Received 4 November 2020; revised 12 December 2020; accepted 23 December 2020. Date of publication 1 January 2021; date of current version 28 January 2021.

Digital Object Identifier 10.1109/OJCOMS.2020.3047888

Cross-Layer MAC/Routing Protocol for Reliable Communication in Internet of Health Things

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This work was supported in part by the Victoria University Sydney Campus, and in part by the Yayasan UTP Fundamental Research Grant (YUTP-FRG) under Grant 015LC0-039.

ABSTRACT Internet of Health Things (IoHT) involves intelligent, low-powered, and miniaturized sensors nodes that measure physiological signals and report them to sink nodes over wireless links. IoHTs have a myriad of applications in e-health and personal health monitoring. Because of the data's sensitivity measured by the nodes and power-constraints of the sensor nodes, reliability and energy-efficiency play a critical role in communication in IoHT. Reliability is degraded by the increase in packets' loss due to inefficient MAC, routing protocols, environmental interference, and body shadowing. Simultaneously, inefficient node selection for routing may cause the depletion of critical nodes' energy resources. Recent advancements in cross-layer protocol optimizations have proven their efficiency for packet-based Internet. In this article, we propose a MAC/Routing-based Cross-layer protocol for reliable communication while preserving the sensor nodes' energy resource in IoHT. The proposed mechanism employs a timer-based strategy for relay node selection. The timer-based approach incorporates the metrics for residual energy and received signal strength indicator to preserve the vital underlying resources of critical sensors in IoHT. The proposed approach is also extended for multiple sensor networks, where sensor in vicinity are coordinating and cooperating for data forwarding. The performance of the proposed technique is evaluated for metrics like Packet Loss Probability, End-To-End delay, and energy used per data packet. Extensive simulation results show that the proposed technique improves the reliability and energy-efficiency compared to the Simple Opportunistic Routing protocol.

INDEX TERMS Internet of Health Things (IoHT), wireless communication, cross-layer protocols, wireless body area networks (WBAN), opportunistic routing, MAC protocols, energy efficiency, reliability, relay-selection.

I. INTRODUCTION

THE INTERNET of Health Things (IoHT) are an extension of Internet of Things (IoT) dedicated for sensing physiological signals from patients and elderly for eHeatlh applications. The IoHTs also include a vital sensor technology in e-health related applications for remote and local monitoring of the patient and elderly [1]. In IoHTs, sensors are used to sense physiological signals from the human body and send it to a local server or remote server over multiple links and nodes. These small sensors are resource-constrained nodes attached to human-body in an invasive and non-invasive manner to measure different human-body states for healthcare or elderly-care-based applications. Depending on the condition being monitored, the role of reported data by sensors plays a crucial role in saving lives and road to a healthy recovery. Therefore, the signals sensed by the sensors and data communicated are of critical importance [2]. Moreover, these sensor nodes are smaller in number than Wireless Sensor Networks (WSN), where sensor nodes are quite in abundance, hence the power resource of each sensor node in IoHT is of critical importance [3].

IoHTs have many applications in different sectors of the military, healthcare industry, sports, psychology, aged-care homes, and entertainment industry [4]. For instance, in the military, IoHTs can be used for intelligence, command and control, surveillance, and several other tasks. In industry, IoHTs can help in managing inventory, product quality control, and security authentication systems. In entertainment, IoHTs can help audio-video transmission and interfacing with human body movements and gestures, e.g., wearable audio-video devices and new generation video gaming systems. In sports, IoHTs can assist in monitoring the athlete's activity, e.g., pulse rate, calories burned, fat to muscle percentage, and body humidity content. Wearable IoHTs are comprised of body sensor nodes in order to monitor and report various physiological conditions for humans. These body sensors forming a wireless network are called Wireless Body Area Networks (WBAN). Because of close relevance and applicability of proposed work for WBANs and IoHTs, we will be using these terminologies interchangeably.

The sensors in IoHTs are connected via a wireless channel and are actively sensing and reporting various signals from the human body. Different types of sensor nodes can exist in a IoHT. On-body sensors reside on the body, and implanted sensors are placed inside the body [5]. These sensor nodes can act as source nodes to send the sensed data. Any of the sensor nodes in the network can act as a relay to forward the data received from other sensors towards the Internet or sink node. In a centralized architecture, the sink node is responsible for local data collection and then forwarding it to the server, whereas, relay node plays the role of a bridge for other nodes in both centralized and distributed architecture [6]. The standards for WBANs in IoHTs have been developed by IEEE 802.15.6 Task Group [7]. The considered realization of IoHTs is shown in Fig. 1.

Reliable and energy-aware communication for sensors is a vital performance metric in IoHTs [8], [9]. The unreliable and energy-unaware communication in IoHTs may disrupt or hamper with the data collected by body sensors on a patient, which may cause severe effects and have life-endangering consequences. The hospital staff may not be notified in a sufficient amount of time about the patient's alarming situation, which may hinder proper monitoring. For more details of dependability issues in IoHTs and essential factors, readers are referred to the survey presented in [9]. The use of IoHTs in medical and elderly aged-care applications demands for reliability and long-lasting power, where critical conditions and medical conditions need to be monitored remotely.

For successful and reliable communications, the impact of environmental interference and body shadowing should be minimized. Body shadowing can negatively affect the performance of sensor nodes in IoHT [10]. The communication between front and back body sensors may not be feasible in a IoHT [11]. The simple solution of increasing the transmit power may not be an appropriate solution in the case of IoHTs. The reason behind this is the requirements of the extended lifetime of sensor nodes and efficient power consumption, and the limitations of Specific Absorption Rate (SAR) [12]. However, relay nodes can be used for reliable communication in IoHTs [13], [14]. In relay-assisted communication for WBANs and IoHTs, there are proactive and reactive modes of relaying [15]. In pro-active modes, specific (opportunistic) sensor nodes are selected as relays to forward the data, whereas, in reactive modes, all neighboring nodes serve as relays at some point.

The relaying is an essential mechanism in ad-hoc WSN in general, and in IoHTs in particular, as relays consume significantly higher power, hence with decreasing lifetime. The outage behavior of various relaying schemes from PHY and MAC perspective are well studied in [16]. Furthermore, relays are proven to be an efficient forwarding mechanism in IoHTs if used adequately considering the underlying resources of the nodes [17]. However, redundant nodes can not be deployed solely for the purpose of relaying as it may not be satiable for the subjects as well to have several sensor nodes. Therefore, the use of an intelligent relay selection mechanism paves the way for having one relay with optimal performance [18]. This puts emphasis on intelligent and smart relay selection mechanisms. The use of relays also paves the way to avoid packet redundancy, the need for retransmissions and depletion of network resources for repeated transmission. The cooperative and coordinated relay selection mechanism, that considers the underlying node resources, not only increases the network lifetime, but also is a good solution for efficient load management.

Another simple packet routing based mechanism is known as broadcast flooding, where each node broadcasts their packets to their neighbors to be forwarded toward the sink node. Although, this simple solution increases the success probability of received packets at the sink node but at the cost of heavy packet redundancy. Such redundant packets incur significant costs on limited network resources. Moreover, such a solution may make the routing job easier but it may increase packet collisions and causes significant contention issues at MAC layer [19]. Thus, such MAC-unaware routing based protocols might not be effective as it has been previously, until the introduction of cross-layer protocols for wireless networks [20]. The cross-layer protocols are efficient solutions where the network and MAC layer present a unified framework to elevate the overall system's performance. The cross-layer protocols employ efficient packet forwarding decisions in conjunction with traffic, congestion, and contention conditions.

In this article, we propose an opportunistic MAC/Routing cross layer protocol to improve the reliability by using a timer-based approach for the relay selection mechanism, which is an extension of our work proposed earlier in [21]. In this work, we have extended Cross-layer Opportunistic MAC/Routing (COMR) protocol for IoHT scenario where multiple WBANs are considered. This work specifically considered IoHTs where multiple WBANs can coordinate

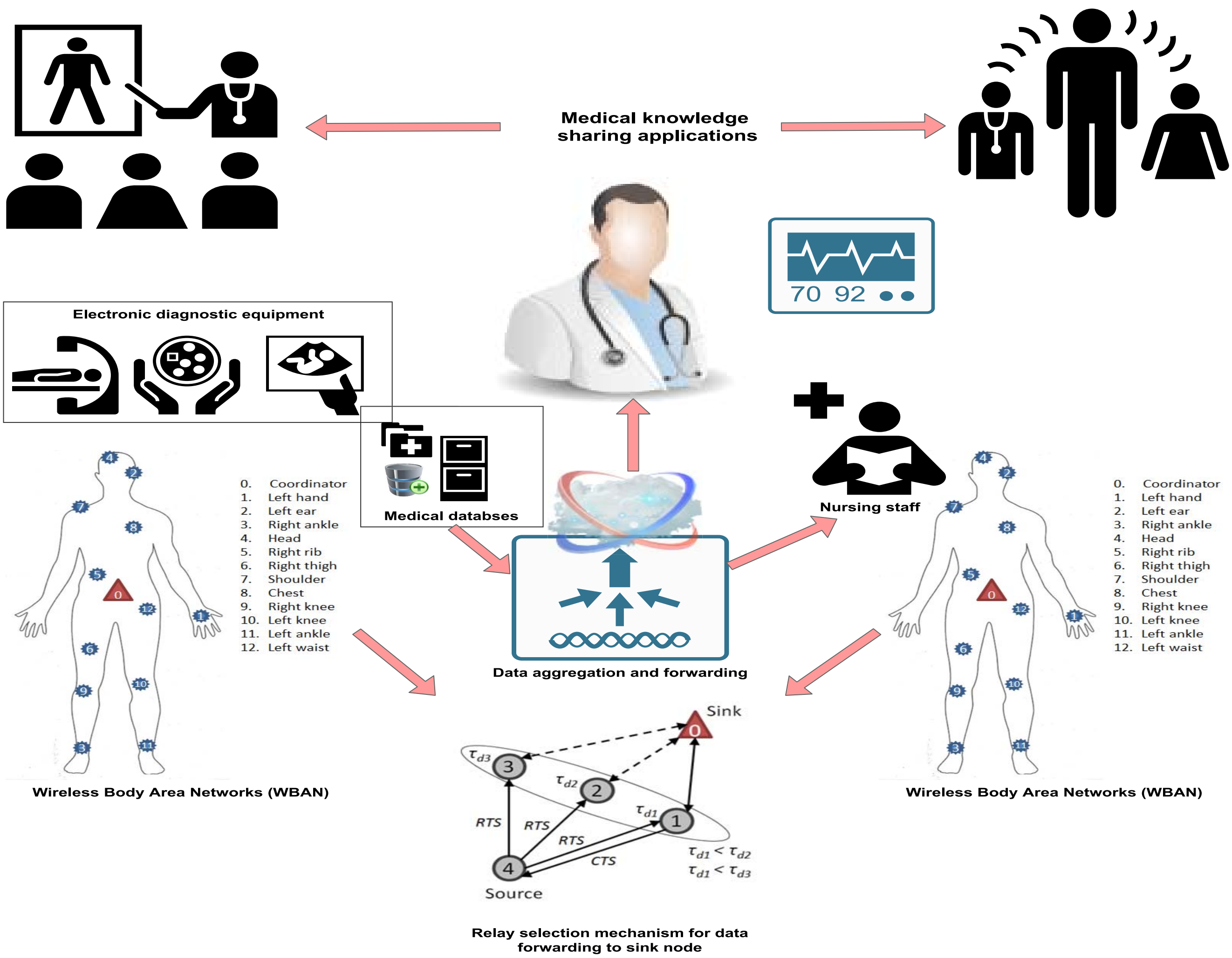

FIGURE 1. The realization of considered sensor networks in Internet of Health Things, where local sensor sense physiological signals of the subject to nearby sink/relay node for data forwarding.

