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An Energy-Efficient and Cooperative Fault-Tolerant Communication Approach for Wireless Body Area Network

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ABSTRACT The tremendous advancement in embedded systems, miniaturization, and wireless technology had allowed Wireless Body Area Networks (WBAN) to have overwhelming applications in e-healthcare, entertainment, sports/games training, etc. WBAN is a special type of wireless sensor network where bio-sensors are attached or embedded to a single human-body designed to connect various bio-sensors and applications, operate autonomously and observe different vital signs of a human body remotely. Despite its enormous benefits and applications, some of the key challenges in designing heterogeneous WBAN is their energy-efficiency, reliability, and fault-tolerance among the installed bio-sensors. Due to the criticality of services related to WBAN applications, it is imperative to have a high degree of reliability and fault-tolerance, especially in the case of health-care monitoring applications where continuous monitoring of patient's vital information is required for diagnosis. However, in health-care applications, interference and body fading occur, which affect the communication among nodes and gateway, which reduces the reliability and fault-tolerance of the network. To address these issues, in this paper, we have proposed an energy-efficient fault-tolerant scheme to improve the reliability of WBANs. The proposed scheme adopted the cooperative communication and network coding strategy to minimize channel impairment and body fading effect and hence reduces the ensued faults, bit error rate, and energy consumption. Based on the proposed scheme, a case study was designed for remote Sepsis monitoring. The system identifies tracking indicators using cooperative communication to reduce hospital re-admissions and mortality rates. The proposed scheme performance is also evaluated via extensive simulations using various metrics. From the results obtained, it is evident that the proposed scheme reduces energy consumption, delay, and bit error rate, thereby increasing the throughput and reliability in WBAN.

INDEX TERMS Fault-tolerance, reliability, WBAN, cooperative communication, Sepsis disease.

I. INTRODUCTION

The recent development in sensing and communication technology and its seamless adaptation in common applications introduced a new category of Wireless Sensor Network (WSN) named as Wireless Body Area Network (WBAN). WBAN is a special class of WSN in which low-power and tiny devices called bio-sensors are fixed on entity-body or even implanted under the skin of a human body to monitor numerous physiological changes [1]. The underlying architecture of WBAN consists of various bio-sensors devices, a Personal Digital Assistant (PDA)/Gateway, and a Medical Server/Medical Database. The bio-sensors are deployed on the human body, while the PDA/gateway forwards the data to the medical server at the far end, as shown in Figure 1. The exact number of devices is varying depending on the scenario; a maximum of 256 nodes can be considered for WBANs applications [2]. Bio-sensors have scarce resources in terms of energy and memory, and the PDA has more resources as compared to bio-sensors [3]. Biosensors are devices that can sense biological activities in the human body. Once deployed, it is difficult to replace them in real-time because of the implantation process and mobility of a patient in WBANs. Due to the patient's mobility, the communication channels may be affected.

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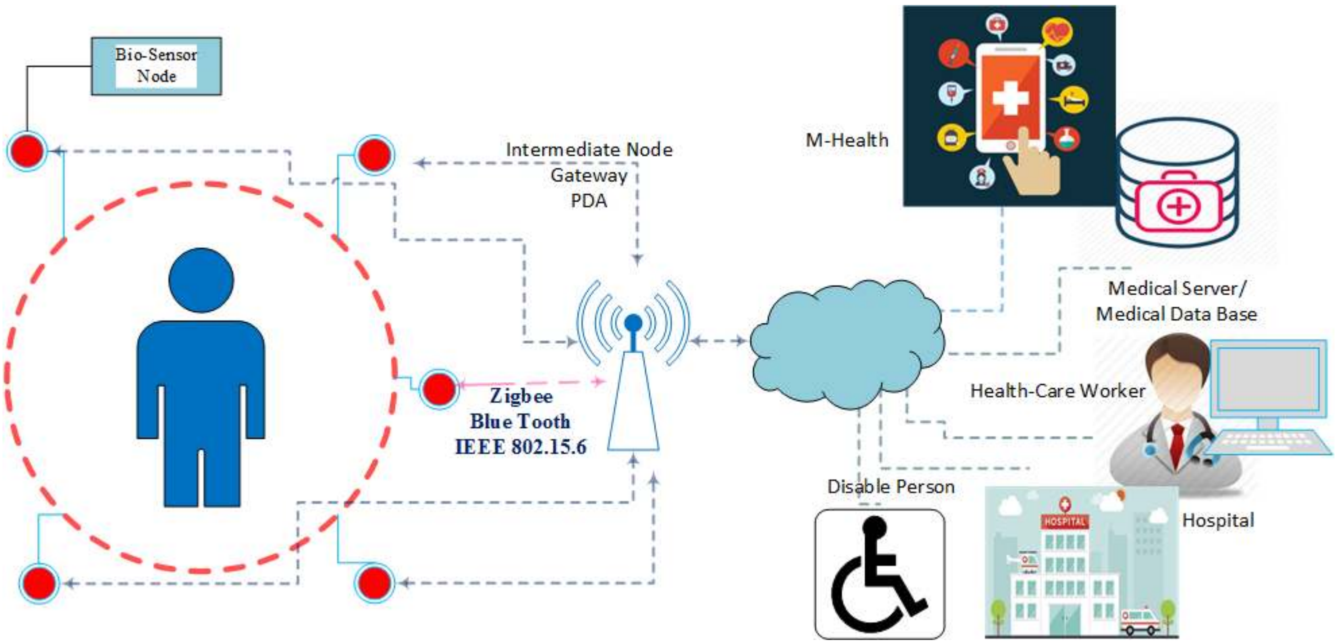

FIGURE 1. General architecture of wireless body area network.

A. HIGH-LEVEL DESCRIPTION

Since WBAN is primarily concerned with life-critical monitoring and health-care applications. However, due to the nature of wireless communication, the connectivity and data transmission are affected. Therefore, in WBAN, reliable and fault-free data to be transmitted to the medical database/server is required. If unreliable and faulty data is transferred to the server, medical professionals and doctors will ultimately make a wrong decision, which may cause a severe threat or even endanger the life of the patient [4]. In this context, reliability and fault-tolerance in WBANs applications are highly required.

B. MOTIVATION

In the existing literature, various schemes have been proposed to improve reliability and fault-tolerance in WBANs, the most common techniques include routing-based, clustering-based, QoS-based, and cooperative-sensing based approaches. In heterogeneous WBAN, bio-sensors associated to a single body are grouped into a cluster. Further, in the same domain, creating cooperation and trust is also proposed to achieve fault-tolerance and reliability. Another useful approach is collaboration in WBANs, called Collaborative-WBANs, where data is gathered and analyzed from multiple bodies. Collaborative-WBANs provide a platform where the exchange of data and cooperative processing have been performed between multiple WBANs. Cooperative-WBANs adopt multiple bodies and multi-base station (MB-MBS) architecture, where many bodies communicate with many BS. Moreover, using a cooperative approach, the overdo data transfer is minimized significantly. As a result, it achieves an enhanced throughput and low latency, so the energy-efficiency of the specific network is improved significantly [5], [6]. However, to the best of our knowledge, no work has been found that considered cooperative sensing and network coding for Sepsis disease. Though some of the proposed schemes used a cooperative communication approach for other objectives, however, the detail performance evaluation of these approaches has not been provided. Therefore, we have been motivated to address the issue of reliability and fault-tolerance in WBAN.

