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Dynamic Connectivity Establishment and Cooperative Scheduling for QoS-Aware Wireless Body Area Networks

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***Abstract*—In a hospital environment, the total number of Wireless Body Area Network (WBAN) equipped patients requesting ubiquitous healthcare services in an area increases significantly. Therefore, increased traffic load and group-based mobility of WBANs degrades the performance of each WBAN significantly, concerning service delay and network throughput. In addition, the mobility of WBANs affects connectivity between a WBAN and an Access Point (AP) dynamically, which affects the variation in link quality significantly. To address the connectivity problem and provide Quality of Services (QoS) in the network, we propose a dynamic connectivity establishment and cooperative scheduling scheme, which minimizes the packet delivery delay and maximizes the network throughput. First, to secure the reliable connectivity among WBANs and APs dynamically, we formulate a selection parameter using a price-based approach. Thereafter, we formulate a utility function for the WBANs to offer QoS using a coalition game-theoretic approach. We study the performance of the proposed approach holistically, based on different network parameters. We also compare the performance of the proposed scheme with the existing state-of-the-art.**

***Index Terms*—Wireless Body Area Network, Biomedical monitoring, Smart Health, QoS, Cooperative Packet Scheduling, Dynamic Connectivity Establishment, Coalition Game Theory, Performance Analysis.**

I. INTRODUCTION

WBANs are useful for remote monitoring of physiological conditions of patients. In a typical WBAN architecture, several on-body sensors sense the physiological parameters of patients and transmit the sensed data to Local Processing Units (LPUs). Thereafter, LPUs send the aggregated data to the Access Points (APs) for further processing [1], [2]. In a hospital environment, several WBANs may coexist in the presence of multiple APs. Therefore, in such a scenario, multiple WBANs attempt to send their data to the APs. Further, as WBANs are inherently mobile in nature, a WBAN architecture inherits the traits of a group-based model [3], in which each WBAN is composed of several heterogeneous body senors. Group-based mobility and changes in the body posture of WBANs have serious implications on the performance of WBAN communication, specially connectivity between a WBAN and an AP.

High-Level Description: In WBAN-based applications, the patient equipped with body sensor nodes moves from one location to another to fulfill their medical requirements. However, due to movement of WBANs, the connectivity among WBANs and LPUs gets affected, which inherently increases the service delay. Additionally, in a particular location, there can exist multiple WBANs in order to get the adequate connectivity from an AP. However, due to limited bandwidth, all WBANs may not get the adequate connectivity with an AP. Thus, the QoS requirements of WBANs gets affected, which necessitates a dynamic connectivity establishment algorithm for WBANs in order to minimize the service delay of the network and also to maximize the QoS requirements of WBANs.

Motivation: The paper attempts to address the overall crisp objective of dynamic connectivity establishment and cooperative packet scheduling, while taking into consideration the issues of mobility, interference and coexistence. The following specific challenges motivate the rationale behind the present study.

- Due to the mobility of WBANs, the connectivity between them and the APs decreases over time, which inherently increases the packet delivery delay and the energy consumption rate of the body sensor nodes.
- In the presence of dynamic limb/body movements, the link-qualities of intra-BAN and inter-BAN communication units decrease significantly, which depletes the resource-pool of body sensor nodes and LPUs. Thus, it is necessary to provide QoS to WBANs in terms of service delay and network throughput.
- The coexistence of WBANs in a particular area increases the mutual and cross-technology interference among themselves, which inherently decreases the network throughput and resource pool of the body sensors.
- In a link-failure situation, it is very crucial to provide dynamic connectivity to critical WBANs among multiple coexisting WBANs to send the former's medical data with minimum packet delivery delay.
- Due to the coexistence of multiple WBANs in a particular area, the QoS of each WBAN decreases due to the uncertainty in strong connectivity among WBANs and APs. Therefore, it is necessary to provide strong dynamic connectivity between WBANs and APs in the presence of multiple WBANs and APs in an area.

Contribution: For minimizing the packet delivery delay, while ensuring continuity in connectivity between WBANs and APs, we proposed a dynamic connectivity establishment scheme. The scheme is particularly useful in WBANs with transient connectivity. Additionally, the proposed scheme endeavors to provide QoS services to the WBANs in terms of service delay and throughput in a critical emergency situation. The main *contributions* of this work are summarized as follows:

- Dynamic connectivity establishment for WBANs to manage transient connectivity between them and the APs, caused by factors such as body shadowing [4] and mobility of WBANs.
- The proposed scheme opts for dynamic connectivity with an AP, in the presence of multiple WBANs in a critical emergency situation, in hospital environments.
- After addressing the dynamic connectivity problem, we propose to form coalition game to minimize the service delay and schedule the packets of different WBANs cooperatively.
- We prove the existence of Nash Equilibrium for the proposed coalition game to obtain a stable formation for the WBANs through cooperative packet scheduling. Further, a Markov model is used to analyze the stable coalition formation.
- We also propose a dynamic cooperative packet scheduling algorithm for use among WBANs, to minimize the service delay and increase the network throughput.

Our work is organized as follows. In Section II, we briefly elaborate the related work on cooperative communications. Section III describes the problem statement and mathematical model of the system. Section IV proposes the characterization of WBANs. In Section V and VI, we formulate the dynamic connectivity establishment problem and coalition game formation for WBANs. Section VII

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describes the stability analysis of the coalition game. Section VIII presents the results of simulation and Section IX concludes the work.

II. RELATED WORK

Cooperation and scheduling are two important issues in WBANs, which are required to provide reliable and ubiquitous healthcare services. Therefore, several research works [5], [6], [7], [8], [9], and [10] attempted to address these problems. We review some specific relevant existing literature below, which form the motivation behind this work.

Scheduling Approaches: Interference from coexisting WBANs degrades the performance of each WBAN in terms of networks throughput and energy consumption. To minimize the effect of interference from co-existing WBANs, Cheng and Huang [5] proposed a graph coloring-based inter-BAN scheduling scheme, in which a dense sensor architecture is implemented using spatial-reuse coloring and scheduled the body sensors in different time slots [5]. Similarly, to minimize the effect of interference, Xie *et al.* [6] proposed a Clique-Based WBAN Scheduling (CBWS) algorithm, in which WBANs are partitioned into different groups, which are activated in different time slots. Interference from the coexisting WBANs not only affects the inter-BAN communication, but also affects the intra-BAN communication. Therefore, Prabh and Hauer [8] proposed an opportunistic MAC protocol (BANMAC), which predicts the received signal strength and renders reliable communication. Further, Zhisheng *et al.* [9] proposed a QoS driven scheduling scheme, in which a threshold value is maintained to adjust the transmission order of WBANs and to assign optimal slots according to the QoS requirements of the WBANs. Similarly, Torabi *et al.* [10] proposed both static and dynamic scheduling schemes, by placing the relay body sensors to increase the packet delay ratio. In this work, for placing the relay body sensors, extra transmission cost is required. Therefore, a cost-effective dynamic scheduling approach is proposed for WBANs. Samanta *et al.* [11] proposed a link-qaulity-aware resource allocation scheme for WBANs in order to provide fair resources to them. Similarly, Samanta *et al.* [12] analyzed the performance of WBANs in a critical emergency situations for varying traffic scenario. Additionally, Samanta and Misra [13] proposed an energy-efficient and distributed network cost minimization framework for WBANs. Zhou *et al.* proposed a distributed video scheduling approach with delay-centric information control for wireless multimedia networks [14]. Zhou *et al.* [15] proposed an adaptive video scheduling approach to analyze the impact of execution time. Yi *et al.* [16] proposed a priority-aware capacity sharing scheme for WBANs. Similarly, Yi *et al.* [17] proposed an incentive mechanism for transmission scheduling in WBANs. Yi and Cai [18] proposed a priority-aware truthful mechanism for delay-sensitive packet transmission in WBANs. These works mainly focus on multimedia data scheduling with homogeneous data rate and equal priority. These approaches are not appropriate for WBAN-based communications, as body sensor nodes have heterogeneous data rates and QoS requirements. Also, in WBANs, body sensor nodes send the medical data using different user priorities based on the different traffic designations[1] [19].

Cooperative Communications: Several pieces of existing literature (e.g. [20], [21], [22], and [23]) noticed the problem of cooperative communication in the theme of WBANs. WBANs send data to medical experts through the existing communication infrastructures such as cellular networks, WiFi, and IEEE 802.15.6-based networks. In this context, Maman *et al.* [20] proposed a possible extension of WBANs from On-Body to Body-to-Body cooperation at different network levels such as propagation, protocols and localization applications. Similarly, Chen *et al.* [21] proposed a mechanism for cooperative communication using ultra-wideband (UWB) for WBANs, in which a group of on-body sensors communicates with other similar groups. Xigang *et al.* [22] also proposed an energy-efficient cooperative communication mechanism for WBANs and analyzed the performance for direct transmission, single-relay cooperation, and multi-relay cooperation. In [24] and [23], cooperative communication mechanisms for use in cellular networks is studied to provide QoS services to mobile nodes by forming coalition among them.

Table I: Table of Notations

Parameters	**Values**
$\mathcal{B}$	Set of WBANs
$\mathcal{A}$	Set of APs
$\mathcal{Q}$	Set of coalitions
$\mathcal{U}_i$	Utility of WBAN B_i
D_{avg}	Average delay
d_w	Transmission delay
d_p	Propagation delay
d_Q	Queuing delay
D_i	Total delay of WBAN B_i
Φ_i	Criticality index of WBAN B_i
f_{S_i}	Final selection parameter
$\mathcal{T}_{tot}$	Total packet transmission cost
$\mathcal{T}_{th}$	Threshold Packet transmission cost
$T_{\mathcal{Q}_g,\mathcal{Q}_{g'}}$	State transition probability matrix
$\mathcal{F}(\mathcal{Q}_g\|\mathcal{Q}_{g'})$	Feasibility condition
$\mathbb{P}^{g,g'}$	Transition probability
$\omega_i(\mathcal{Q}_g,\mathcal{Q}_{g'})$	Probability of split and merge operations
BW_{req}	Required Bandwidth
BW_i^{Av}	Available bandwidth

Synthesis: Most of the existing pieces of literature assume that WBANs connect to APs contentiously, but due to change in link states, connectivity gets affected. In this work we improve the existing state-of-the-art by proposing a solution for ensuring continuous connectivity in WBANs even in presence of group mobility of nodes and body shadowing effects during medical emergency situations. Further, in contrast to the existing literature, we consider the criticality index of each WBAN for cooperative scheduling and QoS-awareness of WBANs. It may be noted that most of the existing literature focus on scheduling for avoiding interference among coexisting WBANs. However, the considered problem differs from existing works in many ways, as it considered some unique features of WBANs. The unique features are summarized as follows:

- For this problem, we used a unique property of WBANs, i.e., *criticality index*[2] in order to quantify the medical conditions of WBAN-equipped patients and also to provide seamless connectivity to them. As the criticality index of WBANs increases, the medical packet generation rate of body sensor node increases rapidly, which inherently increases the energy consumption rate and also increases the resource requirements of body sensors. Thus, in this problem, we consider to minimize the total packet transmission delay and maximize the network throughput of WBANs.
- On the other hand, unlike the existing models, we considered different delay factors in order to minimize the total packet transmission delay. In the proposed model, we have mathematically modeled each of the delay factors in the context of WBAN-based

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[1] Here, the medical data packets are given higher user priority according to the IEEE 802.15.6 standard.

[2] It denotes the critical emergency situations of medical patients, while considering several physiological states.

communications.