for data forwarding. The key idea is to use timer-based approach to smartly select the appropriate relay sensor node for data forwarding. The timer-based approach incorporates the metrics for residual energy and Received Signal Strength Indicator (RSSI). The neighboring nodes of the source wait for a timer value before sending a Clear-To-Send (CTS) packet in response to a Request-To-Send (RTS) packet. The value of this timer will be smallest for the sensor node, that has the maximum amount of remaining battery and also is closest to the sink node. The first node to reply will be selected as the relay node. The performance metrics for the analysis are network lifetime, Packet Loss Probability (PLP), End-To-End (ETE) delay, and energy used per data packet. We simulate the proposed protocol for two different environments: (1) WBAN; (2) Multiple WBAN (multi-WBAN). The multi-WBAN setup is a realization of IoHT setup where extended sensor nodes coordinate to relay the data. Furthermore, multi-WBAN implementation has intra-WBAN and inter-WBAN scenarios. Relay nodes of different IoHTs may and may not help each other in inter-WBAN and intra-WBAN, respectively. Simulation results show that COMR elevates the reliability of WBAN and multi-WBAN in comparison to Simple Opportunistic Routing (SOR). In multi-WBAN, the inter-WBAN performs better than the intra-WBAN in terms of reliability.

The organization of the remainder of this article is as follows. Section II presents the discussions on related work. In Section III, we explain the COMR protocol, followed by energy consumption calculations and performance metrics. In Section IV, we describe the simulation models and analyze the results for IoHTs (i.e., WBAN and multi-WBAN) scenarios. In the end, we conclude this work in Section V.

II. RELATED WORK

In [22], the authors have proposed a reliable WBAN model using network coding and targeting throughput as the major performance metric. In [23], [24], the authors have evaluated the performance of Simple Opportunistic Routing (SOR) protocol for WBAN, and the results show that reliability is improved. In [24], further investigation has been done on the performance of SOR in WBAN with different path loss models. However, the random relay selection mechanism does not guarantee improvement in reliability. Thus, an intelligent and smart relay selection mechanism that cares for limited underlying resources of sensors is required.

Multi-WBANs have been analyzed in [25], [26], but the authors focused only on security issues related to intra-WBAN and inter-WBAN communication. The wireless sensors based system has been developed and tested for a multiple patient environments in [27]. A simple Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) based medium access control (MAC) communication protocol was used to send the physiological signals to the sink node. In [28], the authors have used on-body opportunistic relaying to improve coexistence and interference mitigation in WBANs. The authors have studied ETE reliability of vital signs to monitor a patient using multiple WBANs in [29]. The proposed solution provides mobility support and prioritizes the vital signs transmission. However, the methodology has not been explained in detail.

In [30], a routing protocol for ad-hoc wireless networks was proposed, which used a normalized remaining battery life-based cost function. The relay node is not selected for routing if its battery life is less than 20%. Another approach that considered multiple parameters like remaining power, transmission power, and the probability of re-transmission were proposed in [31] for energy-aware routing in ad-hoc networks. An additive routing metric based on normalized residual energy and normalized transmission power was proposed in [32]. Two weights were used in the additive metric equation that may be adjusted to favor either of the two terms. A Minimum Battery Cost Routing (MBCR) approach, which considers normalized residual battery, was proposed in [33]. The disadvantage of this technique was that the metric was used for a full routing path, and the best path may contain sensors which has very low remaining battery power. A concave metric named as Minimum-Maximum battery Cost Routing (MMBCR) to avoid low battery capacity paths and to minimize transmit power consumption was proposed for mobile ad-hoc networks in [34]. The authors in [35], [36] and [37] also developed routing metrics which included residual energy. In [38], the authors proposed a concave routing metric based on hop count, transmission power, and residual energy for ad-hoc wireless networks. Authors in [39] considered residual energy as a cost for routing metric in mobile ad-hoc networks and suggested to avoid relay nodes having residual energy lower than 10%. Another work in [40] proposes iM-SIMPLE routing protocol which considers the cost function based on high residual energy and proximity to sink node as cost function.

Authors in [41] use RSSI value to compute path loss and compare it with a threshold value for routing decision. The RSSI based selection of paths is a compromise between short paths over a few unreliable links and long paths over several reliable links [42]. A combination of hop count, RSSI, and residual energy was used in a metric using fuzzy logic for WBANs in [43]. However, control overhead is the drawback of this technique.

Authors in [44] present a system architecture that controls slotted communication in WBANs and is synchronized by using periodic beacons from the sink node. Beacon and non-beacon modes for IEEE 802.15.6 network were discussed in [7]. Beaconing from the host or the hub in a WBAN was also used in [45], [46]. In the work of [47], [48], beacons were sent by the hub or the network coordinator in a WBAN for synchronization and exchanging control information.

A timer-based approach depending on Channel State Information (CSI) was used for WSNs in [49]. Another research work in [50] proposes use of timer based on the distance for routing in wireless networks. Another approach using timer and channel quality was applied for opportunistic relaying in [51]. In this work, a normalized channel quality metric was used.

A comprehensive overview of design guidelines for metric composition specifically for networks with limited power and high loss ratio was stated in [52]. In [21], authors have proposed a cross-layer opportunistic MAC/routing technique for WBAN. The cross-layer approach improves reliability, network lifetime, ETE delay, and energy efficiency. Further investigation is required to analyze this cross-layer opportunistic MAC/routing technique for WBAN. The technique also needs to be tested on a multi-WBAN environment, where many WBANs may co-exist, e.g., a medical ward scenario having multiple patients.

III. MAC/ROUTING CROSS LAYER PROTOCOL

In this section, we will be presenting the detailed methodology of the proposed cross-layer opportunistic protocol. First, COMR is discussed for WBANs, followed by the extension of COMR for IoHT setup (i.e., Multi-WBANs).

A. COMR FOR WBANS

We employ the four-way handshake mechanism of RTS-CTS-DATA-ACK in this protocol, as shown in Fig. 2. If the medium is sensed idle for a period of Distributed Inter-Frame Spacing (DIFS), the sending/source sensor then issues a broadcast of RTS packet and then waits to reply RTS packet. This waiting time is called τ_w and defined in (1). Whereas, if the medium is occupied or in use, the source node performs back-off by choosing a random *slot*. This waiting time (τ_w) can be analytically expressed as,

$$\tau_w > \tau_{tx(rts)} + \tau_{tx(cts)} + \tau_{p(rts)} + \tau_{p(cts)} + (slot \times \tau_s) + \tau_{d(max)} \quad (1)$$

In (1), τ_w represents the waiting duration during which the source node waits for the reply of CTS. The *tx* represents the transmission time in general, and $\tau_{tx(rts)}$ and $\tau_{tx(cts)}$ denotes the RTS and CTS transmission times, respectively. Moreover, the symbol τ_s and τ_d represent the length of the slot and the length of added metric, respectively. The τ_d is also defined in (2). The RTS and CTS propagation duration are denoted as $\tau_{p(rts)}$ and $\tau_{p(cts)}$, respectively.

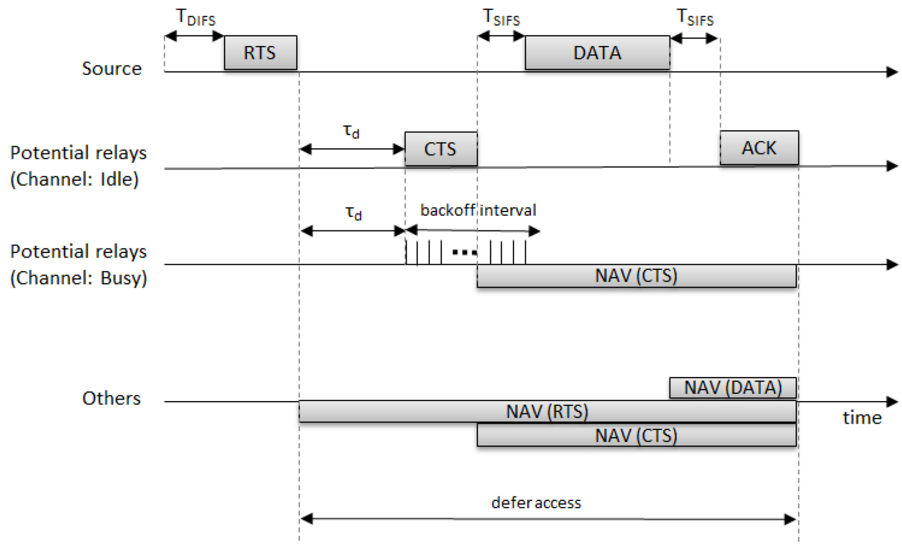

FIGURE 2. The typical four-way RTS-CTS-DATA-ACK handshake mechanism, where channel access is granted to the node that responds with CTS packet [52].

Once the source node which is ready to transmit sends an RTS packet, all the neighboring nodes in the vicinity then attempt to reply with a CTS packet after their timer expiry. This timer is known as τ_d and is defined in (2). The first sensor or neighbor node that sends a CTS packet is then selected to play the role of the relay node. Hence, all the neighboring sensor nodes are then informed by the CTS packet that this node is selected as relay. After this update, the sensor nodes then can go to sleep to preserve their energy for the duration of the Network Allocation Vector (NAV). This duration is represented as,

$$\tau_d = m_e + m_\gamma \quad (2)$$

In (2), τ_d is the timer value in milliseconds which is an additional parameter that integrates m_e, i.e., the metric for residual energy and m_γ, i.e., the metric for RSSI. The value of the maximum τ_d needs to be less than τ_w value such that (1) is satisfied.

