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RESEARCH ARTICLE

Enhanced Probabilistic Route Stability (EPRS) Protocol for Healthcare Applications of WBAN

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ABSTRACT Wireless Body Area Network (WBAN) is among the most promising technologies for enhancing life quality. WBANs enable constant monitoring of physiological processes by implanting or wearing small, low-power, intelligent sensor nodes in or on the human body. These sensor nodes may be placed either invasively or non-invasively. Patient data must be disseminated reliably and promptly for WBAN's healthcare apps to function. For this reason, medical teams may use real-time apps for sharing vital information like blood pressure, an ECG, and an EEG. Critical data packets are delay-sensitive and must arrive at sink nodes within the time constraints that satisfy QoS for WBAN. However, networks' unpredictable and dynamic nature (node mobility, link partitioning) makes reliable data transfer a challenging task. Additionally, postural mobility and ultra-short wireless range cause rapid topology changes, resulting in network partitioning. The network partitioning causes failure of data delivery to the sink or coordinator and causes a delay as well. In the case of normal data, it is not a big issue, but it is not tolerable for emergency data because it may be life-threatening. Consequently, compromising the link reliability and stability results in higher delays, increased packet re-transmissions, and decreased throughput performance. Therefore, we propose an Enhanced Probabilistic Route Stability (EPRS) scheme to address these issues. The proposed EPRS scheme introduces a cost function called *Link Assessment Cost (LAC)* that makes coherent decisions regarding route reliability in determining whether an active route is a good candidate for routing and satisfying QoS requirements. The LAC is based on two critical factors about link status, i.e., *Route Stability Factor (RSF)* and *Expected Probability of link* $E(p)$. Based on these factors, a score is assigned to a link that determines the status (likelihood) of a link, either *connected* or *disconnected*. In this way, the multi-facet EPRS selects the most stable and reliable routes despite the disconnection in the networks, thereby improving the route stability and throughput, minimizing the end-to-end delay, route discovery calls, and re-transmissions as depicted by simulation results.

INDEX TERMS Link quality, quality of service, routing protocol, wireless body sensor networks, network partitioning.

I. INTRODUCTION

Wireless networks are gaining in popularity and playing an increasingly important part in the field of communication. The development of low-power, low-cost, nano-sized biomedical sensor nodes for real-time data recording results from technological advancements in digital microelectronics, wireless communication infrastructure, and ambient intelligence. Wireless Body Area Network (WBAN) is the name of the network of these Nano-sized biomedical sensor nodes

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installed on the human body [1], [2]. Typically, patient data is collected by sensor nodes put on various body areas to diagnose diseases in their early stages. The Wireless Body Sensor Network (WBSN) is a self-organizing network made up of biomedical sensor nodes that coordinate and operate in an ad-hoc fashion without any established infrastructure and report the occurrence of interests to a sink or base station. The Wireless Body Sensor Network (WBSN) could be seen as a low-cost way to improve the quality of life through monitoring and reporting services in medical and non-medical applications. The WBAN transfers patient data to a centralized place for medical diagnosis. Thus, data must arrive at the end station reliably and securely.

Wireless communication is error-prone, so losing vital data packets might endanger the patient's life. Therefore, WBAN needs a reliable mechanism to transmit patient data to the end station. Routing protocols are essential for the safe delivery of data packets within anticipated time limits and the fair use of network resources in wireless communication, among other things [3], [4]. However, owing to the specific difficulties WBANs, routing protocols proposed for other networks like DTN, WSN, and MANET cannot be employed in their original form [3]. Since WBANs face various issues, including overheating, timely dissipation of crucial data packets, network disconnections caused by postural body movements, network lifespan, and QoS requirements. Therefore, new routing protocols must be developed to address specific issues and meet the needs of WBAN. A frequent change in topology caused by the ultra-limited wireless range and postural movement results in network partitioning. It becomes aggravated by unpredictable R.F. attenuation caused by body parts and garments blocking the transmission.

Consequently, the communication between on-body and off-body sensor nodes becomes inconsistent and unreliable. Therefore, to mitigate the effects of network partitioning, the routing protocols should be designed to minimize end-to-end latency, packet loss, and transmission energy consumption and maximize route stability and reliability. The positions like standing, sitting, waving the arms, walking, and sprinting constitute postural body movements. The nodes should be capable of disseminating data reliably (without being lost due to unstable links) under these dynamic postural body movements.

To the best of our knowledge, less research has been carried out to address routing issues in WBAN being faced due to postural body movements and ultra-low transmission range. In order to examine the effects of network partitioning due to posture body movement in WBAN, a network of 16 biosensor nodes is positioned on various body locations. These biosensor nodes exchange information with the coordinator or sink node. The range parameter is altered to replicate the body sensor nodes' ultra-low transmission range. Based on postures, the topology and network change dynamically. A pre-determined sequence of body movements has been followed, such as static position (patient on-bed), confined mobility, standing position, walk and run. Each sequence lasts for 50 seconds. The impact of these changing postures has been examined in terms of an average number of route breakages and average packet delay, as shown in Figures 1 and 2, respectively.

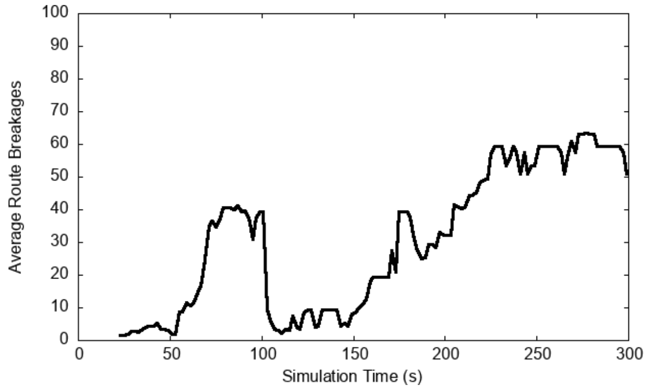

FIGURE 1. Impact of network partition on route breakages.