- Additionally, in the existing works, the packet transmission rate of sensor nodes is assumed to be homogeneous in nature, but in case of WBANs, the same of body sensor nodes is heterogeneous. Also, according to the IEEE 802.15.6 standard, each body sensor node has different user priority to transmit its data packets. Therefore, the proposed model is better suited for use in WBAN-based communications.
- The existing models only consider the homogeneous traffic flows for the data communication process, but the proposed model is suitable to heterogeneous traffic flows in the network.
- Beside this, the existing models do not consider the group-based mobility, whereas the proposed model considers group-based mobility in order to incorporate the effects of dynamic postural partitioning and variation of link-qualities in the network.

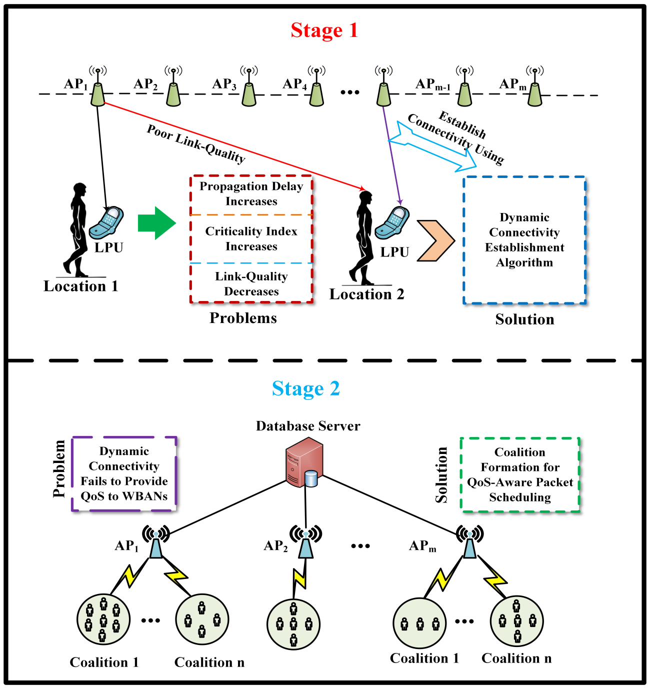

Figure 1: Overall proposed architecture of WBANs

III. System Model

In Figure 1, we present the system model of WBAN architecture showing coalitions connected to multiple APs.

A. Communication Architecture

Let, in a hospital, n number of WBANs in a set, $\mathcal{B} = \{B_1, B_2, \cdots, B_n\}$ coexists, in the presence of m number of APs, $\mathcal{A} = \{A_1, A_2, \cdots, A_m\}$, where $n \neq m$[3]. Each WBAN B_i consists of h number of heterogeneous body sensors, $B = \{b_1, b_2, \cdots, b_h\}$ and connects to an AP A_j to transmit its data with up-link rate r_{ij} and down-link rate Ξ_{ji}. In the proximity of each AP, several WBANs get access and transmit data to the medical experts. However, if multiple WBANs attempt to send their data at the same time, the packet delivery ratio decreases, and the delay in packet forwarding increases. As WBANs transmit medical data, end-to-end delay in medical data transmission is not desirable. The data packets arrive at coordinator by poisson process and the transmission of data packets coordinated according to their data packets priority.

Any WBAN B_i sends its packets to an AP directly or by taking help of other WBANs $\bar{\mathcal{B}} = \{B_1, B_2, ...B_{\bar{n}}\}$, $B_{\bar{n}} \in \{\mathcal{B} - B_i\}$ at the price c_{ij}^{r} per data by cooperative packet scheduling in a particular coalition. Let us assume that a critical WBAN B_i sends packets to the destination or shares the time t of another WBAN B_k in the same coalition, which is in the normal condition and does not have packets to send. To share the cooperative time slot t, the critical WBAN B_i pays the price c_{ik}^{t} per packet for sending its packet. The cost of data transmission and time slot sharing by the APs are assumed to be zero. In this scenario, a rational WBAN can form coalition under a particular AP and the selection of the AP among multiple APs is done dynamically. Inside a particular coalition, WBANs help one another to send the packets of the critical WBANs using cooperative packet scheduling.

B. Packet Delivery Delay Calculation

Let D_i denote the total packet delivery delay, which represents the duration from when a packet originates from a WBAN, B_i, to when it is received by its destination AP [25]. The total packet delivery delay not only depends on the transmission delay d_t[4], but also depends on the propagation delay d_p, nodal processing delay d_{nod}, and queuing delay d_Q.

1) Transmission Delay: $d_w^{b_i}$ is the packet delay during transmission of packets from body sensors to the LPUs at time t_s and $E_{\Pi}[W(s_t, \psi_t, \pi)]$ is the expected value of amount of data packet generated from the body sensors. The data generated from these sensors depend on the state of the body sensors s_t (i.e., active or sleep mode), channel condition ψ_t, and the number of data packets π generated. The expected rate of packet transmission from the body sensors to the LPUs is $\frac{\sum_{t'=1}^{t_s} E_{\nu}[W(s_t,\psi_t,\pi)]}{t_s}$, where t_s denotes total duration of packet transmissions. Therefore, $d_w^{b_i}$ is calculated as:

$$d_w^{b_i} = \lim_{t_s \to \mathbb{T}} t_s \frac{\sum_{t'=1}^{t_s} E_{\Pi}[W(s_t, \psi_t, \pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[W(s_t, \psi_t, \pi)]} \tag{1}$$

$d_w^{B_i}$ is the delay incurred by a packet during transmission from LPUs to an AP at time t_Q and $E_{\Pi}[Q(s_t, \psi_t, \pi, L_i)]$ is the expected rate of data packets transmitted from the WBANs. Data transmission from the WBANs depends on the state of the WBANs s_t, channel condition ψ_t, number of data packets π, and the distance between WBANs and their associated AP. The expected rate of packet transmission from the WBANs to the associated AP is $\frac{\sum_{t'=1}^{t_s} E_{\nu}[Q(s_t,\psi_t,\pi,L_i)]}{t_Q}$, where t_Q denotes total duration of packet transmissions. Therefore, $d_w^{B_i}$ is calculated as:

$$d_w^{B_i} = \lim_{t_Q \to \mathbb{T}} t_Q \frac{\sum_{t'=1}^{t_s} E_{\Pi}[Q(s_t, \psi_t, \pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[Q(s_t, \psi_t, \pi)]} \tag{2}$$

The total transmission delay is defined as, $d_t = d_w^{b_i} + d_w^{B_i}$. Here, W is defined as a stochastic process comprised of three distinct tuples – state of body senors, channel condition and number of data packets. Similarly, Q is defined as a stochastic process comprised of three distinct tuples – state of WBAN, channel condition and number of data packets. $\mathbb{T}$ denotes the total transmission time period.

2) Propagation Delay: Propagation delay is defined as the ratio of propagation distance L and the propagation speed S. The parameter $d_p^{b_i}$ is the propagation delay corresponding to body sensor b_i and $d_p^{B_i}$ is the propagation delay corresponding to WBAN B_i.

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[3] In our work, we assume that the number of WBANs in a hospital environment is more than the number of APs.

[4] Π denotes the communications between LPUs to APs and ν denotes the communications between body sensors to LPUs.

The propagation delay, $d_p^{b_i}$, of sensor node, b_i is is calculated from the expected value of $E[p(L_{b_i}, S)]$. $E[p(L_{b_i}, S)]$ depends on the distance L_{b_i} from body sensor to LPU and the propagation speed S of light. Therefore, $d_p^{b_i}$ is calculated as:

$$d_p^{b_i} = E[p(L_{b_i}, S)] \tag{3}$$

Here, $p(L_{b_i}, S)$ is the function of the propagation distance and the propagation speed. We have, $p(L_{b_i}, S) = \frac{L_{b_i}}{S}$. The propagation delay, $d_p^{B_i}$, of WBAN, B_i is calculated from the expected value $E[p(L_{B_i}, S)]$, which depends on the distance L_{B_i} from WBAN to AP and the propagation speed S. Therefore, $d_p^{B_i}$ is calculated as:

$$d_p^{B_i} = E[p(L_{B_i}, S)] \tag{4}$$

Here, $p(L_{B_i}, S)$ is the function of the propagation distance and the propagation speed. We have, $p(L_{B_i}, S_B) = \frac{L_{B_i}}{S}$. The total propagation delay is calculated as:

$$d_p = E[p(L_{b_i}, S)] + E[p(L_{B_i}, S)] = \frac{(L_{b_i} + L_{B_i})}{S} \tag{5}$$

3) Queuing Delay: Let, the length of the WBAN queue be l_Q and the packet transmission delay of sensor node and WBAN be $d_w^{b_i}$ and $d_w^{B_i}$, respectively. Then, the queuing delay d_Q is calculated as:

$$\begin{aligned} d_Q =& l_Q(d_w^{B_i} + d_w^{b_i}) = l_Q\Bigg[\lim_{t_Q \to \mathbb{T}} t_Q \frac{\sum_{t'=1}^{t_Q} E_\Pi[Q(s_t, \psi_t, \pi)]}{\sum_{t'=1}^{t_s} E_\nu[Q(s_t, \psi_t, \pi)]} \\ &+ \lim_{t_s \to \mathbb{T}} t_s \frac{\sum_{t'=1}^{t_s} E_\Pi[W(s_t, \psi_t, \pi)]}{\sum_{t'=1}^{t_s} E_\nu[W(s_t, \psi_t, \pi)]}\Bigg] \end{aligned} \tag{6}$$

The queue length of the WBAN depends on the *load factor*, which represents the ratio of the link transmission rate and the maximum transmission rate.

4) Total Delay: The total delay of packet forwarding is denoted as the total sum of *transmission delay*, *propagation delay*, *nodal processing delay*, and *queuing delay*. Therefore, the total delay is calculated as:

$$\begin{aligned} D_i =& d_{nod} + d_Q + d_p + d_w \\ =& d_{nod} + (1 + l_Q)\Bigg[\lim_{t_Q \to \mathbb{T}} t_Q \frac{\sum_{t'=1}^{t_Q} E_\Pi[Q(s_t, \psi_t, \pi)]}{\sum_{t'=1}^{t_s} E_\nu[Q(s_t, \psi_t, \pi)]} \\ &+ \lim_{t_s \to \mathbb{T}} t_s \frac{\sum_{t'=1}^{t_s} E_\Pi[W(s_t, \psi_t, \pi)]}{\sum_{t'=1}^{t_s} E_\nu[W(s_t, \psi_t, \pi)]}\Bigg] \\ &+ (E[p(L_{b_i}, S)] + E[p(L_{B_i}, S)]) \end{aligned} \tag{7}$$

From the benefit of less delay using cooperative scheduling within a same coalition among WBANs increases the overall performance of the proposed scheme.

C. Privacy and Security in Cooperative WBANs

For cooperative communication among WBANs, security and privacy are crucial concerns. Consequently, it is also necessary to address the security and privacy issues of WBANs for cooperative packet scheduling among them. In this work, we consider that WBANs send their own criticality index to other coexisting WBANs in a particular coalition to schedule the packets efficiently and cooperatively. As WBANs share their own criticality indices to others, privacy of medical data shared among coexisting WBANs should be handled. However, it may be carefully observed that, in this work, the WBANs do not share the medical data to other coexisting WBANs. They only send the criticality index, which is only one bit information included in the MAC header. Therefore, we used a prediction-based privacy preservation mechanism for reliable routing to protect the criticality index of WBANs, as proposed by Liang *et al.* [26]. Further, this paper mainly focuses on the prioritized cooperative packet scheduling approach for WBANs in a critical emergency situation to minimize the packet delivery delay and to provide fair QoS to WBANs.