As shown in Fig. 3, value of τ_d lies between t_1 and t_2. If the channel is sensed idle or free, a contending sensor node will then issue CTS after τ_d. Otherwise, the node decides to invoke back-off mechanism by randomly choosing a time duration between t_2 and t_3. The maximum duration of this back-off period will be Contention Window (CW) size times τ_s.

For the data packets from source to destination node, the relaying node can be chosen based on either one or combination of multiple parameters of the node. These parameters may include remaining battery power, and proximity to the destination node. Depending on the design objective of the cross-layer protocol, the selection of the node for relaying or as sink can be based on these parameters. We consider a network (N, L) with N number of nodes connected through L wireless links. For any source S to the sink node D, our goal is to find the most reliable next-hop relay to successfully forward the data. Let us suppose that R_T encloses all

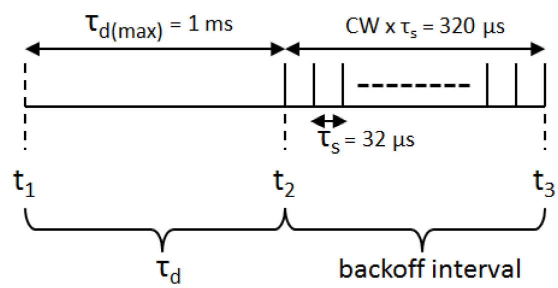

FIGURE 3. The time-domain representation of CTS contention based mechanism, where sensor transmits CTS packet after τ_d if channel is sensed idle or invokes back-off otherwise [52].

the possible relays for S, where T is the number of neighboring relay nodes. We define R_r as the most reliable relay node, such that $R_r \in R_T$. The selection of R_r is based on maximum reliability, which can be mathematically described as follows.

$$\forall(S, D)\exists R_r|\tau_{d(Rr)} < \tau_{d(Rr')} \wedge R_r \in R_T$$
$$Rr = max\left(\sum_{i=1}^{T} Ri\right) \quad (3)$$

In (3), R_i is reliability of i^{th} relay node in R_T, R_r is reliability of R_r, $\tau_{d(R_r)}$ is the value of time R_r takes to reply with a CTS packet and $\tau_{d(R_r')}$ is the value of delay for any node other than R_r. The R_r will have the lowest τ_d value and will be the first one to reply.

Each node checks the residual energy threshold according to (4). 10% residual energy is considered low battery [39]. Therefore, we have assumed that a node with residual energy lower than 10% will not be considered for relaying, according to equation (4).

$$e_r > (0.1 \times e_i) \quad (4)$$

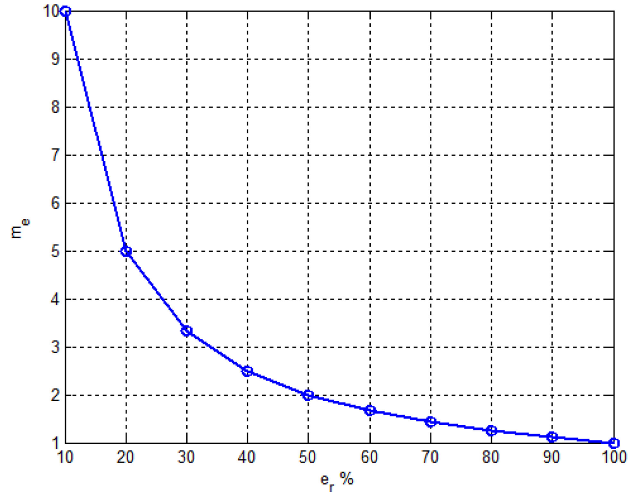

FIGURE 4. Metric for residual energy (m_e) as a function of residual energy (e_r).

Packet Type	Source Address	Destination Address	γ_{source}	NAV	FCS

FIGURE 5. Modified RTS packet format for COMR protocol with RSSI of received beacon packet.

In (4), e_i denotes the initial remaining energy of the sensor node, and e_r is the current remaining energy; both are in Joules. Thus, we can represent the residual energy metric as,

$$m_e = \omega_e \times \frac{e_i}{e_r} \tag{5}$$

In (5), m_e is the metric for residual energy and $\omega_e \in (0, 1]$ is a tunable constant which depends on the preference given to m_e in τ_d, while ensuring $\tau_d < \tau_w$. The node with higher residual energy will have lower value of τ_d and vice versa, because of the inverse relationship between m_e and e_r. This inverse relation is beneficial for a balanced division of power consumption among sensors in WBAN. Figure 4 depicts the graphical representation of (5). It can be seen that the value of m_e is inversely related to residual energy.

In our system model, we assume that all sensor nodes on the human body are placed on the front-side, and have equal transmission powers. Moreover, the sink node has all the sensors within its transmission range.

The sink node periodically broadcasts beacon packets, and each node keeps a record of the RSSI of the received signal [53], [54]. The RTS packet also has the value of RSSI of the beacon packet, which was received by the source node. The modified RTS packet format has been shown in Fig. 5. If the condition given in (6) is met then this potential relay node is allowed to contend. This mechanism enables the data forwarding and routing towards the sink [53], [54].

$$\gamma_{relay} > \gamma_{source} \tag{6}$$

where, γ_{relay} and γ_{source} denotes the RSSI of beacon signal at relay and source nodes, respectively. Also, the RSSI metric

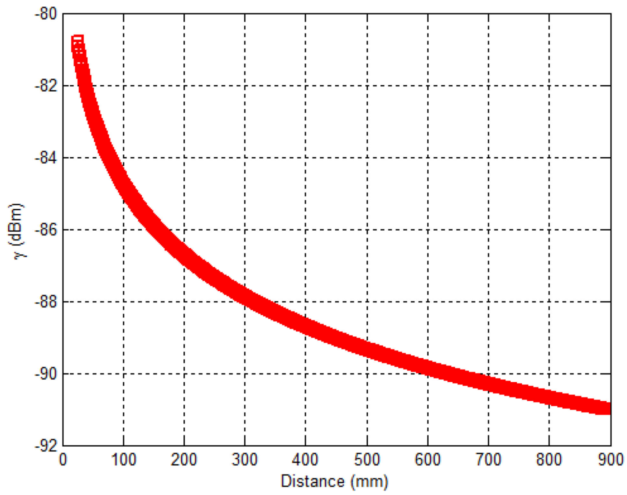

FIGURE 6. RSSI (γ) versus distance for IEEE 802.15.6 CM 3A. RSSI decreases as the transmitter-receiver distance increases.

can be written as,

$$m_\gamma = \omega_\gamma \times \frac{\gamma_{rts}}{P_{prt}} \tag{7}$$

where, P_{prt} is the threshold for the power of received signal, and γ_{rts} is the power of received signal (RTS) at relay node, in milliwatts. The $\omega_\gamma \in (0, 1]$ denotes a tunable constant which can be refined according to the priority assigned to m_γ in τ_d, while keeping $\tau_d < \tau_w$.

For this work, we consider the IEEE 802.15.6 Channel propagation Model 3A [55], where its performance analysis was also done in our earlier work in [56]. The mathematical description of this model is given as,

$$L(d) = a\log(d) + b + N_\sigma \tag{8}$$

where, $L(d)$ refers to the path-loss as a function of distance d between transmitter and receiver, while a and b represent the constants that can be configured depending on environmental conditions. The N is noise mapped as a Gaussian random variable with a standard deviation of σ. The impact of distance over RSSI of γ is shown in Fig. 6.

The impact of varying ω_γ over RSSI of γ_{rts} is shown in Figure 7 for IEEE 802.15.6 CM 3A. The value of m_γ is relatively increasing with the value of γ_{rts}, hence, the τ_d will have comparatively lower values because of its proximity to the source node.

Figure 8 explains the variations in τ_d with respect to residual energy for different values of γ_{rts}. It can be seen that the τ_d values decrease with increasing residual energy and decreasing γ_{rts}. Therefore, a node that is in the closest proximity to the sink node among the neighbors of the source node and has the highest residual energy will have the lowest value of τ_d. The concept of timer-based relay selection mechanism in COMR protocol is shown in Fig. 9. Each node will calculate its τ_d and wait for it to expire, as shown in Fig. 10. The node with lowest τ_d will be the first one to

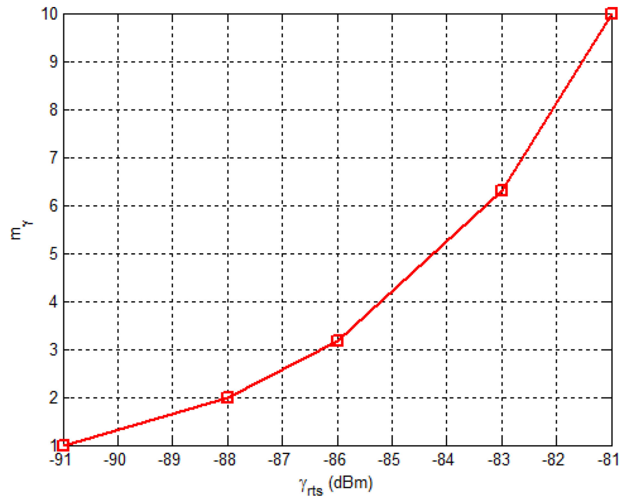

FIGURE 7. Metric for RSSI (m_γ) is directly proportional to RSSI of RTS packet (γ_{rts}). Smaller γ_{rts} will indicate a smaller value of m_γ.

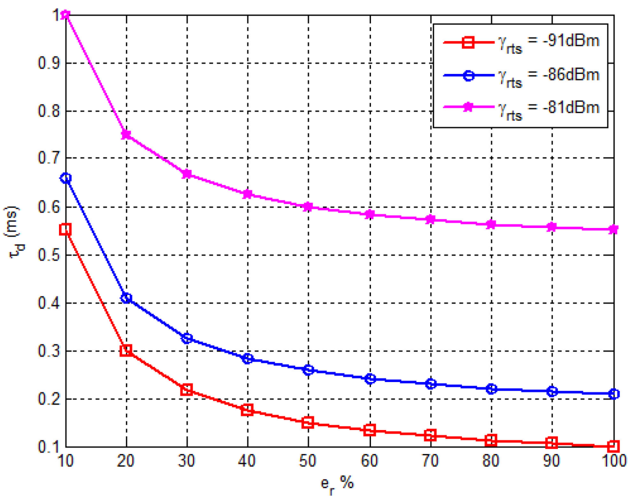

FIGURE 8. Timer τ_d is inversely proportional to residual energy (e_r). For different values of RSSI of RTS packet (γ_{rts}), lower γ_{rts} will result in a smaller value of τ_d.