A significant variation in the performance of delay and route breakages has been observed as the sequence of body postures changes. These route breakages result in a storm of route discoveries and thereby flood the network with routing packets. Moreover, transmission disruption due to network partitioning also compromises route stability. Similarly, the packet delay also experiences variation in performance due to link breakages, interference, and route maintenance call. Such transmission disruption affects the flow of data packets as nodes have to wait to find new routes. Therefore, some effective schemes that deal with route instability due to the postural body and network partitioning should be designed.

Moreover, most of the existing routing protocols [5], [6], [7], [8], [9], [10] for WBAN focus exclusively on temperature awareness, hotspot detection, and energy consumption for data transfer over the multi-hop path. However, one of the significant limitations of these routing protocols is that they overlook optimized end-to-end route discovery due to network partitioning resulting from postural movements. These existing routing protocols exhibit compromised network performance when dealing with time-critical WBAN. The time constraint WBAN demands the dissemination of critical data packets reliably and timely. However, link reliability and stability are highly affected due to network partitions, resulting in higher delays, increased packet retransmissions, compromised throughput, and network lifetime performances. This research work is inspired by [11] to address the abovementioned limitations. This paper makes the following contributions:

- We present the vulnerabilities (as depicted in Figure 1 and Figure 2) of existing routing protocols through simulations in partitioned networks due to postural body movements. The route stability has been significantly compromised, undermining these networks' benefits.

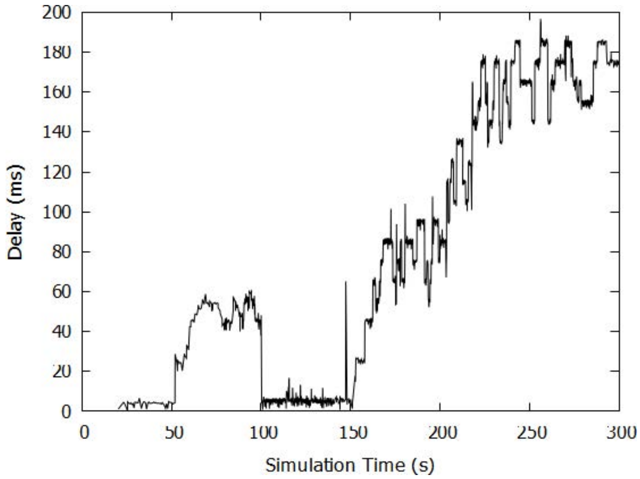

FIGURE 2. Impact of network partition on delay performance.

- We proposed an improved routing scheme named Enhanced Probabilistic Route Stability (EPRS), which makes a coherent decision regarding reliable and unreliable links. The route stability factor and expected positive probability of the link (to remain connected during the time slot T) have been incorporated. This multi-faced strategy provides optimized and stable routes in disconnected WBANs due to postural body movements.
- The effectiveness of the Link Assessment Cost (LAC) metric has been validated using simulation results (Figure 5) that show that the proposed EPRS scheme selects reliable/stable links.
- We carry out the performance evaluation of the proposed scheme with existing state-of-the-art under varying traffic loads.

II. RELATED WORK

Numerous routing methods have been put out in the WBAN domain, and they take a variety of goals into account. There are two standard routing strategies. First, it suggests that the MAC layer and routing functions may be integrated using a basic cross-layer strategy. This method lets you use link quality parameters, but it makes things more complicated. The second method involves building a routing layer on top of the MAC layer, where link quality is assessed using a selected number of parameters that are controlled at the routing layer. The complexity is minimal since the two layers in this second method are distinct. Nadeem et al. [12] introduces the SIMPLE protocol for WBAN, where the parent node, or forwarder, with the highest residual energy and the closest proximity to the sink, is chosen using a cost function. Nodes having a lower cost function value are chosen to be parent nodes. The distance parameter enables effective packet delivery to the sink, whereas the residual energy parameter balances energy consumption among the sensor nodes. The ECG and glucose monitoring nodes are situated next to the sink. Both sensors provide vital information for the patient and have low attenuation and greater reliability. As a result, the sink receives constant data transmissions from these sensors. Other sensors transmit their data to the sink through the forwarder node and follow their parent node.

Distance Aware Relaying Energy Efficient (DARE) is introduced by A. Tauqir et al. [13] to monitor patients in multi-hop Body Area Sensor Networks (BASNs). Through the use of on-body relays that are fastened to the chest of each patient, the sensors communicate with the sink to reduce energy use. Since they acquire and transmit information to the sink node, the attached body relays retain more energy resources than the body sensors where just a few sensor nodes continuously monitor patient data, while others only do so when they detect a certain threshold stage. In order to protect delicate human body tissues from heat damage, the protocol specifies minimum energy requirements for the sensors. The study's findings show a higher packet delivery ratio, a longer network lifespan, and a longer period of stability. However, the propagation latency is rather long.

Co-LAEEBA, which extends the LAEEBA protocol [14], makes use of the cost function to choose the best route to sink. They call it the cooperative routing mechanism [15]. Cooperative routing, on which this architecture is built, ensures greater performance by locating cooperative nodes using the shortest path route method. Channel deficiencies are taken into account in this study: shadowing, path loss, cumulative noise effects, etc. Reference [16] presents a priority-based TDMA in which the transmission schedules are determined by the priorities of the data packets. This protocol minimizes network power consumption by dynamically adjusting the super-frame structure in accordance with the volume of traffic.

