{rand}, to reconnect with the current AP, A_j, for transmitting its remaining data packets. If the corresponding link quality is not recovered within t_{rand} time, the WBAN tries to connect with an available AP, $A_k \in \mathcal{A}$, $k \neq j$, using the election parameter $\mathcal{Z}$, as discussed in Section IV. After connecting to the AP, A_k, the available bandwidth, W, is subdivided into $\mathcal{Y}$ number of sub-channels, which is represented as a set $\mathcal{S} = \{S_1, S_2, \cdots, S_\mathcal{Y}\}$. The number of sub-channels from the channel with the bandwidth, W, are calculated based on the link quality, and it is expressed as [13]:

$$\mathcal{Y}(W,\mathcal{S}) = \frac{W}{N}\log\left(1 + \frac{\Upsilon P_{W,\mathcal{S}}|\mathcal{G}_{W,\mathcal{S}}|^2}{\sigma^2}\right) \tag{23}$$

where Υ is the bit error rate (BER), $|\mathcal{G}_{W,\mathcal{S}}|$ is the channel gain, and σ is the interference noise due to the presence of coexisted WBANs.

After calculating the number of sub-channels in Equation (23), their allocation to the WBAN, B_i, is calculated as follows:

$$\mathcal{J} = \sum_{j=1}^{\mathcal{Y}}\sum_{i=1}^{T}\Phi_i^t\mathcal{R}(B_i, S_j) \tag{24}$$

where Φ_i^t is the criticality index of the WBAN, B_i, at time t, and it is calculated as [14]:

$$\Phi_t = \left|\frac{(\Theta_{uc}-\Theta_t)^2 - (\Theta_t - \Theta_{lc})^2}{(|\Theta_{uc}| + |\Theta_{lc}|)^2}\right| \tag{25}$$

where Θ_{uc} and Θ_{lc} are the upper range and lower range of a health parameter of a WBAN. $\Theta_t = \frac{(\Theta_{uc}+\Theta_{lc})}{2}$ is defined as the measured value of the particular health parameter at time t. In Equation (25), $\mathcal{R}_{(B_i,S_j)}$ denotes the allocation of corresponding sub-channel based on the link quality. Therefore, $\mathcal{R}_{(B_i,S_j)}$ is mathematically expressed as:

$$\mathcal{R}_{(B_i,S_j)} = \sum_{i=1}^{\mathcal{Y}}\psi_{(B_i,S_j)}\mathcal{Y}(W,\mathcal{S}) \tag{26}$$

where $\psi_{(B_i,S_j)}$ is a binary number used to decide whether link quality of the allocated sub-channel meets required threshold value. This is mathematically expressed as:

$$\psi_{(B_i,S_j)} = \begin{cases} 1, & \text{if } \mathcal{I}^t_{ij} < \mathcal{I}^{th}_{ij} \\ 0, & \text{otherwise} \end{cases} \tag{27}$$

Therefore, we formulate a joint optimization problem from Equations (12) and (24) as follows:

$$\begin{aligned} &\text{Maximize } \left(\sum_{j=1}^{\mathcal{Y}}\sum_{i=1}^{N}\Phi_i^t\mathcal{R}_{(B_i,S_j)} - \sum_{i=1}^{N}\mathcal{L}^i_\mathcal{T}\right) \\ &\text{subject to } \quad \mathcal{L}^i_\mathcal{T} \leq \mathcal{L}^{th}_\mathcal{T} \text{ and } \Phi^t_i \geq \Phi^t_{th} \end{aligned} \tag{28}$$

C. DSCA: Proposed Algorithm

The proposed algorithm is divided into two sub-algorithms — selection of critical LPUs and sub-channel allocation to the LPUs with load balance. As discussed in Section IV, link quality between a WBAN and an AP changes due to the mobile nature of the WBANs. Therefore, we need to choose the critical LPUs according to their requirements (please refer to Equation (25)). Therefore, based on the criticality index, a set of WBANs are selected for which we need to allocate the sub-channels. The algorithm for selections of critical LPUs, and therefore, sub-channel allocation is presented in Algorithm 1. The worst-case time complexity of the selection of critical WBANs algorithm is $O(N^2)$, where N is the total number of the WBANs. Also, the worst-case time complexity of the sub-channel allocation algorithm is $O(k^3)$, where k is the total number of critical WBANs. Intuitively, we derive the worst case time complexity of the proposed DSCA as $O(n^3)$.