C. RATIONALE AND CONTRIBUTION

WBANs are usually susceptible to interference and body fading, plummeting reliability, and throughput. Hence, a promising solution is required to enhance reliability and fault-tolerant communication for the persistent monitoring of patients and the data required for timely diagnosis. In WBANs, where multipath fading is a prevalent phenomenon, Multiple-In Multiple-Out (MIMO) technology based on spatial diversity is a promising solution. However, to place a MIMO antenna on tiny sensors is not a practical solution. The workaround for this problem is the proposition of virtual MIMO using cooperative diversity with different cooperative communication protocols for the tiny sensors of WBAN [7]–[9]. Each sensor conveys other sensors' data acting as a collaborator providing spatial diversity, in addition to transmitting its data. Such technique(s) achieves considerable diversity gain, thereby reducing the fading effect, hence improving the link quality. In our proposed work, we adopt the same virtual MIMO or cooperative communication strategy for improving reliability and reducing fault-tolerance for Sepsis disease monitoring. We believe that there is a dominant line of sight path components that exist in WBAN, so we adopt the Rician fading model for our cooperative communication protocol. In our proposed scheme, we also use network coding to improve throughput and reliability. The base station uses Log-likelihood-Ratio (LLR) as the decoding technique, which is also known as the soft-decision decoding technique. To the best of our knowledge, no one used the cooperative communication and network coding techniques for improving reliability and throughput for Sepsis disease monitoring.

The performance of the proposed system is evaluated via extensive simulations using various metrics in MATLAB. The results obtained demonstrate that the proposed scheme reduces energy consumption, delay, and bit error rate, thereby increasing the throughput and reliability.

The rest of the paper is organized as follows. Section II discusses the state-of-the-art in cooperative communication, network coding, and routing approaches. In Section III, we discuss our proposed novel energy-efficient and fault-tolerant communication approach. In Sections IV, the performance evaluation is carried out to examine the proposed scheme by using different parameters. Finally, the conclusion and future work are provided in Section V.

II. LITERATURE SURVEY

In this section, the state-of-the-art schemes in WBAN of different authors are critically reviewed. In the reported literature, many solutions have been proposed over the time to address the issue of reliability and fault-tolerance. However, there are still many weaknesses that have not been appropriately addressed, and there are some common drawbacks in these schemes, e.g., high energy expenditure and Bit Error Rate (BER) [13], [29], [34].

MIMO (Multiple Input Multiple Output) technologies is an efficient way in a multi-path fading environment, but since multiple antennae cannot be placed in such a lower power bio-sensors. Therefore, the cooperative approach is an effective alternative to provide a virtual MIMO environment for WBAN [9], [10]. Moreover, one of the proposed schemes used the weighted medium fault detection algorithm, which performs communication of data based on neighbor node weights but does not give a solution to the high failure rate of the monitoring area. Apart from this, distributed and clustering-based approaches with nodes cooperation give efficient results in terms of fault-tolerance and reliability. In the presence of node failures or link failures, trust, and reliability in the network are improved. The novelty of the proposed research work is bio-sensor based cooperation in WBAN to improve fault tolerance and reliability, which further improves the quality of service in critical infrastructure.

Zonu *et al.*, in [11], [12], proposed a BodyQoS. This QoS (Quality of Service) based system has asymmetric architecture, in which most of the processing is performed at a resource-rich aggregator while limited processing is performed on bio-sensor nodes. In this scheme, an adoptive resource scheduling approach is used, which minimizes channel impairment. However, the main limitation of this scheme is that the gateway node is overloaded due to heavy processing, which delays the critical data communication in the network, causing reliability degradation. Guowei Wu *et al.*, in [13], proposed an Adaptive Fault Tolerance Communication Model (AFTCM) for improving fault-tolerance in WBANs. In which the bandwidth reservation approach is adopted before communication. The scheme minimizes channel impairments and assures the reliability of the data in the network, and fault-tolerance priority queue is created based on real-time data. The main contributions of the proposed scheme are lower latency than BodyQoS, low packet loss and the high-reliability ratio [11], [12]. However, one of the main limitations of this scheme is that the fault-related information is not updated in real-time.

Similarly, Abdu Rahim et at., in [14], proposed an energy-efficient cooperative sensing MIMO-based scheme for WBANs. The Bit Error Rate (BER) is examined throughout data communication using a network coding approach. Furthermore, according to the simulation results, this scheme gives better results than contemporary schemes. The notable strengths of this scheme are: Low BER, accept and sustenance patient mobility, Low communication cost, Low energy requirements. Nevertheless, the proposed scheme is implemented using two sensors devices, and it can be generalized for more sensors with a more generalized application of WBANs. S Movassaghi *et al.*, in [15], addressed some of the fault management issues in cooperative communication. More specifically, the issue that each relay node accomplishes decoding of the received information from all sensor devices and then again re-code and sends it to the BS (Base Station). At BS, all signals are decoded and received the actual information. Moreover, with increasing number of relay nodes, large number of BER of messages will be communicated to the BS. Which is not an energy-efficient solution and is also causing a delay in the network. Though, the author proposed the network coding base cooperative communication scheme to minimize network delay. However, it incurs additional processing at each relay node, and therefore it affects the reliability of critical services.

Yousaf *et al.* [16] proposed a three-stage incremental relay base cooperative communication scheme for WBANs. In which, different Number of BERs of the cooperative nodes are selected as a relay node. Further, it assumed that all sensor nodes are within WBAN are cooperating with each other and send cooperative data to the sink. Finally, an analytical expression is also derived for the proposed scheme. The main contributions of this research work are: first 3-stage incremental cooperative communication which outperforms the contemporary single stage, a two stages and direct cooperative communication schemes and 2nd the Propose scheme also perform better in term of PER (Packet Error Rate) and at the same cost of direct single and two stages incremental cooperative schemes. However, if the number of relay nodes is increased, we have to pay extra cost on the restricted WBANs, which makes this solution impractical.

Paul and Babu [17] proposed a technique for the frame length optimization to maximize the energy efficiency in ultra-wideband 203.15.6 (UWB) WBANs. They considered both the direct as well as incremental relay-based cooperative schemes are to optimize the length of the medium access control (MAC) frame body, while for analysis, they considered the path loss model with shadowing. From the analysis of results, an increase in optimal frame length and extension of hop length has been observed in case of a cooperative communication scheme as compared to direct communication for both in-body as well as on-body propagation models. Since radio frequency signals experience high attenuation in WBANs, and shadowing effects due to body posture and movements further deteriorates the channel. Therefore, under these environments, adoption of cooperative communication techniques improves the energy efficiency and support larger frame lengths.

Elsalamouny *et al.* [18] proposed a fault-tolerant and reliable WBAN-based architecture with the support of two main protocols, i.e., low power Wi-Fi (IEEE 802.11n) and Long Term Evolution (LTE). They examined data that are forwarded through a cooperative multi-path. Moreover, a smart band aggregate sensed information from all sensor nodes and transferred the aggregated information to a BS. Likewise, a copy of the information is also sent from the smart band to the patient's smartphone device. On the patient's smartphone, software exists which processes the incoming sensory information. Then further explicit action will be sent back to the smart band, which further contacts the actuators and further forwarded to BS. In Simulation results, 95% confidence performed on the maximum of 33 runs have been achieved. The proposed system was first tested without external interference, and then the Adaptive learning-based load balancing technique is proposed for future work. In [19], a proactive and reliable smart healthcare Network Coding-Based Fault-Tolerant Mechanism (NCFM) is proposed for WBAN. Which first used a greedy grouping algorithm for the division of the topology into numerous logical units, and then construct linear coding combinations based on spanning tree (ST). When the gateway receives a sufficient number of BER of liners encoding combination, then the original packets can be recovered even if fault occurs in the transmission. This mechanism improves packet delivery ratio and reduced end-to-end delay.