IV. CHARACTERISTICS OF WBAN

A. Behavioral Condition of the WBANs

In a hospital environment, two types of WBAN patients are present — *critical* and *normal*.

Definition 1. A WBAN is said to be *critical*, if the criticality index of the WBAN is greater than the threshold criticality index. A critical WBAN always attempts to send its data as fast as possible. This is because, in emergency situations, the patients in serious conditions need to send their data to the medical server soon, so that immediate and real-time treatment is possible.

$$\Phi_i > \Phi_{th} \tag{8}$$

where Φ_i and Φ_{th} denote the criticality index of WBAN B_i and the threshold criticality index, respectively.

Definition 2. A WBAN is said to be *normal*, if the criticality index of a WBAN is less than the threshold criticality index. Therefore, the WBANs that are in the normal condition do not require to send their data immediately for further processing.

$$\Phi_i < \Phi_{th} \tag{9}$$

The *criticality matrix*, Υ_{net}, of all the WBANs at different time instants in a particular hospital area is calculated as:

$$\Upsilon_{net} = \begin{pmatrix} \Phi_{1,1} & \cdots & \Phi_{1,j} & \cdots & \Phi_{1,t_1} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \Phi_{i,1} & \cdots & \Phi_{i,j} & \cdots & \Phi_{i,t_2} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \Phi_{n,1} & \cdots & \Phi_{n,j} & \cdots & \Phi_{n,t_{\bar{t}}} \end{pmatrix} \tag{10}$$

In a particular situation, suppose a critical WBAN B_i attempts to deliver its packets to a dynamically selected AP with probability $\mathbb{P}_i$. In a critical situation, if a WBAN gets help from other normal WBANs through cooperative scheduling, then the probability of sending a packet is $\mathbb{P}_u$, which means that the cost of transmission c_{ik}^t per packet for sharing the time from other normal WBANs is greater than 0, where $\sum_{u=1}^{N} \mathbb{P}_u = 1$. If the critical WBAN does not get any help from other normal WBANs to send its data, then the probability of sending data will be 0. So, the probability of sending packet using cooperative scheduling is denoted as:

$$\mathbb{P}_i = \begin{cases} \mathbb{P}_u, & \text{if } c_{ik}^t > 0 \\ 0, & \text{otherwise} \end{cases} \tag{11}$$

B. Upgradation of Behavioral State

Even though, WBANs are of two types — *critical* and *normal* – each WBAN is not aware of the others' medical conditions. By applying Bayes' theorem, and using the approach given in [27], WBANs can be made to mutually share the medical conditions of one another. In each coalition, WBANs participate in cooperative packet scheduling. Therefore, cooperation is performed based on the health criticality of the WBANs. Within every coalition, each WBAN shares its criticality index Φ_i through, beacon massages to the other WBANs to know each others conditions. Two situations may arise — $\Phi_{ij}^{t_x}(r_{cri})$ and $\Phi_{ij}^{t_x}(r_{nor})$, $\Phi_{ij}^{t_x}(r_{cri})$ denote that, at time t_x, WBAN B_i sends its criticality index value to the WBAN B_j and gets the cooperative response with probability $(1 - p_R)$, and $\Phi_{ij}^{t_x}(r_{nor})$

denotes that, at the time t_x, the WBAN B_i sends the criticality index to WBAN B_j and gets the cooperative response with probability p_R. Therefore, using Bayes' theorem, the probability of a WBAN being *critical* is denoted as:

$$\mathbb{P}_{ij}^{t_x+1}(r_{cri}) = \frac{\mathbb{P}_{ij}^{t_x}(1-p_R)}{\mathbb{P}_{ij}^{t_x}(1-p_R) + (1-\mathbb{P}_{ij}^{t_x})(1-\tau_{ij}^{t_x+1})(1-p_R)}$$

Using Bayes' theorem, similarly, the probability of a WBAN being normal is denoted as:

$$\mathbb{P}_{ij}^{t_x+1}(r_{nor}) = \frac{p_R\mathbb{P}_{ij}^{t_x}}{p_R\mathbb{P}_{ij}^{t_x} + (1-\mathbb{P}_{ij}^{t_x})(\tau_{ij}^{t_x+1} + (1-\tau_{ij}^{t_x+1})p_R)}$$

At time $t_x + 1$, the probability of WBAN B_i that WBAN B_j does not need cooperation to deliver a packet using cooperative packet scheduling, when WBAN B_j is critical, is denoted by $\tau_{ij}^{t_x+1}$. We get the value of $\tau_{ij}^{t_x+1}$ using the following two equations:

$$\mathbb{P}_{ij}^{t_x}(1-p_R) + (1-\mathbb{P}_{ij}^{t_x})(1-\tau_{ij}^{t_x+1})(1-p_R) = \frac{\Phi_{ij}^{t_x+1}(r_{cri})}{\Phi_{ij}^{t_x+1}}$$

$$p_R\mathbb{P}_{ij}^{t_x} + (1-\mathbb{P}_{ij}^{t_x})(\tau_{ij}^{t_x+1} + (1-\tau_{ij}^{t_x+1})p_R) = \frac{\Phi_{ij}^{t_x+1}(r_{nor})}{\Phi_{ij}^{t_x+1}}$$

Using these equations, we calculate the value of $\tau_{ij}^{t_l+1}$, which is represented as follows:

$$\tau_{ij}^{t_x+1} = \begin{cases} 1 - \dfrac{\frac{\Phi_{ij}^{t_x+1}(r_{cri})}{\Phi_{ij}^{t_x+1}} - \mathbb{P}_{ij}^{t_x}(1-p_R)}{(1-\mathbb{P}_{ij}^{t_x})(1-p_R)}, & \text{if } \Phi_{ij}^{t_x+1}(r_{cri}) > 0 \\ \dfrac{\frac{\Phi_{ij}^{t_x+1}(r_{nor})}{\Phi_{ij}^{t_x+1}} - p_R}{(1-p_R)(1-\mathbb{P}_{ij}^{t_x})}, & \text{if } \Phi_{ij}^{t_x+1}(r_{nor}) > 0 \end{cases}$$

V. DYNAMIC CONNECTIVITY ESTABLISHMENT

In this section, we discuss the selection of an AP dynamically among multiple APs in a hospital environment in the presence of multiple WBANs. Also, we prove the requirement of dynamic selection of AP in medical emergency situations. A dynamic AP is chosen based upon different selection parameters — *available bandwidth*, *received signal strength*, *residual energy*, and *criticality of the WBANs.*

A. Requirement of Dynamic Connectivity Establishment

When a WBAN moves from one area to another, and gets connected to an AP, then the AP is to be chosen in a dynamic manner. As the WBAN moves from one place to another, then the service delay of getting access from an AP also increases. This may lead to packet loss, thereby affecting the patients. We now present some of the theoretical results, which assume a hospital environment.

Theorem 1. *Suppose a WBAN B_i is in the location $L_{\mathcal{X}}$ at time t. If the WBAN B_i moves from location $L_{\mathcal{X}}$ to location $L_{\mathcal{X}'}$ at time $t+1$, then the service delay*[5] *increases, i.e., $D_{diss}^{\mathcal{X}'} >> D_{diss}^{\mathcal{X}}$*[6]*.*

Proof. We consider a case in which a WBAN B_i changes its location $L_{\mathcal{X}}$ from location $L_{\mathcal{X}'}$. The service delay in the location $L_{\mathcal{X}}$ of WBAN B_i for AP A_j is given by:

$$\begin{aligned} D_{diss}^{\mathcal{X}} =& C_{i,L_{\mathcal{X}}}^{t} \Bigg[d_N + \Bigg\{ \lim_{t_Q \to \mathbb{T}} t_Q \frac{\sum_{t'=1}^{t_Q} E_{\Pi}[Q(s_t,\psi_t,\pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[Q(s_t,\psi_t,\pi)]} \\ & + \lim_{t_s \to \mathbb{T}} t_s \frac{\sum_{t'=1}^{t_s} E_{\Pi}[W(s_t,\psi_t,\pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[W(s_t,\psi_t,\pi)]} \Bigg\} (1+l_Q) \\ & + (E[p(L_{b_i},S)] + E[p(L_{B_i},S)]) \Bigg] \end{aligned}$$

After changing the location from $L_{\mathcal{X}}$ to $L_{\mathcal{X}'}$ at time $t+1$, if the total Euclidean distance $\mathcal{D}_{ij}^{L_{\mathcal{X}'}}$ at location $L_{\mathcal{X}'}$ between WBAN B_i and AP A_j increases than the Euclidean distance $\mathcal{D}_{ij}^{L_{\mathcal{X}}}$ between WBAN B_i and AP A_j at initial location $L_{\mathcal{X}}$ (i.e., $\mathcal{D}_{ij}^{L_{\mathcal{X}'}} >> \mathcal{D}_{ij}^{L_{\mathcal{X}}}$). Then, the propagation delay of WBANs increases at location $L_{\mathcal{X}}$ than propagation delay at location $L_{\mathcal{X}'}$, (i.e., $d_p^{L_{\mathcal{X}'}} >> d_p^{L_{\mathcal{X}}}$). Consequently, it is to be noted that the criticality of WBANs changes with time and location. Therefore, along with the increase in the Euclidean distance if the criticality C_i^{t+1} of WBAN, B_i, in location $L_{\mathcal{X}'}$ at time $t+1$ increases, than the criticality $C_{i,L_{\mathcal{X}}}^{t}$ of WBAN, B_i, in location $L_{\mathcal{X}}$ at time t, (i.e., $C_{i,L_{\mathcal{X}'}}^{t+1} >> C_{i,L_{\mathcal{X}}}^{t}$). Hence, the total service delay after change of location from $L_{\mathcal{X}}$ to $L_{\mathcal{X}'}$ along with the consideration of criticality[7] is given by:

$$\begin{aligned} D_{diss}^{\mathcal{X}'} =& C_{i,L_{\mathcal{X}}}^{t+1} \Bigg[d_N + \Bigg\{ \lim_{t_Q \to \mathbb{T}} t_Q \frac{\sum_{t'=1}^{t_Q} E_{\pi}[Q(s_t,\psi_t,\Pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[Q(s_t,\psi_t,\pi)]} \\ & + \lim_{t_s \to \mathbb{T}} t_s \frac{\sum_{t'=1}^{t_s} E_{\Pi}[W(s_t,\psi_t,\pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[W(s_t,\psi_t,\pi)]} \Bigg\} (1+l_Q) \\ & + (E[p(L_{b_i},S)] + E[p(L_{B_i}+L_{B_j},S)]) \Bigg] \end{aligned} \tag{12}$$

From the reformulated Equation, we see that when a WBAN moves from one location to another, then the propagation delay increases (while distance between WBAN and AP increases). Therefore, the total data dissemination delay also increases with the increase in the propagation delay and criticality of WBANs. Hence, the increased data dissemination delay initiates the problem of dynamic connectivity establishment between WBANs and APs, when a WBAN moves from one place to another along with the consideration of WBAN criticality. If a dynamic AP is not selected among multiple APs, then there will be loss of medical data, which is not desirable in medical emergency situations. Hence, the proof concludes. ☐

Proposition 1. *If the total data dissemination delay D_i increases along with the increase in the criticality, C_i^t, of WBANs, then the throughput ξ of the WBANs decreases.*

Proof. Let D_i be the total data dissemination delay and ξ_i the throughput of the i^{th} WBAN B_i. Therefore, the total throughput of multiple WBANs is $\xi = \sum_{i=1}^{n} \xi_i$. Suppose a total of w packets with packet size S_p is successfully received by an AP A_j at time t_g, then the throughput of the network is $\xi_g = C_i^t \frac{w \times S_p}{t_g}$. If the data dissemination delay increases along with the criticality, C_i^t, of WBANs, then the total number of packets successfully received by the AP A_j at time t_h reduces, i.e., $w < v$, where v is the total number of packets received by AP A_j, as the total packet delivery delay increases. Then, the throughput of the network is $\xi_h = C_i^t \frac{v \times S_p}{t_h}$ Therefore, the total throughput of the network decreases, as the packet delivery delay increases, along with the increase in the criticality of WBANs, i.e., $\xi_g < \xi_h$. Hence, the proof concludes. ☐

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[5] Here, the service delay is defined as the total packet delivery delay of a WBAN in association with its criticality index.