The WASP [17] cross-layer, tree-based protocol, which aims to provide high network stability and minimal latency, is one example of a similar effort that has concentrated on routing strategies to achieve sufficient performance in multi-hop topologies. The research described in [17], looks at distributed transmission coordination-based MAC-routing cross-layer challenges in the presence of particular routing architectures. In [17], the authors discuss an energy-efficient slotted MAC in the context of the on-body packet-routing protocol known as Wireless Autonomous Spanning Tree (WASP). This cross-layer method provides routing-specific energy reduction at the MAC layer by tailoring the MAC slot allocation for the underlying routing tree. While using a similar tree-based cross-layer method, the protocol in [18] aims to speed up packet delivery across an on-body spanning tree. It schedules nodes' transmission using the Time Division Multiple Access (TDMA) protocol. On the other hand, the Controlling Access with Distributed Slot Assignment protocol (CICADA) [19] is a multi-hop TDMA scheduling-based low-energy cross-layer routing protocol for WBANs. By establishing a Lognormal distribution for connection probability rather than a circular coverage zone, CICADA improves dependability. Additionally, it offers two-way communication, enhancing the WASP protocol.

Quwaider and Biswas [20] introduced a routing system that is able to sustain changes in the network. To enhance the chance that a data packet would get to the sink node, they implemented a store and forward technique. A data packet may be stored by each sensor node. Each node in the source-to-destination route stores the data packet and sends it to the next node. A data packet's end-to-end latency and energy consumption increase when it is kept and then retransmitted.

However, Sensor nodes on or in the human body have the ability to move since the body is continually in motion. The distance between sensor nodes will fluctuate continually with body motions. Due to the frequent construction and breaking of certain linkages between nodes, this would result in significant topological partition issues. Delay Tolerant Network (DTN) is the name of this kind of network, and designing and implementing its routing protocol is challenging. Even certain BSN features make it difficult to directly use technology from WSNs. For instance, when sensor equipment is placed on or inside a human body, the body's electrical properties might affect radio communications. The network's topology will often alter due to human activity. Therefore, researchers should either propose new technology to fulfill the unique demands of BSN communications or enhance the current WSN technology to use in BSN communications correctly [11], [21].

Unlike other protocols discussed above, a delivery estimation-based routing protocol is an example of a routing protocol for networks with a delay-tolerant feature. The PRoPHET (Probabilistic Routing Protocol utilizing History of Encounters and Transitivity) protocol operates on the reasonable assumption that node mobility is not completely random. The authors make the assumption that nodes in a DTN have a tendency to visit some locations more often than others and that node pairs with a history of frequent encounters are more likely to maintain connections in the future [22].

A safe, privacy-based scheduling method for real-time transmission in WBANs was developed by Barua et al. [23], where a Secure-Key distribution mechanism improves security. Additionally, the terms ''high'' and ''low'' priority classes are specified. Real-time applications are given a high priority whereas other forms of traffic are given a low priority. Real-time applications for electronic health have a secure, delay-sensitive method with the suggested protocol.

In order to provide the groundwork for data transmission, a group of experts worked on developing effective routing algorithms. They used postural data and the delay tolerant network (DTN) concept [24], [25], [26]. By avoiding nodes with a high storage/buffering latency brought on by topological disconnections, the developers of [25] seek to reduce end-to-end delay. They create a probabilistic packet-based routing technique based on distance vectors. This approach captures multi-scale topological locales in human postural motions using a stochastic link cost formulation. It is predicated on the idea that if a link is now connected, there is a set chance that it will stay so in the next time window. However, in practice, this presumption may not be accurate. Several DTN routing variations are discussed in the WBAN context in [26]. They imply that a connection has a constant level of quality (ignoring link quality differences in routing). It is illogical, as we previously explained, because of node mobility and R.F. energy absorption. They call for each node to sometimes go up to two hops away from the sink while having unrealistically limited mobility.

The authors in [27] and [28] noted the multi-hop issue that arises while gathering data from the patient's body, and because of traffic congestion, WBAN sensors experience inconsistent energy consumption. They suggested the tree-based energy-efficient routing system (EERS) to accomplish multi-hop routing with minimal overheads. Additionally, the suggested approach provided an end-to-end routing connection using WBAN sensors with adaptive transmission power in an energy-efficient way.

ALOHA and CSMA/CA provisions with slotted TDMA topology form the foundation of the work [29], the WBAN, on the other hand, is set up in a star topology, with each sensor linked to a sink node. This design is not energy efficient in circumstances where numerous sensors are implanted near one another,

Using a priority-guaranteed CSMA/CA mechanism in CAP and CFP to manage a massive volume of data, [29] proposes a hybrid priority-guaranteed MAC protocol for WBANs. This hybrid technique gives each B.N. a separate back-off period-based priority.

Similarly, there are numerous concerns about the connection reliability of mobile networks due to increased mobility. The authors in [30] presented energy conservation and a stable routing algorithm for inter-WBAN communication since the presence of energy-efficient connections has stability uncertainty. The suggested approach incorporates a cost function that accounts for the node residual energy and its distance from the sink. For distributed WBANs, the algorithm's route selection takes into account each node's maximum objective function when forwarding packets. In light of this, the authors in [31] develop a WBAN-specific dynamic power control mechanism that distributes power using body posture information to conserve energy.

In [32] the two-hop star topology extension is suggested. The authors make the assumption that the coordinator may send data directly to all sensor nodes without using a relay node. The cost and energy use of the nodes rise as a result. A two-hop extension protocol that enables the resource-equipped hub to broadcast packets directly to the downlink relayed nodes has been proposed by [32] in order to decrease the energy consumption and overhead for relaying nodes. The authors also employed the Energy efficient media access strategy, which contains a collection of keyframes as static postures based on keyframes [33]. BNC will choose nodes for transmission that do not have a shadowing impact.