In [20], Salayma *et al.*, proposed TDMA-based techniques to improve energy efficiency and reliability in WBAN. The author first proposed a method which allowed nodes to bypass channel deep fading by distributing a node sleep time according to their channel status adaptively. Furthermore, in the following method, to each node, time slots are allocated dynamically according to scheme requirements. Both schemes enhanced energy efficiency and reliability of WBAN by synchronized node adaptive technique. However, the proposed schemes do not guaranty the transmission of critical data in the cause of fault in the network.

To address the connectivity problem and provide Quality of Services (QoS) in WBAN, Samanta and Misra [21] proposed a dynamic connectivity establishment and cooperative scheduling scheme, which is based on game theory to maximize network throughput and minimized the packet delivery delay. The selections of parameters are formulated based on a pricing-based approach. To handle, the cooperation between WBANs, an optimal cooperative packet scheduling algorithm is proposed and formulated a utility function for the WBANs to offer QoS using a coalition game-theoretic approach. They analyzed the performance of the proposed approach holistically, based on different network parameters. However, the authors only addressed the issue of WBAN's connected with APS and chose a dynamic AP for the critical WBANs.

Cicio lu and Çalhan [22] proposed an IoT-based WBANs solution for disaster case management. The proposed model guaranteed to save the life of a human by using location determination and vital sign communication. Furthermore, a fuzzy logic-based algorithm is developed to select a more appropriate wireless technology. The authors further analyzed the delay, throughput, and power consumption and found good results. Similarly, in [23], the authors proposed a scheme which considered specific absorption rate, using specific battery level and different priority of the bio-sensor node for HUB selection in WBANs.

To the best of our knowledge and from the literature review, we believe that none of the work has considered cooperative sensing and network coding for Sepsis disease to improve reliability, energy consumption, and throughput in WBANs. Besides, some of the proposed schemes used a cooperative communication approach; however, the detail performance evaluation of these approaches has not been provided. Therefore, to address the issue of reliability and fault-tolerance in WBAN, in the next section, we explain our proposed scheme.

III. THE PROPOSED COOPERATIVE COMMUNICATION APPROACH

A. SYSTEM MODEL AND DESIGN

In this section, we explain the system model and network design of the proposed cooperative communication approach to enhance reliability and fault-tolerance in WBANs. The proposed system model and the design are based on heterogeneous sensor networks, i.e., five bio-sensors nodes are attached to or in the human body, along with a gateway node deployed in a two-dimensional area, as shown in Figure 2. By heterogeneous network, we mean a network where we considered two categories of sensors: sensors collecting critical data and non-critical data. For example, for Sepsis monitoring, the temperature and heart-rate data are more critical than the others for the identification of Sepsis disease. We defined two classes of priorities based on the priorities defined in the IEEE 802.15.6 standard, as shown in Table 1. In our evaluation, we used class-0 for non-critical sensors and class-2 for critical sensors [24], [25]. The bio-sensors

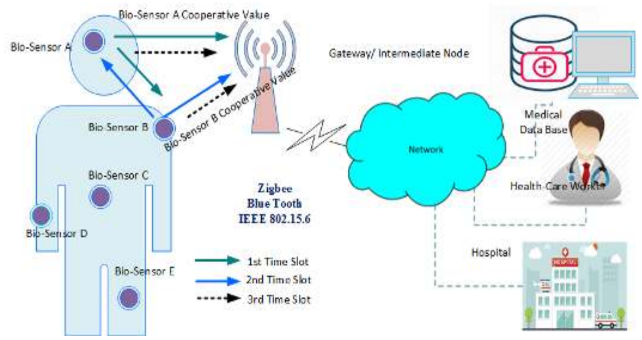

FIGURE 2. The proposed cooperative communication model for WBANs.

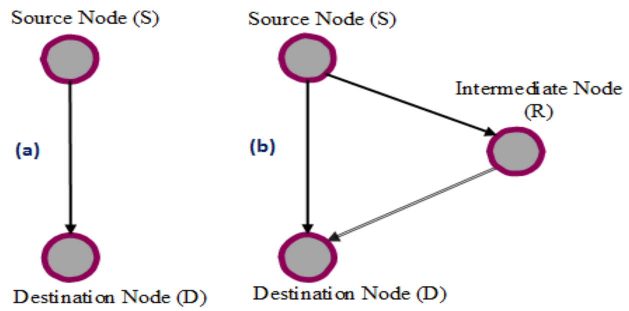

FIGURE 3. Source to destination data transmission – Cooperative communication scenario.

TABLE 1. Contention window for different traffic.

UP	CW_{min}	CW_{max}	Traffic designation
0	16	64	Background
1	16	32	Best Effort
2	8	32	Excellent effort
3	8	16	Controlled load
4	4	16	Video (VI)
5	4	8	Voice (VO)
6	2	8	High priority medical data or Network Control
7	1	4	Emergency or Medical implant event report

and gateway are in cooperation to minimize the channel impairment and fading effect. Furthermore, bio-sensors are being in cooperation with each other in WBANs medical or some other critical environment. The planted/deployed bio-sensors will sense critical vital signs of the patient and send the generated data packets through a gateway to the medical server for further processing and analysis. Typically, in the proposed system design, a single-hop communication model is used; however, in some specialized healthcare and medical applications, a multi-hop communication model is also used.

The cost of energy expenditure is measured during the sending and receiving of the packets. Therefore, a typical energy consumption model [26] is used in the proposed system for energy consumption during the sending and transmitting of *l-bits* data, as shown in Eq. (1) below:

$$\begin{cases} \mathrm{e_{t}{=}l}\left(\mathrm{E_{elect}} + \varepsilon \mathrm{fs\ d^2}\right) \\ \mathrm{e_{t}{=}l(E_{elect}} + \varepsilon_{\mathrm{amp}}\ \mathrm{d^4)} \\ \mathrm{e_{t}{=}l\ (E_{elect})} \end{cases} \tag{1}$$

where e_t and e_r represents the energy costs while transmitting and receiving. E_{elect} is the cost function for selecting the path for l bits data with the estimated distance d from the source S to destination D.

Let us suppose, the reliability factor is denoted as ρ and the maximum energy cost of a node is denoted as E_{max}. Furthermore, End-to-End (E2E) delay, denoted by (τ_i), is reduced, which is referred to as the minimum time while sending a packet successfully to the medical server. Hence, the statistical formula is given as:

$$\begin{cases} E_{\boldsymbol{max}} = E_{\boldsymbol{it}} + E_{\boldsymbol{ir}} \\ \varphi = \sum_{i=0}^{n} \vartheta(i)/N \\ \tau_i = \min\left(\sum_{j=1}^{m} \tau_{ij}\right) \end{cases} \tag{2}$$

In the Eq. (2) above, E_{it} *and* E_{ir} represent the energy cost of sensing and transmitting packets for a bio-sensor and $E_{\boldsymbol{max}}$ is the total energy consumption of a node ϑ (i) and τ_i is the maximum time for the generation of m packets during the data gathering and communication process, if ϑ (i) $=$ 1, it means that a node has successfully transmitted the sensed data to the medical server; otherwise ϑ $(i) = 0$ indicating the unsuccessful transmission.