[6] Here, $D_{diss}^{\mathcal{X}'}$ and $D_{diss}^{\mathcal{X}}$ denote the service delay for location $L_{\mathcal{X}'}$ and $L_{\mathcal{X}}$, respectively.

[7] It is to be noted that the age, sex, location, environment and height has grater impact on the criticality index of patients.

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B. Selection Parameters

In Section V-A, it shown that when the WBANs move from one location to another, the service delay from an AP increases. Therefore, in critical situations, medical data packets may be lost due to the selection of inappropriate APs. Therefore, to send data packets with minimum delay, we need to choose a dynamic AP, depending upon different selection parameters of an AP, which are defined below:

- **Euclidean Distance**: Euclidean distance from a WBAN B_i, coordinated as (x_i, y_i), to an AP A_j, coordinated as (a_j, b_j), is denoted as:

$$\mathcal{D}_{ij} = \sqrt{(x_i - a_j)^2 + (y_i - b_j)^2} \tag{13}$$

- **Available Bandwidth**: As proposed by [28], we consider e to be the number of active APs for a short time span with the utilization factor η, where $\eta < 1$ and $e \subseteq m$. $\eta < 1$ indicates that the AP is under-loaded. The available bandwidth for a new WBAN with $0 \leq \eta \leq 1$ is expressed as:

$$BW_i^{Av} = \frac{BW \log_2(1 + \frac{H}{O})(\eta + (1 - \eta)(1 + e))}{e + 1} \tag{14}$$

where BW is the bandwidth for an available channel and $\frac{H}{O}$ is the signal-to-noise ratio (SNR).

- **Criticality Index of WBAN**: The Criticality Index (CI) of a WABN is denoted as Φ_i. If the CI of a WBAN is $\Phi_i > \Phi_{th}$ [29], then the patient with the WBAN is in critical condition. If the CI of a WBAN is $\Phi_i < \Phi_{th}$, then the WBAN is in normal condition. The criticality of a WBAN, B_i, at time t, denoted as $C_i^t = 1$ when the WBAN is critical condition. When the WBAN is in a normal condition, then $C_k = 0$. Thus, we have,

$$C_i^t = \begin{cases} 1, & \text{if } \Phi_i > \Phi_{th} \\ 0, & \text{if } \Phi_i < \Phi_{th} \end{cases} \tag{15}$$

- **Normalized RSSI of an AP**: Suppose the $RSSI$ value of a particular AP is $RSSI$, the maximum RSSI value is $RSSI_{max}$, and the minimum $RSSI$ value is $RSSI_{min}$ [30]. Then the normalized $RSSI$ value, which is denoted as $RSSI_i$, is defined as:

$$RSSI_i = \left| \frac{(RSSI - RSSI_{max}) \times 100}{(RSSI_{max} - RSSI_{min})} \right| \tag{16}$$

where $RSSI_i$ is the normalized $RSSI$ value of an AP A_j. $RSSI_{min}$ and $RSSI_{max}$ are the minimum and maximum $RSSI$ values of an AP, A_j.

- **Residual Energy of WBAN**: As mentioned in [31], the residual energy E_{re} of a WBAN is the difference between the initial energy E_0 and the energy consumed during transmission and receiving $E_{con} = E_{tarn} + E_{rec} = K(E_{elect} + \varepsilon_{amp}) \times d^2 + KE_{elect}$. The residual energy of a WBAN is expressed as:

$$E_i^{re} = E_0 - \left\{ K(E_{elect} + \varepsilon_{amp}) \times \mathcal{D}_{ij}^{\S} + KE_{elect} \right\} \tag{17}$$

where ε_{amp} is the energy required by the amplifier circuit and E_{elect} is the energy required to run the electronic circuit in the WBANs. § denotes the path loss exponent (it varies within the range 2.45 - 3.25) and K is the packet size and $\mathcal{D}_{ij}$ is the distance between AP and WBAN.

Formulation of Selection Parameter: We discussed several selection parameters to choose a dynamic AP. Based on these parameters, we formulated a selection parameter $\mathcal{S}_i$, which is expressed as:

$$\mathcal{S}_i = \left[\left(\frac{BW_i^{Av}}{BW_{tot}} + \frac{RSSI_i}{RSSI_{max}} + \frac{E_i^{re}}{E_{ini}} + C_i^t \right) - \left(\frac{\mathcal{D}_{ij}}{\mathcal{D}_{max}} \right) \right] \tag{18}$$

where BW_{tot} denotes the total bandwidth capacity of an AP, E_{ini} denotes the initial energy of WBAN, $\mathcal{D}_{max}$ denotes the maximum distance between WBANs and APs. We consider another parameter γ_i to choose a dynamic AP for use in both normal and critical situations. We have,

$$\gamma_i = \begin{cases} 1, & \text{if } E_{ini} \leq E_i^{re} \text{ and } RSSI_{max} \leq RSSI_i \leq RSSI_{min} \\ 0, & \text{otherwise} \end{cases} \tag{19}$$

Therefore, the final selection parameter to choose a dynamic connectivity is mathematically expressed as:

$$f_{\mathcal{S}_i} = \gamma_i \left[\left(\frac{BW_i^{Av}}{BW_{tot}} + \frac{RSSI_i}{RSSI_{max}} + \frac{E_i^{re}}{RE_{ini}} + C_i^t \right) - \left(\frac{D_{ij}}{D_{max}} \right) \right] \tag{20}$$

C. Algorithm for Dynamic Connectivity Establishment

In medical emergency situations, to get connected to a dynamic AP with minimum delay, we propose an algorithm, that named Establishment of Dynamic Connectivity (EDC), increases the data packet delivery ratio. The worst-case time complexity of the EDC algorithm is $O(N^2)$, where N is the total number of WBANs.

Algorithm 1 Establishment of Dynamic Connectivity (EDC)

```
Inputs:
  • $\mathcal{B}$: Set of WBANs.
  • $\Phi_i$: Criticality Index of a WBAN.
  • $E_{re}$: Residual energy.
  • $BW_{Av}$: Available Bandwidth and $RSSI_i$.
Output: Selection of a dynamic AP, $A^*$.
Initialize the set of available APs $A_{all} = \{A_1, A_2, ..., A_j\}$.
Initialize the no of WBANs $B = \{B_1, B_2, ..., B_n\}$.
Initialize the optimal set $A^* \leftarrow \phi$.
while $(A \neq \phi)$ do
    $\forall B_i \in B$, Compute $\Phi_i$
    if $\Phi_i \geq \Phi_{th}$ then
        $\forall A_j \in A$, Compute $f_{(S_i)}$
        $A \leftarrow arg \;\; max_{A_i \in \phi}\{f_{(S_i)}\}$
        $A_{all} \leftarrow A_{all} \setminus \{A\}$
        $A^* \leftarrow A^* \cup A$
        if $(A^* \geq 2)$ then
            Find the dynamic AP comparing the $C_i$.
        else
            Serve the request to WBAN using dynamic AP.
        end if
    else
        Repeat the requests for lower critical WBANs.
    end if
end while
```

VI. COALITION GAME FOR COOPERATIVE SCHEDULING

To model cooperative packet scheduling among WBANs, we used coalitional game theory. Specifically, we used *transferable unit* (*TU*) to design coalition game. The overall timeline of cooperative packet scheduling is shown in Figure 2.

A. Requirement of Coalition Formulation

Dynamically choosing connectivity is not sufficient to provide effective medical service to the critical WBANs, as realistically, in the proximity of a particular AP, several WBANs also attempt access at the same time. But due to channel and residual bandwidth constraints, it is not possible for an AP to secure solution all WBANs at a particular instant of time in a particular time-period. Therefore, under

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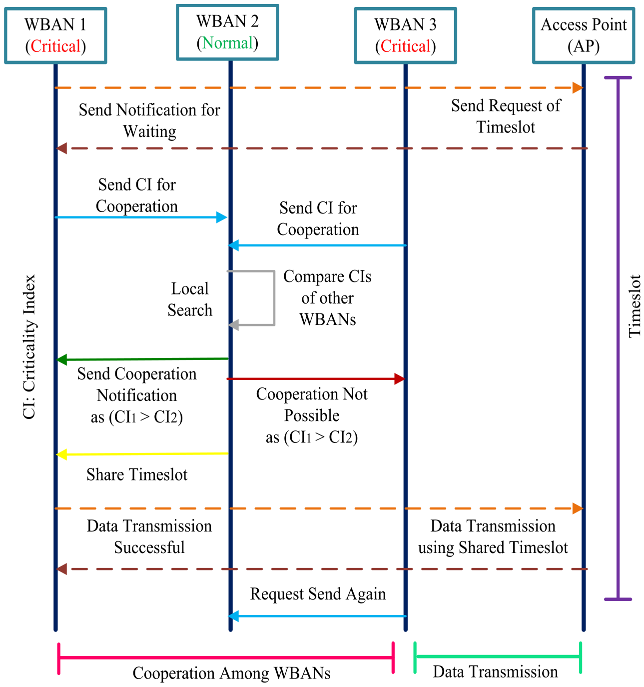

Figure 2: Timeline diagram of cooperative scheduling

uncertainty conditions, both critical and normal WBANs are present and they are not aware of the criticality conditions of one another. In such a scenario, it is essential to provide medical services to the critical WBANs before giving access to the normal ones, so that the critical WBANs can send their data as fast as possible reduced packet delivery delay. For offering service to the critical WBANs, and sending data in real-time, the proposed scheme forms coalition among WBANs to send data packets using cooperative packet scheduling.