As WBANs inherently possess mobility, body mobility might impair the network performance in WBANs, according to Maskooki et al. [34]. Node mobility could be a challenge, particularly in terms of energy efficiency. The solution to this body mobility issue is hence an opportunistic routing. The goal of this protocol is to send data as long as feasible under LOS (Line of Sight) situations. A relay node placed appropriately might be used to implement the concept. This suggestion implies that a sensor node is positioned on the chest and that the sink node is situated on the wrist. When the wrist is in front of the body when the user is walking, the sensor node will sometimes send a LOS signal, but other times it will transmit an NLOS signal (when the wrist is behind the body). While the sensor node uses the relay node, which is in the LOS position to both the sink and sensor nodes, to send data to the sink node while the hand node is in the NLOS position, the sensor node directly transmits data to the sink node when the hand node is in the LOS position. The sensor node will take advantage of every opportunity to utilize the relay node in order to continue sending data under LOS circumstances as long as feasible.

The guaranteed time slots are dynamically assigned based on the traffic load in the low-delay traffic-adaptive MAC (LDTA-MAC) protocol for WBANs [35] aims to fix some of IEEE 802.15.4's issues. Based on the volume of traffic, this protocol assigns slots on a dynamic basis. For each successful GTS allocation request, data packets are sent in the current super-frame. However, LTDA-MAC does not take into account the data packets' priorities or back-off values. The contention access period (CAP), contention-free period (CFP), and inactive period (I.P.) in the super-frame may be dynamically adjusted for QoS provisioning in terms of energy and latency using the ATLAS design [36]. The authors in [37] proposed an MCDR routing protocol for the partitioned network. In this scheme, the source nodes choose the subsequent node to transmit the data to the sink. Until the data reaches the sink, this procedure is repeated. It starts by selecting the subsequent node, using the distance to the sink node as a parameter. The second criterion for choosing the next node is the nearby nodes' remaining energy. A multiple-criteria decision analysis approach is utilized with these two criteria. In a multi-sink scenario for partitioned wireless sensor networks, MCDR is devised and put into practice. Furthermore, the authors in [38] proposed a link reliable protocol named SRE that optimizes the performance of WBAN by designing a link cost function based on the link's reliability, energy, and Specific Absorption Rate (SAR). Depending on the kind of data, the Tripe-EEC protocol modifies its multi-hop route selection parameters [39]. The least amount of relay nodes and temperature increase are used in a data channel for regular data. Critical or on-demand data is routed via minimal latency pathways depending on priority.

For applications including health monitoring, Pandit et al. [40] suggested the energy-efficient multi-constrained MAC (eMC-MAC) protocol. By classifying the traffic into five categories—urgent packets (U.P.s), critical packets (C.P.s), reliability-constrained packets (R.P.s), delay-constrained packets (D.P.s), and regular packets—the eMC-MAC protocol effectively manages heterogeneous multimedia traffic (N.P.s). The identical traffic class packets are, however, ordered in ascending order of remaining lifespan. The eMC-MAC protocol's super-frame structure is implemented to provide high-priority traffic with a better chance of obtaining GTSs. During the CFP, it also added urgent transmission slots (UTSs) at pre-determined intervals. By pre-empting R.P. or C.P. packets, these UTSs enable urgent packets to be broadcast at any point throughout the super-frame. By guaranteeing fairness among the various traffic packets, it also prevents famine. According to the findings of the simulation, eMC-MAC performs better in terms of delivery latency and reliability than PLA-MAC and McMAC.

Moreover, software defined networking (SDN) approach will be considered to support the QoS requirements of heterogenous traffic load in IMS [41]. The IEEE 802.15.4 super-frame structure is the foundation of the PNP-MAC [42] protocol. Through quick, pre-emptive slot allocation, non-preemptive transmission, and super-frame modifications, it may adapt quickly to applications with a variety of needs. However, since CFP has a set length, having a lower data rate will result in less time and energy spent staying awake. Once again, if the data flow is large, the fixed idle period (I.P.) may force a lot of crucial and high-priority data to wait for the next super-frame. Any data created during the I.P. will be lost or forced to wait in this case, which is not practical for emergency data. Reiterating that only requests for GTS, not data packets, are accepted during the CAP period, this delay may be considered for certain applications. The traffic load on sensor nodes and the priority consideration are out of balance. Due to their larger traffic loads and greater back-off, low-priority sensors may not be able to deliver all of the data and instead drop them, which may be a serious issue for medical treatments.

The literature review above suggests that addressing optimized end-to-end route discovery due to network partitioning due to postural body movement is quite challenging. While bearing these issues and constraints in mind, we propose an Enhanced Probabilistic Route Stability (EPRS) routing protocol for WBANs to provide optimized and stable routes in disconnected WBANs due to postural body movements. Table 1 provides a summary and comparison of the related work. Each scheme is compared in terms of related QoS parameters such as protocol design, route stability, disconnected network, link status prediction, network overhead and traffic pattern.

III. PROPOSED ROUTING SCHEME

Most of the existing routing protocols for WBAN focus exclusively on temperature awareness, hotspot detection, and energy consumption for the data transfer over the multi-hop path. However, one of the significant limitations of these routing protocols is that they overlook optimized end-to-end route

TABLE 1. Summary table.