We use Jain's fairness index [15] to calculate the fairness among WBANs for the proposed scheme as follows:

$$\mathcal{F}_\mathcal{L} = \frac{\sum_{i=1}^{N}|\mathcal{L}^i_\mathcal{T}|^2}{N|\sum_{i=1}^{N}\mathcal{L}^i_\mathcal{T}|^2} \tag{29}$$

Lemma 1. *The obtained fairness in Equation (29) is balanced, if and only if the sub-channels are allocated to the set of critical WBANs.*

Proof. The data rate at each sub-channel having the capacity, C_{B_i,S_i}, is calculated as $\xi_{C_{B_i,S_i}}$. During transient link quality state, data rate in the network is minimized [16]. Therefore, the data rate through all sub-channels is very very less than the maximum achievable rate, mathematically, $\sum_{j=1}^{N}\sum_{i=1}^{\mathcal{Y}}\xi_{C_{B_i,S_i}} << \Pi$, where Π is the maximum data rate through the channel. Consequently, it is obvious that the network cannot achieve the fairness, while the link qualities in the network are transient in nature. Therefore, we can conclude that if the sub-channels are allocated adequately to the critical WBANs (i.e., very low data rate due to transient link quality), maximum fairness can be achieved. □

VI. PERFORMANCE EVALUATION

In this Section, we simulate the performance of the proposed scheme using MATLAB simulation software. Table I depicts the simulation parameters used for performance evaluation. We consider the residual energy of each WBAN as $5J$ [2]. The communication range of a sensor node is considered as 2-5m [11]. We adopt the same mobility model for the WBANs as proposed by Nabi *et al.* [3]. Maximum 16 sub-channels are considered according to the IEEE 802.15.4 standard[3] and the measurement frequency of link quality as $20 - 15$ms. The

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[3] www.cs.berkeley.edu/~prabal/teaching/cs294-11-f05/slides/day21.pdf

Algorithm 1: Proposed Algorithm

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Input: Set of LPUs, $\mathcal{B}$, Set of APs, $\mathcal{A}$, Queue size, $\mathcal{Q}$,
       Set of body sensors, $B$
Output: Sub-channel assignment matrix, $\mathcal{M}[1..\tilde{\mathcal{B}}_c][1..\mathcal{Y}]$

1  Selection of a Critical LPU
2  for $i = 1$ to $N$ do
3      Calculate $\Phi_i^t$ for each WBAN, $B_i \in \mathcal{B}$;
4      if $\Phi_i^t < \Phi_{th}^t$ then
5          Include $B_i$ into the criticality WBAN set $\tilde{\mathcal{B}}$;
6  for $i = 1$ to $K \in N$ do
7      for $j = 1$ to $m \subseteq M$ do
8          if $\exists B_j \in \tilde{\mathcal{B}}$, $\mu_{ij} \neq 1$ then
9              Calculate $\mathcal{L}_{\mathcal{T}^k}$ according to Equation (11);
10             if $\mathcal{L}_{\mathcal{T}^k} < \mathcal{L}_{\mathcal{T}^{th}}$ then
11                 Select $B_j$ as the critical LPU;
12                 Include $B_j$ in the critical LPU set, $\tilde{\mathcal{B}}_c$;
13                 Go to Sub-channel allocation, Step 15;