B. THE COOPERATIVE COMMUNICATION MODEL

In this section, the communication model of the proposed energy-efficient and fault-tolerant cooperative communication approach is explained in detail. As shown in Figure 2, a generic WBAN is installed involving a human-body, bio-sensors, a gateway node, and a remote Base Station (BS).

A simplified scenario derived from Figure 2 is shown in Figure 3. For encoding/decoding from S source node to the destination D node, an XOR operation is used. Furthermore, relay nodes R have been used for two-hop communication. The Nr nodes are using TDMA (Time Division Multiple Access) mechanisms to avoid channel interference and noise because in TDMA, a specified time slot is allocated to each bio-sensors. We have used the Path-Loss radio propagation model proposed in [27] and given as a function below in Eq. (3).

$$\mathrm{P_{dB}\ (d) = P_0(dB) + 10n \log\left(\frac{d}{d_0}\right) + X_e(dB)} \tag{3}$$

where $\mathrm{d_0}$ is a reference distance, which is considered to be 10cm, n is the path-loss exponent, $X_e.dB$ is a zero-mean normal random variable.

The destination node sends an acknowledgment (ACK) if packet delivery is successful from the source node S. However, sometimes the packet is dropped by an intermediate node, and not received by the destination node due to communication errors caused by the environment or user mobility.

TABLE 2. Cooperative value generation.

	T1	T2	T3	T4	T5	T6
Bio-sensor A	Tx (S_A)	Rx (S_B)	Rx (S_C)	Rx (S_D)	Rx (S_E)	Rx (S_{GW})
Bio-sensor B	Rx (S_A)	Tx (S_B)	Rx (S_C)	Rx (S_D)	Rx (S_E)	Rx (S_{GW})
Bio-sensor C	Rx (S_A)	Rx (S_B)	Tx (S_C)	Rx (S_D)	Rx (S_E)	Rx (S_{GW})
Bio-sensor D	Rx (S_A)	Rx (S_B)	Rx (S_C)	Tx (S_D)	Rx (S_E)	Rx (S_{GW})
Bio-sensor E	Rx (S_A)	Rx (S_B)	Rx (S_C)	Rx (S_D)	Tx (S_E)	Rx (S_{GW})
Gateway GW	Rx (S_A)	Rx (S_B)	Rx (S_C)	Rx (S_D)	Rx (S_D)	Tx (S_{GW})

Hence, a negative ACK (NACK) is sent back to the source node *S,* which allows it to re-transmit the packet.

The distance from the source *S* to the destination *D* is denoted as P_s–P_d distance from the source *S* to the intermediate node *R* is denoted as $S - R$ and distance from the intermediate node *R* to destination *D* node are denoted as $R - D$ respectfully as seen in Figure 3.

The cooperative network coding approach establishes cooperation among all bio-sensors that involves communication in WBAN. Therefore, when needed, this process is repeated. Besides, whenever a new node joins the network or if a node leaves the network due to failure, the same process is repeated. The tabular representation of cooperative network coding and sharing of vital information is shown in Table 2, where *Tx* and *Rx* represent the transmitted and received physiological value, respectively. While *T* represents the time slot (interval) for a specific activity. In time slot T1, sensor A transmits, and all other sensors, including the gateway, are receiving. Similarly, in T2, sensor B transmits, and all others receive. Furthermore, it is considered that all the bio-sensors in WBAN, having power P_A, P_B, P_C, P_D, and P_E, respectively. So, the fading co-efficient among bio-sensor nodes and between bio-sensor nodes and the gateway are modeled using the Rician fading model [14]. Similarly, the noise level is also calculated using zero-mean Additive-White-Gaussian noise (AWGN) [28]. Furthermore, binary phase-shift keying (BPSK) are considered, where $x = -1$ or $x = +1$.

In the proposed approach, a signal-to-noise ratio (SNR) is calculated using the formula shown in Eq. (4) below:

$$\frac{E_b}{N_0} = \frac{P_{coop}}{2\sigma_n^2} \tag{4}$$

Furthermore, at the 1[st] level, each bio-sensor sends common cooperative data to other and GW, i.e. z_A, z_B, z_C, z_D, z_C, z_E with cooperative values, as shown in table 2.

And at the 2[nd] level, each bio-sensors sends common cooperative data to BS through GW, i.e. $z_A \oplus z_B$, $z_A \oplus z_C$, $z_A \oplus z_D$, $z_A \oplus z_E$, $z_B \oplus z_C$, $z_B \oplus z_D$, $z_B \oplus z_E$, $z_C \oplus z_D$, $z_C \oplus z_E$ and $z_D \oplus z_E$ so on up to the maximum bio-sensors level, as shown in table 3. The cooperative data is transmitted using TDMA. Using the cooperative approach, we compare how the correlation between the R_x receiving antennas of bio-sensors affects the correlation of their immediate powers (P_i) [29]. It is noted that correlation may be positive or negative, but the positive correlation is most likely to occur. The reason being that bio-sensors are in cooperative mode, and they relay each other data. Furthermore, this received data is being tabulated and analyzed at BS; tabulation is performed in the following manner, as shown in Eq. (5), as shown at the bottom of this page. In Eq. (5) above y_{Ad}, y_{Bd} up to y_{Ed} are the signals received at the BS from all five bio-sensors by using a cooperative communication strategy. Similarly h_{Ad}, h_{Bd} up to h_{Ed} is the channel between bio-sensors *A*, *B*, *C*, *D*, *E*, and GW respectfully, while $z_A \oplus z_B \oplus z_C \oplus z_D \oplus z_E$ representing signal received during the cooperative

$$\begin{bmatrix} y_{Ad} \\ y_{Bd} \\ y_{Cd} \\ y_{Dd} \\ y_{Ed} \end{bmatrix} = \begin{bmatrix} h_{Ad} & 0 & 0 & 0 & 0 \\ y_{Bd} & h_{Bd} & 0 & 0 & 0 \\ y_{Cd} & 0 & h_{Cd} & 0 & 0 \\ h_{Dd} & 0 & 0 & h_{Dd} & 0 \\ y_{Ed} & 0 & 0 & 0 & h_{Ed} \end{bmatrix} \begin{bmatrix} z_A \\ z_B \\ z_C \\ z_D \\ z_A \oplus z_B \oplus z_C \oplus z_D \oplus z_E \end{bmatrix} + \begin{bmatrix} nA_{GW} \\ nB_{GW} \\ nC_{GW} \\ nD_{GW} \\ nE_{GW} \end{bmatrix} \tag{5}$$

$$L(z_{Si}) = \ln \frac{p(y_{d1}|z_{Si} = +1, h_{Si.BS})}{p(y_{d1}|z_{Si} = -1, h_{Si.BS})} \tag{6}$$

TABLE 3. Bio-Sensor 'A', 'B', 'C', 'D', 'E', and Gateway 'GW' Cooperative network coding values.