Reference	Protocol Design	Route stability	Disconnected Network	Link status prediction	Network overhead	Traffic pattern
[12] SIMPLE	Energy Conservation	No	No	No	Moderate	Uniform
[13] DARE	Energy Conservation	No	No	No	Moderate	Uniform
[14] LAEEBA	Link-Aware & Energy-Efficient	No	No	No	Low	Uniform
[15] Co-LAEEBA	Link-Aware	No	No	No	Low	Uniform
[16] PLA-MAC	QoS-Aware	No	No	No	Low	Uniform
[17] WASP	Cross-Layer & Tree-Based	No	No	No	High	Uniform
[19] CICADA	Cross-Layer & Tree-Based	No	No	No	High	Uniform
[19] CICDA	Cross-Layer Scheduling-Based & Energy Conservation	No	No	No	High	Uniform
[20] OBSFR	Location-Based	Yes	No	No	High	Uniform
[11] PRPLC	Probabilistic-Routing	Yes	Yes	No	High	Dynamic but static traffic load
[25] PLCF	Store-and-Forward	Yes	Yes	No	High	Uniform
[26] PRMPL and DVRPLC	Store-and-Forward	Yes	Yes	No	High	Uniform
[27] EERS	Tree-Based & Energy Conservation	No	No	No	High	Uniform
[28] PMAC	Cross-Layer	No	No	No	Moderate	Uniform
[30] ESR	Energy Conservation	Yes	No	No	Moderatre	Uniform
[32] 2HDD	Energy Conservation	No	No	No	Low	Uniform
[33] PA-DPLM	Energy Conservation	No	Yes	No	Moderate	Uniform
[35] LDTA-MAC	QoS-Aware	No	No	No	High	Uniform
[36] ATLAS	Energy Conservation	No	No	No	Moderate	Uniform
[38] MCDR	Cross-Layer	Yes	No	No	Low	Uniform
[39] SRE	Link reliability & Delay-Aware	Yes	No	No	Low	Uniform
[40] Emc-MAC	QoS-Aware	No	No	No	Low	Uniform
[42] PNP-MAC	Qos-Aware	No	No	No	High	Uniform
Proposed Protocol EPRS	Route reliability and stability	Yes	Yes	Yes	Low	Dynamic and varying traffic loads

discovery due to network partitioning resulting from postural movements. Thereby, these existing routing protocols exhibit compromised network performance when it comes to dealing with time-critical WBAN. The time constraint WBAN demands the dissemination of critical data packets reliably and timely. However, link reliability and stability are highly affected due to network partitions, resulting in higher delays, increased packet re-transmissions, and compromised throughput performances. Therefore, this paper presents an Enhanced Probabilistic Route Stability (EPRS) scheme that provides optimized and stable routes in disconnected WBANs due to postural body movements. The proposed EPRS scheme uses *Link* Assessment Cost (LAC) function to make routing decisions, as represented by Equation (1). The LAC is based on two critical factors about link status, i.e., *Route Stability Factor (RSF)* and *Expected Probability of link* $E(p)$.

$$LAC_{i,j}^{curr} = RSF_{i,j}^{Curr} + E(p)_{i,j}(t) \tag{1}$$

The factor $RSF_{i,j}^{Curr}$ refers to the current link status (either connected or disconnected) during a time slot t. Based on the current status, RSF assigns a score to the link, such as $0 \leq RSF \leq 1$. Similarly, the factor $E(p)$ refers to the expected positive probability of a link remaining connected at time t. It addresses the issue of uncertainty on the part of the link and determines the likelihood of the link remaining connected for the time slot t. The $E(p)$ uses Beta Probability Density Function (PDF) because it represents the status of the link where outcomes are binary such as connected or disconnected.

If the link is connected, the RSF score is evaluated using Equation (2), whereas if the link is disconnected, the RSF score is evaluated using Equation (3). If the link remains connected for longer, the score of RSF asymptotically reaches 1, indicating that the link is reliable. However, if the link is disconnected, the RSF decreases by the rate determined by β and asymptotically reaches zero, which indicates the link is unreliable.

$$\begin{aligned} RSF_{i,j}^{connected} =& RSF_{i,j}^{Prev} + (1 - RSF_{i,j}^{Prev}) \\ & \times \delta, \quad if\ \ Link\ L_{i,j}\ is\ connected \end{aligned} \tag{2}$$

$$\begin{aligned} RSF_{i,j}^{disconnected} =& RSF_{i,j}^{Prev} \\ & \times \delta, \quad if\ \ Link\ L_{i,j}\ is\ disconnected \end{aligned} \tag{3}$$

The cost of RSF is dynamically evaluated based on the value of δ, as in Equation (4), over a window of length (window) measured in a number of slots for the duration of time T. The term $L_{i,j}$ refers to the variable that keeps track of the link's connectivity during the current time slot. If the link is connected, the value of $L_{i,j} = 1$, otherwise the value of $L_{i,j}= 0$. This way, the value of δ is in the range of $0 < \delta < 1$.

$$\delta_{i,j}^{curr} = \sum\nolimits_{t}^{t-Window} L_{i,j}/Window \tag{4}$$

In addition to the RSF, the expected positive probability $(E\,(p)_{i,j}\,(t))$ of the link is evaluated by each node on the link $L_{i,j}$. $E(p)_{i,j}\,(t)$ incorporates the Beta probability density function [43] to evaluate the positive probability of link $L_{i,j}$ as modeling, the link assessment is characterized by uncertainty. Probability is one of the most appropriate ways to deal with uncertainty to address [44]. The following are the main reasons that lead to the selection of the beta Probability Density Function (PDF):

i It represents the status of links where outcomes are binary such as connected (reliable) or disconnected (unreliable).
ii A strong foundation in statistical theory.
iii Only two parameters ($\alpha and \beta$) are required for computing probability, making it pertinent for resource-constrained sensor nodes.