Theorem 2. *Let us assume that n number of WBANs get access from an AP at time instant t. After some duration of time $\triangle t$, again m number of critical WBANs joins the same AP. As the number of critical WBANs increases, the network traffic also increases. In this scenario, the available bandwidth of an AP also decreases, i.e., $BW_i^{Av} < BW_{th}$.*

Proof. Let us assume that under an AP A_j, n WBANs receive services. Therefore, we calculate the available bandwidth BW_i^{Av} using Equation (14). After time duration $\triangle t$, m critical WBANs join the same AP A_j. In a WBAN, different body sensors transmit with different data rates. Therefore, each critical WBAN needs different bandwidth to send data packets. The total required bandwidth for m number of WBANs is expressed as:

$$BW_{req} = \sum_{i=1}^{m} BW_i \tag{21}$$

If the available bandwidth BW_{Av} does not fulfill the required bandwidth BW_{req} of m critical WBANs, i.e., $BW_{Av} < BW_{req}$, we have,

$$C_i^t \left[1 - \frac{1}{2}\eta \right] B \log_2(1 + \frac{H}{O}) < BW_{req} \tag{22}$$

$$\implies 2C_i^t \left[1 - \frac{BW_{req}}{B \log_2(1 + \frac{H}{O})} \right] < 1$$

where, the utilization factor of an AP $\eta = 2C_i^t \left[1 - \frac{BW_{req}}{B \log_2(1+\frac{S}{N})}\right]$. Therefore, $\eta < 1$ denotes that the AP is over-loaded. Therefore, with the increase in the criticality of WBANs C_i^t, the AP becomes over-loaded. Hence, the AP is unable to give access to the present critical WBANs. Then, among the m WBANs, the ones that are in critical situation will be unable to send packets. Therefore, the packet delivery delay of critical WBANs also increases. To give access to WBANs, we orchestrate a coalition game among the critical WBANs. □

B. Coalition Game Formulation Among WBANs

We promote the formulation of coalition game among those multiple WBANs that are in the proximity of selected AP using DCE. Then, the WBANs perform cooperative packet scheduling among one another and help the critical WBANs to transmit their data packets immediately without incurring much delay. The process of *Coalition formulation* is shown below:

Definition 3. Coalition formation for n person games with transferable unit (TU) is denoted as $(\mathcal{N}, \mathcal{U})$, where $\mathcal{N} \in \{1, 2, \cdots, n\}$ and $\mathcal{U}$ is a real-valued function defined as $\mathcal{R} \rightarrow \mathcal{R}_{+}$, such that the every coalition $\mathcal{Q} \subseteq \mathcal{N}$ [32]. $\mathcal{U}$ is defined as the characterization operator of the coalition game presented on the set $2^{\mathcal{N}}$ of all coalitions, [32]. The coalition game for TU has the following properties — (a) $\mathcal{U}(\phi) = 0$. (b) If n_1 and n_2 are two disjoint sets $(n_1 \cap n_2) = \phi$ of coalitions, then the super additive formula is, $\mathcal{U}(n_1) + \mathcal{U}(n_2) \leq \mathcal{U}(n_1 \cup n_2)$.

In the WBAN architecture, n number of WBANs $B_i \in \{B_1, B_2, ...B_n\}$ form multiple coalitions $\mathcal{Q}$, where $\mathcal{Q} \in \{\mathcal{Q}_1, \mathcal{Q}_2, ..., \mathcal{Q}_h\}$ under a particular AP, which is chosen by the WBANs dynamically. The subset $m \subsetneq n$ coalition of total players is mentioned as the grand coalition. The basic elements of the coalition game and the formulation of the coalition game among WBANs for the proposed architecture is described as follows:

- ***Players***: The n number of WBANs represented as the set $\mathcal{B} \in \{B_1, B_2, \cdots, B_n\}$ are termed as the players.
- ***Category***" In a coalition, two categories of WBANs are present *critical* and *normal*, which area denoted as $\mathcal{C}_c$ and $\mathcal{C}_n$. Each WBAN is aware of its own category of being normal and critical, but they are not aware of the criticality status of the other WBANs. The critical ones are associated with patients who are in medical emergency situations so they process their data immediately. The probability of a WBAN being critical is denoted as Υ_i, whereas that of a WBAN being normal is denoted as $(1 - \Upsilon_i)$. $\mathcal{C}_t$ is the category of a dynamic AP, which is known to all WBANs in the coalition. For a specific period of time, there will not be any change in the category of WBANs, and it is not possible for a WBAN to be critical and normal at the same time.
- ***Utility***: The utility of each WABN is denoted as $\mathcal{U}_i$, and it is defined as the difference between the cost for cooperative packet scheduling and the payoff of the WBANs in terms of packet delivery delay.
- ***Action***: Action is taken by each WBAN by calculating its own utility. Depending upon the utility obtained, a WBAN decides to join or leave a particular coalition.

We formulate the coalition game with *transferable unit* (*TU*), in which each individual WBANs utility, which is calculated in terms of the difference between the delivery delay and the price of cooperative packet scheduling, is transferred randomly to the other WBANs. Therefore, this leads to them formulation of a stable coalitional structure.

Definition 4. *Cohesive game*: A coalitional game with TU is declared to be cohesive [33], when the value of the coalition formed by the set of all players n is not less than as large as the sum of the values of any division of n, i.e.,

$$\mathcal{Q}(n) \geq \sum_{l=1}^{l} \mathcal{Q}(n_l) \tag{23}$$

for every coalitions $\mathcal{Q} \in \{\mathcal{Q}_1, \mathcal{Q}_2, \cdots, \mathcal{Q}_l\}$ of $\mathcal{Q}$.

Definition 5. *Disjoint game*: A coalitional game with TU is declared to be disjoint, as the two coalitional structure, respectively, $\mathcal{Q}_1$ and $\mathcal{Q}_2$, are disjoint. This is mathematically expressed as [33]:

$$\mathcal{U}(\mathcal{Q}_1) \cap \mathcal{U}(\mathcal{Q}_2) = \phi \tag{24}$$

Definition 6. *Split and Join*: In a coalition game, each player calculates its payoff before joining any coalition and spliting from any coalition. So, among different coalitions, the coalition that gives more payoff to players tries to join that coalition. The mathematical property of this preference is expressed as:

$$\mathcal{Q}_i \succeq \mathcal{Q}_j \tag{25}$$

This equation defines that if $\mathcal{Q}_i$ and $\mathcal{Q}_j$ are two coalitions, a WBAN B_i tries to join any one of the two coalitions. The WBAN B_i calculates the payoff for each of two coalitions, after which it determines which of the two coalitions yields more payoff to that WBAN. Such a WBAN gives preference $\succeq$ to join that particular coalition, i.e., $\mathcal{Q}_i \succeq \mathcal{Q}_j$.

Definition 7. *Shapely value*: Defined as one of the solution approach for the cooperative game formulation. For each coalitional structure, the value allocates a unique density function to all the users in the coalition of the total excess produced by each coalition [32]. The value that player i gets from a coalitional game $(\mathcal{U}, n)$ is expressed as:

$$\phi_i(\mathcal{U}) = \sum_{\mathcal{Q} \subseteq n \setminus \{i\}} \frac{|\mathcal{Q}|! - (n - |\mathcal{Q}| - 1)!}{n!} \Big(\mathcal{U}(\mathcal{Q} \cup \{i\}) - \mathcal{U}(\mathcal{Q})\Big) \tag{26}$$

Definition 8. *Bell number*: It satisfies a recurrence relation involving binomial coefficients, which is defined as [32]:

$$\Theta_{n+1} = \sum_{n=0}^{k} \binom{n}{k} \Theta_k \tag{27}$$

where Θ_k denotes the how to partition the coalitions and k denotes the small set of $k = (0, n)$ items removing the set containing the first item.

C. Formulation of Utility Function

The utility function, $\mathcal{U}_{B_i}$, of WBAN, B_i, for cooperative packet scheduling in medical emergency situations is expressed as [23]:

$$\mathcal{U}_{B_i}(\mathcal{D}_i, \mathcal{T}_i) = \nabla_i \big(1 - \mathbb{D}_i - \mathcal{T}_i\big) \tag{28}$$

where $\mathbb{D}_i = \frac{D_i}{D_{avg}}$ denotes the *delay factor*, $\mathcal{T}_i = \frac{\mathcal{T}_{tot}}{\mathcal{T}_{th}}$ denotes the *packet transmission cost factor* and ∇_i denotes the profit of helping other coexisting WBANs. Therefore, the utility function is expressed as:

$$\mathcal{U}_{B_i}(\mathcal{D}_i, \mathcal{T}_i) = \nabla_i \Big(1 - \frac{D_i}{D_{avg}} - \mathcal{T}_i\Big) \tag{29}$$

The properties that an utility of a WBAN must satisfy are as follows :

i) The utility function of WBANs is considered to be non-decreasing, as each WBAN is interested to send its medical data with minimum delay. This is mathematically expressed as:

$$\frac{\partial \mathcal{U}_{B_i}(\mathcal{D}_i, \mathcal{T}_i)}{\partial \mathcal{D}_i} \geq 0 \tag{30}$$

ii) The double derivative of the proposed utility function is considered to be decreasing, so that the packet delivery delay decreases and the network throughput increases. Mathematically, it is expressed as:

$$\frac{\partial^2 \mathcal{U}_{B_i}(\mathcal{D}_i, \mathcal{T}_i)}{\partial \mathcal{D}_i^2} \leq 0 \tag{31}$$

At time t_Ψ, a WBAN B_i sends its packets to the dynamic AP A_j. Then, the reserving cost for sending the packet to a dynamic AP A_j with in a coalition $\mathcal{Q}$ is $\mathcal{T}_{(t_\Psi, \mathcal{Q})}$. The cost for sending a packet at time t_Ψ is expressed as:

$$\mathcal{T}_{(t_\Psi, \mathcal{Q})} = \Bigg(\sum_{i=1}^{N} \mathcal{P}_{t_\Psi} \times P_{(t_\Psi, B_i)}\Bigg) \tag{32}$$

where $\mathcal{P}_{t_\Psi}$ denotes the unit packet transmission cost for Ψ^{th} time slot and $P_{(t_\Psi, B_i)}$ denotes the number of packet transmitted from a WBAN B_i. If there are τ time slots available for critical WBANs in associated with critical patients, then the critical WBANs use the time-slots of the normal WBANs to send their packets through cooperative packet scheduling. For this the critical WBANs pay a penalty cost for using time-slots through cooperative packet scheduling. This is expressed as:

$$\mathcal{T}_{(t_\Psi, \mathcal{Q}, penl)} = \begin{cases} p_u\big(P_{(t_\Psi, tot)} - P_{(t_\Psi, B_i)}\big), & \text{if } \Phi_i > \Phi_{th} \text{ and} \\ & \mathcal{T}_{t_\Psi} < \mathcal{T}_{t_\Psi}^{th} \\ 0, \quad \text{otherwise} & \end{cases} \tag{33}$$

where $P_{(t_\Psi, tot)}$ denotes the expected number of packet to be transmitted from a WBAN at time-slot Ψ. The total cost $\mathcal{T}_i$ for sending packet from a WBAN to an AP is formulated as:

$$\mathcal{T}_{tot} = \mathcal{T}_{(t_\Psi, \mathcal{Q})} + \mathcal{T}_{(t_\Psi, \mathcal{Q}, penl)} \tag{34}$$

where $\mathcal{T}_{(t_\Psi, \mathcal{Q}, penl)}$ represents the penalty cost due to the absence of available time for cooperative scheduling. The utility maximization of a WBAN B_i is formulated as:

$$\text{Maximize } \mathcal{U}_{B_i}(\mathcal{D}_i, \mathcal{T}_i) = \nabla_i \Big(1 - \gamma_i \frac{D_i}{D_{avg}} - \lambda_i \frac{\mathcal{T}_{tot}}{\mathcal{T}_{th}}\Big) \tag{35}$$

$$\text{Subject to } \mathcal{T}_{tot} \leq \mathcal{T}_{th} \ \& \ \Phi_i > \Phi_{th} \tag{36}$$

where γ_i and λ_i are non-negative constants of cost for cooperative packet scheduling and the packet delivery delay. Therefore, the total expression for the utility function is expressed as in Equation (37).

D. Algorithm for Distributed Cooperative Packet Scheduling

In this section, we propose a distributed cooperative packet scheduling algorithm among different WBANs in the communication range of a dynamic AP.