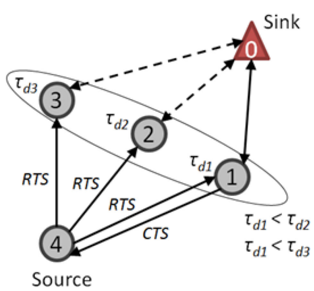

FIGURE 9. Realization of relay selection approach for proposed COMR protocol based on smaller τ_d and proximity to sink node.

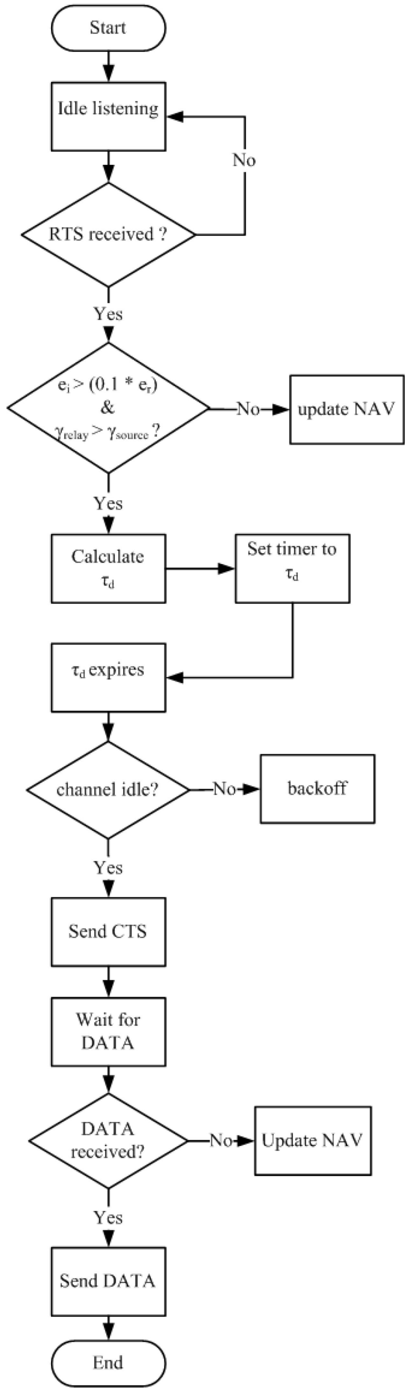

FIGURE 10. Flow chart of the algorithm for a potential relay node in COMR protocol.

reply with a CTS packet in response to an RTS packet from the source node and will be selected as the relay node.

The summary of COMR protocol for a potential relay node is shown in Fig. 10. The relay node forwards the data packets toward the sink node. An ACK packet is sent as a response to each data packet. The relay node repeats the same process as the source node in order to send the data toward the sink.

B. COMR PROTOCOL FOR MULTI-WBANS AND IOHTS

In this section, we extend the COMR protocol for IoHTs, where multiple WBANs are coordinating to relay the data towards the sink node. This setup for IoHTs is simulated using multiple WBAN setup. Each WBAN is known by a numerical Identity (ID) in multi-WBAN. We analyze two

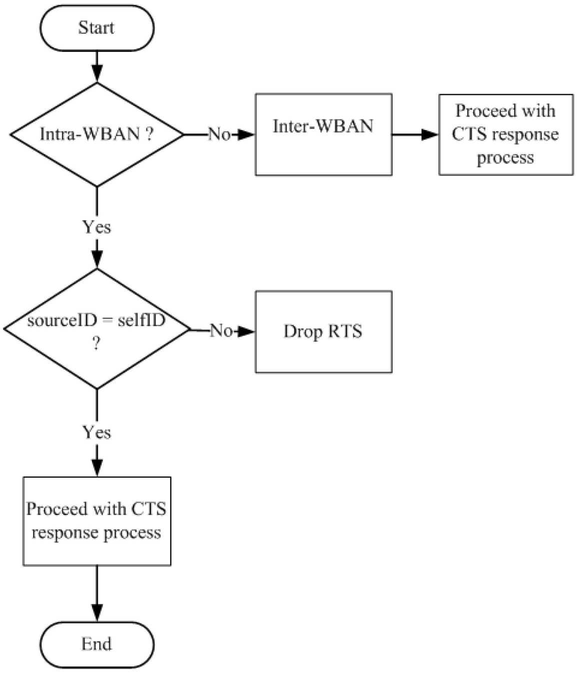

FIGURE 11. **Flow chart of the algorithm for COMR protocol describing the CTS response to an RTS packet in a multi-WBAN. The node will contend only when the source node belongs to the same WBAN in intra-WBAN. Whereas, the node will contend regardless of this condition in inter-WBAN.**

scenarios for multi-WBAN, i.e., intra-WBAN and inter-WBAN. In intra-WBAN, there will be no communication between the nodes of different WBANs. Nodes having the same ID may help each other using COMR. Whereas, in inter-WBAN, a node can forward the data of any other node regardless of the ID. We assume that all the sink nodes will further send the data to one medical center. For multi-WBAN, Fig. 11 presents the additional operations necessary in COMR protocol and explains the CTS response to an RTS packet. In the case of intra-WBAN, an ID match with the source node is required for a node to start contention. Whereas, the node will always contend to send CTS response in inter-WBAN without matching any ID.

C. ENERGY CONSUMPTION CALCULATIONS

In narrowband transceivers, IEEE 802.15 Task Group 6 mentions that the energy consumption rate for receiving radio is comparatively higher than the power consumption rate of transmitting radio [57]. In this work, we have considered a worst-case scenario, where the listening radio, which is in idle state, consumes equivalent energy as the receiving radio, which is also further given in Table 1. The nodes which are in sleep mode consumes the least amount of energy.

The energy consumed by nodes during simulations is calculated based on the nodes state. The power consumption by any node is a product of time and the particular state in which node stayed for this time as power consumption rate, also expressed in (9). For our modeling, we have assumed that the initial energy of all the nodes is the same, while sink nodes have unlimited energy resources. The aggregated

TABLE 1. **Power consumption rate for different radio state.**

Radio State	Power Consumption Rate (mW)
Transmission	2.93
Reception	3.1
Idle listening	3.1
Sleep	0.05

energy consumption can then be expressed as,

$$E_T = \sum_{i=1}^{n} P_i t_i \tag{9}$$

where, E_T is the total consumed energy, n is the number of radio states, P_i is the power consumption rate of state i, and t_i is the time spent in state i.

D. PERFORMANCE METRICS

The communication reliability in this work is measured as probability of packet loss, since each packet contains vital information and more critical in health and elderly care related applications of WBAN and multi-WBAN. In this work, the performance of the proposed cross-layer protocol is assessed in simulations based on the following performance metrics,

- *Packet Loss Probability (PLP):* The Packet Loss Probability (PLP) is defined as the probability of packets lost during transmission from the source node to sink node. The Packet Delivery Ratio (PDR) is the ratio of packets received by the sink node to the total number of packets sent be the source node. Once the source node transmits the packet, it will either successfully be delivered or it will be lost. Hence, these two events result in a total probability of 1. Therefore, the PLP can be then written as,

$$PLP = 1 - PDR \tag{10}$$

  The objective is to minimize the PLP of WBAN which makes it more reliable.
- *End-to-End Delay (ETE):* The End-to-End (ETE) delay is the total amount of time it takes for a packet since it is generated at the source node to the time it is received at the sink node. The ETE delay combines the delay of queuing, transmission, propagation, and processing.
- *Network Lifetime:* Network lifetime is an important metric for sensor networks in order to envision durability. A number of definitions have been used for network lifetime in different research works. Since WBAN deals with critical data, e.g., vital signs, the death of a single node may greatly affect the system performance. Therefore, we define network lifetime as the time by which the first node has depleted all of its energy [58]. A WBAN having a higher network lifetime will be more durable.
- *Energy Efficiency:* We define energy efficiency as the inverse of energy used per data packet, which is the

TABLE 2. Simulation parameters.

Parameter	Value
Data Rate (kbps)	250
Modulation Type	DBPSK
Transmission Power (dBm)	-15
P_{prt} (dBm)	-91
Standard deviation of X (σ)	3.8
a (dB)	6.6
b (dB)	56.53
Standard deviation of N (σ)	3.8
Transmission range (mm)	890
Size of RTS packet (bytes)	9
Size of CTS packet (bytes)	7
Size of ACK/Beacon packet (bytes)	5
Payload size (bytes)	10, 30, 50, 70, 90
Number of nodes	4,6,8,10,12
Packet interarrival time (s)	0.1, 0.125, 0.167, 0.25, 0.5
Maximum number of retransmissions	2
Slot length (μs)	32
Contention window size	10
τ_w (ms)	3
ω_e	0.00005
ω_γ	0.00005
ID	1, 2, 3
e_i (Joules)	0.25
Simulation field (WBAN) (mm)	2000 × 2000
Simulation field (multi-WBAN) (mm)	6000 × 6000
Simulation time (s)	100
Simulation runs	30

average energy used per individual data packet that is received at the sink node.

Based on the proposed design, modeling, and analysis of COMR given in this section, we will be performing a comparative performance analysis of COMR for WBAN and multi-WBANs in the next section.

IV. RESULTS AND ANALYSIS

In the simulation work, we test and evaluate the performance of the COMR protocol for a WBAN and a multi-WBAN and compare it with Simple Opportunistic Routing (SOR). We adopt the physical layer parameters like radio characteristics for our simulation setup in accordance with the IEEE 802.15 Task Group 6 [59]. Moreover, all the nodes are assumed to be static. The details of simulation parameters, along with the values and units are given in Table 2. The Castalia [60] has been used to perform extensive simulations in different setups for comparative performance analysis of WBANs and multi-WBANs.

A. SIMULATION MODEL FOR WBAN

We only considered sensor nodes on the front-side, and back-side of the body, and all the sensors are assumed to be static. However, the nodes on the head, shoulder, and wrist may be able to connect with the nodes on the back-side of the body. All the nodes are within the coverage range of the sink node (denoted as 'O'), which is placed at the center of the body. We have tried to emulate the actual body area networks in our simulation models. The considered network topology use in our simulation is presented in Fig. 12.