TxA	Cooperative data
YB	$z_A h_{AB}+n_{AB}$
YC	$z_A h_{AC}+n_{AC}$
YD	$z_A h_{AD}+n_{AD}$
YE	$z_A h_{AE}+n_{AE}$

Tx_D	Cooperative data
Y_A	$z_D h_{DA}+n_{DA}$
Y_B	$z_D h_{DB}+n_{DB}$
Y_C	$z_D h_{DC}+n_{DC}$
Y_E	$z_D h_{DE}+n_{DE}$

Tx_B	Cooperative data
Y_A	$z_B h_{BA}+n_{BA}$
Y_C	$z_B h_{BC}+n_{BC}$
Y_D	$z_B h_{BD}+n_{BD}$
Y_E	$z_B h_{BE}+n_{BE}$

Tx_E	Cooperative data
Y_A	$z_E h_{EA}+n_{EA}$
Y_B	$z_E h_{EB}+n_{EB}$
Y_C	$z_E h_{EC}+n_{EC}$
Y_D	$z_E h_{ED}+n_{ED}$

Tx_C	Cooperative data
Y_A	$z_C h_{CA}+n_{CA}$
Y_B	$z_C h_{CB}+n_{CB}$
Y_D	$z_C h_{CD}+n_{CD}$
Y_E	$z_C h_{CE}+n_{CE}$

Rx_{GW}	Cooperative data
Y_{Ad}	$z_A h_A . h_{GW}+n_A . n_{GW}$
Y_{Bd}	$z_B h_B . h_{GW}+n_B . n_{GW}$
Y_{Cd}	$z_C h_C . h_{GW}+n_C . n_{GW}$
Y_{Dd}	$z_D h_D . h_{GW}+n_D . n_{GW}$
Y_{Ed}	$z_E h_E . h_{GW}+n_E . n_{GW}$

phase of WBAN communication. Finally nA_{GW}, nB_{GW} up to nE_{GW} denote the AWGN in all communication in WBAN. Moreover, it is assumed that all five bio-sensors are reliable because associated with a single WBAN. In the proposed network, we used the same policies. For decoding of the received signals, i.e., z_A, z_B, z_C, z_D, z_E Long-Likelihood Ratio (LLR) technique is used. LLR is a well-known soft-decision decoding method, the formula for decoding of received signals at the BS for fading channel is given as,

In Eq. (6), as shown at the bottom of the previous page. z_{Si} is the physiological signal from any bio-sensor, $h_{Si.BS}$ is the fading channel from a S_i to BS, and y_{d1} is the received signal at the BS. On putting the computed value of $p(y_{d1}|z_{Si} = +1, h_{Si.BS})$ and $p(y_{d1}|z_{Si} = -1, h_{Si.BS})$ in eq (6), we get the following calculated value.

$$L(z_{Si}) = \frac{2y_{d1}h_{Si.BS}}{\sigma^2} \tag{7}$$

Using equation (7), LLR can be calculated for signals received at the BS by cooperative network coding.

1) ALGORITHMIC REPRESENTATION AND FLOW CHART OF THE COOPERATIVE COMMUNICATION APPROACH

To further elaborate on the proposed cooperative communication process, in this section, we present the algorithm and the flow-chart of the whole process. The simple flow chart is depicted in Figure 4, which illustrates how the proposed scheme performs bio-sensor cooperation using a network coding approach. The bio-sensors cooperation generated value is sent to the medical server for further analysis. The medical server may also reply with the necessary feedback based on the value saved in their medical database. Any change(s) in the network, if detected, is also updated based on the checking and comparing the newly received value and the values saved previously in the medical database.

The algorithm demonstrates the steps of the proposed solution that are elaborated as follows. The variables used are power P, $h_{Si.BS}$, S_{XCoop}, y_{d1}, z_{Si} the signal of bio-sensors and, for cooperation among bio-sensors nodes and fading calculation.

We deployed five bio-sensors A, B, C, D, and E on a human body, as shown in Figure 2. These bio-sensors are co-operating with each other and send their vital data in an aggregated manner to the medical server or BS for further analysis. The sensed information and initial parameters are shared in the first stage of the network establishment. Furthermore, future communication in WBANs is mostly based on the session established at the first stage.

The detail of the algorithm for the proposed approach and their steps are given below: using cooperative network coding, the packet transmission ratio is minimized significantly, which ultimately reduces the BER ratio. Due to

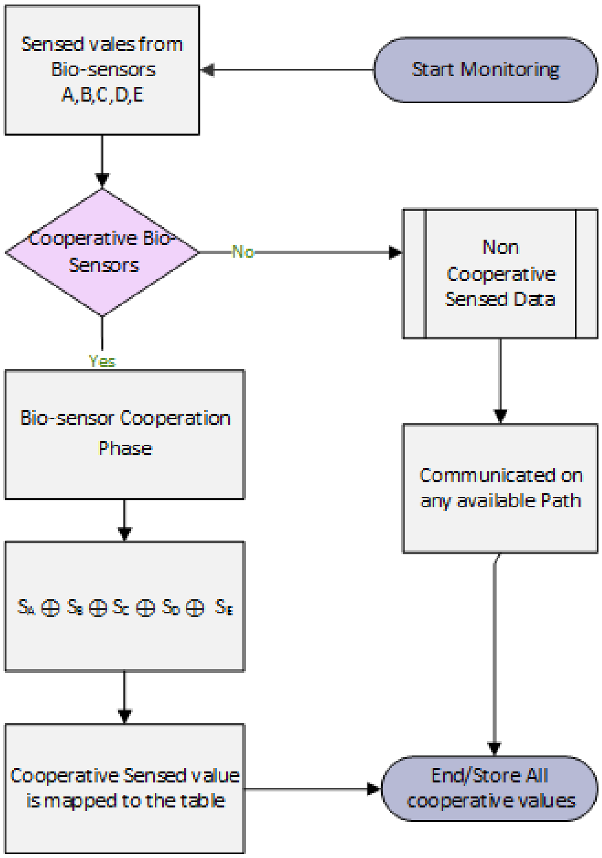

FIGURE 4. Flow chart of the proposed scheme.

Algorithm 1 Cooperative Network Coding Approach

START

Requirement: P, h_{AD}, S_{XCoop}, y_{d1}, S_{GW}

for each session T **do**

1. **If** Bio-sensor A, B, C, D, E generate $\rightarrow$ $S_{A,}$, S_B, S_C, S_D, $S_{E,}$ **Then**
2. Broadcast $S_{A,}$, S_B, S_C, S_D, $S_{E,}$ $\rightarrow$ A, B, C, D, E & GW

   else,
3. Bio-sensor A transmit $\rightarrow$ $S_{ACoop} = S_A \oplus S_B \oplus S_C \oplus S_D \oplus S_E$

   Repeat for B, C, D, E
4. B, C, D, E receives $\rightarrow$ $S_A \oplus S_B \oplus S_C \oplus S_D \oplus S_D$
5. Gateway GW received $\rightarrow$ $S_{ACoop} \oplus S_{GW}$

   Repeat for B, C, D, E

end if

8. Calculate $L(z_{Si}) = \ln \frac{p(y_{d1}|z_{Si}=+1, h_{Si.BS})}{p(y_{d1}|z_{Si}=-1, h_{Si.BS})}$
7. Gateway GW update their table

$$S_{GW\ Coop} \rightarrow S_{A\ Coop} S_{B\ Coop} S_{C\ Coop} S_{D\ Coop} S_{E\ Coop}$$

end for

END

---

reduced traffic, critical data has less chance to face errors in transmission. Furthermore, due to reduced communication of bio-sensors, body fading effects are also reduced due to which the fault-tolerance in WBAN increases.

