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MIQoS-RP: Multi-Constraint Intra-BAN, QoS-Aware Routing Protocol for Wireless Body Sensor Networks

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ABSTRACT Wireless Body Sensor Networks (WBSNs) are becoming increasing popular in a number of healthcare applications. A particular requirement of WBSNs in a healthcare system is the transmission of time-sensitive and critical data, captured by heterogeneous biosensors, to a base station while considering the constraints of reliability, throughput, delay and link quality. However, the simultaneous communication among various biosensors also raises the possibility of congestion on nodes or transmission links. Consequently, the likelihood of a number of untoward situations increases, such as disruption (high delays), packet losses, retransmissions, bandwidth exhaustion, and insufficient buffer space. The significant level of interference in the network leads to a higher number of collisions and retransmissions. The selection of an optimized route to cope with these issues and satisfy the QoS requirements of a WBSN has not been well-studied in the relevant literature. In this regard, we propose a multi-constraint, Intra-BAN, QoS-Aware Routing Protocol (referred to as MIQoS-RP) which introduces an improved, multi-facet routing metric to optimize the route selection while satisfying the aforementioned constraints. The performance of the proposed protocol is evaluated in terms of average end-to-end delay, throughput and packet drop ratio. The comparison of MIQoS-RP with the existing routing protocols demonstrates its efficacy in terms of the selected criteria. The results show that the MIQoS-RP achieves improved throughput by 22%, average end-to-end delay by 29% and packet drop ratio performance by 41% as compares to existing schemes.

INDEX TERMS Multi-constraint, wireless body sensor network, route discovery, quality of service, link quality, interference.

I. INTRODUCTION

A WBSN is used to monitor various parameters in a healthcare system (such as emergency and lifestyle) and a non-healthcare system(such as sports and security) [1], [2]. AWBSN provides a biosensor-to-biosensor communication session. These biosensors (implanted or attached to the body) are used to sense and collect physical data such as temperature, Electrocardiogram (ECG), blood pressure, glucose, etc. via Body Sensor Units (BSUs)and transmit it to its final destination (gateway, base station, personal display assistant) via the Body Control Unit (BCU for further analysis (as shown in Figure 1) [3], [4]. Moreover, biosensors in an Intra Body Area Network (Intra-BAN) have low bandwidth and high surrounding interference. As they share a medium for data transmission, therefore, they also face contention from other nodes. However, with the advancements in multimedia and video streaming applications, QoS requirements of users have drastically changed. Delivering required QoS to users offers a dedicated challenge in wireless networks due to the associated constraints. The emergence of real-time applications requires the exchange of information in real-time. For instance, a healthcare system dealing with an emergency situation entails the delivery of a time-sensitive data

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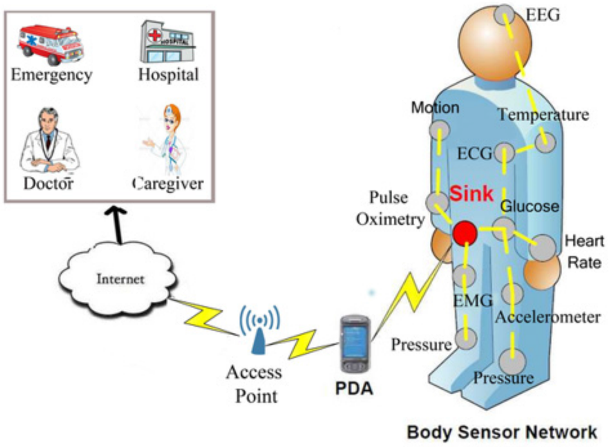

FIGURE 1. The architecture of the WBSN [5].

captured by biosensors within a given time frame. With this constraint, arise a number of issues which significantly affect the overall performance of a WBAN, such as the likelihood of intra-network interference among various nodes which adversely affect the buffer space and packet drop ratio.

In the route discovery phase, a variety of routes between two or more biosensor nodes are discovered according to their routing requirements. In the relevant literature, the majority of existing routing protocols [5]–[7] do not consider the design requirements for optimized WBSN such as wireless network interference and link quality. As a result, the network performance is degraded by packet loss, delay and retransmission. Moreover, due to simultaneous communication and movement of various biosensor nodes, the wireless link between them disconnects. This link failure results in the increased loss of critical data packets. To minimize the link failure, various routing protocols are designed to explore a suitable route for on-demand (single-hop) and continuous data (multi-hop) [8].

However, the distance of a biosensor node to the sink node is proportional to its energy consumption. In a single-hop network, a distant biosensor node consumes more energy in data transmission and dies earlier than the node closer to the sink node [9].

Furthermore, the majority of the existing routing protocols focus on selecting end-to-end routes either using a single metric (temperature, energy and hop-count) or composite metrics (temperature with a hop-count, energy with hop-count) while overlooking QoS requirements for data delivery in terms of link quality. As route selection depends on the characteristics of the network, routing metrics must consider the network requirements, resource constraints, realistic interference model and time-varying characteristics of the wireless channel. Some routing protocols that take into account some of these characteristics are Expected Transmission Time (ETT) and Expected Transmission Count (ETX) for link quality metrics [10], [11].

However, the modern QoS demand, raised from the recent advancements in multimedia applications, has limited the adaptation of these routing metrics (ETX and ETT). ETX metric, estimated by forward and reverse delivery ratio [12], finds a route to transmit a minimum number of data packets to a destination node. ETX has a few limitations such as (i) it is not designed for a heterogeneous environment, (ii) it prefers shorter paths, (iii) it considers loss rate by assuming delivery ratio of forward and reverse data packets, and (iv) it does not consider network interference, bandwidth and mobility. ETT is the expected amount of time required for data packet transmission by considering bandwidth, packet size, link capacity, delay and loss ratio [13]. ETT performs well when there is no network interference. Both ETX and ETT overlook the interference issue while selecting routes.