14 Sub-channel Allocation for LPUs
15 Compute the probabilistic link quality according to
   Equation (14);
16 for $i = 1$ to $m \subseteq M$ do
17     for $j = 1$ to $|\tilde{\mathcal{B}}_c|$ do
18         Calculate $\mathcal{I}_{ij}^{t+1}$ for each $\exists B_j \in \tilde{\mathcal{B}}_c$;
19         if $\mathcal{I}_{ij}^{t+1} < \mathcal{I}_{ij}^t$ then
20             Calculate selection parameter according to
               Equation (20);
21             Calculate available bandwidth for
               connectivity establishment;
22         Calculate $\mathcal{Y}(\mathcal{W}, \mathcal{S})$ according to Equation (23);
23         for $k = 1$ to $\mathcal{Y}$ do
24             Store values in sub-channel assignment
               matrix, $\mathcal{M}[1..\tilde{\mathcal{B}}_c][1..\mathcal{Y}]$;
25             Calculate $\mathcal{J}$ according to Equation (24) to
               show the allocation;
```

sensor nodes placed in a WBAN form a start topology, and the hop-count between any sensor node and the LPU is one.

Table I: Simulation Parameters

Parameter	Value
Simulation area	$500\,m \times 500\,m$
Number of WBANs	50
Initial energy of a WBAN	5 J
Sensor nodes in each WBAN	8
Number of access points	10
Communication range of a sensor	2-5 m
WBAN topology	star topology [17]

A. Benchmark

The performance of the proposed scheme, DSCA[4], is evaluated by comparing with the existing state-of-art, i.e., SIMPLE [18], and, ATTEMPT [19]. The SIMPLE, is a multi-hop routing protocol for WBAN architecture to achieve higher throughput and network lifetime. In this protocol, the authors proposed a cost function to select the forwarding node based on residual energy and distance to the sink. Similarly, the ATTEMPT, is also a multi-hop routing protocol for heterogeneous WBAN architecture, which supports the mobility of the WBANs. In this protocol, direct communication is used for the real-time traffic, and multi-hop communication technology is used for normal traffic. To analyze the performance of the proposed scheme, different performance metrics are considered — network path loss, throughput, fairness index, and residual energy of each WBAN. Additionally, we present the results with *confidence interval* to show the variances.

B. Results and Discussion

We show the performance of the proposed scheme, DSCA, compared with the existing schemes discussed in Section VI-A.

1) Network Path Loss: Network path loss is the difference between the transmitted power of a sensor node and the received power at the LPU [18]. Mathematically,

$$PL(dB) = 10n\log_{10}\left(\frac{d}{d_0}\right) + 10\log_{10}\frac{(4\pi d_0 f)^2}{c} + X\sigma \quad (30)$$

where d_0 is the reference distance[5] between the sensor node and the LPU. Therefore, d is the current distance between the sensor node and the LPU after movement. n, f, c denote network path loss exponent, operating frequency, and speed of light, respectively. X denotes the Gaussian random variable, σ is the variance. Figure 2(a) shows the network path loss of the network for different schemes. We consider the path loss exponent to be in the interval $3 - 4.5$, with frequency 2.4 GHz, as explained in Equation (30). As the link quality and the distance vary between the body sensor nodes and the LPUs, the path loss of the network increases. However, the proposed scheme, DSCA, is able to reduce the network path loss, while considering the link quality and the fairness index for resource allocation among the WBANs.

In Figure 2(b), we also present the number of dead nodes in the network for varying number of rounds. We see that with an increase in the number of rounds, the number of dead nodes increases in the network. However, it performs better than the existing schemes, when the link quality and fairness index are considered. Intuitively, we can say that the network lifetime increases using the proposed scheme than the existing schemes as the number of dead nodes is less in case of the DSCA scheme.

2) Throughput: Figure 2(c) shows the cumulative throughput of the network. Throughput is the indicative of the packets successfully received at the LPU. As a WBAN has critical and

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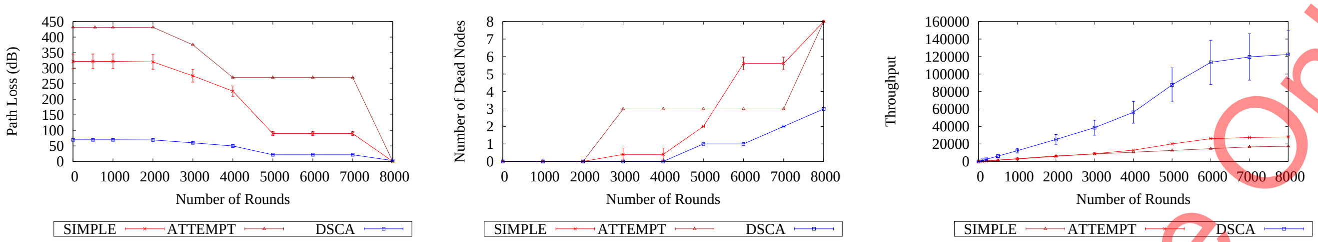
[4] In the rest of the paper, we mention the proposed scheme as DSCA.

[5] Due to mobility, distance between the sensor node and the LPU varies with time.



(a) Network path loss between body sensor and LPU

(b) Number of dead nodes in the network

(c) Network throughput

Figure 2: Analysis of path loss, number of dead nodes, and network throughput with different number of rounds