Channel Modeling: In WBAN, channel modeling is a complex task as compared to traditional wireless channel modeling due to the environment and different tissues in the human body. Normally the divergence in the channel in WBAN is due to the posture and body movement as well as due to antenna placement [14]. These issues can be resolved using various techniques, like antenna placement, choosing a suitable frequency, and controlling body movement due to the environment. Several mathematical models exist for WBAN channel modeling; some of the existing body fading models address the issue of reflection and body movement [30]. Among all, Rician distribution is considered to be one of the best fading distribution models for WBAN. The channel is classified into CM1∼ CM4 (Channel Model), according to [31], developed by the IEEE802.15.6 Task group. CM1 refers to a channel that exists inside the body, CM2 refers to channel surface as well as inside the body, CM3 refers to channel surface of body and CM4 refers to channel off-body and surface of the body as shown in Table 4.

Therefore, we used the Rician model in our implementation, which addressed the Line-of-sight (LOS) as well as Non-Line-of-Sight (NLOS) situations [32]. We have used the IEEE 802.15.6 standard. This standard proposed three approaches for coexistence in WBANs, i.e., Beacon shifting technique to avoid collisions, channel hopping, which is applied in schedule MAC access, and CSMA/CA medium access approach [33]. In the channel hopping technique, we used the random channel mechanism where every channel has an equal probability of selection. In our scenario, a single WBAN used a fixed channel for its intra-BAN communication. For low power WBAN, the narrowband spectrum has 79 channels.

C. CASE STUDY: REMOTE SEPSIS MONITORING SYSTEM

In the preceding sections, we have presented the cooperative communication system model with network coding process in detail. In this section, we present a case study based on the proposed cooperative communication system model. In this case study, we designed a platform for remote Sepsis monitoring system, which identifies tracking indicators using cooperative communication to reduce hospital re-admissions and mortality rates. Sepsis is a specific condition caused due to bacterial infection in the blood, which is called septicemia. Septicemia is found to be the leading cause of Sepsis. The most current definition of Sepsis is a "life-threatening condition caused due to host response to an infection" [34]. The body usually releases certain chemicals in the bloodstream to fight with an infection. Sepsis occurs whenever the body's response to these chemicals is out of balance. The severe cause of Sepsis is the septic shock, which needs emergency-based treatment. According to the health-care survey, the US spends $ 17.8 per year on hospital re-admissions, in which the leading cause is Sepsis [35]. About 3 million new-burns children suffer from Sepsis each year. Sepsis is a leading

TABLE 4. WBAN channel model frequency bands and channel bandwidths [33].

Channel Model	Scenario	Description	Frequency Band	Bandwidth
CM1	S1	Implant-to-Implant	402-405 MHz	300 kHz
CM2	S2	Implant-to-Body Surface	402-405 MHz	400 kHz
	S3	Implant-to-External	402-405 MHz	400 kHz
CM3	S4	Body-Surface-to-Body Surface (LOS)	13.4, 50, 400, 600, 900 MHz, 2.2, 3.1-10.5 GHz	1 MHz
	S5	Body-Surface-to-External (N-LOS)	Same as S4	1 MHz
CM4	S6	Body-Surface-to-External (LOS)	900 MHz, 2.4, 3.1, 10.5 MHz	499 MHz
	S7	Body-Surface-to-External (N-LOS)	900 MHz, 2.4, 3.1, 10.5 MHz	499 MHz

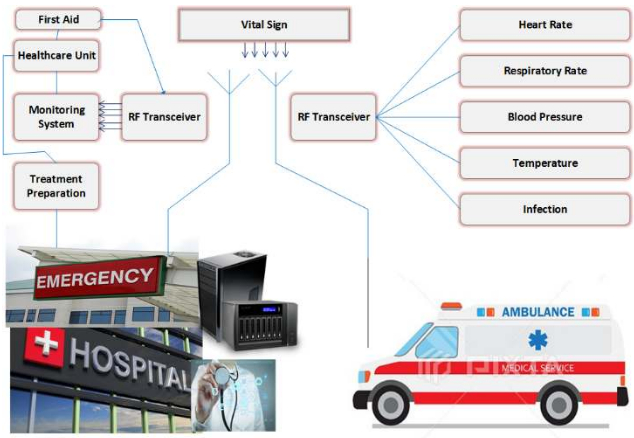

FIGURE 5. Proposed case study scenario.

cause of death in the Intensive Care Unit (ICU). It is also one of the main sponsors to hospital re-admission rates; Sepsis poses a significant health-care problem in many countries.

Similarly, the lack of knowledge and improper training may further endorse the importance of Sepsis monitoring at home. Therefore, cooperative communication-based reliable and fault-tolerant solution is a significant contribution to this issue. Some of the common indicators of Sepsis include infection, elevated breathing and heart rate, fever, and high blood pressure. This disease is currently served at the hospital because outside the hospital; there is used to be no practical way to monitor the Sepsis indicators. For this purpose, we have proposed a WBAN-based scenario in this case study for Sepsis identification and diagnosing. In this scenario, five bio-sensors are fitted on the patient body, which senses and monitors the five basic indicators causing Sepsis. The detailed scenario is presented in Figure 5, where the five basic indicators are sensed and measured. And using cooperative communication, the patient is diagnosed in real-time to ensure reliability.

The Scenario of Paramedics/Ambulance/Emergency Department at Hospital: In case of an emergency, five vital signals of a patient are sensed by bio-sensors attached to a body, which can easily indicate the health-care status of the patient suffering from Sepsis disease. Proper knowledge and accurate measurement of the diagnosis process are necessary to save the emergency patient's life. The use of the WBAN-based cooperative communication network coding approach leads to efficient and reliable treatment of the patient.

Moreover, the use of WBAN-based technology avoids tangling wires in the emergency department at the hospital or maybe at home. The readings of vital signs can be sent quickly to the health-care unit using WBAN technology, which provides an opportunity for the doctor(s) to analyze and diagnose the status of the patient at the early stage and prepare the treatment in advance. Meanwhile, the doctor can send feedback to the remote healthcare user by using some means, such as sending an ambulance and proposing the first aid suggestions for the patient. Hence, the health-care user can take essential steps to assist the emergency patient.

Sepsis has a profound impact on the life of an individual. According to the World Health Organization, the epidemiological burden of Sepsis is difficult to determine globally; however, it is estimated that it affects more than 30 million people worldwide every year, potentially leading to six million deaths. Developing a standard technique for this disease can lead to the quality lives of an individual. To diagnose Sepsis patients using WBAN cooperative communication, one needs to track or sensed many effects through bio-sensors. This WBAN solution gives an efficient solution to diagnosis

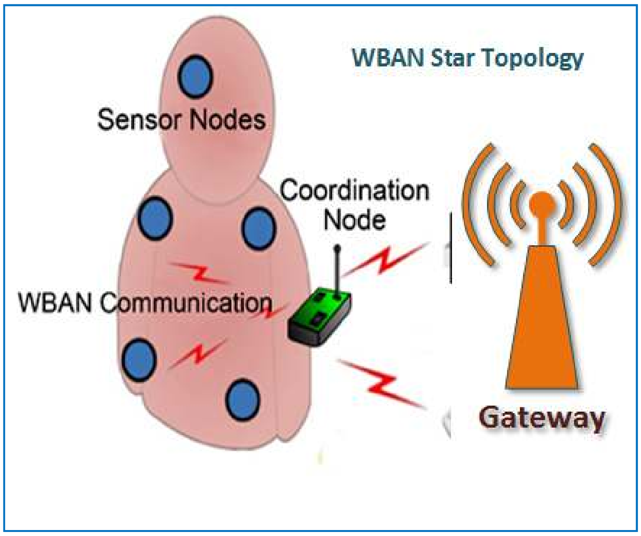

FIGURE 6. Simulation topology.

the patient suffering from Sepsis. The important aspect of this case study is to identify the new areas of application of the proposed research.