We address these issues in this paper by proposing a routing protocol, referred to as MIQoS-RP, which selects an optimal end-to-end route by considering a composite metric such as., Link Quality Metric (LQM). LQM overcomes the limitation of both ETX and ETT metrics via Link Delay (LD), Link Interference Ratio (LIR) and Link Delivery Ratio (LDR). Our proposed scheme is the extension of our prior work on an Interference-aware Routing Protocol (I-RP) for WBAN [14]. I-RP estimates the surrounding interference via the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method. In contrast, MIQoS-RP uses a more realistic approach to estimate interference, delay and delivery ratio of a link for route selection.

The scientific contribution of this paper can be summarized as follows.

- We perform an in-depth, critical analysis of the existing routing protocols for WBAN and highlight their shortcomings. We further analyze the impact of interference on a WBAN under a high traffic load and demonstrate that the interference drastically deteriorates a WBSN's performance.
- We propose a multi-constraint, QoS-aware routing protocol for the healthcare application of WBAN to minimize end-to-end delay, packet drop ratio and retransmission rate in critical data transmission.
- We integrate a link quality metric with the route discovery scheme of the proposed routing protocol to optimize the route selection by considering multiple constraints such as link delay, link delivery ratio and link interference ratio.
- We evaluate the efficacy of the proposed protocol with that of the existing protocols and demonstrate that our proposed protocol has a superior performance.

The rest of the paper is organized as follows. Section 2 discusses the existing routing protocols for WBAN and highlights their limitations. Section 3 further describes the vulnerabilities of the existing WBAN routing schemes under interference. Section 4 gives an in-depth overview of our proposed routing protocol. Section 5 describes the experimental results. Section 6 concludes the paper.

II. RELATED WORK

QoS-aware routing not only discovers the optimal routes between two or more biosensor nodes, but also satisfies the QoS requirements of a wireless network. Many QoS-aware routing protocols have been proposed that consider temperature, hop-count and energy metrics for their route selection. A secure and temperature-aware routing protocol for WBSN, presented in [7], integrates the security primitive with thermal-aware routing to avoid hotspot nodes in the selected routes. Similarly, a priority-aware, distance vector routing protocol [15] uses hop-count with the transmission rate as a route selection metric.

Most of the routing protocols consider the intra-BAN communication to broadcast data to the sink node by using single-hop and multi-hop communication in a star or mesh topology. In a single-sink frame work, a sink node is deployed in the network [5], [16]. Whereas, in multi-sink frameworks, many sink nodes are deployed [17]–[19]. However, the transmission method can be either single (multi-hop) [20] or hybrid (single-hop and multi-hop) [21]. Multi-hop communication is widely used in WBSN to minimize energy consumption, network interference and excessive heat radiations from the batteries of the biosensor nodes. It also allows the network to adapt to some changes in the environment for better performance.

Most of the existing routing protocols for WBSN are energy and temperature constrained. Not only their route selection methods are not optimized, but they are also entirely based on either temperature or hop-count as cost function. In most cases, the power source is either inaccessible or is very difficult to replace which entails a rigorous energy optimization technique to save energy. To counter this limitation, various energy-aware routing protocols have been proposed in the past few decades which use multi-hop communication [5], [20], [22]. Some routing protocols consider a cost function metric (distance and remaining energy) for route selection [5], [21]–[25]. The least-cost function is used to select a forwarder node to transmit the clustered data towards the sink node. Other routing protocols consider a shortest-path routing algorithm for route selection [26]–[28]. Furthermore, a large number of routing protocols [6]–[8], [29]–[37] for WBSN also address the heating or hotspot issue. The routing mechanism of these routing protocol is limited to either selection of shortest routes (based on hop count) or indentifies hotspot nodes (based on temperature of nodes). However, these routing schemes do not optimize the route selection by keeping in view more realistic and dynamic conditions of network such as interference, QoS or link quality issues. Few WBSN routing protocols consider ETX [11], [38], [39] and ETT [10] link quality metrics for route selection.

The network interference problem is also explored in the literature [40]–[49]. In [49], an Interference Aware Multipath Routing (IAMR) protocol is proposed for Wireless Sensor Networks (WSNs). The IAMR uses two rounds of the request and reply cycles. In the first round, it discovers the shortest path from source to destination. In the second round, two routes are selected with minimum interference levels.

A more recent work classifies network interference and inter-network interference mitigation schemes for ZigBee-WBAN [48]. Interference Avoidance Algorithm (IAA) is proposed to prevent co-channel interference in WBAN [44]. Their proposed algorithm assumes a Flexible Time Division Multiple Access (FTDMA) mechanism between relays and coordinators. Other interference mitigation schemes, presented in [42], [43], consider multiple WBANs. Their designed channel assignment is based on the detection and prediction of social interaction.

From the relevant literature, it is evident that most of the existing routing protocols do not optimize the route selection. In most of the schemes, biosensor nodes select a minimum hop-count route to transmit the data packets to the sink node. To minimize the network overhead, most of the existing schemes discover routes based on the shortest time interval and shortest distance among biosensor nodes. However, the shortest route or shortest time interval is not appropriate solutions and lead to data loss without consideration of a suitable link quality metric. The selection of an unstable link can cause data retransmissions or data loss. Moreover, it is also observed that existing routing protocols do not integrate channel interference in route discovery decisions. Thus, they also lead to the selection of poor links for data transmission that do not satisfy the QoS requirements. On the other hand, channel interference severely affects the reliability, throughput and delay of a WBSN.