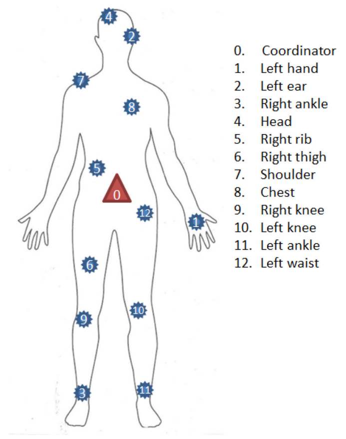

FIGURE 12. Network topology for WBAN. It consists of 12 sensor nodes and 1 sink node. Sink is placed at the center of the body.

We have initially considered 12 sensor nodes to assess the performance as a function of payload sizes in the data packets and for different inter-arrival times. To assess the performance of varying node density, we deploy four source nodes at the hand, ear, ankle, and the head. Then, we incrementally increase the number of potential relay nodes from 0 to 8 on other parts of the body. The performance is then assessed based on the performance metrics defined in Section III-D.

B. RESULTS AND DISCUSSIONS FOR WBAN SIMULATIONS

1) THE IMPACT OF VARYING PAYLOAD SIZE

The results presented in Fig. 13(a) show that increasing the payload size, in turn, increases the total network lifetime. Since the transmission time is high, it decreases the overall energy consumption due to a low power consumption rate compared to the reception or the idle listening radio state. It improves the network lifetime, which is longer for COMR in comparison to SOR. Because of the better division of power consumption load in COMR, the nodes having higher residual energy are more likely to win the contention. The comparative performance advantage of COMR against SOR is in consistent throughout the increasing payload size from 10 bytes to 90 bytes.

Figure 13(b) presents the variation in PLP with varying payload size. PLP increases with the increase in payload size because the channel occupancy time increases for a larger payload size, which may increase the possibility of channel access failure. Also, during the transmission of longer packets, false idle channel detection is possible for the contending nodes. This factor also increases the packet collisions. The PLP is high for SOR as compared to COMR. The random relay selection mechanism in SOR leads to packet loss because of limited resources of the relay node. A relay node selected may not have directed the packets toward the sink and instead forwards it in the opposite direction, or it may die faster due to low residual energy. This amplifies the loss

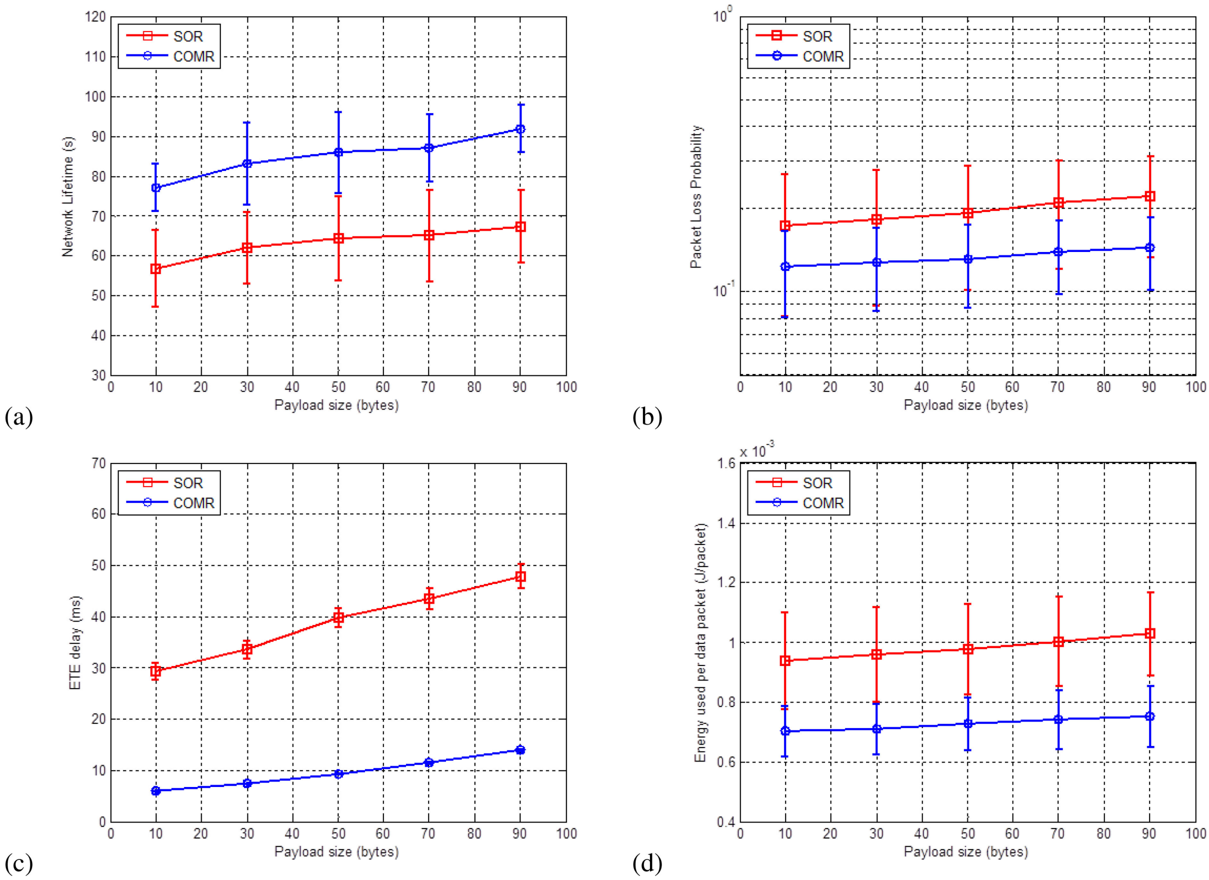

FIGURE 13. **The impact of varying payload size in a WBAN consisting of 12 nodes and $e_i = 0.25$J : (a) Network lifetime, (b) PLP, (c) ETE delay, (d) Energy used per data packet.**

of packets in SOR. On the contrary, the relay selection mechanism in COMR solves these issues and improves the packet receiving rate at the sink node. Consequently improving the reliability of COMR compared to SOR.

The simulation results for ETE delay as a function of payload size as demonstrated by Fig. 13(c). The ETE delay increases when we increase the payload size. Since the transmission time is high, the channel is in the busy state for a substantial amount of time. This happens when the payload size is big which ultimately increments the channel access delay, and in turn, the ETE delay is increased. The ETE delay metric performance is also linked with PLP metric especially for increasing payload size. The COMR, as shown in the results, select relay nodes in such a way that the data is always routed towards the direction of sink node, while reducing the number of hops between the source node and sink. Whereas, random selection of relay nodes may cause in forwarding the data further away from the sink node and increase in number of hops in SOR. This is one of the reasons for the increases of ETE delay, as shown in the results of SOR in comparison to COMR performance. The values of ETE delay are within the requirements of most medical applications [59].

The energy of the sensor nodes in WBANs is a critical resource for the long-life of WBANs and increases the network lifetime. Figure 13(d) depicts the increase in energy used per data packet with respect to increasing payload size. This rise in energy used per data packet is because the number of received packets at the sink has decreased for a larger payload size due to the rise in channel access failure probability. The packet loss and the overall energy consumption are comparatively higher in SOR. This is the reason why the energy used per data packet is higher for SOR in comparison to COMR. Therefore, COMR has shown better performance in terms of energy preservation as compared to SOR.

2) THE IMPACT OF VARYING SENSOR NODE DENSITY

In this subsection, we will be evaluating the performance of varying the sensor node density (i.e., number of nodes in WBAN) and discussing its impact on network lifetime. The simulation results presented in Fig. 14(a) shows the network lifetime as a function of increasing the node density (i.e., increasing number of node in WBAN). The overall network lifetime decreases as the number of nodes in WBAN increase because of the accumulated increase in the aggregate energy consumption.

This increase in energy consumption is because of a higher number of packets being transmitted and received in the network. The COMR prioritizes the nodes with higher residual energy as compared to nodes with limited energy left.

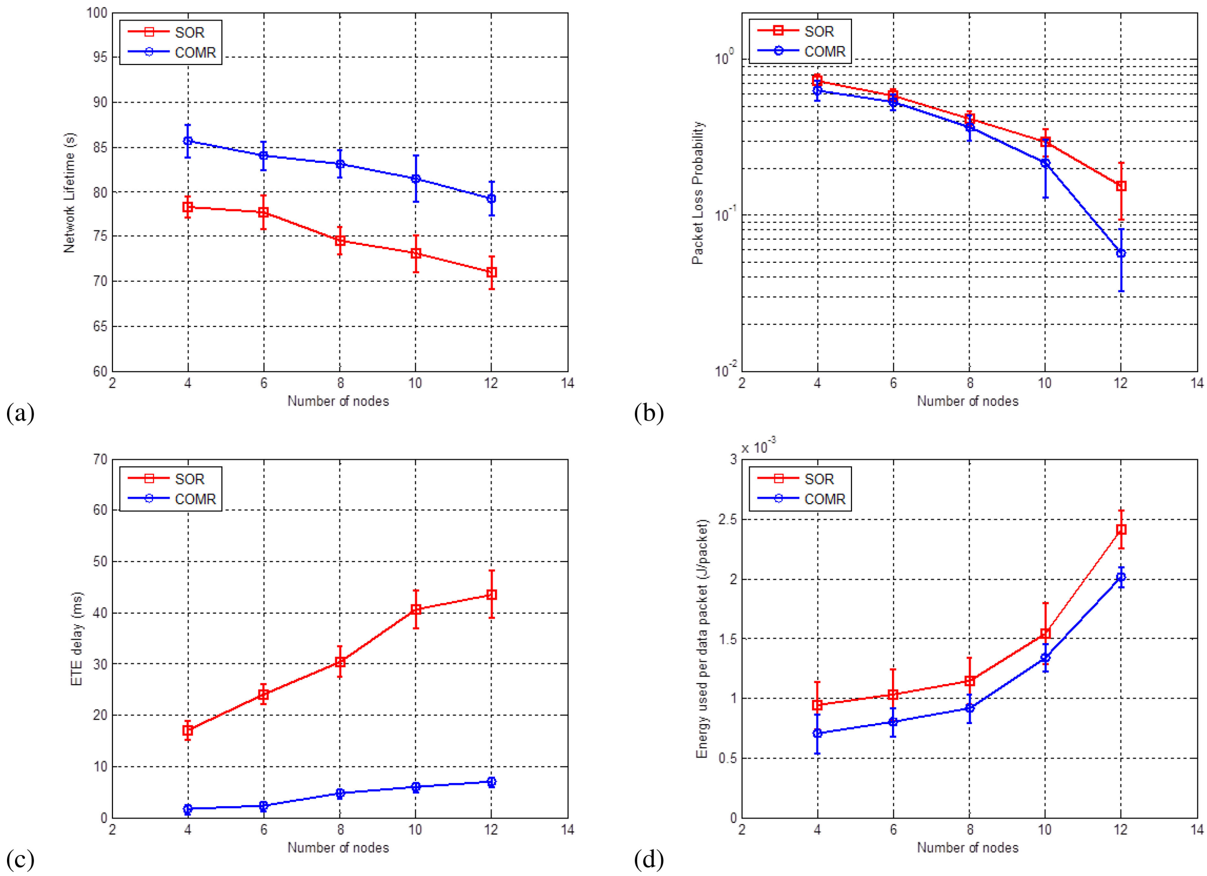

FIGURE 14. The impact of varying number of nodes using a payload of 10 bytes in a WBAN and $e_i = 0.25$J : (a) Network lifetime, (b) PLP, (c) ETE delay, (d) Energy used per data packet.