Equation (5) defines the Beta distribution function as:

$$P\,(x) = Beta\,(\alpha, \beta) = \int_{0}^{1} u^{\alpha-1}(1-u)^{\beta-1}du \tag{5}$$

where α and β are two indexed parameters, $\alpha > 0$ and $\beta > 0$.

The beta PDF can be represented in terms of Gamma function (Γ) as in Equation (6):

$$f\,(p\,|\,\alpha, \beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma\,(\alpha)\,\Gamma(\beta)} p^{\alpha-1}(1-p)^{\beta-1} \tag{6}$$

where $0 \leq p \leq 1\ and\ \alpha, \beta > 0$.

The probability expectation value for beta PDF is defined in Equation (7):

$$E\,(p) = \frac{\alpha}{\alpha+\beta} \tag{7}$$

where α and β denote the positive (connected links) and negative (disconnected links) outcomes, respectively, the probability of an outcome may be calculated by setting the values for a and b as shown below, where a indicates the number of positive outcomes and β the number of negative outcomes, respectively.

$$\alpha = a + 1\ and\ \beta = b + 1$$

The expected PDF defined in Equation 7 can be expressed as:

$$E\,(p) = \frac{a+1}{(a+1)+(b+1)} \tag{8}$$

Based on the RSF factor, Equation (8) can be re-written in the form to represent the expected probability of positive of the link $L_{i,j}$ as in Equation (9)

$$E(p)_{i,j} = \frac{RSF_{i,j}^{connected} + 1}{\left(RSF_{i,j}^{connected} + 1\right) + \left(RSF_{i,j}^{disconnected} + 1\right)} \tag{9}$$

where $RSF_{i,j}^{connected}$ and $RSF_{i,j}^{disconnected} \geq 0$

Based on the observations provided by *RSF* and E(P), the link cost function, *LAC*, makes a coherent decision regarding the link as either a good link or a bad link. If the LAC value for the particular link is either 1 or near 1, it is considered

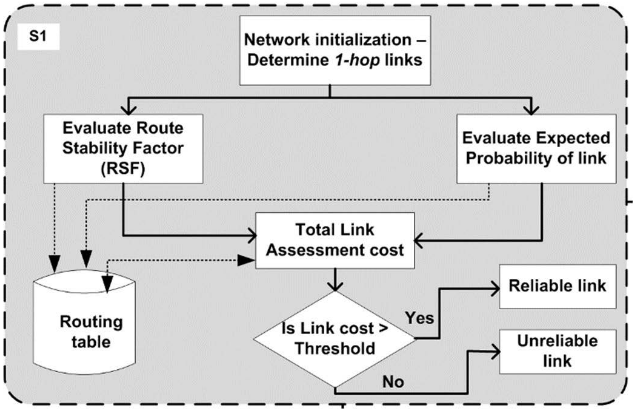

FIGURE 3. Design of ESRP scheme.

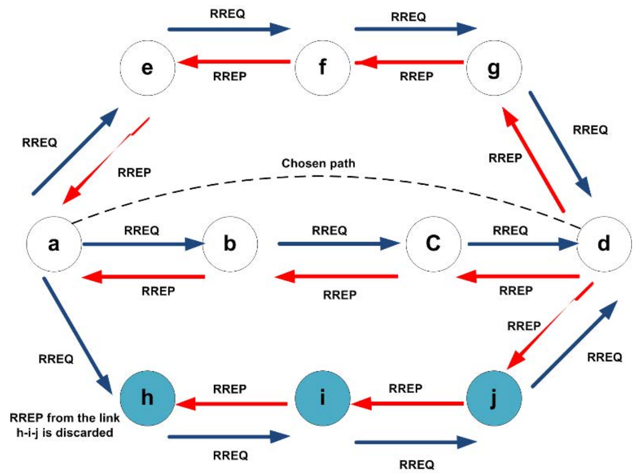

FIGURE 4. Route selection using ESRP.

a good link. On the contrary, if the LAC value of the link is either 0 or near 0 is regarded as a bad link. The threshold value Ø is used to differentiate between good and bad links. If the $LAC > Ø$, the link is considered a reliable link and otherwise ($LAC < Ø$) unreliable. At network initialization, LAC is assigned a neutral value of 0.5. Afterward, based on the link status, the LAC value is either incremented or decremented. In this way, the multi-facet proposed EPRS scheme selects the most stable and reliable routes, thereby significantly improving the route stability, throughput, and network lifetime and minimizing the end-to-end delay, route discovery calls, and re-transmissions.

Figure 3 shows the design and implementation flow of the proposed EPRS scheme.

The proposed EPRS scheme enhances the default route discovery process of the on-demand AODV routing protocol. The AODV protocol was chosen because of its distinctive features, including its on-demand nature, which allows nodes to identify routes whenever they need to, as well as its ability to do both broadcast and unicast routing, give fresh/latest route information, be more scalable, and produce less control packet routing overhead. Route Request (RREQ) and Route Reply (RREP), two important control packets, are used by AODV to find a route. The proposed EPRS scheme customizes the default RREQ and RREP control packets of AODV for selecting stable and reliable routes in the route discovery phase. To achieve this goal, EPRS introduces a composite routing function called LAC that incorporates the Route Stability Factor (RSF) and Expected Positive Probability ($E(p)$ of the link. The RREP packets are updated to contain RSF and $E(p)$ values. Consider a network scenario shown in Figure 4 where node a is the source and node d is the destination node.