The highlighted issues entail the development of an efficient route discovery mechanism that can integrate the channel interference, link delay and link delivery ratio in route selection decisions in intra-BAN communication.

III. IMPACT OF INTERFERENCE ON WBAN

This section explains how the interference in the links compromises the benefits and creates a bottleneck in the performance of WBAN. The healthcare applications are extremely delay-sensitive which require critical data to reach an intended destination within the specified time limits. The information being delivered beyond the maximum allowed time may bring a detrimental impact on the overall system. We simulate a network scenario where three traffic flows with a high data rate (250 Kbps) generate a random and significant amount of traffic on the links. Figures 2 and 3 shows the substantial variations in the delay and throughput over time. It can be seen that as the traffic increases, it strains the communication channels, thereby affecting the flow of data. Moreover, it increases the probability of packet drop ratio and retransmissions. Furthermore, it results in an increased number of route maintenance calls that suspend the data forwarding activity and flood a high number of control packets in the network. These factors significantly contribute to the compromised network performance under high data rates (especially throughput and delay) as depicted by Figures 2 and 3. Hence, an effective routing scheme must

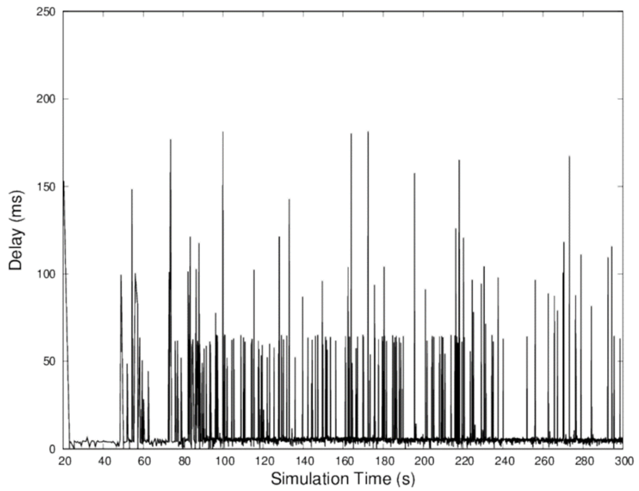

FIGURE 2. Substantial variations in the delay performance over time.

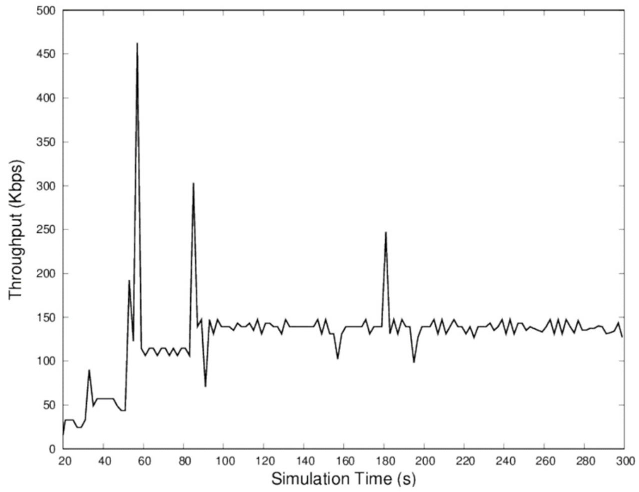

FIGURE 3. Substantial variations in throughput performance over time.

be devised that can counter the effects of the interference. The next section provides the detail of the proposed routing protocol.

IV. THE PROPOSED SCHEME

This section provides an in-depth overview of our proposed routing scheme for WBSN, referred to as MIQoS-RP, which comprises a network model and a multi-constraint, Intra-BAN QoS-aware routing mechanism.

A. NETWORK MODEL AND ASSUMPTIONS

The network architecture of the proposed Intra-WBSN consists of five small heterogeneous biosensor nodes, one sink node and ten relay/adjacent nodes that are randomly deployed in the network (as shown in Figure 4). Each sensor node interacts with other nodes via the multi-hop mesh topology and considers LQM for the route selection. In multi-hop, a source node interacts with the destination node through multiple routes, while the mesh topology provides a peer-to-peer communication session. If a biosensor node fails, the other nodes of the network continue to work.

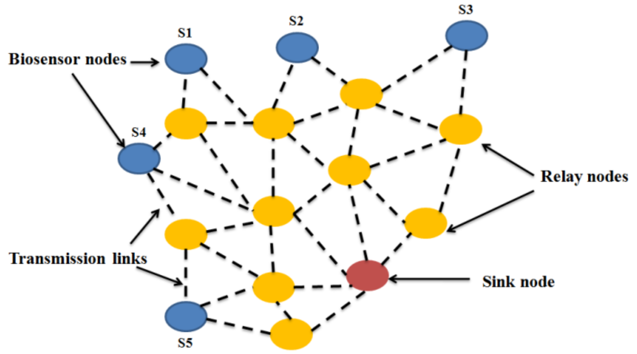

FIGURE 4. Network model of the proposed Intra-WBSN.

The proposed Intra-WBSN is represented by a Connectivity Graph, $CG = (N, K, LQM)$. Here, represents the group of all sensor nodes (biosensor and relay nodes) and is represented as $N = \{S_n \cup R_n$. S_n represents the class of all biosensor nodes $S_1, S_2, S_3, \ldots S_n$, and R_n indicates a class of all relay nodes $\{R_1, R_2, R_3, \ldots R_n\}$. K denotes the group of interaction links among various sensors and sink nodes. LQM signifies the link quality metric, used for the optimized route selection.

We use the following assumptions in the network model.

(i) The network does not have any inter-, extra-BAN communication, inter-network interference and mobility.
(ii) A biosensor and its adjacent nodes act as source and onward nodes respectively that broadcast the data packets to the destination node.
(iii) The biosensor nodes have sufficient energy for data transmission.