This also does the work of load balancing for even power consumption among the sensor nodes for relaying. This factor plays an important role in increasing network lifetimes of WBANs in COMR as opposed to SOR.

Figure 14(b) depicts the effects of increasing the sensor node density in WBAN on PLP. An increase in the number of sensor nodes increases the probability of selecting a more appropriate relay node, which is based on residual energy. Hence, this in turn, also increases the number of packets that are successfully delivered to sink via these relays. This factor, in turn, then decreases the PLP for COMR as compared to SOR. The COMR in this context proves to be a reliable choice by increasing the successful delivery of a higher number of packets. This happens because of an intelligent relay selection mechanism of COMR that chooses relay, which routes the data towards the sink node and also has higher residual energy. Hence, effectively relaying the data toward the sink node while preserving overall energy consumption during the process. As discussed before, randomly selecting any sensor node without considering the residual energy or its underlying resources may degrade the overall performance. Therefore, COMR has higher reliability as compared to SOR.

The rise in ETE delay as the number of nodes increase is shown in Fig. 14(c). The increasing trend for ETE delay shown in these results may be because of a higher number of nodes in a path between the source node to the sink node. In the proposed COMR protocol, the relay selection method prefers the sensor nodes, which are closer and on-route to the sink node, hence reducing the ETE delay for packets. This is also the factor for better performance of COMR for ETE delays as compared to SOR.

Figure 14(d) describes the increase in energy used per data packet with increasing node density. This trend is because of increasing overall energy consumption when the number of nodes is increased. Packet loss and energy consumption are higher in SOR as compared to COMR. This increases the energy used per data packet in SOR as compared to COMR. Therefore, COMR also has the potential to be energy-efficient than SOR.

3) THE IMPACT OF VARYING PACKET INTERARRIVAL TIME

Figure 15(a) shows the improvement in network lifetime for increasing packet interarrival time. Lower energy consumption for lesser network traffic is the reason why network lifetime improves for higher packet interarrival time. COMR has a better network lifetime in comparison to SOR. This is because of better power consumption load division in COMR as it chooses relays with higher residual energy.

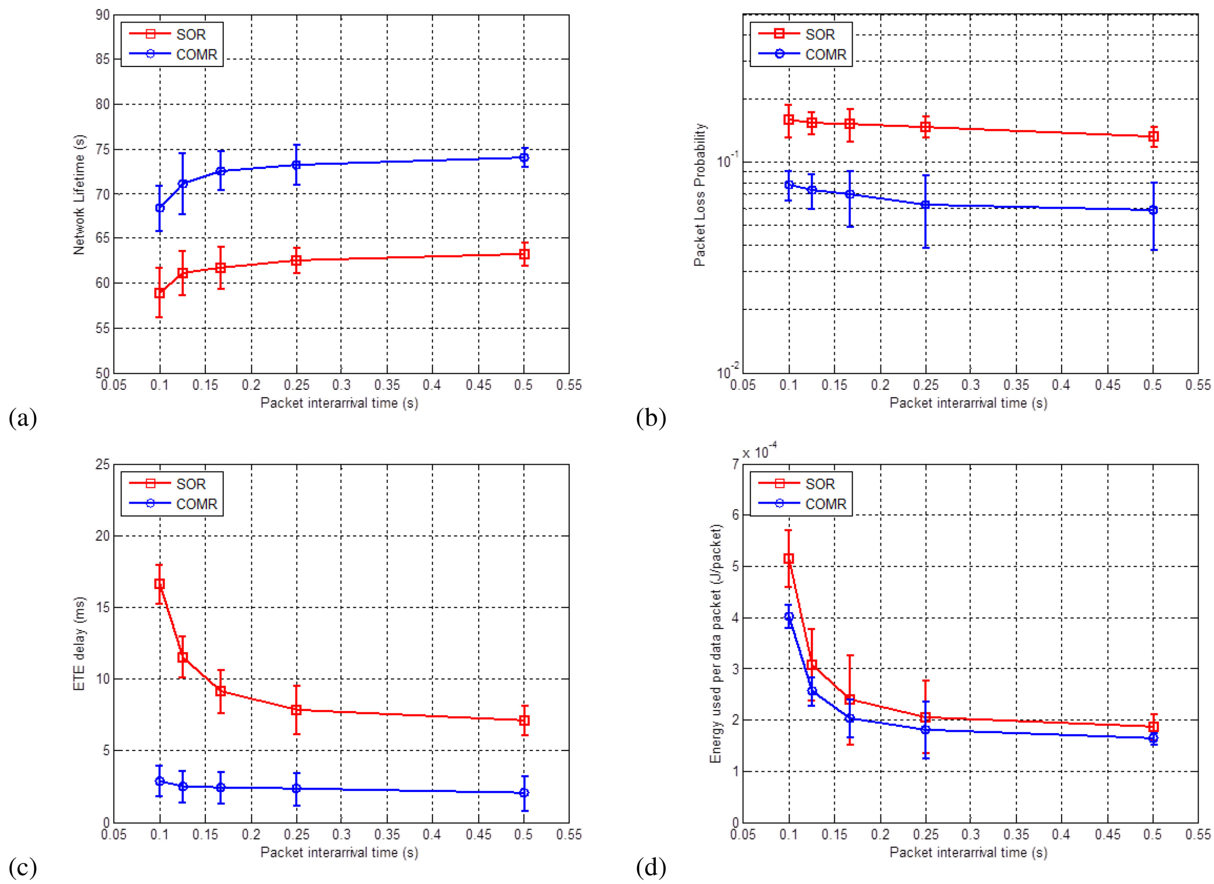

FIGURE 15. The impact of varying packet interarrival time using a payload of 10 bytes in a WBAN consisting of 12 nodes and $e_i = 0.25$J : (a) Network lifetime, (b) PLP, (c) ETE delay, (d) Energy used per data packet.

As shown in Fig. 15(b), PLP decreases with respect to an increase in packet interarrival time. The reason for this decrement is that higher packet interarrival time has lesser network traffic and lower chances of a collision of packets. This increases the number of packets received at the sink node and decreases the PLP. PLP for COMR is lower than SOR because the relay selection mechanism in COMR makes sure that the selected relay node has the highest residual energy and will move the data packets toward the sink node. Whereas in SOR, a random relay selection mechanism may not always be helpful for successful data transmission. Thus, COMR is more reliable than SOR.

ETE delay decreases with increasing packet interarrival time, as shown in Fig. 15(c). This decrease is because of the fact that lesser network traffic produces lesser RTS transmissions and, in turn, decreases the number of times the nodes have to contend. The ETE delay for SOR is comparatively higher than COMR, as shown and discussed in the previous subsection.

Figure 15(d) presents simulation results of energy consumption for each data packet with respect to packet interarrival time. The energy used per data packet decreases with increasing packet interarrival time. This is because the network traffic is lesser for higher packet interarrival time that causes a decrease in overall energy consumption and improvement in energy efficiency. Energy used per data packet for COMR is lower than SOR, making it more energy-efficient. This is due to lower energy consumption and lower packet loss in COMR.

C. SIMULATION MODEL FOR MULTI-WBAN

We only consider front-body and on-body sensors in a static multi-WBAN. However, the nodes on the head, shoulder, and wrist in each WBAN may be able to communicate with any back-body nodes. The sink node identified by node '0' is placed at the center of each body. The network topology is shown in Fig. 16. This simulation model resembles the placement of sensor nodes on three coexisting WBANs in a multi-patient environment. In terms of the number of nodes and sink nodes, the network model is similar to the one that has already been explained in the previous part.

In [28], the separation between two mobile WBANs was chosen to be 6 m. The recommended distance between two patients in a ward is 2.44 m, according to [61]. In [62], the authors recommend this distance to be at least greater than 2 m. The report [63] declared a spacing less than 2.7 m between the centers of two coexisting beds in a medical ward to be insufficient. Therefore, we assume the distance between two WBANs to be 2.75 m.

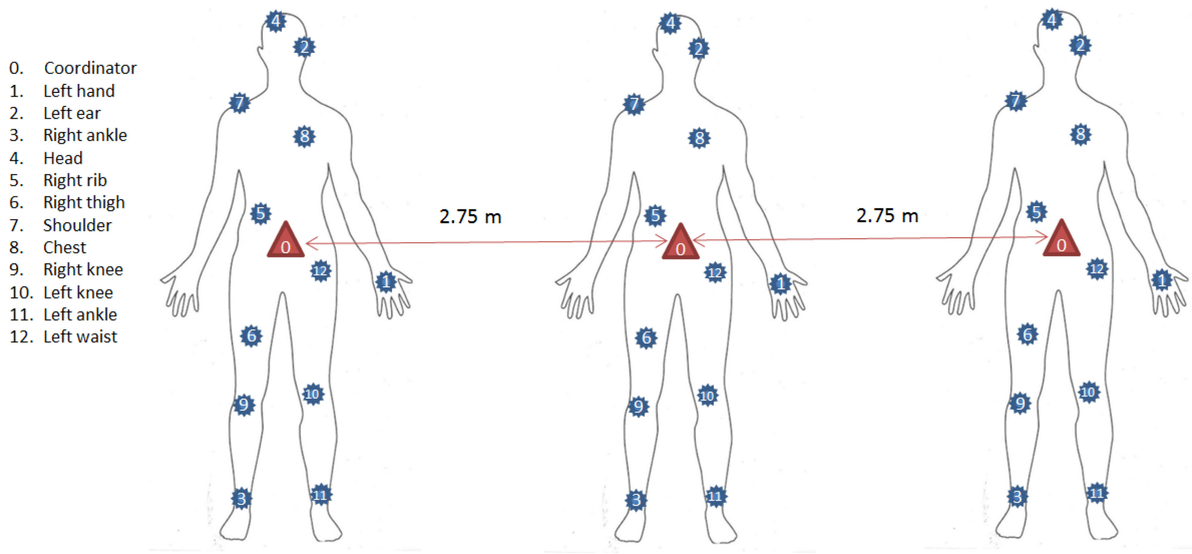

FIGURE 16. Network topology for multi-WBAN. Each WBAN consists of 12 sensor nodes and 1 sink node. Sink is placed at the center of the body in each WBAN. The separation between two co-existing WBANs is 2.75 m.

