On Energy Efficient Cooperative Routing in Wireless Body Area Network

By

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CIIT/FA12-REE-039/ISB

MS Thesis

In

Electrical Engineering

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Declaration

I, Sidrah Yousaf, *CIIT/FA12-REE-039/ISB*, hereby declare that I have produced the work presented in this thesis, during the scheduled period of study. I also declare that I have not taken any material from any source except referred to wherever due that amount of plagiarism is within acceptable range. If a violation of HEC rules on research has occurred in this thesis, I shall be liable to punishable action under the plagiarism rules of the HEC.

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It is certified that Ms. Sidrah Yousaf, CIIT/FA12-REE-039/ISB has carried out all the work related to this thesis under my supervision at the Department of Electrical Engineering, COMSATS Institute of Information Technology, Islamabad and the work fulfills the requirements for the award of the MS degree.

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DEDICATION

I dedicate this thesis to my parents and brothers who supported me throughout this process and sacrificed so much for me.

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I am heartily grateful to my supervisor, Dr. Nadeem Javaid, whose encouragement, guidance and insightful criticism from the beginning to the final level enabled me to have a deep understanding of the thesis.

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ABSTRACT

On Energy Efficient Cooperative Routing in Wireless Body Area Network

Energy efficient and reliable communication is extremely crucial in most of the applications of Wireless Body Area Networks (WBANs). Communication between sensor nodes is the major cause of energy consumption that limits the network lifetime, and hence, disrupts WBAN's operation. Moreover, unreliability in wireless communication caused by the channel impairments, such as shadowing and fading, further exacerbate the situation. In this thesis, we investigate a multi-hop and three cooperative routing schemes to improve Energy Efficiency (EE) and reliability of WBANs. Firstly, we propose a protocol; Critical data transmission in Emergency with Mobility support in WBANs (CEMob), which utilizes both single-hop and multi-hop communication modes and avoids continuous data transmission to preserve energy of sensor nodes. Performance comparison of CEMob is made with contemporary routing protocols, Adaptive Threshold-based Thermal-aware Energy-efficient Multi-hop ProTocol (ATTEMPT) and Reliability Enhanced-Adaptive Threshold based Thermal-unaware Energy-efficient Multi-hop ProTocol (RE-ATTEMPT). Simulation results show that CEMob is 71% and 55% more energy efficient than ATTEMPT and RE-ATTEMPT, respectively. Later on, to improve the achieved throughput by CEMob, we introduce the concept of cooperative routing in Cooperative Critical data transmission in Emergency for Static WBANs (Co-CEStat). In this protocol, network throughput is enhanced by propagating independent signal through different paths. Simulation results reveal that Co-CEStat has 51% and 52% more throughput than its counterpart protocols, RE-CEStat (static CEMob) and RE-ATTEMPT, respectively. Availability of multiple links, for the propagation of same data, increases reliability of network at the cost of extra energy consumption by cooperative nodes. To improve EE and Packet Error Rate (PER) of Co-CEStat, we further analyze incremental cooperative communication schemes with different number of relays. We propose a new incremental cooperative communication scheme with 3-stage relaying and compare it with already existing incremental cooperative schemes in literature. Taking into account the effect of PER, analytical expressions for EE of proposed 3-stage cooperative communication scheme are also derived. Our proposed scheme proves to be more reliable with less PER at the cost of some extra energy consumption. In the last, 3-stage incremental relaying and contemporary 2-stage incremental relaying schemes are implemented in two routing protocols; Incremental Cooperative Critical data transmission in Emergency for Static WBANs (InCo-CEStat) and Enhanced InCo-CEStat (EInCo-CEStat), respectively. Simulation results of incremental cooperative protocols are compared with Co-CEStat and it is observed that incremental cooperation is more energy efficient than cooperation approach utilized in Co-CEStat. Results also reveal that EInCo-CEStat proves to be more reliable than InCo-CEStat with 12% more throughput and has less PER by providing three redundant links for a source node. Whereas, InCo-CEStat proves to be more energy efficient with 24% more stability period than EInCo-CEStat, by utilizing two cooperative links for a single source node.