B. THE MULTI-CONSTRAINT, INTRA-BAN, QOS-AWARE ROUTING SCHEME

The proposed routing scheme is based on two phases, i.e., initialization phase and MIQoS-aware routing phase. Each segment is described in detail in the following sections.

C. INITIALIZATION PHASE

During the initialization phase, the biosensor nodes determine the number of adjacent nodes within their transmission range and evaluate the values such as LD, LDR and LIR for protocol operation. These values are estimated by exchanging some control packets until all the nodes evaluate and exchange the values with their adjacent nodes. The average LD between two adjacent nodes is determined by exchanging the hello packets to compute the time difference between the sent and received acknowledgment packets, as shown in Equation 1. The LDR is determined by the percentage of the sent and the acknowledged hello packets on a specified link (l), as shown in Equation 2.

$$LD_l = \frac{HelloPacket_{Ack} - HelloPacket_{sent}}{2} \tag{1}$$

$$LDR_l = \frac{Number\ of\ HelloPacket_{Ack}}{Number\ of\ HelloPacket_{sent}} \tag{2}$$

The low-power radios in WBAN are highly sensitive to interference and noise which strains the communication links and leads to high number of collisions, retransmissions and packet losses. Furthermore, it also reduces the data delivery capacity of WBAN that brings a significant impact on healthcare applications. Therefore, the dissemination of critical data packets requires the design of a realistic routing metric that incorporates link quality in pursuit of interference and noise. The proposed routing protocol introduces LIR that addresses this vulnerability by capturing a neighbor's (or surrounding) interference using a ratio between Signal to Interference Noise Ratio (SINR) and Signal to Noise Ratio (SNR). For instance, if l denotes a transmission link between two nodes S1 and R1, the Link Interference Ratio (LIR) for a node S1 in the link l is defined in Equation 3.

$$LIR_l = \frac{SINR_l(s_1)}{SNR_l(s_1)} \tag{3}$$

SINR and SNR are evaluated based on a packet's signal strength and data rate at which the node transmits the packets. The integrated outcome of Equation 1, 2, and 3 leads to the formation of LQM of a particular link which is the sum of LD_l, LDR_l and LIR_l as shown in Equation 4.

$$LQM_l = \sum\nolimits_{link \in r} (\min(LIR_l) + \min(LD_l) + \min((1 - LDR_l))) \tag{4}$$

A route satisfying the QoS requirements with *Min* (LQM_l) is selected as an optimal route which has minimum delay and interference and increased delivery ratio on the link l.

D. MIQoS-AWARE ROUTING PHASE

The proposed QoS-aware routing scheme extends the routing procedure of the traditional routing protocol, such as, Ad-hoc On-demand Distance Vector (AODV),by which the hop-count metric is replaced with an optimized routing metric (LQM). The AODV is an on-demand or reactive routing protocol which discovers a route from a source to the destination only when it is required. In the route discovery stage, the Route Request (RREQ) packet is transmitted to the nodes adjacent to source until it finds the destination node (as shown in Figure 5). The RREQ packet consists of some attributes such as sender and receiver sequence number, sender and receiver IP address, hop-count and broadcast ID. When the adjacent node receives a RREQ packet, it creates a reverse Route Reply (RREP) packet while it discards the redundant RREQ packets. At last, the destination node creates a reverse minimum hop-count by a RREP packet to the source node immediately after receiving the RREQ packet.

As shown in Figures 5 and 6, the network model comprises the biosensors (S1-S5), relays (R1-R10) and a sink node. The route selection procedure is initiated by S1 node. S1 transmits the RREQ packet to every relay node until it reaches the sink node. When the sink node receives the RREQ packet, it generates the RREP packet to S1 by constructing a reverse minimum hop-count route Sink→R7→R2→S1. However, in MIQoS-RP, the traditional RREP and RREQ packets are modified to incorporate LIR, LD and LDR in routing decisions. Moreover, this strategy of multi-facet routing makes a more informed decision in terms of the transmission link delay, interference and delivery ratio. Algorithm-1 describes the overall process of the proposed routing protocol. During the initialization phase in MIQoS-RP, the values of LD, LIR and LDR are computed and are added to the RREP packet. The route selection procedure is initiated by S1 node. S1 transmits the RREQ packet to every relay node until it reaches the sink node. When the sink node receives the RREQ packet, it generates the RREP packet for S1. S1 might get several RREPs via several routes and calculates the LQM cost (for each of the notified route). The route with the minimized cost Sink→R9→R7→R2→R1→S1 is selected that ensures the QoS demands thereby leading to improved network performance as shown in Figure 6.

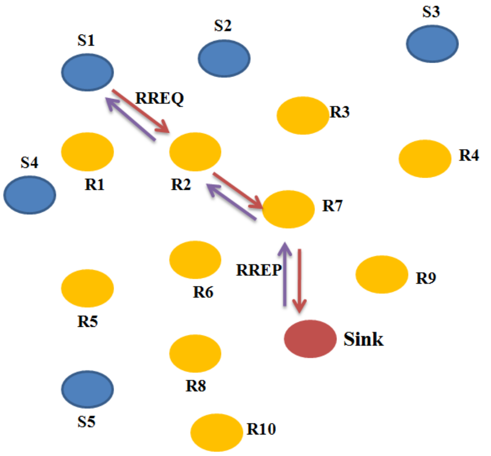

FIGURE 5. **Route selection mechanism of AODV routing protocol.**

V. RESULTS AND DISCUSSION

This section presents the simulation results of the proposed scheme. The proposed scheme is simulated using NS-2 and the simulation parameters are given in Table 1. The efficacy of the proposed MIQoS-RP is observed under heavy network loads (50 – 250 Kbps) to fairly examine the impact of congestion/interference on the links. The overall performance is assessed through average end-to-end delay, throughput and packet drop ratio.