Node **a** must first broadcast the RREQ packet to its neighbors to start the route discovery process in order to choose a reliable path for data delivery to the destination node **d**. The neighboring nodes create a reverse route entry for node **a** and pass the RREQ to the neighboring node. The same procedure is repeated until the route request packet arrives at the destination. Node **d** the destination, unicasts RREP packets to node **a** through the reverse route. The RREP packet is updated by each intermediary node along the reverse route with the most recent RSF and E(p) data for that specific link. The source nodes may receive multiple RREP packets for several routes. This assists node **a** in computing LAC (based on the RSF and E(p) values) for every RREP it receives. The link has the higher aggregated value selected. Therefore, the source nodes discard the RREP from the link $\boldsymbol{h} \longrightarrow \boldsymbol{i} \longrightarrow \boldsymbol{j}$ as it is below the threshold. However, the aggregated LAC value for the links $\boldsymbol{a} \longrightarrow \boldsymbol{b} \longrightarrow \boldsymbol{c} \longrightarrow \boldsymbol{d}$ and $\boldsymbol{a} \longrightarrow \boldsymbol{e} \longrightarrow \boldsymbol{f} \longrightarrow \boldsymbol{g} \longrightarrow \boldsymbol{d}$ is higher than the threshold. Based on the ESRP's link cost function, the source node selects the link $\boldsymbol{a} \rightarrow \boldsymbol{b} \rightarrow \boldsymbol{c} \rightarrow \boldsymbol{d}$ as the LAC value for this link is higher than its counterpart. Algorithm-1 shows the route selection mechanism of the EPRS scheme.

IV. SIMULATION AND RESULT DISCUSSION

The performance of the proposed EPRS scheme is evaluated using popular network simulator-2 (NS-2), incorporating simulation parameters presented in Table 2.

The performance of the proposed EPRS scheme is evaluated in two different scenarios. The Link Assessment Cost (LAC) analysis is presented in partitioned-WBAN due to postural body movements in the first scenario. In the second set of experiments, the performance of EPRS is compared with the existing state-of-art (SRE, MCDR, and AODV) in terms of throughput, route stability, end-to-end delay, and normalized routing load under varying data rates. The reason for varying traffic loads is to analyze the status of the link fairly.

Figure 5 shows the evidence of link activity with respect to time. The proposed EPRS scheme uses LAC to estimate the actual status of the link. The LAC is based on two important factors RSF and expected positive probability. The integrated outcome of these two factors leads to selecting the most reliable links, as it is mentioned that LAC falls within the

Algorithm 1 Route Selection Process of EPRS

begin
while {TRUE} **do**
foreach of the $Link(i, j)$ **do**
$LAC(i, j) \leftarrow$ **call procedure** $LINK\_ASSESMENT(Link(i.j))$
end
end while
end
procedure $LINK\_ASSESMENT(Link\ (i, j))$
Input: $Link\ (i, j)$, $Hello(i, j)$
Output: $LinkReliablity(i, j)$ **in terms of** $LAC(i, j)$
begin
set $W(t) \leftarrow Windowlength$
Compute $RSF_{i,j}$ and $E(P)_{i,j}$
$LAC(i, j) \leftarrow RSF_{i,j}$ and $E(P)_{i,j}$
if the link is connected, **then**
$RSF^{connected}_{i,j} = RSF^{Prev}_{i,j} + (1-RSF^{Prev}_{i,j}) \times \delta$
else if the link is disconnected, **then**
$RSF^{disconnected}_{i,j} = RSF^{Prev}_{i,j} \times \delta$
if $LAC > \emptyset$
set $Link\_Status \leftarrow TRUE \triangleright connected$
else if $LAC < \emptyset$
set $Link\_Status \leftarrow FALSE \triangleright disconnected$
return $LAC(i, j)$
end procedure

TABLE 2. Simulation parameters.

Parameters	Values
Simulation time	500s
Area	2m x 2m
Window length W(t)	15s
Transport layer protocol	UDP
MAC protocol	IEEE 802.15.4
Routing protocols	EPRS, SRE, MCDR, AODV
No. of sensor nodes	5
No. of relay nodes	10
No. of the sink node	1
Packet size	100 bytes
Traffic type	CBR
Traffic load	50 Kbps – 250 Kbps

range of $0 \leq LAC \leq 1$. The LAC's value near 1 indicates that the link remains connected for longer, thereby increasing its reliability index. A threshold value of $\emptyset = 0.5$ is used to determine reliable and unreliable links. If LAC values are below the threshold, the link is considered unreliable. However, the link is considered reliable if the value is above the threshold. As the nature of the link is dynamic, it depends upon the current conditions of the link. An unreliable link at time T, can become a reliable link at time $T + 1$ based on its RSF and $E(p)$ evidence.

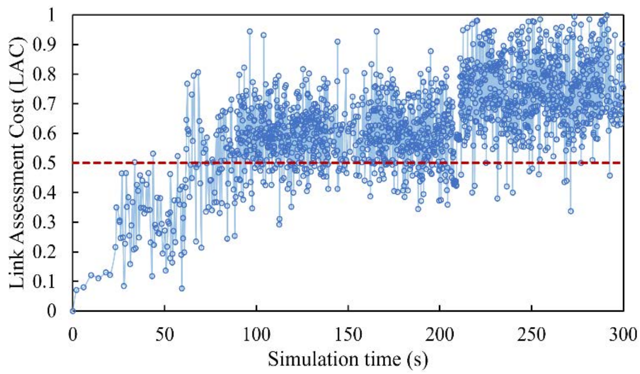

FIGURE 5. Analysis of LAC.

Similarly, a reliable link may become unreliable if it remains disconnected. Therefore, figure 5 depicts that LAC coherently makes an effective decision regarding the actual status of the link. The multi-facet approach adopted by LAC leads to selecting the most stable links. Figure 6 shows the performance comparison of the EPRS scheme with existing SRE, MCDR, and AODV routing protocols, under varying data rates (50 Kbps – 250 Kbps).