LIST OF PUBLICATIONS

1. S. Ahmed, N. Javaid, S. Yousaf, et al., "Co-LAEEBA: Cooperative Link Aware and Energy Efficient protocol for Wireless Body Area Networks", accepted in *Computers in Human Behavior (in press)*, 2014 (IF=2.2).

2. S. Yousaf, et al., "CEMob: Critical Data Transmission in Emergency with Mobility Support in WBANs", *The 28th IEEE International Conference on Advanced Information Networking and Applications (AINA-2014),* Victoria, Canada, 2014. (Chapter 3 in thesis)

3. M. Akbar, N. Javaid, S. Yousaf, et al., "TRP: Tunneling Routing Protocol for WSNs", *The 28th IEEE International Conference on Advanced Information Networking and Applications (AINA), Victoria*, Canada, 2014.

4. S. Yousaf, et al., "Co-CEStat: Cooperative Critical Data Transmission in Emergency in Static Wireless Body Area Network", *The 9th IEEE International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA'14),* Guangzhou, China, 2014. (Chapter 4 in thesis)

5. S. Yousaf, et al., "Incremental Relay-based Co-CEStat Protocol for Wireless Body Area Networks", *The 9th IEEE International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA'14)*, Guangzhou, China, 2014. (Chapter 5 in thesis)

6. S. Yousaf, et al., "Reliable and Energy Efficient Incremental Cooperative Communication for WBANs", submitted in *IEEE ICC (International Conference on Communcation) SAC-Communications for E-Health*, 2015. (Chapter 5 in thesis)

7. S. Yousaf, N. Javaid, et al., "Incremental Cooperative Communication for Improving Reliability in WBANs", submitted in *IEEE transactions on Mobile Computing*. (IF=2.9) (Chapter 5 in thesis)

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Chapter 1

Introduction

1.1 Wireless Body Area Networks

Health monitoring systems combined with wireless communication create a class of Wireless Sensor Networks (WSNs), known as Wireless Body Area Networks (WBANs). Such networks consist of tiny computing devices, called sensor nodes, along with a central unit called sink. These sensors may be placed in wearable objects such as belts, headsets, wrist watches, etc., or may be attached to or implanted inside the human body to make WBAN. The IEEE 802.15 Task Group 6 has approved the standard for the physical layer and Medium Access Control (MAC) layer for short range on-body, in-body or off-body wireless communications [1]. Initially, the main idea behind WBANs was the provision of remote monitoring of vital signs of patients suffering from chronic diseases such as asthma, heart attack and diabetes. Nowadays, WBANs may also be utilized in sports, military or security applications. Such networks come with great number of applications such as, detection of human body postures and activities, monitoring of diet and support for other health crisis.

1.1.1 Motivation

WBANs are supposed to operate properly for long duration of time without any battery recharge or replacement, especially for in-body (*implanted*) sensors. Therefore, energy management is one of the major concerns for WBAN protocols so that recharging and replacement of batteries is as infrequent as possible and network is responsive for longer period of time (*Network lifetime*). Continuous data sensing and transmission, and greater distance between communicating nodes may cause more energy consumption. Therefore, routing protocols are needed which are capable to prolong the time interval before the death of the first node (*stability period*) and network lifetime of WBANs to increase the overall network throughput.