All biosensor nodes are deployed in the same configuration as shown in Figure 4. Figure 7, 8 and 9 show the performance comparison of the proposed MIQoS-RP and the existing routing schemes. The simulation outcomes demonstrate that the MIQoS-RP shows a better performance as compared to TTRP

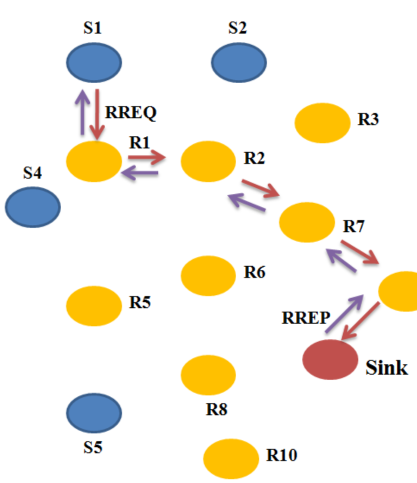

FIGURE 6. Route selection mechanism of MIQoS-RP.

TABLE 1. Simulation parameters.

Parameters	Values
Deployment Area	2m x 2m
Sink node	1
Biosensor nodes	5
Relay nodes	10
Propagation model	TwoRayGround
Transmission range of nodes	50cm
Network interface type	WirelessPhy
IEEE 802.15.4 standard	Default values
Traffic type	CBR
Transport layer protocol	UDP
Traffic Load	50,100,150,200,250 kbps
Packet Size	100 bytes
Simulation Time	1000 seconds
Routing Protocols	MIQoS-RP, PA-AODV and TTRP

and PA-AODV. The route selection mechanism of TTRP is focused on energy efficiency and temperature awareness. Similarly, PA-AODV is based on QoS and makes use of transmission rate and hop-count for route selection. Figure 7 further shows that MIQoS-RP achieves a higher throughput compared to TTRP and PA-AODV schemes. As the network load increases, the supply of data traffic also increases in the network, therefore, initially all schemes shows increased throughput. However, when the throughput reaches the saturation stage, it starts to decline. Since TTRP and PA-AODV cannot deal with high traffic load, their throughput starts plummeting. The increased network traffic strains the communication channels and hinders the flow of data packets which also affects the throughput performance. MIQoS-RP makes a more informed decision regarding surrounding interference using LIR, thereby leading to the selection of the links having least interference. As a result, the flow of the data packets remains consistent and significantly contributes to an improved throughput.

Algorithm 1 MIQoS-Aware Route Discovery Scheme

```
Begin
Set $n_{curr} \leftarrow$ Current node
Set $n_{prev} \leftarrow$ Upstream node
Set $n_{next} \leftarrow$ Downstream node
Set pkt $\leftarrow$ Control/Data packet
Set $l_{curr} \leftarrow$ Current link
Set $l_{neigh} \leftarrow$ Neighbor link
Set LD $\leftarrow$ Link Delay
Set LDR $\leftarrow$ Link Delivery Ratio
Set LIR $\leftarrow$ Link Interference Ratio
Set LQM $\leftarrow$ Link Quality Metric
  procedure route discovery
  while link exists do
    Broadcast the RREQ pkt
        Intermediate node $n_{curr}$ receives pkt from upstream.node $n_{prev}$
    Call sub procedure LQM
        Consult routing table for next hop node to the destination
    if no link to destination exists, then
        Call procedure route discovery
    else
        Drop pkt
    return
    end if
end while
//When an Intermediate node receives RREQ packet
//Check whether it is the destination of the route request
  if Intermediate node is destination node, then
    Send acknowledgment pkt
  else
        Rebroadcast and update RREQ pkt
        to it's downstream $n_{next}$ adjacent node
    Call sub procedure LQM
        Consult routing table for next hop node
        to the destination
  end if
  end procedure
  sub procedure LQM
  while link is active do
    Compute the values of $LD_l$, $LDR_l$ and $LIR_l$ for $LQM_l$
    $LD_l = \frac{HelloPacket_{Ack} - HelloPacket_{sent}}{2}$
$LDR_l = \frac{Number\ of\ HelloPacket_{Ack}}{Number\ of\ HelloPacket_{sent}}$
    $LIR_l = \frac{SINR_l(s_1)}{SNR_l(s_1)}$
        if $LDl_{curr} < LDl_{neigh}$ && $LIRl_{curr} < LIRl_{neigh}$ && $LDRl_{curr} > LDRl_{neigh}$ then
      $LQMl_{curr} = \sum_{link \in r}(LIRl_{curr} + LDl_{curr} + LDRl_{curr})$
      Selects Min $(LQM_{l_{curr}})$
else
  Select alternate link as $l_{curr}$ and find the values
      of $LD_l$, $LDR_l$ and $LIR_l$ for $LQM_{l_{curr}}$
end if
  end while
  end sub procedure
  End
```

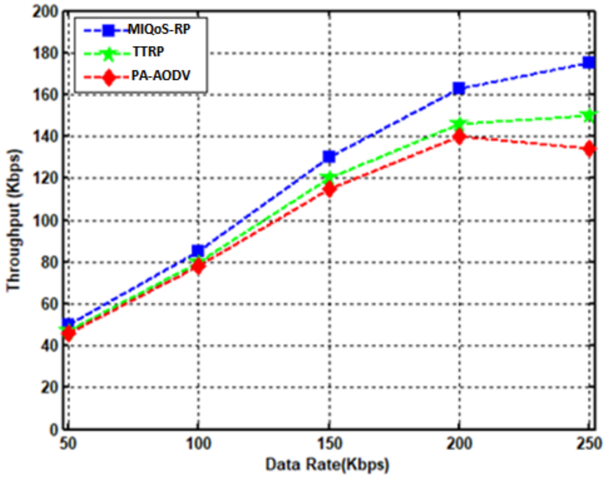

FIGURE 7. Throughput at various transmission rates.