VII. STABILITY ANALYSIS FOR COALITION GAME

In this section, we discuss the issue of stability of coalitions formed by WBANs to transmit data packets through cooperative scheduling. We show the Markov model and Nash equilibrium conditions for the stable structure of the coalition.

A. Markov Model Analysis for Coalition Game

To show the stability of coalitions, we formulate a *Discrete Time Markov Model* [34]. The state-space of cooperative scheduling for

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$$\mathcal{U}_i = \nabla_i \left[1 - \gamma_i \frac{d_{nod} + (1+l_Q)\left[\lim\limits_{t_Q \to \mathbb{T}} t_Q \frac{\sum_{t'=1}^{t_Q} E_{\Pi}[Q(s_t,\psi_t,\pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[Q(s_t,\psi_t,\pi)]} + \lim\limits_{t_s \to \mathbb{T}} t_s \frac{\sum_{t'=1}^{t_s} E_{\pi}[W(s_t,\psi_t,\pi)]}{\sum_{t'=1}^{t_s} E_{\nu}[W(s_t,\psi_t,\pi)]} \right]}{\lim\limits_{t \to \mathbb{T}} \frac{\sum_{t'=1}^{T} E(s)}{\varrho}} \right.$$

$$\left. + \gamma_i \frac{(E[p(L_{b_i},S)] + E[p(L_{B_i},S)])}{\lim_{t \to \mathbb{T}} \frac{\sum_{t'=1}^{T} E(s)}{\varrho}} - \lambda_i \left\{ \left(\sum_{i=1}^{N} \mathcal{P}_{t_\Psi} \times P_{(t_\Psi, B_i)} \right) + \mathcal{T}_{(t_\Psi, \mathcal{Q}, penl)} \right\} \right] \tag{37}$$

Algorithm 2 Distributed Cooperative Packet Scheduling

```
Input:
  • Set of WBANs: $\mathcal{B} = \{B_1, B_2, \cdots, B_n\}$.
Output: Optimal and stable coalition structure.
At $t = 0$, WBANs under a dynamic AP $A_j$ are partitioned into $\mathcal{Q}_l^t = \{\mathcal{Q}_1^t, ..., \mathcal{Q}_n^t\}$, where $\bigcup_{i=1}^{n} \mathcal{Q}_i^t = \mathcal{Q}_l^t$
for $i = B_1$ to $i \leq B_n$ do
    $B_i$ observes the payoff in terms of $\mathcal{D}_i(\mathcal{Q}_K^i(t))$ and $\mathcal{T}_k(\mathcal{Q}_K^i(t))$ for $\mathcal{Q}_K^i(t)$
    Compute utility $\mathcal{U}_i(\mathcal{Q}_l^t)$ for $B_i$
    Update the utility value $\mathcal{U}_i(\mathcal{Q}_l^t) = \mathcal{E}[\gamma_i \mathcal{D}_{(\mathcal{Q},i,\phi_i)} - \lambda_i \mathcal{T}_{(\mathcal{Q},i,\phi_i)}]$, where $\gamma_i$ & $\lambda_i$ are constants.
    WBAN $B_i$ randomly selects a coalition $\mathcal{Q}_k^{t+1}$ to split and join that coalition.
    if $\mathcal{U}_i(\mathcal{Q}_k^{t+1}) > \mathcal{U}_i(\mathcal{Q}_l^t)$ then
        $B_i$ joins the new coalition $\mathcal{Q}_k^{t+1} = \mathcal{Q}_k^{t+1} \cup \{B_i\}$
        $B_i$ splits the old coalition $\mathcal{Q}_k^t = \mathcal{Q}_k^t \setminus \{B_i\}$
        Each $B_i \in \mathcal{Q}_k^{t+1}$ calculates $\tau_{nm}^{t_l+1}$
        Store value of $\tau_{nm}^{t_l+1}$ in $C[B_i][\tau_{nm}]$
        if $C[B_i][\tau_{nm}] > C[B_{i+1}][\tau_{nm}]$ then
            The remaining super frame time $t_{rem}$ is allocated to the critical WBANs.
        else
            Wait to deliver the packets of the critical WBANs.
        end if
    else
        $B_i$ remains in the same coalition $\mathcal{Q}_k^t$
    end if
end for
```

the coalition formulation game is composed of coalition structures, which are defined as follows:

$$\varphi = \{\mathcal{Q}_1, \mathcal{Q}_2 ....., \mathcal{Q}_h\} \text{ where } \; h = \{1, 2, ..., B_n\} \tag{38}$$

where Θ_I is the bell number, given total I WBANs, $I \in n$.

For dynamic cooperative packet scheduling, any WBAN can join any coalition at any instant of time depending its utility value, as the WBANs are mobile in nature. Therefore, we perform Markov Model Analysis to check the stability of coalition formulation. The state transition probability matrix $T_{\mathcal{Q}_g,\mathcal{Q}_{g'}}$ is expressed as:

$$T_{\mathcal{Q}_g,\mathcal{Q}_{g'}} = \begin{pmatrix} \mathcal{P}_{(\mathcal{Q}_1,\mathcal{Q}_1)} & \cdots & \mathcal{P}_{(\mathcal{Q}_1,\mathcal{Q}_{g'})} & \cdots & \mathcal{P}_{(\mathcal{Q}_1,\mathcal{Q}_n)} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathcal{P}_{(\mathcal{Q}_g,\mathcal{Q}_1)} & \cdots & \mathcal{P}_{(\mathcal{Q}_g,\mathcal{Q}_{g'})} & \cdots & \mathcal{P}_{(\mathcal{Q}_2,\mathcal{Q}_n)} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathcal{P}_{(\mathcal{Q}_{B_I},\mathcal{Q}_1)} & \cdots & \mathcal{P}_{(\mathcal{Q}_{B_I},\mathcal{Q}_{g'})} & \cdots & \mathcal{P}_{(\mathcal{Q}_{B_I},\mathcal{Q}_{B_I})} \end{pmatrix} \tag{39}$$

where $\mathcal{P}_{(\mathcal{Q}_g,\mathcal{Q}_{g'})}$ is defined as the probability of changing coalition from $\mathcal{Q}_g$ to $\mathcal{Q}_{g'}$. The elements of $\mathcal{P}_{(\mathcal{Q}_g,\mathcal{Q}_{g'})}$ is expressed as:

$$\mathcal{P}_{(\mathcal{Q}_g,\mathcal{Q}_{g'})} = \begin{pmatrix} \mathbb{P}^{g,g'}_{(1,1)} & \cdots & \mathbb{P}^{g,g'}_{(1,l')} & \cdots & \mathbb{P}^{g,g'}_{(1,B_I)} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbb{P}^{g,g'}_{(l,1)} & \cdots & \mathbb{P}^{g,g'}_{(l,l')} & \cdots & \mathbb{P}^{g,g'}_{(l,B_I)} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbb{P}^{g,g'}_{(B_I,1)} & \cdots & \mathbb{P}^{g,g'}_{(B_I,l')} & \cdots & \mathbb{P}^{g,g'}_{(B_I,B_I)} \end{pmatrix} \tag{40}$$

where $\mathbb{P}^{g,g'}_{(l,l')}$ is the probability that the coalition structure moves from g to g'. $\mathbb{P}^{g,g'}_{(l,l')}$ is at row $(g-1)B_I$ and column $(g'-1)B_I$ of matrix $\mathcal{P}_{(\mathcal{Q}_g,\mathcal{Q}_{g'})}$. Let $\mathcal{H}_{g,g'} \subseteq \mathcal{Q}$ denote the set of WBANs, who are part of performing the merge and split operations in the coalition, which result in the change of coalition structure from $\mathcal{Q}_g$ to $\mathcal{Q}_{g'}$.

Let, $\mathcal{F}(\mathcal{Q}_g|\mathcal{Q}_{g'})$ denote a feasibility condition of WBAN. In a particular time instant, if the coalition shape $\mathcal{Q}_{g'}$ is outstretch from $\mathcal{Q}_g$ i.e., $\mathcal{Q}_g \to \mathcal{Q}_{g'}$, then the situation is true; otherwise it is false.

$$\mathcal{F}(\mathcal{Q}_g|\mathcal{Q}_{g'}) = \begin{cases} 1 & \text{if } \mathcal{Q}_g \to \mathcal{Q}_{g'} \\ 0 & \text{otherwise} \end{cases} \tag{41}$$

Then, the transition probability $\mathbb{P}^{g,g'}$ is expressed as:

$$\mathbb{P}^{g,g'} = \begin{cases} \prod\limits_{i \in n} \Omega \times \omega_i(\mathcal{Q}_g, \mathcal{Q}_{g'}) & \text{if } \mathcal{F}(\mathcal{Q}_g|\mathcal{Q}_{g'}) = 1 \\ 0 & \text{otherwise} \end{cases} \tag{42}$$

where Ω defines the probability of the split and merge operations of a WBAN in a particular coalition, and $\omega_i(\mathcal{Q}_g, \mathcal{Q}_{g'})$ is the probability that the strategy of the i^{th} WBAN B_i changes. The coalition structure also changes from $\mathcal{Q}_g$ to $\mathcal{Q}_{g'}$. The decision-based rule is expressed as:

$$\omega_i(\mathcal{Q}_g, \mathcal{Q}_{g'}) = \begin{cases} \Psi & \text{if } \mathcal{H}_i(t \in t_t, \mathcal{Q}_{g'}, C_i) \leq \mathcal{H}_i(t \in t_t, \mathcal{Q}_g, C_i) \\ \varrho & \text{otherwise} \end{cases} \tag{43}$$

where $\mathcal{H}_i(t \in t_t, \mathcal{Q}_{g'}, C_i)$ and $\mathcal{H}_i(t \in t_t, \mathcal{Q}_g, C_i)$ denote the probability of being in the coalition $\mathcal{Q}_{g'}$ of WBAN B_i at time t and the probability of being in the coalition $\mathcal{Q}_g$ of WBAN B_i at time t with criticality C_i, respectively. When the coalition structure moves from $\mathcal{Q}_g$ to $\mathcal{Q}_{g'}$, then the strategic value $\omega_i(\mathcal{Q}_g, \mathcal{Q}_{g'})$ of i^{th} WBAN B_i is assigned Ψ, where $0 < \Psi \leq 1$. A WBAN is in the rotational condition when the coalition structure changes. The WBAN can join any coalition at any time. Therefore the value of Ψ value is assigned randomly for different coalitions. Otherwise, the decision value $\omega_i(\mathcal{Q}_g, \mathcal{Q}_{g'})$ of the i^{th} WBAN B_i is assigned a very small amount ϱ, where $\varrho < 0$ (e.g. $\varrho = 10^2$).

Definition 9. If the decision value $\omega_i(\mathcal{Q}_g, \mathcal{Q}_{g'}) > 0$, then the coalition is stable. However, if the $\omega_i(\mathcal{Q}_g, \mathcal{Q}_{g'}) < 0$, then the coalition is unstable, [34].

From Definition (7), it may be inferred whether the Markov Model for the coalition is stable or not. If time t is allotted to the WBANs, we calculate the static probability of a Markov Chain.

B. Nash Equilibrium Condition

We discuss below the equilibrium condition of the coalitions formed by the WBANs. The Nash equilibrium specifies the situation of reaching Pareto optimal situation. The payoff of each WBAN depends on the probability of cooperative packet scheduling from the other WBANs.