Figure 6(a) shows the comparison of end-to-end delay performance. The significant network traffic (congestion) level on the links under heavy traffic load and the increased number of route discoveries (due to reduced route stability) diminishes the end-to-end delay performance of SRE, MCDR, and AODV protocols. The increased number of route discovery calls suspends the data transmission till alternate routes are formed. Moreover, high packet re-transmissions and losses also contribute to the compromised end-to-end delay performance. However, due to high route stability, the EPRS protocol minimizes the packet re-transmission and flow of routing packets, thereby exhibiting improved end-to-end delay performance.

Figure 6(b) presents the analysis in terms of normalized routing load. The Normalized Routing Load (NRL) refers to the routing overhead generated due to the network's flow of non-data and non-ACK packets. These include routing packets of protocols such as RREP, RREQ, and RERR packets and probe packets such as Hello packets. NRL also refers to the ratio of data packets to the routing/control packets flowing in the network. The existing schemes SRE, MCDR, and AODV incur high routing overheads due to an increased number of route discoveries. The number of route discoveries increases due to the selection of less reliable/stable routes. Consequently, the storm of route maintenance calls floods the network with a high volume of routing packets while limiting the bandwidth for data packets. However, EPRS proves to be more cost-effective as it provides more stable routes which remain connected for a longer duration, thereby minimizing the flow of routing packets.

Figure 6(c) depicts the route stability performance of proposed and existing schemes. One significant benefit of the

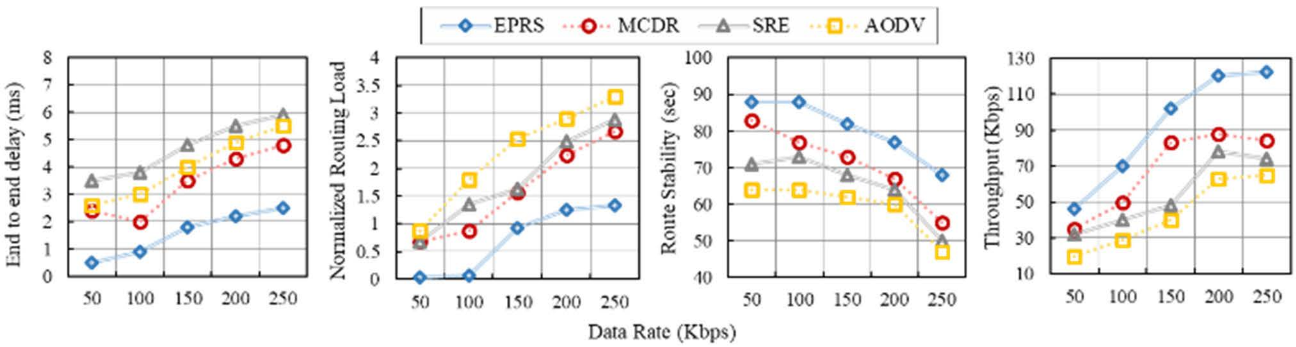

FIGURE 6. **Performance comparison of the EPRS scheme.**

proposed EPRS scheme is improving route stability/route lifetime. Route stability refers to the average duration of time for which a route remains connected. The route stability is directly related to the route breakage notifications. If the number of route breakage notifications is high, the route stability will be reduced [45], [46]. The LAC component of the EPRS scheme intelligently evaluates the status of the link (either connected or disconnected) and makes informed decisions. The RSF factor and expected positive probability of link $E(p)$ incorporate the link having a high probability of remaining connected. Based on these factors, LAC evaluates the reliability index of a link. The link is called reliable if the reliability index is higher than the threshold (LAC $>$ Ø). These factors significantly contributed to the improved route stability performance of EPRS. On the other hand, the SRE, MCDR, and AODV routing protocols do not provide any mechanism to deal with route stability in partitioned networks. Therefore, exhibit reduced stability performance. The SRE and MCDFR routing protocols incorporate energy efficiency, a distance of a node from the sink, and node density around the coordinator node for evaluating the link's status. However, these parameters are insufficient to estimate the actual status of the link based on dynamic conditions of the link, such as varying traffic on the link and network disconnections due to postural body movements.

Finally, figure 6(d) shows the throughput analysis of proposed and existing schemes. The throughput performance is significantly affected by route stability. The longer the route remains stable and connected, the flow of data remains consistent, allowing more packets to reach the destination within time constraints. As shown in Figure 6(d), as more data packets are supplied in the network, all the schemes exhibit increased throughput performance. However, when it reaches the saturation point, the throughput performance for the SRE, MCDR, and AODV declines. The high network load strains the communication channels, resulting in increased route breakages, re-transmissions, and high overhead. On the contrary, the proposed EPRS protocol exhibits improved throughput performance as the most reliable links are selected for packet forwarding.

V. CONCLUSION

The healthcare application of WBAN demands timely dissemination of critical data packets and high route stability. However, the network disconnections due to postural body movements in WBAN significantly affect the route stability and lead to the selection of unreliable links. The proposed EPRS routing protocol offers a cost-effective solution for routing critical data packets and makes a dynamic decision in distinguishing reliable and unreliable links in partitioned WBAN. The EPRS uses the route stability factor and the expected positive probability of the link remaining connected. The integrated outcome of these factors leads to selecting the most stable links in the networks. The simulation results demonstrate the improved performance of the EPRS protocol. In the future, we intend to incorporate QoS and link quality parameters so that a more enhanced version of EPRS is designed by keeping in view the QoS constraints of WBAN.

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