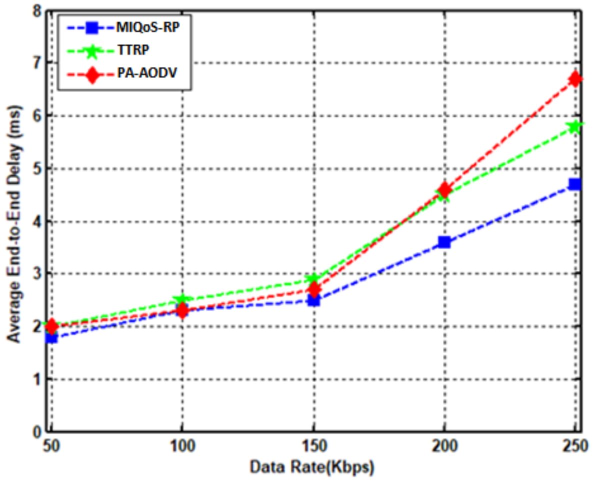

FIGURE 8. Average end-to-end delay at various transmission rates.

Figure 8 shows the performance evaluation of MIQoS-RP, TTRP and PA-AODV in terms of average end-to-end delay. Both TTRP and PA-AODV exhibit an increased number of retransmissions under intense data traffic, consequently, leading to a high delay. Moreover, the increased number of route maintenance calls suspends the data forwarding activity that also affects the throughput and delay performances.

Figure 9 shows the performance evaluation of MIQoS-RP, TTRP and PA-AODV in terms of packet drop ratio. As mentioned earlier, the increased traffic load strains the communication channel, leading to a high number of retransmissions, therefore, it also contributes to a high number of packet drops. The route selection metric LQM incorporates the LDR in route selection which keeps a record of packet delivery ratio on each of the links. Hence, the proposed routing protocol discovers the link with decreased packet drop ratio and increased packet delivery ratio.

From the simulation results, it is evident that the proposed routing scheme is capable of selecting an optimal route which, in turn, results in more stable communication links and significantly improves the network performance in terms of delay, reliability and throughput. The results show that MIQoS-RP achieves improved throughput by 12% and 22%, average end-to-end delay by 18% and 29%, and packet drop ratio performance by 30% and 41% at 250 kbps as compared to the TTRP and PA-AODV respectively.

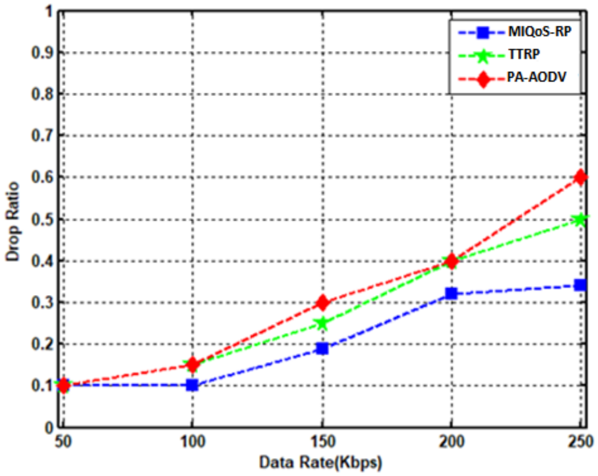

FIGURE 9. Packet drop ratio at various transmission rates.

VI. CONCLUSION

The healthcare applications of WBSN entail a timely and reliable delivery of critical data pertaining to patients. The routing protocols designed in this context are primarily focused on selecting optimal routes for reliable data transmission and maintaining a desired QoS level. However, the WBSN network performance is constrained by link quality and channel interference which adversely affect the network's throughput, data delivery time, and packet drop ratio.

In this paper, we have addressed these issues by proposing a multi-constraint, QoS-aware routing protocol, referred to as MIQoS-RP, which addresses the problem of route discovery with the constraints of high delivery ratio, less network interference and delay. The simulation results presented in the paper demonstrate that compared to the existing routing protocols, such as PA-AODV and TTRP, our proposed routing protocol exhibits a much better performance by maintaining a satisfactory level QoS level.

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REFERENCES

[1] F. T. Zuhra, K. A. Bakar, A. Ahmed, and M. A. Tunio, "Routing protocols in wireless body sensor networks: A comprehensive survey," *J. Netw. Comput. Appl.*, vol. 99, pp. 73–97, Dec. 2017.

[2] B. Abidi, A. Jilbab, and M. E. Haziti, "Wireless sensor networks in biomedical: Wireless body area networks," in *Europe and MENA Cooperation Advances in Information and Communication Technologies*. Cham, Switzerland: Springer, 2017, pp. 321–329.

[3] J. Shen, S. Chang, J. Shen, Q. Liu, and X. Sun, "A lightweight multi-layer authentication protocol for wireless body area networks," *Future Gener. Comput. Syst.*, vol. 78, pp. 956–963, Jan. 2018.

[4] M. M. Hassan, K. Lin, X. Yue, and J. Wan, "A multimedia healthcare data sharing approach through cloud-based body area network," *Future Gener. Comput. Syst.*, vol. 66, pp. 48–58, Jan. 2017.

[5] V. Ayatollahitafti, M. A. Ngadi, J. B. M. Sharif, and M. Abdullahi, "An efficient next hop selection algorithm for multi-hop body area networks," *PLoS ONE*, vol. 11, no. 1, Jan. 2016, Art. no. e0146464.