D. SIMULATION RESULTS FOR MULTI-WBAN

In this section, we present and discuss the simulation results for the Multi-WBANs scenario where the communication between multiple WBANs is considered. As the number of sensor nodes increase, so does the complexity of selecting the appropriate relay for data forwarding. We consider this factor and discuss its impact on the results.

1) THE IMPACT OF VARYING PAYLOAD SIZE

Figure 17(a) shows the impact of increasing the payload size in a packet as a function of network lifetime. The power consumed to transmit the packets is relatively smaller than the power consumed by the nodes when their radio states are either in reception or sleep mode. A similar trend can be observed in Figure 17(a) where the network lifetime increases in direct proportion with an increase in the payload size. In the COMR relay selection mechanism, the residual energy of the candidate node is considered, which also plays an important role in improving the overall network lifetime. This is another reason for better performance of COMR as compared to SOR for increased overall network lifetime as a function of the increase in the payload size. The network lifetime of COMR in intra-WBAN is better in comparison to inter-WBAN. The reason behind this is greater packet forwarding in inter-WBAN, which consumes additional energy causing the nodes to die faster.

As shown in Fig. 17(b), an incremental increase in payload size also results in an increase of PLP. This increase in PLP is also because of the fact that the contending sensor nodes to access the wireless channel have to wait for a longer period of time because of the increased transmission times for longer packets (because of larger payload size). Therefore, the other contending node has to wait more, and also in-flight packets are probable for collisions as well. Moreover, the competing nodes have to experience failures for channel access, and this also has contributed to an increase in the ETE delay results, as shown in the previous subsection. In accordance with the theoretical understanding that random relay selection may not be feasible for higher reliability, this has also been proven in the simulation results as COMR proves to be more reliable than SOR, as shown in Fig. 17(b). In COMR, the relay selection mechanism helps to increase the successful delivery of packets from source to sink nodes. The PLP for COMR in the inter-WBAN setup is comparatively lower than the PLP for intra-WBAN setup. This is due to the coordination between nodes of multiple WBANs in inter-WBAN. It provides additional support to the nodes in terms of opportunistic forwarding. Thus, an inter-WBAN is more reliable than an intra-WBAN.

Figure 17(c) shows the simulation result in which it explores the relationship between ETE delay and the payload size. The ETE delay increases for the packets with larger payload sizes, which in turn also occupies the channel for a longer duration. The other nodes with packets in the queue have to wait for the channel to be sensed idle. This waiting period also increases when the payload size is increased. The COMR outperforms SOR in terms of ETE delay because COMR selects such relay nodes that the data packets are moved toward the sink node, and the number of hops between the source and the sink is minimum. The ETE delay for COMR in inter-WBAN is higher as compared to intra-WBAN. This increment in ETE delay is because of the packets which are forwarded by relays of co-existing WBANs in inter-WBAN.

Figure 17(d) shows that the energy used per data packet increases when we increase the payload size. This is because a larger payload size decreases the number of received packets at the sink node as the probability of channel access failure increases. Energy used per data packet is

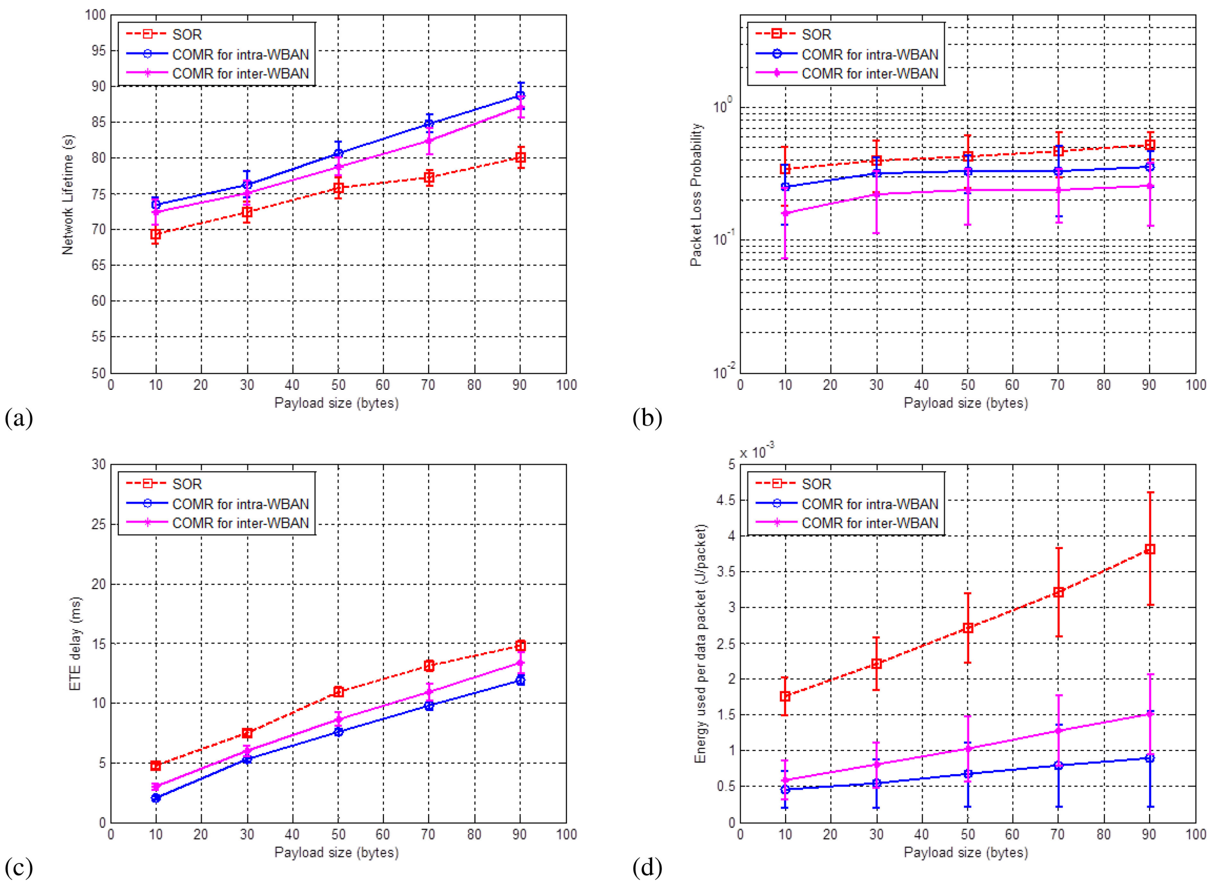

FIGURE 17. The impact of varying payload size in a multi-WBAN consisting of 36 nodes and $e_i = 0.25$J : (a) Network lifetime, (b) PLP, (c) ETE delay, (d) Energy used per data packet.

lower for COMR as compared to SOR, making it more energy-efficient. This is due to the higher number of received packets and lower energy consumption in COMR. The energy used per data packet is higher for COMR in inter-WBAN than intra-WBAN. The forwarding of packets between nodes of co-existing WBANs in inter-WBAN is the reason behind this increment in energy consumption. Therefore, an intra-WBAN is more energy-efficient than an inter-WBAN.

2) THE IMPACT OF VARYING NUMBER OF NODES

Figure 18(a) shows the changes in network lifetime with a varying numbers of nodes. Network lifetime decreases with the increase in the number of nodes. This is because of the increase in overall energy consumption as the number of nodes increase, causing the network lifetime to decrease. The network lifetime of COMR is higher than SOR because of the selection of relay nodes having higher residual energy in COMR. Network lifetime for inter-WBAN is lower than intra-WBAN because of higher energy consumption resulting from inter-network packet forwarding in inter-WBAN.

Figure 18(b) depicts the variations in PLP with respect to the changes in the number of nodes. A higher number of nodes increases the number of possible relays and, in turn, increases the number of packets received at the sink node. This decreases the PLP. PLP for SOR is higher than COMR. This is due to the lower number of packets received at the sink node in SOR as the relay selection is random. PLP for COMR in inter-WBAN is lower than intra-WBAN. This is because of the multihop forwarding between the nodes of multiple WBANs in inter-WBAN, increasing the overall number of received packets, and making it more reliable than intra-WBAN.

Changes in ETE delay with varying number of nodes are shown in Fig. 18(c). ETE delay increases for a higher number of nodes. This happens due to the increase in the number of possible relays and, in turn, the number of hops. However, COMR minimizes the total number of hops by choosing the relay nodes which are closest to the sink node. Therefore, the ETE delay for COMR is lower than SOR. ETE delay for COMR in inter-WBAN is higher as compared to intra-WBAN because of additional packet forwarding and a number of hops in inter-WBAN.

Figure 18(d) describes the energy used per data packet versus the number of nodes. It increases with the increase in the number of nodes. This is because of the fact that a higher number of nodes in the network increases the number of nodes staying in receiving or idle listening radio state and consume more energy. This amplifies the total energy consumption in the network, decreasing energy efficiency.