There may be different modes of communication in WBANs. In case of single-hop communication, sensors/nodes transmit their data directly to sink. As, energy consumption is directly proportional to the distance between communicating nodes, therefore, nodes which are at a greater distance from sink die sooner because of more energy consumption. In multi-hop communication, nodes which are at greater distance from sink, utilize intermediate nodes to forward their data to sink. However, multi-hop communication causes increase in the energy consumption of forwarding/intermediate nodes which are closer to the sink. A solution is proposed in RE-ATTEMPT[2], which guarantees balanced load distribution among nodes and extends network lifetime by utilizing multi-hop communication for distant nodes. In the proposed routing protocol, sensor nodes in the network are equipped with different amount of energies (*heterogeneous network*) and are placed according to their energy levels. Moreover, direct communication is used for the delivery of emergency data, whereas, multi-hop communication is utilized for the delivery of normal data. However, continuous data transmission causes extra energy consumption in RE-ATTEMPT.

In case of WBANs, the sensed information is always critical, therefore, information loss is least acceptable. There is always a chance of link failure or reception of erroneous data due to any type of channel impairments. So, protocols assuring reliable delivery of information, are required to be designed. Conventional cooperative communication is realized to be an efficient technique to achieve higher energy savings, reliable delivery of information and to overcome the effects of channel impairments like fading and noise in communication system. Through co-operative communication information loss is avoided by exploiting the broadcast nature of wireless channel. It utilizes multi-cast mode in which a single source node transmits its data to more than one node by exploiting more than one links at a same time. Such schemes provide spatial diversity and may improve energy efficiency as well [3]. The main idea behind this is if a signal experiences a noise on a certain path at particular instant, then other independent path may carry the same signal with less noise or fading. Physical movement of body parts also causes variable path loss due to shadowing [4, 5]. By introducing the concept of cooperative diversity, both Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER) of signal can be improved at receiver end.

There may be single-relay based or multiple-relay based cooperative communication. For the selection of cooperative relays, both opportunistic or deterministic approaches may be used. In opportunistic selection, node that forwards a packet is determined on-the-fly and depends on packet receiving node. Whereas, in deterministic approach, the node that is supposed to forward the packet, is predetermined.

Although, cooperative routing significantly increases the rate of successfully received packets, however, it is not necessary that it also enhances the overall network performance in terms of Packet Error Rate (PER) and energy consumption. Conventional cooperative networks make an inefficient use of the channel resources because relays always forward the source signal to the destination regardless of the channel conditions.

For a specific relay selection, the relaying strategy can be fixed, selective or incremental. In fixed relaying, relays always forward the received data after certain processing on it. Whereas, selective relaying makes use of instantaneous channel information to decide between relay forwarding and source re-transmission in second phase. In incremental relaying [6,8], a short feedback, indicating success or failure of sent data, from the destination is used. Relay(s) is (are) allowed to forward signal only when direct transmission fails otherwise source continues with the next data packet. This approach reduces energy consumption and total transmission time of a network. Incremental relaying adapts to channel conditions and increases spectral efficiency by saving channel resources. Incremental relaying protocols are extensions of incremental redundancy protocols, or hybrid Automatic-Repeat reQuest (ARQ) [6]. In conventional cooperation schemes, sophisticated combining techniques at destination are required for achieving spatial diversity advantage. However, in incremental cooperation scheme, the destination has to process only one signal at a time during certain transmission phase. Thereby, avoiding complex systems at destination side.

1.1.2 Our Contribution

In this research, our aim is to design such protocols which help to maximize lifetime, stability period and throughput of WBAN.
A network layer protocol, CEMob, is proposed to achieve higher stability period with less energy consumption than some already designed WBAN protocols; Adaptive Threshold-based Thermal-aware Energy-efficient Multi-hop ProTocol (ATTEMPT) [7] and RE-ATTEMPT. Greater distance between nodes causes more energy to be consumed, so less distant node is selected for data forwarding. Efficient choice of next sensor node, to which information is to be sent, is made on the minimum hop count strategy. To preserve energy of sensor nodes, CEMob replaces continuous data transmission in RE-ATTEMPT and ATTEMPT by non-continuous threshold-based data transmission. Sensed data by sensor nodes is transmitted only when currently sensed data is different from previously sensed and transmitted data. Thereby, reducing the energy consumption by the whole network. Arm's mobility is also considered in CEMob and three different postures are taken into consideration.
For further enhancement in stability period and network lifetime, we give the concept of non-continuous transmission in Residual Energy based Critical data transmission in Emergency in Static WBANs (RE-CEStat). Normal nodes select their corresponding forwarder node with greater residual energy. Performance upgrades and significant increase in the stability period and network lifetime is observed due to less energy consumption of nodes.
Furthermore, we propose another protocol, Co-CEStat, in which cooperative rout-