IV. PERFORMANCE ANALYSIS

We analyzed the performance of the proposed cooperative fault-tolerant communication approach using MATLAB simulator. MATLAB simulation is suitable for the low-powered wireless network's analysis, such as WBAN. For performance evaluation, the simulation-based experimentation is conducted using different parameters. Simulation and parameter setup is performed according to [36] and elaborated in Table 5 based on the scenario given in Figure 6.

A. SIMULATION SETTINGS

For implementation and simulation, we considered a network area of 15 $m^2 \times 15\, m^2$, where various WBANs can exist. In the experimental setup, the IEEE 802.15.6 wireless standard is used, which provide low power and short-range, within the surrounding area of the human body. For data forwarding, star topology is used between bio-sensors and GW node, shown in Figure 6.

The initial residual energy of each WBAN is considered as 5 Joules, and the sensing range of bio-sensor is considered between 0.5→1.5 meters.

The packet transmission rate of bio-sensors is considered as 4 packets/second, and each packet has a size of 512 bytes.

$$E_{rem} = E_{total} - (E_t + E_r + E_l) \tag{8}$$

In Eq. (8) E total E_{total} is the total initial energy, E_t and E_r represent the energy consumption in transmission and reception of data respectively, while E_l is the amount of energy drain during the failures or interference conditions.

Moreover, to emulate the realistic environment, generally, two types of radio transceivers are frequently used and integrated with the IEEE 802.15.6 standard, i.e., Nordic (nRF2401A) and Chipcon (CC2420). We preferred to use Nordic nRF2401A transceiver as it is a low power transceiver and better than Chipcon CC2420. Table 5 shows the above-mentioned parameters used in our simulation. For mobility support, we considered the group-based mobility approach, which means that each WBAN is considered a group or cluster according to the work of [37].

TABLE 5. Simulation parameters.

Parameter	Value
Simulation area	15 m × 15 m
Initial residual Energy	5 J
Sensors/Devices	6 (5 Bio-Sensor, 1 GW)
Transmitting Energy E_{TX}	16.7nJ/bit
Receiving Energy E_{RX}	36.1nJ/bit
Data Aggregation Energy (E_{DA})	5nJ/ bit
Packet size (b)	512 bytes
Agent trace	On
Simulation time	50 sec

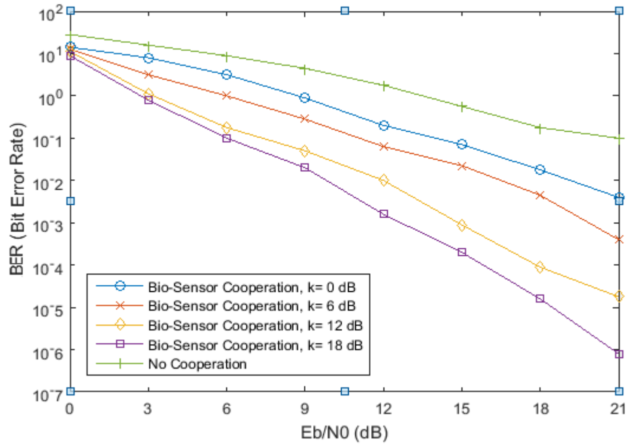

FIGURE 7. Performance analysis of bio-sensors cooperation.

B. SIMULATION RESULTS AND ANALYSIS

Using the above-mentioned simulation setup and parameters, we performed various experiments and obtained a various set of results.

Experiment 1 (Cooperative Communication Aspect): In the first experiment, we simulated the cooperative communication aspect of the proposed approach. Figure 7 shows the result of five bio-sensors cooperation in a dynamic WBAN using a Rician fading channel. In the given simulation, various Rician k-factors were consider i.e. k = 0 dB, k = 6 dB, k = 12 dB, k = 18 dB for WBAN system. K is the ratio of the power of direct path concerning the power of other scattered paths in LOS communication. With the increase in k-factor, some aspects of LOS also increase, which reduces the probability of fading in WBAN. Resultantly, a significant

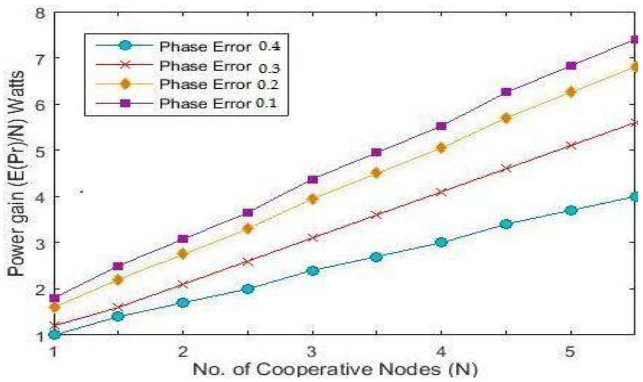

FIGURE 8. Power gain with respect to the number of cooperative nodes in the presence of fading and channel noise.

improvement is achieved in reducing the BER due to the cooperative network coding.

Figure 7 clearly shows that whenever the k-factor is increased, then the LOS signal is increased; consequently, the fading effect is reduced significantly. For instance, with k=18 dB, the LOS is the most foremost path, as shown while fading is condensed significantly. Hence, the BER performance improves when the k-factor increases. Furthermore, it is clear that the performance of BER is improved with a diversity order. For WBAN communication, minimal acceptable targeted BER is 10^{-1}, but in general non-coding, the value of BER is 10^{-3}.

Experiment 2 (Power Gain With Cooperative Nodes): In the proposed approach, an average power gain due to bio-sensor cooperation is shown in Figure 8. Different phase errors (e.g., 0.1, 0.2, 0.3, and 0.4) are considered here due to replication and body fading effect. From the results shown in Figure 8, it can be seen that with the increase in the number of cooperative bio-sensors, the power gain of the network grows. This prolongs the network lifetime of the bio-sensor nodes, ultimately increases the network lifetime notably. Thus, using a cooperative network coding approach, the power backup is extended significantly.

Experiment 3 (Energy Gain With Sensor Cooperation and Non-Cooperation): In this experiment, the comparison of cooperative and non-cooperative bio-sensor communication is demonstrated with respect to BER. The graph shown in Figure 9 illustrates that, in the cooperative approach, 2-4 bio-sensors and 5-10 are compared with the non-cooperative network coding approach. In this experiment, when the number of bio-sensors is increased, we will get more generalized results. Whenever the number of cooperation of bio-sensor increases, the packet drop ratio automatically decreases; consequently, it decreases BER. Therefore, the ratio of re-transmission will also decrease, which minimizes the energy consumption of the resource-constrained WBANs. Using this approach, a single bio-sensor node lifetime will be increased; hence the overall network lifetime will be maximized. The number of transmission paths and cooperative nodes produces an effect similar to the spatial diversity, which leads to a significant gain in BER. The BER

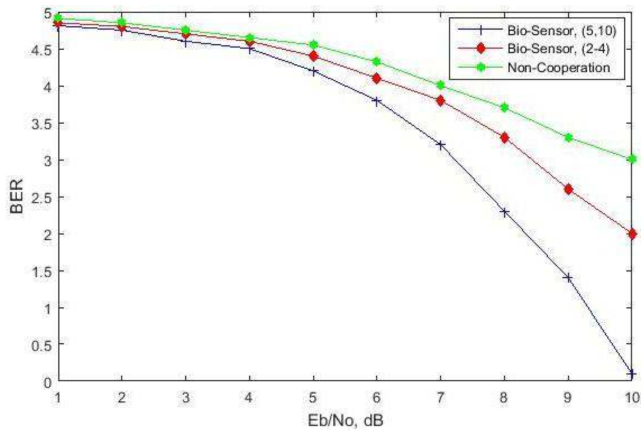

FIGURE 9. BR in the presence of Bio-Sensor cooperation and Non-cooperation and total transmission energy Eb/No, dB.