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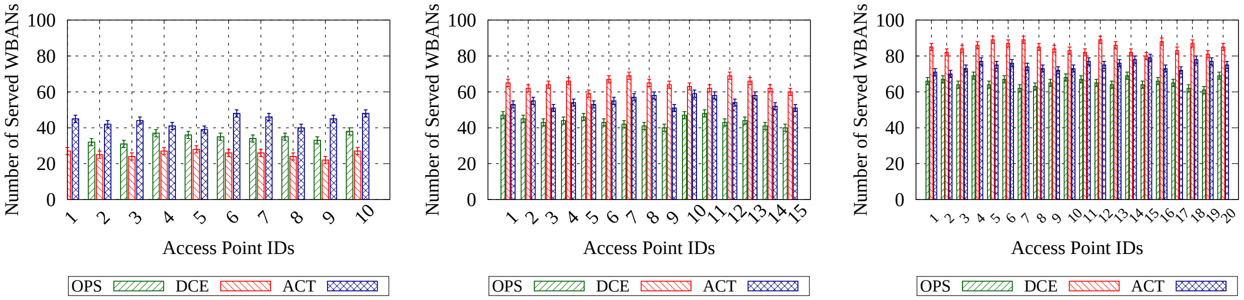
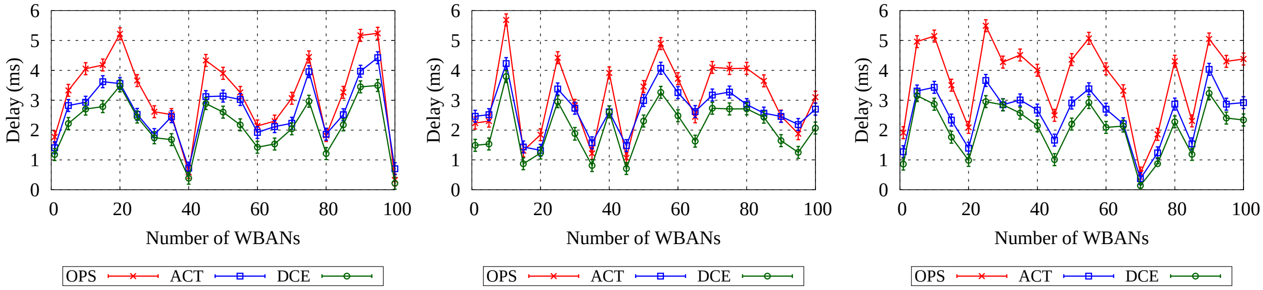


(a) Number of APs 10 (b) Number of APs 15 (c) Number of APs 20

Figure 3: Analysis of served WBANs with fixed number of APs



(a) Number of APs 10 (b) Number of APs 15 (c) Number of APs 20

Figure 4: Analysis of delay with fixed number of WBANs

Definition 10. A coalition $\mathcal{Q}_i$ is *Nash stable*, if the WBANs in the present $\mathcal{Q}_P$ coalition get the maximum utility compared to the previous collation $\mathcal{Q}_q$, i.e., $\mathcal{U}(\mathcal{Q}_p) > \mathcal{U}(\mathcal{Q}_q)$, [35].

In a critical situation, the critical WBANs always attempt to maximize their utility through cooperative packet scheduling in a particular coalitional structure $\mathcal{Q}$. However, if any critical WBAN as does not get the maximum utility, those WBANs will be left behind. Therefore, they decide to leave the coalition and join a new coalition in which they get more utility. If all the WBANs in the present coalition get appropriate or fair amount of utility, then we can say that the coalition is stable.

Proposition 2. *A Unique Nash Equilibrium (UNE) condition exists for multiple WBANs if among* $2^{\mathcal{N}}$ *coalitions an optimal coalition* $\mathcal{Q}^*$ *is in the state of Nash equilibrium, as mentioned [36].*

Proof. Using the coalition game-theoretic approach, if n WBANs are present, where $\mathcal{N} \in \{1, 2, ..., n\}$, then total $2^{\mathcal{N}}$ number of coalitions can be constructed. A WBAN B_i in a coalition $\mathcal{Q}_p$ calculates the utility $\mathcal{U}_i$. If the utility of the WBAN $\mathcal{U}_i$ in the existing coalition decreases, then the WBAN tries to connect to a new coalition $\mathcal{Q}_q$ [24]. This is a result of the finite number of divisions of the set $\mathcal{N}$ (given by the Bell number) and of the definition of the change rule. Suppose a division $\mathcal{Q} = \{\mathcal{Q}_1, \mathcal{Q}_2, \cdots, \mathcal{Q}_M\}$, if the division follow this criteria,

$$(\mathcal{Q}_M, \mathcal{Q}) \geq (\mathcal{Q}_k \cup i, \mathcal{Q}_i) \tag{44}$$

Then, a division $\mathcal{Q}$ is Nash-stable, while the existing WBAN has no intention to move from its present coalition to a new one in $\mathcal{Q}$, or to deviate and act alone. This concludes the proof. □

VIII. PERFORMANCE ANALYSIS

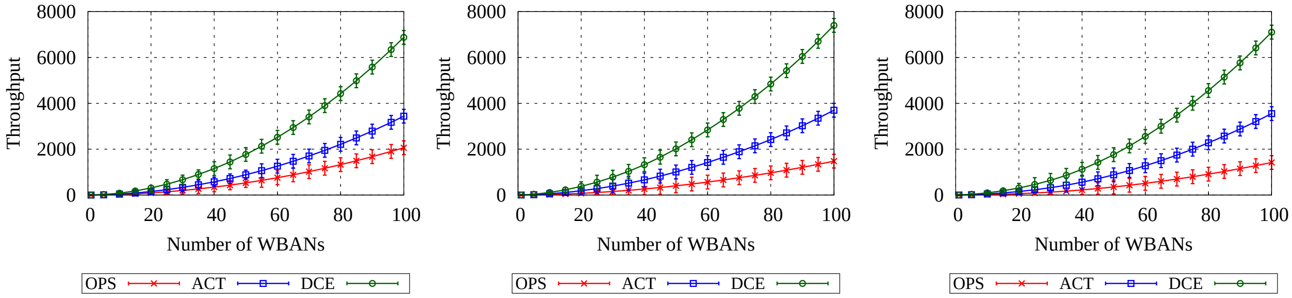
We analyze the performance of the proposed DCE scheme using MATLAB. Table II depicts the simulation parameters used for performance evaluation. We considered an area of 5 km × 5 km, where the number of WBANs varies from $100 - 300$. Each WBAN consists of 10 body sensor nodes and 1 LPU. The residual energy of WBAN is considered to be 0.5 J. The WBAN uses the one-hop star topology to send its data packets and follow the regulations of MAC standard of IEEE 802.15.6.

A. Simulation Settings

To analyze the performance of the proposed scheme, DCE, we considered group-based mobility of WBANs [3]. We also considered the single-hop star topology for data transmission between sensor nodes and LPUs, where the sensor nodes are placed on the body according to [37]. It minimizes the energy consumption rate of sensor nodes. The data rate of sensor nodes for medical applications varies from 10 Kbps to 10 Mbps. The simulation setting of WBANs is configured according to the IEEE 802.15.6 standard [19]. Also, the distance between sensor node and LPU is set to 1 meter. For our experiment, we considered intra-BAN channel with Rician fading, with pass loss exponent 3.6 [38], [39]. Similarly, we considered inter-BAN channel with Rayleigh fading with path loss exponent 3. We choose radio data rate of 250 kbps and super-frame of length 0.1 second. We performed the experiments for 50 rounds and showed the 95% confidence intervals in the graphs.

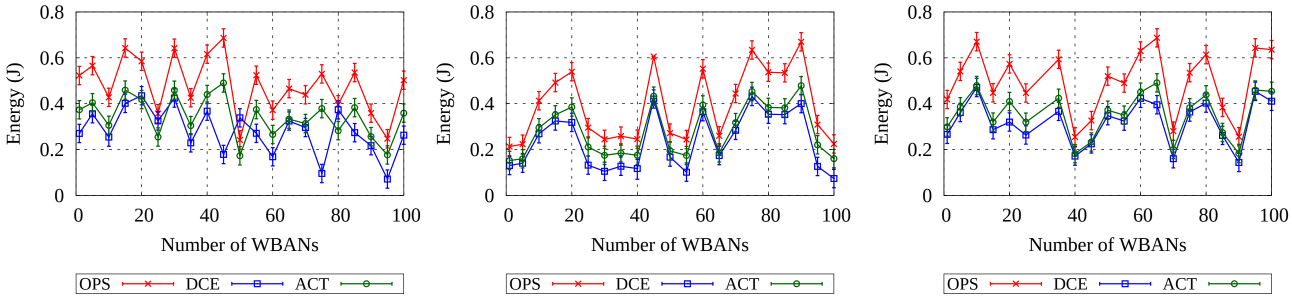
B. Benchmark

The performance of the DCE scheme is evaluated by comparing with the existing state-of-the-art — the *OPS algorithm* proposed by Prabh and Hauer [8] and *ACT algorithm* proposed by Thepvilojanapong *et al.* [40]. The OPS algorithm proposed an opportunistic packet scheduling scheme for WBANs. In this scheme, the authors showed that the changes in human body shadowing result in significant fluctuations in the received signal strength. Also, they



(a) Number of APs 10 (b) Number of APs 15 (c) Number of APs 20

Figure 5: Analysis of throughput with fixed number of WBANs



(a) Number of APs 10 (b) Number of APs 15 (c) Number of APs 20

Figure 6: Analysis of energy consumption with fixed number of WBANs

Table II: Simulation Parameters

Parameter	Value
Simulation time (second)	250
Number of WBANs	100-300
Number of APs	10-20
Energy consumption of Tx-circuit	16.7 nJ
Energy consumption of Rx-circuit	36.1 nJ
Energy consumption of Amplifier-circuit	1.97 nJ
Threshold SINR	5-15 dB
Distance between sensor nodes and LPUs	0.5-1.5 m
Packet rate	4 packets/sec
Packet size	512 Bytes
Fundamental frequency	2.4 GHz

showed that regular movements also affect the signal strength. To manage connectivity, they designed an opportunistic MAC protocol, named BANMAC [8], which achieves high reliability, even with low transmission power for opportunistic packet scheduling. In ACT algorithm, Thepvilojanapong *et al.* [40] proposed an adaptive channel and time allocation to manage the collision of data packets in the presence of higher density of WBANs in a particular area. To avoid the collision of packets, an adaptive channel and time allocation algorithm is proposed for intra-BAN and inter-BAN communications of WBANs. These two benchmark algorithms mainly address the scheduling problems by providing reliable MAC protocol and adaptive channel allocation algorithm for WBANs to increase the packet delivery ratio. However in this paper, we also propose a dynamic connectivity and cooperative packet scheduling algorithm to minimize the service delay and maximize the throughput of WBANs in the presence of poor link-quality. Therefore, the upper mentioned existing state-of-the-arts are the best suitable ones for the comparison with the proposed one.

C. Performance Metrics

- *Delay*: It is presented as the distinction between packet transmission time from the WBANs and the packet receiving time at the AP.
- *Throughput*: It is defined as the difference between the number of packets received at an AP and the number of packets transmitted from the WBANs per unit time. It is defined as:

$$\tau = \frac{\mathcal{P}_{rec} - \mathcal{P}_{tran}}{t} \tag{45}$$

  where $\mathcal{P}_{tran}$ is the number of packets transmitted from the WBANs and $\mathcal{P}_{rec}$ is the number of packets at the APs, in per unit time t.
- *Number of Served WBANs*: It is defined as the total number of WBANs getting access from an AP.
- *Success Rate*: It is presented as the total number of critical WBANs getting connectivity among 100 WBANs.
- *Coalition Size*: It denotes the number of WBANs present in a particular coalition and participating in cooperative packet scheduling.
- *Switch Operations in Coalition Formation*: It refers to the change in the structure of the coalitions per second or the leaving and joining rate of the WBANs of a coalition.
- *Payoff*: Payoff of the WBANs denotes the individual profit or the utility of each WBAN from a coalition participating in cooperative packet scheduling.