[6] G. R. Kanagachidambaresan and A. Chitra, "TA-FSFT thermal aware fail safe fault tolerant algorithm for wireless body sensor network," *Wireless Pers. Commun.*, vol. 90, no. 4, pp. 1935–1950, Oct. 2016.

[7] A. R. Bhangwar, P. Kumar, A. Ahmed, and M. I. Channa, "Trust and thermal aware routing protocol (TTRP) for wireless body area networks," *Wireless Pers. Commun.*, vol. 97, no. 1, pp. 349–364, Nov. 2017.

[8] N. Javaid, Z. Abbas, M. S. Fareed, Z. A. Khan, and N. Alrajeh, "M-ATTEMPT: A new energy-efficient routing protocol for wireless body area sensor networks," *Procedia Comput. Sci.*, vol. 19, pp. 224–231, Jan. 2013.

[9] F. Ullah, A. H. Abdullah, M. Q. Jan, and K. N. Qureshi, "Patient data prioritization in the cross-layer designs of wireless body area network," *J. Comput. Netw. Commun.*, vol. 2015, pp. 1–21, Nov. 2015.

[10] L. Zhou, B. Zheng, J. Cui, and B. Geller, "Media-aware distributed scheduling over wireless body sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2011, pp. 1–5.

[11] L. Liang, Y. Ge, G. Feng, W. Ni, and A. A. P. Wai, "A low overhead tree-based energy-efficient routing scheme for multi-hop wireless body area networks," *Comput. Netw.*, vol. 70, pp. 45–58, Sep. 2014.

[12] D. S. J. D. Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Wireless Netw.*, vol. 11, no. 4, pp. 419–434, Jul. 2005.

[13] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. 10th Annu. Int. Conf. Mobile Comput. Netw. MobiCom*, 2004, pp. 114–128.

[14] A. Ahmed, I. A. Halepoto, U. A. Khan, S. Kumar, and A. R. Bhangwar, "I-RP: Interference aware routing protocol for WBAN," in *Proc. Int. Conf. Mobile Web Intell. Inf. Syst.*, 2018, pp. 63–71.

[15] J. K. Jayabarathan, A. Sivanantharaja, and S. Robinson, "Quality of service enhancement of mobile adhoc networks using priority aware mechanism in AODV protocol," *Wireless Pers. Commun.*, vol. 96, no. 4, pp. 5897–5909, Oct. 2017.

[16] M. M. Monowar, M. Mehedi Hassan, F. Bajaber, M. A. Hamid, and A. Alamri, "Thermal-aware multiconstrained intrabody QoS routing for wireless body area networks," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 3, Mar. 2014, Art. no. 676312.

[17] Z. Khan, S. Sivakumar, W. Phillips, and B. Robertson, "QPRD: QoS-aware peering routing protocol for delay sensitive data in hospital body area network communication," in *Proc. 7th Int. Conf. Broadband, Wireless Comput., Commun. Appl.*, Nov. 2012, pp. 178–185.

[18] Z. A. Khan, S. Sivakumar, W. Phillips, and B. Robertson, "A QoS-aware routing protocol for reliability sensitive data in hospital body area networks," *Procedia Comput. Sci.*, vol. 19, pp. 171–179, Jan. 2013.

[19] Z. Ullah, I. Ahmed, K. Razzaq, M. K. Naseer, and N. Ahmed, "DSCB: Dual sink approach using clustering in body area network," *Peer-to-Peer Netw. Appl.*, vol. 12, no. 2, pp. 1–14, 2017.

[20] T. Rashid, S. Kumar, A. Verma, P. R. Gautam, and A. Kumar, "Pm-EEMRP: Postural movement based energy efficient multi-hop routing protocol for intra wireless body sensor network (Intra-WBSN)," *TELKOMNIKA (Telecommun. Comput. Electron. Control)*, vol. 16, no. 1, p. 166, Feb. 2018.

[21] N. Javaid, A. Ahmad, Q. Nadeem, M. Imran, and N. Haider, "IM-SIMPLE: IMproved stable increased-throughput multi-hop link efficient routing protocol for wireless body area networks," *Comput. Hum. Behav.*, vol. 51, pp. 1003–1011, Oct. 2015.

[22] N. Kaur and S. Singh, "Optimized cost effective and energy efficient routing protocol for wireless body area networks," *Ad Hoc Netw.*, vol. 61, pp. 65–84, Jun. 2017.

[23] R. Kachroo and D. R. Bajaj, "A novel technique for optimized routing in wireless body area network using genetic algorithm," *J. Netw. Commun. Emerg. Technol.*, vol. 2, pp. 90–97, Apr. 2015.

[24] B. Shilpa, S. G. Hiremath, and G. Thippeswamy, "ERM: Efficient routing mechanism to route data in wireless body sensor networks," *Int. J. Appl. Innov. Eng. Manage.*, vol. 6, no. 3, pp. 135–141, 2017.

[25] S. Ahmed, N. Javaid, M. Akbar, A. Iqbal, Z. A. Khan, and U. Qasim, "LAEEBA: Link aware and energy efficient scheme for body area networks," in *Proc. IEEE 28th Int. Conf. Adv. Inf. Netw. Appl.*, May 2014, pp. 435–440.

[26] R. Satyaprasad and K. Rajasekhararao, "Detecting and preventing black hole and wormhole attacks in wireless biosensor network using path assignment protocol," *Biomed. Res.*, Special Issue, pp. 204–209, 2016.

[27] S. Ahmed, N. Javaid, S. Yousaf, A. Ahmad, M. M. Sandhu, M. Imran, Z. A. Khan, and N. Alrajeh, "Co-LAEEBA: Cooperative link aware and energy efficient protocol for wireless body area networks," *Comput. Hum. Behav.*, vol. 51, pp. 1205–1215, Oct. 2015.