ing is exploited to increase the average packet rate of our existing scheme. Protocol is implemented by selecting a shortest path between nodes and then performance is improved by using cooperation between nodes. Our proposed cooperative protocol gives higher throughput than our previously designed protocols.

Later on, we analyze three different communication schemes given in [8]. Comparison of direct communication and incremental cooperative communication schemes is given in this research paper. Performance evaluation shows that incremental two relay based cooperative communication performs well in terms of PER at the cost of Energy Efficiency (EE). Results are produced for both on-body and in-body sensor nodes. We then propose our new incremental three relay based cooperative communication scheme by considering on-body WBAN. Enhanced performance of proposed scheme is shown in comparison with contemporary schemes in the literature. Later on, proposed three-stage incremental relaying scheme and existing two-stage incremental relaying scheme are implemented in WBAN protocols i.e., InCo-CEStat and EInCo-CEStat, respectively. We also derive analytical expressions for the PER and the EE of proposed three-stage cooperative communication scheme. Simulation results show that the proposed scheme achieves less PER with more diversity, high channel utilisation and less energy consumption than compared conventional cooperative communication scheme.

Chapter 2

Literature Review

2.1 Related Work

To enhance the performance of WSNs and WBANs, many developments and improvements are made in this field. Routing protocols are designed by taking into account some major objectives, such as, energy efficiency, quick and reliable delivery of data, optimal bandwidth utilization, efficient use of available recourses etc. A large number of research is done to achieve these mentioned objectives.
In [2], authors presented a protocol in which positive features of both single-hop and multi-hop communications are utilized. Priority based routing is done in the protocol for normal and critical data transmission. Routes are selected on the basis of minimum-hop count which reduces the delay in transmission.Authors in [7], designed a routing protocol which is energy efficient and support body mobility. Proposed protocol is also thermal-aware and able to change the route in case of hot-spot detection. Direct communication is used for real-time traffic or on-demand data while Multi-hop communication is used for normal data delivery. One of the major challenges in WBANs is sensing of the heat produced by the implanted sensor nodes. The proposed routing algorithm is thermal-aware which senses the link Hot-spot and routes the data away from these links.
Analysis for PER and EE of incremental relay based cooperative communication is made in [8]. Incremental cooperation is compared with direct communication and is proved to be more reliable than direct communication. Simulations are conducted to find optimal distance of relay node from source and destination. Optimal packet size for efficient communication in WBAN is also given in this research.
Survey is presented in [9] in which discussion about types of communication in WBAN and their issues are provided. A detailed investigation of sensor nodes, physical layer, data link layer, and radio technology aspects of WBAN are given in this research.
Another energy efficient routing protocol for WBANs is proposed in [10]. Protocol utilizes threshold approach to preserve energy of sensor nodes. Authors in [11], proposed energy efficient routing protocol by utilizing multi-hop communication in WBAN. A cost function is calculated to select forwarder/intermediate node with high residual energy and minimum distance from sink.
In [12], a comprehensive survey on different design problems and techniques in WSNs is provided. Where, energy efficient routing protocols are classified as flat, hierarchical, query-based, coherent and non- coherent based, negotiation-based, location-based, mobile agent-based, multipath-based and QoS-based. It is stated that location based protocols are useful in increasing the network lifetime. Implementation of appropriate routing protocol also ensures the network connectivity

and reliable data delivery.