D. Results and Discussion

Number of Served WBANs: Figure 3 shows the total number of WBANs served by varying the number of APs in a critical emergency situation. We analyzed the proposed scheme with 100 WBANs and varying number of APs 10, 15, and 20. Figures 3(a), 3(b), and 3(c)

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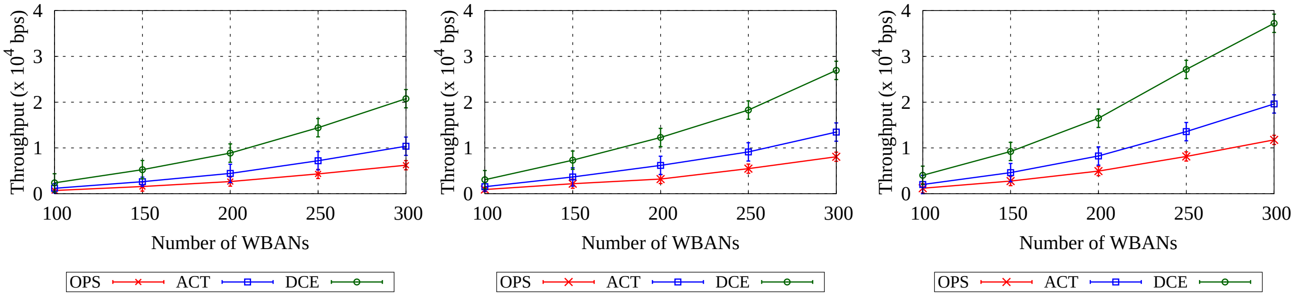
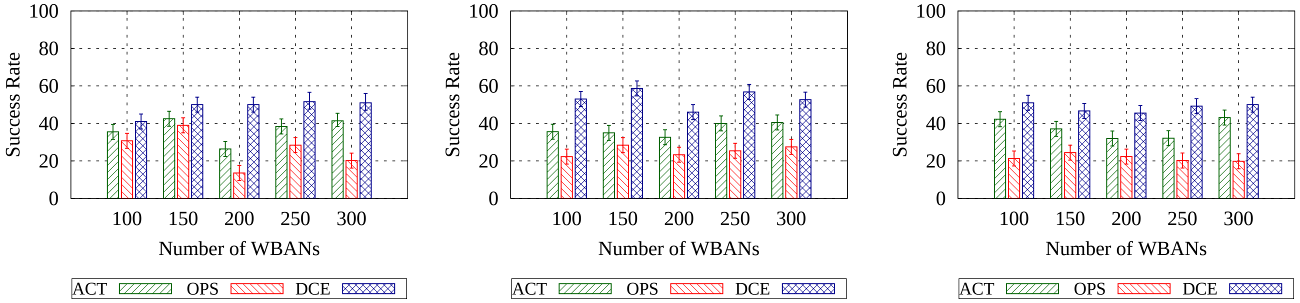


(a) Number of APs 10 (b) Number of APs 15 (c) Number of APs 20

Figure 7: Analysis of throughput with fixed number of APs



(a) Number of APs 10 (b) Number of APs 15 (c) Number of APs 20

Figure 8: Analysis of success rate with fixed number of APs

depict that the total number of served WBANs is more than the existing scheme based on the available bandwidth of the APs. On the other hand, from the figures, we can see that with the increase in the number of APs, the total number of served WBANs from a particular AP increase. Therefore, the critical WBANs can get more services in the presence of multiple APs. We also compared our scheme with the exiting solution, in which it was observed that our scheme outperforms the existing solutions - OPS and ACT.

Analysis of Delay: Figure 4 depicts the delay of each WBAN with fixed number of WBANs and the varying number of available APs. In this figure, we observe that using the proposed scheme, the critical WBANs have less packet delivery delay than the normal ones. As, in our scheme the normal WBANs allows the critical WBANs cooperatively to transmit its data packets. Also, we can observe from figures 4(a), 4(b), and 4(c) that with the increasing number of APs, the packet delivery delay of the critical WBANs decreases. On the other hand, figure 9 shows the average delay of the WBANs by varying the total number of WBANs with fixed numbers of APs. We also compared our scheme with the existing scheme OPS and ACT. However, the proposed DCE scheme outperforms the existing schemes as the existing schemes did not consider the cooperative communication among coexisting WBANs, while considering the criticality index of the same.

Analysis of Throughput: Figure 5 depicts the variation of network throughput for the proposed scheme. We show the network throughput with the fixed number of APs, while varying the number of WBANs. In Figure 5(a), we see that the network throughput of DCE scheme is more than the OPS scheme. With the increase in the number of APs, from Figures 5(b) and 5(c), we can see the network throughput of WBAN architecture for the proposed scheme compared to the existing scheme. Therefore, DCE scheme outperforms the existing scheme OPS and ACT.

Analysis of Success Rate: Figure 8 depicts the success rate of the connection between WBANs and APs. We observe that with the increase in the number of APs in the networks, the success rate of connectivity establishment increases. Therefore, in a link failure situation or in situations of transient connection, a connection with the AP and can send its data. We also compared the proposed scheme with the existing one, in which we showed that the DCE outperforms the OPS and ACT schemes.

Analysis of Energy Consumption: Figure 6 depicts the energy consumption of WBANs for the proposed scheme. From the figure, we can see that, with the increase in the number of APs, the energy consumption of each WBAN decreases. In the proposed scheme, the critical WBANs transmit their packets to the AP using cooperative scheduling. Therefore, the critical WBANs consume less energy than the normal ones. With the increase in the number of APs, the energy consumption of each WBAN decreases. We also compared the proposed solution with the existing scheme OPS, in which DCE outperforms OPS and ACT.

Analysis of Coalition Size: Figure 10(a) shows the analysis of the performance of coalition size for cooperative packet scheduling. Coalition size is defined as the total number of WBANs present in a particular coalition based on the utility factor. We present the average size of a coalition and the maximum size of a coalition in the presence of 15 critical WBANs. From the graph, we observe that the average maximum coalition size expends with the raise in the number of WBANs compared to the average coalition size.

Analysis of Average Payoff: Figure 10(b) shows the payoff of each WBAN participating in cooperative packet scheduling. The payoff of each WBAN defines the profit or the utility of each WBAN in terms of delivery delay. In the figure, we show the average payoff for the non-cooperative approach, the proposed coalition scheme and the optimal coalition partition. For the non-cooperative approach, the

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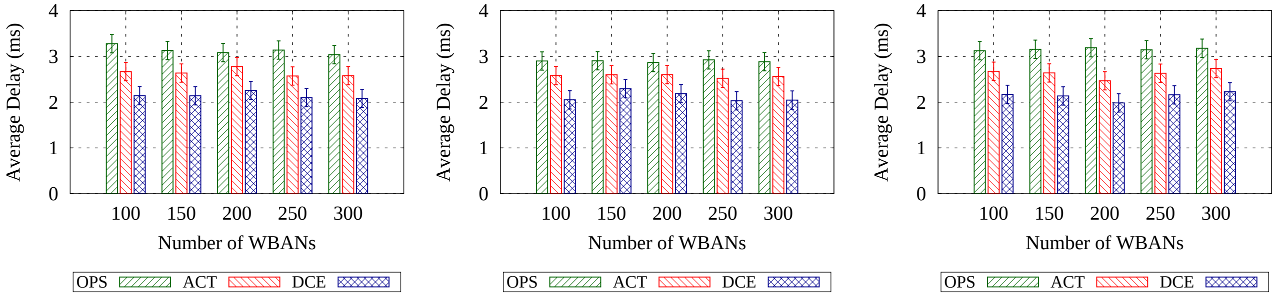
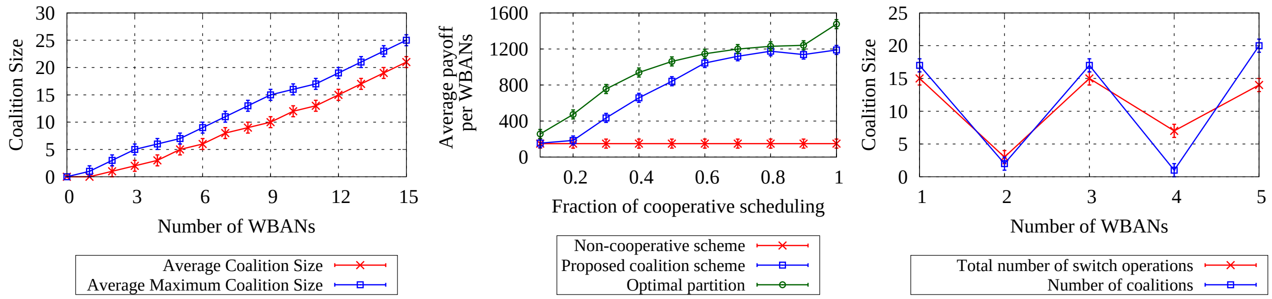


(a) Number of APs 10 (b) Number of APs 15 (c) Number of APs 20

Figure 9: Analysis of delay with fixed number of APs



(a) Coalition size (b) Average payoff (c) Switching Operation

Figure 10: Analysis of coalition formation

payoff of each WBAN does not improve. Rather, it stays consistent throughout, which signifies that the WBANs do not get improved QoS services in terms of packet delivery delay. For the proposed coalition approach, the average payoff of each WBAN increases significantly and the critical WBANs get less packet delivery delay. Consequently, for the optimal partition, the payoff of each WBAN is more compared to the proposed coalition scheme and the non-cooperative game theoretic approach.

Analysis of Coalition Structure: Figure 10(c) depicts the result of switching operation of WBANs resident in a particular coalition. Switching describes the joining and merging operations of WBANs to a coalition with respect to time. In this figure, the total number of coalitions and switching operation in the time period of $0-5$ minutes is observed. Using the proposed dynamic cooperative packet scheduling scheme, the WBANs change their coalitions with time, if the WBANs do not get fair amount of payoff.

IX. CONCLUSION

In this work, we presented a scheme for dynamic connectivity establishment and cooperative scheduling for QoS-aware WBANs. First, we dynamically choose a dynamic AP for the critical WBANs, so as to deal with the transient connectivity problem between WBANs and APs. To manage connectivity, we proposed the Dynamic Connectivity Establishment (DCE) algorithm, which is based on a price-based approach. Finally, critical WBANs in the proximity of an AP form coalitions to ensure QoS between them. In each coalition, the WBANs participate in cooperative packet scheduling to provide services to the critical WBANs. For handling cooperation between WBANs, we proposed another algorithm Optimal Cooperative Packet Scheduling. We compared our proposed schemes with the existing schemes, based on which we show that the former our approach outperform the later.

Future extension of this work includes studying and characterizing the dynamic behavior of link quality between WBANs and APs for the connectivity problem. Another extension of the work is to observe the performance of the proposed solutions in real-life setting for mobile edge computing applications [41]. Consequently, in the presence of transient connectivity, the data rate adaption technique can be implemented to increase the overall performance of WBANs. On the other hand, we intend to address the security and privacy issues of cooperative packet scheduling among WBANs in a critical emergency situations.

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