[28] E. Ben Hamida, M. M. Alam, M. Maman, and B. Denis, "Short-term link quality estimation for opportunistic and mobility aware routing in wearable body sensors networks," in *Proc. IEEE 10th Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2014, pp. 519–526.

[29] J. I. Bangash, A. H. Abdullah, M. A. Razzaque, and A. W. Khan, "Reliability aware routing for intra-wireless body sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 10, Oct. 2014, Art. no. 786537.

[30] J. I. Bangash, A. W. Khan, and A. H. Abdullah, "Data-centric routing for intra wireless body sensor networks," *J. Med. Syst.*, vol. 39, no. 9, p. 91, Sep. 2015.

[31] M. Monowar and F. Bajaber, "On designing thermal-aware localized QoS routing protocol for *in-vivo* sensor nodes in wireless body area networks," *Sensors*, vol. 15, no. 6, pp. 14016–14044, Jun. 2015.

[32] S. Javaid, Z. Wu, H. Fahim, M. M. S. Fareed, and F. Javed, "Exploiting temporal correlation mechanism for designing temperature-aware energy-efficient routing protocol for intrabody nanonetworks," *IEEE Access*, vol. 8, pp. 75906–75924, 2020.

[33] O. Ahmed, F. Ren, A. Hawbani, and Y. Al-Sharabi, "Energy optimized congestion control-based temperature aware routing algorithm for software defined wireless body area networks," *IEEE Access*, vol. 8, pp. 41085–41099, 2020.

[34] A. R. Bhangwar, A. Ahmed, U. Ali Khan, T. Saba, K. Almustafa, K. Haseeb, and N. Islam, "WETRP: Weight based energy & temperature aware routing protocol for wireless body sensor networks," *IEEE Access*, vol. 7, pp. 87987–87995, 2019.

[35] F. Jamil, M. A. Iqbal, R. Amin, and D. Kim, "Adaptive thermal-aware routing protocol for wireless body area network," *Electronics*, vol. 8, no. 1, p. 47, Jan. 2019.

[36] A. A. Ibrahim, O. Bayat, O. N. Ucan, and S. A. Eleruja, "EN-NEAT: Enhanced energy efficient threshold-based emergency data transmission routing protocol for wireless body area network," in *Proc. 3rd Int. Congr. Inf. Commun. Technol.*, 2019, pp. 325–334.

[37] K. S. Kathe and U. A. Deshpande, "A thermal aware routing algorithm for a wireless body area network," *Wireless Pers. Commun.*, vol. 105, no. 4, pp. 1353–1380, Apr. 2019.

[38] L. Liang, Y. Ge, G. Feng, W. Ni, and A. Aung Phyo Wai, "Experimental study on adaptive power control based routing in multi-hop wireless body area networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 572–577.

[39] E. Sarra, S. Benayoune, H. Moungla, and A. Mehaoua, "Coexistence improvement of wearable body area network (WBAN) in medical environment," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 5694–5699.

[40] Z. Zhang, H. Wang, C. Wang, and H. Fang, "Interference mitigation for cyber-physical wireless body area network system using social networks," *IEEE Trans. Emerg. Topics Comput.*, vol. 1, no. 1, pp. 121–132, Jun. 2013.

[41] E.-J. Kim, S. Youm, T. Shon, and C.-H. Kang, "Asynchronous inter-network interference avoidance for wireless body area networks," *J. Supercomput.*, vol. 65, no. 2, pp. 562–579, Aug. 2013.

[42] S. Movassaghi, M. Abolhasan, D. Smith, and A. Jamalipour, "AIM: Adaptive internetwork interference mitigation amongst co-existing wireless body area networks," in *Proc. IEEE Global Commun. Conf.*, Dec. 2014, pp. 2460–2465.

[43] S. Movassaghi, M. Abolhasan, and D. Smith, "Smart spectrum allocation for interference mitigation in wireless body area networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 5688–5693.

[44] M. Jaafar Ali, H. Moungla, and A. Mehaoua, "Interference avoidance algorithm (IAA) for multi-hop wireless body area network communication," 2016, *arXiv:1602.08658*. [Online]. Available: http://arxiv.org/abs/1602.08658

[45] A. Mile, G. Okeyo, and A. Kibe, "Hybrid IEEE 802.15. 6 wireless body area networks interference mitigation model for high mobility interference scenarios," *Wireless Eng. Technol.*, vol. 9, p. 34, Apr. 2018.

[46] S. Adhikary, S. Chattopadhyay, and S. Choudhury, "A novel bio-inspired algorithm for increasing throughput in wireless body area network (WBAN) by mitigating inter-WBAN interference," in *Advanced Computing and Systems for Security*. Singapore: Springer, 2018, pp. 21–37.
[47] A. Meharouech, J. Elias, and A. Mehaoua, "A two-stage game theoretical approach for interference mitigation in Body-to-Body networks," *Comput. Netw.*, vol. 95, pp. 15–34, Feb. 2016.
[48] M. F. Shaik, V. L. N. Komanapalli, and M. M. Subashini, "A comparative study of interference and mitigation techniques in wireless body area networks," *Wireless Pers. Commun.*, vol. 98, no. 2, pp. 2333–2365, Jan. 2018.
[49] Z. Wang and J. Zhang, "Interference aware multipath routing protocol for wireless sensor networks," in *Proc. IEEE Globecom Workshops*, Dec. 2010, pp. 1696–1700.

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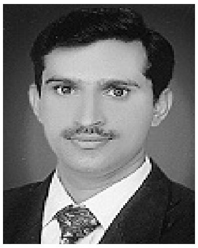

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