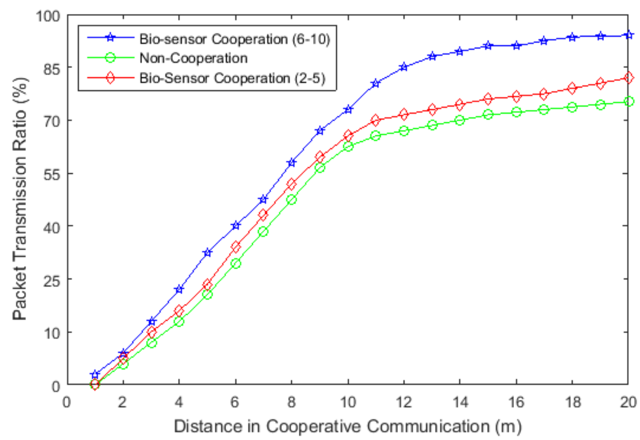

FIGURE 10. Comparison of successful packet transmission probability VS cooperative and non-cooperative nodes.

has an inverse relation with SNR. Thus, in the presence of body fading and interference, the maximum power gain is achieved by using a cooperative approach.

Experiment 4 (Packet Transmission Ratio VS Cooperative and Non-Cooperative Bio-Sensors): Experiment No. 4 shows the comparison of successfully transmitted packets of the non-cooperative and cooperative bio-sensors in terms of distance from the *S-D* link. The graph shown in Figure 10 below demonstrates that for a small distance, the successful packet transmission ratio is almost the same in all cases of cooperative and non-cooperative approaches. While with the increase in the distances from (S-D), i.e., 7 to 10 meters, the packet transmission ratio of cooperative network coding is better as compared to the non-cooperative approach.

Experiment 5 (Energy Saving): Figure 11, shows the energy efficiency of the different number of transmitted nodes in cooperation and without the cooperation and break-even distance. With the increase in break-even distance, the number of nodes involved in the packet transmission is also increased. Therefore, if more bio-sensor nodes are involved in the network, it will consume more energy; however, if using

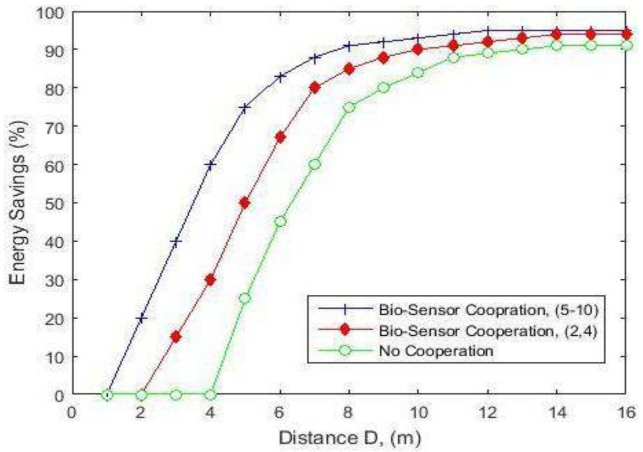

FIGURE 11. Energy efficiency for the various number of cooperative nodes and "Break-even Distance."

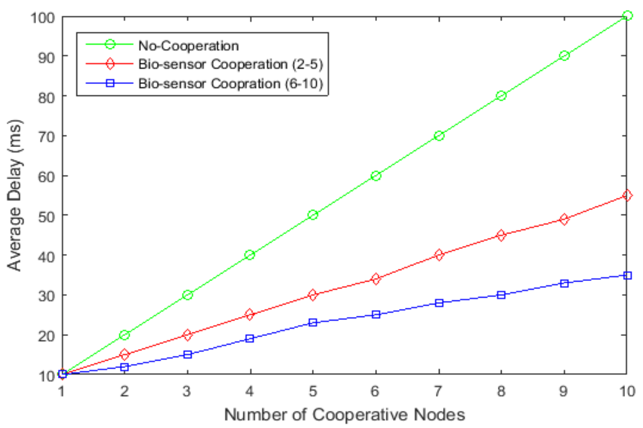

FIGURE 12. Average of cooperative VS non-cooperative strategies.

bio-sensor cooperation will reduce energy consumption significantly. The break-even distances are calculated using different phase error intervals considered for this experiment. The stable position will get at a certain distance on a certain point. At a certain stable point, an increase in energy-saving is achieved with an increase in distances.

Experiment 6 (Average Delay): In this experiment, the average delay incurred by cooperative nodes for various combinations of cooperative nodes is analyzed in Figure 12. The average delay is the time from the creation of a packet up to the time gateway nodes receive it.

In the figure, it's clear that with the increase in the number of cooperative bio-sensors, the average delay becomes very low. Mostly, non-cooperative nodes create an extra delay when the communication path is not free. Moreover, by increasing the packet interval time, the average delay increases. While using a cooperative approach, if we increase the number of cooperative nodes, the average delay increased in a stable manner, as shown in Figure 12. For cooperative bio-sensors 6-10 nodes, the average delay increase is negligible. Ultimately, the reliability and service delivery ratio increase by using a cooperative network coding approach.

V. CONCLUSION AND FUTURE WORK

Due to the sensitive nature of WBAN and application's domain in health and emergency-related services, reliability and fault-tolerance of WBANs are of utmost importance. In this paper, we proposed a novel approach for improving the fault-tolerance and reliability of WBANs in the Sepsis disease monitoring scenario. The proposed cooperative communication approach reduced the energy cost and network delay and increased network reliability and fault-tolerance for critical data exchanges in WBANs. Based on the proposed scheme, a case study was designed for remote Sepsis monitoring. The system identifies tracking indicators using cooperative communication in order to reduce hospital re-admissions and mortality rates. Finally, the simulation and performance analysis of the proposed approach showed that minimizing the exceeding packets' transmission in WBAN, increased energy efficiency by avoiding unnecessary traffic. The proposed scheme also achieved low end-to-end delay, low EBR, avoid packets loss, and packet transmission ratio increased throughput and proved to an effective solution for WBANs.

In the future, the proposed work will be extended to a collaborative, cooperative communication scheme for a real-time cloud-based system. Using a collaborative approach in the real-time monitoring system, the feedback system will be enhanced significantly. Furthermore, we have the plan to take a case study of a large geographic area like a hospital consisting of a large number of bio-sensor devices (i.e., 150 to 256) installed for a healthcare scenario.

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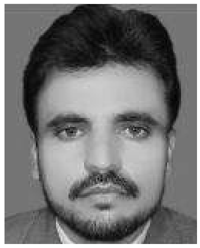

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