In [13], to monitor the daily activities of humans, authors use wearable sensors. Different movements are observed during different activities. Humans perform different movements during different activities. For this purpose, authors used a sensing device called motion node which recognizes the activity and gives accurate measurements.

Many other energy efficient and reliable cooperative communication schemes are proposed to make efficient use of available resources. Authors in [14], proposed a WSN routing protocol for wildfire monitoring. Cooperative communication is utilized to mitigate the effects of shadowing and to improve network lifetime. Transmission quality is enhanced by sharing the resources between nodes. A technique of reinforcement learning by opponent modeling, optimizing a cooperative communication protocol is used which is based on Received Signal Strength Indication (RSSI) and node's energy consumption. Their proposed protocol is energy and quality-of-service aware cooperative routing protocol.

In [15], minimum-power routing problem is solved by proposing the Minimum Power Cooperative Routing (MPCR) algorithm which utilize cooperative communication in wireless network. Routes with minimum transmission power are defined as optimum routes, guaranteeing some certain level of throughput. Routes are constructed as a cascade of the minimum-power single-relay building blocks from the source to the destination.

WBAN is usually assumed to be a single-hop star network, whereas, research shows that conventional multi-hop cooperative relaying has improved the performance of WBANs. Authors in [16], focused on the possible advantages of cooperative transmission for implanted sensors. Spatial diversity of multiple single-antenna terminals is exploited to reduce total power consumed by implanted sensors. A simple Opportunistic Large Array (OLA) technique is proposed to preserve the energy of nodes. OLA is supposed to avoid the overhead caused by cluster and cluster leaders. For the very first time, OLA is used for implanted sensor nodes. Performance is improved by using cooperative relaying.

A protocol for WSN is proposed in [17], in which some nodes use extra energy for cooperative transmission to relieve the nodes, near the sink, of their burden. This protocol extends cooperative transmission range if residual energy of next-hop node is low.

Authors in [18], presented a cooperative WBAN protocol that is able to support multi-hop communication along with cooperation. This protocol extends the cooperation at MAC layer to cross-layered gradient based routing.

In [19], energy consumption and network lifetime of a single-hop network and a multi-hop network are compared. A propagation model is proposed for communication along the human body. Energy efficiency of a line and a tree topology are studied. It is shown that single-hop communication is less efficient for distant nodes from the sink. Author propose a scheme in which dedicated relays or cooperative routing approach or combination of both is utilized to increase the energy efficiency and reliability of network.

In [20], several schemes for multi-hop cooperative relaying are proposed to increase the lifetime of WBANs. Different models are presented for delay spread and mean excess delay in the time-domain. Propagation measurements are made on real human body in a multi-path environment. For analysis different body parts are considered individually. Path loss parameters and time-domain channel characteristics are obtained from the measurement and simulated data.

In [21], authors proposed cooperative WBAN and analyze channel models, system performance and spatial diversity gain for two relays cooperation. Sitting posture of human body is considered to study the on-body radio propagation in time-domain UWB channel.

Authors in [22], utilized cooperative communication to reduce the BER and to improve the network lifetime of WBAN. A mobile device aided cooperative transmission scheme is proposed for BANs. Cooperative transmission is utilized to enhance the transmission reliability and maintain a low transmission power of sensor nodes.

In [23], authors considered the topology for WBAN as a time-varying fully connected network instead of a star structure. It is observed that opportunistic cooperative mechanism based on a decode-and-forward protocol may address the problems in multi-hop mesh topology. This improves the packet error rate probability by using multi-hop links instead of direct link.

Authors in [24] and [25], utilized Cooperative Network Coding (CNC) to improve reliability in WBANs. CNC combines cooperative communications and network coding, in a feed-forward architecture. Packets are transmitted over spatially distinct paths which significantly improve the network throughput due to extra paths for communication. These proposed schemes also provide enhanced self-healing which is a required feature in WBAN. Moreover, these feed-forward techniques are mostly suitable for real-time applications, where retransmissions are an inappropriate alternative.