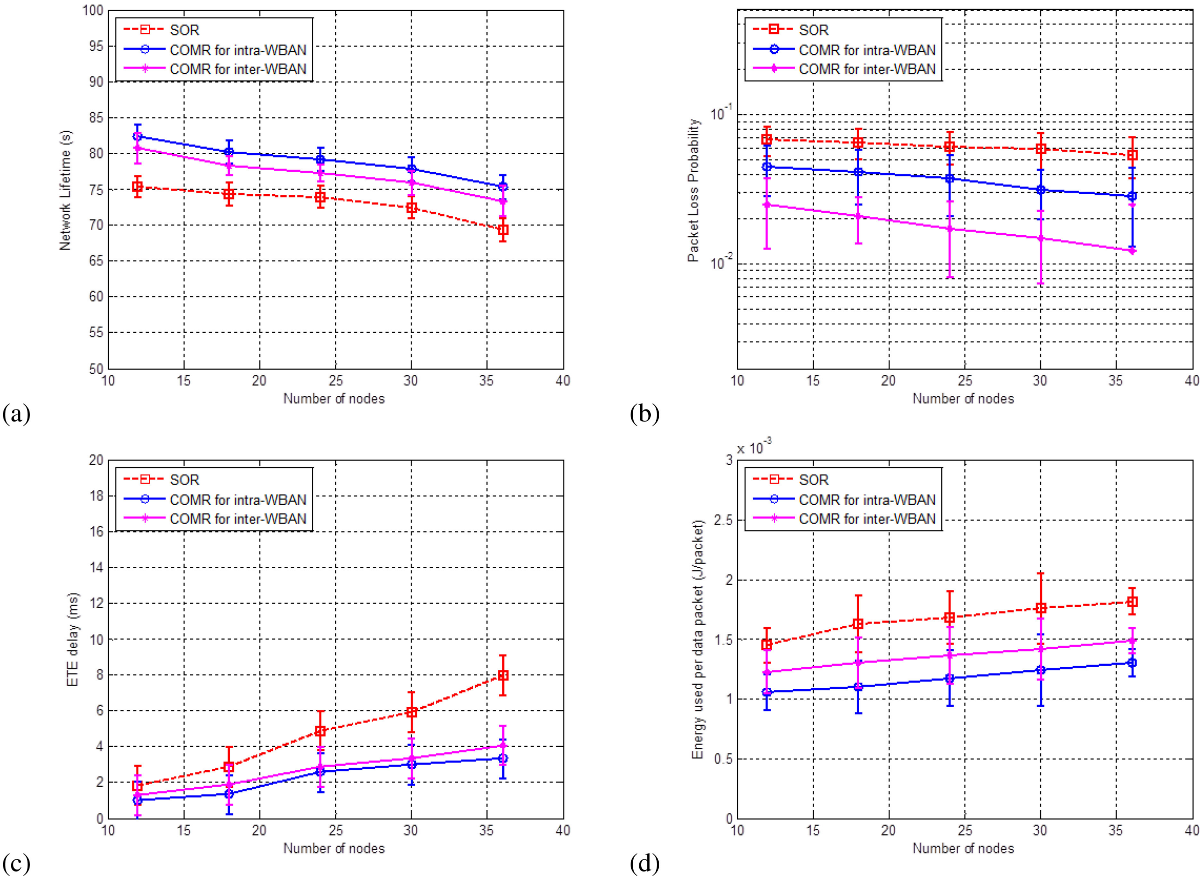

FIGURE 18. **The impact of varying number of nodes using a payload size of 10 bytes in a multi-WBAN and $e_i = 0.25$J : (a) Network lifetime, (b) PLP, (c) ETE delay, (d) Energy used per data packet.**

However, COMR is more energy-efficient, having lower energy used per data packet as compared to SOR due to lower overall energy consumption and a higher number of received data packets. The energy used per data packet of COMR in inter-WBAN is higher than intra-WBAN due to higher energy consumption by the forwarding of packets between co-existing WBANs. Thus, intra-WBAN is more energy-efficient than inter-WBAN.

3) THE IMPACT OF VARYING PACKET INTERARRIVAL TIME

Figure 19(a) shows the improvement in network lifetime for higher packet interarrival time. This is because of lower energy consumption for lesser network traffic, when the packet interarrival time increases. COMR has a better network lifetime in comparison to SOR due to the preference of higher residual energy in the relay selection mechanism in COMR. Inter-WBAN allows the nodes between different WBANs to help each other and act as opportunistic relays. This causes a rise in overall energy consumption in inter-WBAN. Thus, the network lifetime for inter-WBAN is lower than intra-WBAN.

Figure 19(b) shows the decrease in PLP with respect to increasing packet interarrival time. Higher packet interarrival time means lesser network traffic and lower chances of a collision of packets. This increases the number of received packets and decreases the PLP. PLP for COMR is lower as compared to SOR because of the higher number of packets received in COMR as the relay nodes always move the data packets toward the sink node. Whereas random relay selection results in an increase in loss of packets in SOR in comparison to COMR. This makes COMR more reliable than SOR. PLP for COMR in inter-WBAN is lower than intra-WBAN due to the higher number of received packets using multi-hop communication between nodes of multiple WBANs. Hence, an inter-WBAN is more reliable as compared to an intra-WBAN.

As shown in Fig. 19(c), ETE delay decreases with respect to the increase in packet interarrival time. Lesser network traffic decreases the number of times the potential relay nodes contend, and hence, the channel access delay also decreases. This decreases the ETE delay. For COMR, ETE delay is lower as compared to SOR. This is due to the lesser number of hops between the source and the sink in COMR as it chooses the relay nodes which are closest to the sink node. ETE delay for COMR in inter-WBAN is higher than intra-WBAN due to higher packet forwarding and a number of hops in inter-WBAN.

Figure 19(d) shows the decrease in energy used per data packet with respect to increasing packet interarrival

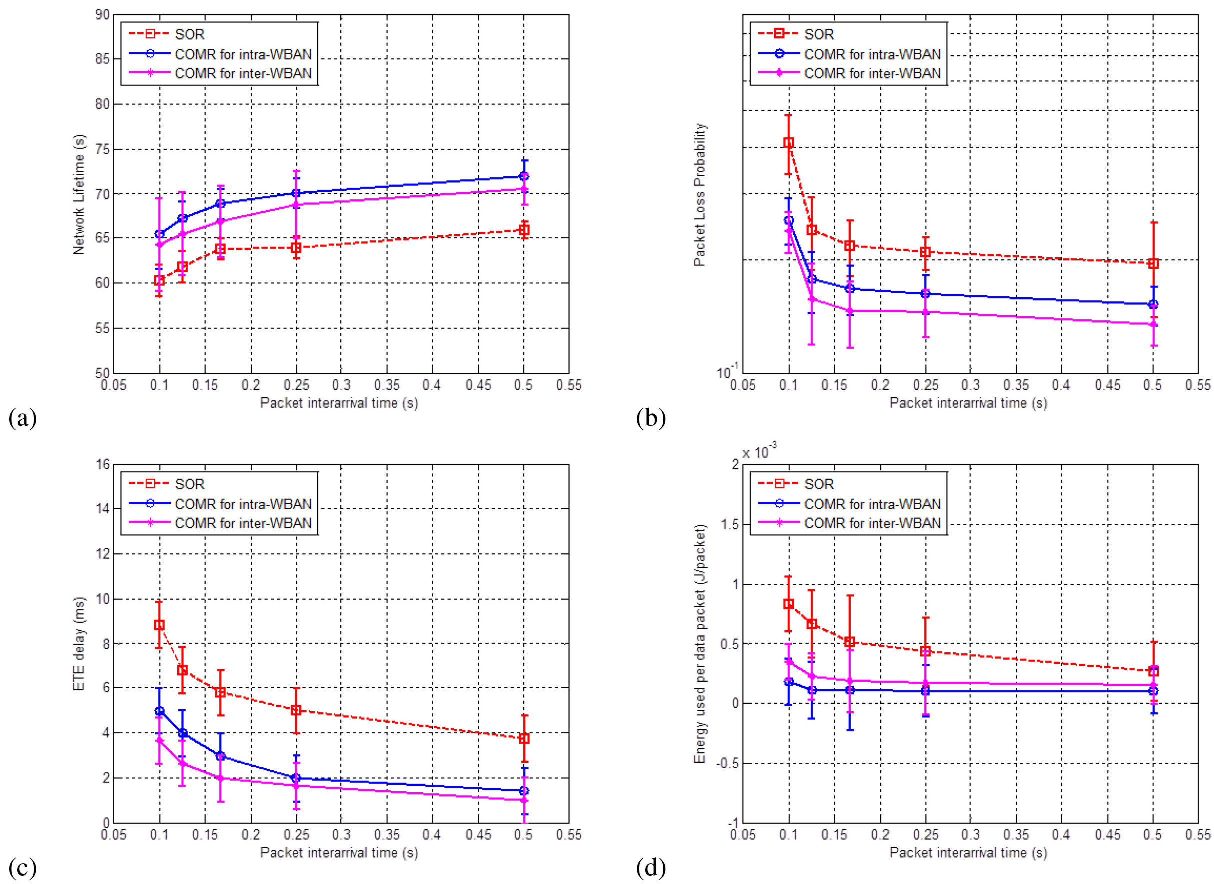

FIGURE 19. The impact of varying packet interarrival time using a payload size of 10 bytes in a multi-WBAN consisting of 36 nodes and e_i = 0.25J : (a) Network lifetime, (b) PLP, (c) ETE delay, (d) Energy used per data packet.

time. This happens because of lesser network traffic, which decreases the overall energy consumption in the network and improves energy efficiency. Energy used per data packet for COMR is lower than SOR, making it more energy-efficient. This is due to the lower energy consumption and a higher number of received packets in COMR. Energy used per data packet for COMR in intra-WBAN is lower in comparison to inter-WBAN. This is because of the additional energy consumption for inter-network forwarding between multiple WBANs in inter-WBAN.

COMR performs better than SOR in terms of reliability, network life, ETE delay and energy efficiency both in WBAN and Multi-WBAN. Moreover, the performance improvements of COMR in Multi-WBAN setup in relation to single-patient WBAN setup show that COMR is scalable and can be used for a multi-patient environment.

V. CONCLUSION

In this research work, we have proposed a cross-layer MAC and Routing protocol (COMR) to improve the reliability of sensor communication in Internet of Health Things (IoHT). The main objective of the proposed work is to improve the reliability of the communication in IoHT along with preserving the energy resource of sensor nodes. The COMR uses a timer based relay selection mechanism that is dependent on RSSI and residual energy. A node closest to the sink and has the highest residual energy is most likely to be selected as the relay node. The performance of COMR and SOR in terms of varying payload size, number of nodes, and packet interarrival time has been evaluated and analyzed in the simulation results modelled for WBANs and multi-WBANs setup. Based on the average results, COMR performs better than SOR. Reliability, network lifetime, ETE delay, and energy efficiency are improved by using COMR compared to SOR for IoHT. For instance, network lifetime is increased approximately by 10% for WBANs, and 7% for multi-WBANs, End-to-End delay for COMR is decreased by 2.5ms for WBANs and 1.3ms for multi-WBANs.

For future considerations, we plan to optimize the COMR protocol protocol to improve reliability further. Additionally, our objective is to analyze other channel models and incorporate the mobility of nodes in the simulation work.

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