important data to send, it requires a scheme which provides less number of packet drops and more number of successful data packets at sink. The proposed scheme DSCA achieves higher throughput than the SIMPLE and the ATTEMPT. From Figure 2(b), we see that the proposed scheme DSCA has more alive nodes, which increases the number of packets sent to sink than the existing ones. Therefore, we see that the proposed scheme, DSCA, outperforms the existing schemes SIMPLE and ATTEMPT in terms of network throughput.

3) Fairness Index: Fairness index measures the fairness among the sensor nodes in terms of available resources. Figure 4(a) shows the fairness index of the WBANs. Due to the variation in the link quality, the communication and computational loads of each sensor node increase as discussed in Section V. Therefore, the fairness among the WBANs decreases with an increase in the number of sensor nodes. As the proposed scheme balances the communication and computational load among the nodes, it provides improved fairness than the SIMPLE and the ATTEMPT schemes.

4) Residual Energy: Figure 3(a) shows the residual energy of WBANs. In the proposed scheme, after predicting the link qualities, each WBAN connects to an AP using Equation (20). We see that the the WBANs have more energy using the proposed scheme, DSCA, than the existing one, SIMPLE and ATTEMPT. Also, Figure 4(c) shows the energy consumption of the each sensor node while performing different operations.

5) Average Packet Drop: Figure 3(b) shows the cumulative number of packets dropped in the network with different schemes — DSCA, SIMPLE, and ATTEMPT. As the link quality changes dynamically, some of the packets are dropped before they are received at the LPU. However, the proposed scheme, DSCA, significantly minimizes the number of packets dropped in the network and it deals with the transient link quality of the WBANs.

6) Average Delay: Figure 3(c) shows the average delay incurred by each packet in the queue before it is transmitted. In the proposed scheme, DSCA, based on predicted link quality, a WBAN chooses a new AP for which it incurs less delay. However, in case of SIMPLE and ATTEMPT, the delay increases as they do not consider transient link quality in the WBAN architecture. As the number of dead nodes increases in the network presented in Figure 2(b), the delay decreases with an increase in the number of rounds. Also, figure 4(b) shows the propagation delay of each sensor node. As each sensor node is placed in different position of the body therefore to transmit the data to the LPU, each sensor incurs different delay.

VII. CONCLUSION

In this paper, we proposed a link-quality aware resource allocation system in WBANs environment. Due to the mobility of the WBANs, the link quality between a WBAN and an AP varies, which, in turn, minimizes the network performance. Therefore, we proposed a distributed sub-channel allocation scheme with load balance to improve the network performance. The proposed scheme consists of two phases. In the first phase, we predicted the temporal link correlation among the links between WBANs and APs. In the second phase, based on the predicted link qualities, WBANs connect to a new AP and the available bandwidth is sub-divided into several sub-channels to allocate them to the critical WBANs.

Currently, in this work, we did not consider any security issues, while allocating the sub-channels to different WBANs. Therefore, the future extension of this work includes the incorporation of security aspects, while allocating the sub-channels to different WBANs. In addition to this, an adaptive feedback controller can also be used to control the packet arrival rate and service rate. However, decreasing service rate may reduce the overall network performance. Therefore, the future extension of this also includes the addition of an adaptive feedback controller, while maintaining adequate network performance.

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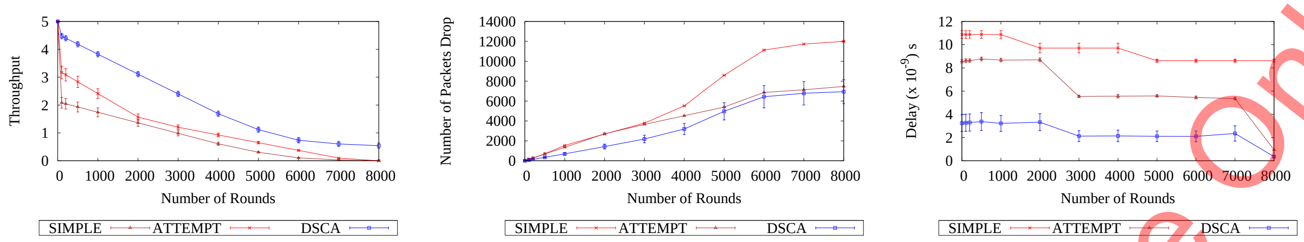
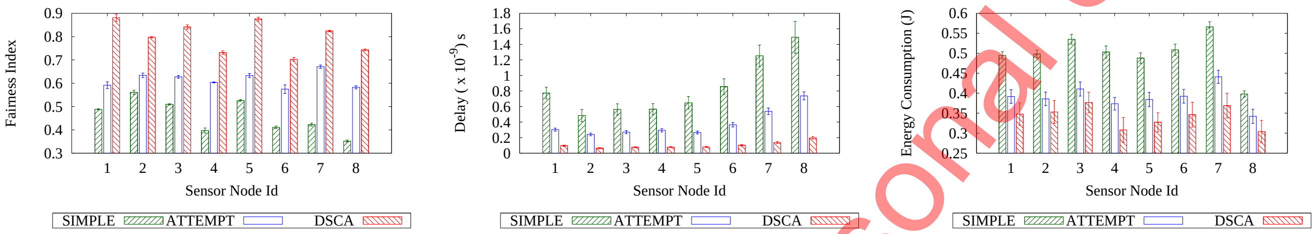


(a) Residual energy of each WBAN (b) Average packet drop (c) Average delay

Figure 3: Analysis of average residual energy, packet drop, and delay with different number of rounds



(a) Analysis of fairness among WBANs (b) Analysis of delay in sensor node (c) Analysis of energy consumption in sensor node

Figure 4: Analysis of fairness index, energy consumption, and delay of the sensor nodes

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