In [26], authors evaluated the performance of cooperative relaying schemes for improving the robustness of WBANs. Some sensors are selected to provide redundant links for other nodes having worst channel conditions. Relay nodes are elected from a statistical perspective. Packet error rate outage probability is taken as performance parameter.

In [27], outage performance and energy efficiency of direct transmission, and single and multi-relay cooperation schemes are analyzed in the context of WBANs. To minimize the energy consumption, authors study the problem of optimal power allocation with the constraint of targeted outage probability.

A protocol is presented in [28] which considers the possibility of outage between two communicating nodes. For bandwidth efficiency, incremental relaying cooperation strategy is used in this paper. Trade-off between gains in the transmit power and the losses due to extra processing and receiving power consumption at the relay and destination nodes required for cooperation is analyzed. Such a trade-off is taken into consideration for the design of a network. Some other system parameters like the power amplifier loss, the required Quality-of-Service (QoS), the relay location, and the optimal number of relays are also considered in this research.

Many other techniques and schemes are implemented for communication in WBAN. A wireless accelerometer sensor module is used to determine the link performance [29]. It records data and traffic lost on different runners and for different transmitter locations around the human body (foot, leg, and arm). Approximate location of nodes are determined for accurate and reliable reception of data. The results also show that the sensor on the wrist gives the best outcome from the locations tested. In [30], authors proposed a framework for the estimation of network lifetime of WBAN. A parametric model for Health Monitoring Network (HMN) is created and probabilistic analysis is used to determine the timing and distribution of time failure in the HMN.

Authors in [31] addressed WBAN data monitoring challenges, by allowing virtual groups to be formed between devices of patients, nurses, and doctors to enable remote monitoring of WBAN data. A new metric, quality of health monitoring, is also introduced to provide feedback on the quality of data received by WBAN. A reliable anycast routing protocol, for Zigbee-based wireless patient monitoring is proposed in [32]. Mobile sensor nodes select the closest sink to forward their data in a Wireless Mesh Network (WMN). This protocol reduces the number of control messages with fast rerouting. This scheme also reduces the latency by using intermediate routers for route recovery. A device for fall monitoring is also implemented on the basis of proposed scheme.

In [33], data transmission scheduling problem is analyzed to make use of sleep mode and opportunistic transmission for energy efficiency. Propagation channel requirements and delay constrains are considered in the design of scheduling policy to save the energy of sensor nodes. Lyapunov optimization formulation is utilized to propose a two-step scheduling algorithm. It is proved that the algorithm can provide worst-case delay which is guaranteed under certain conditions. In [34], authors utilized low cost wake-up radio module to prolong the network lifetime. This radio module is attached with the sensor node. By reducing power consumption in idle state and increasing the sleep time of a sensor nodes, lifetime of a network is extended. A MAC protocol is proposed for WBAN which uses on-demand wake-up radio through a centralized wake-up mechanism. Results of this proposed method are compared with some of the contemporary MAC protocols. Authors in [35] presented an efficient technique to make operation of battery powered devices more reliable and efficient with minimal energy consumption. This paper combines efficient antenna design with a cross layer energy efficient protocol to maximize network lifetime of WBAN. Towards this goal, an efficient system is designed through which performance of WBANs is enhanced.

Chapter 3

CEMob Protocol

3.1 Motivation of CEMob

Reliable and quick transmission of data with low energy consumption of each sensor node is of extreme significance in WBANs. In some situations, monitored parameters require special attention. For example, immediate response is required whenever the sensed information belongs to the class of emergency data. Therefore, single-hop communication is appropriate option for such situations in order to avoid delay. One of the objectives behind this research is to wisely utilize multi-hop and single-hop communication to enhance the overall network performance. In ATTEMPT and RE-ATTEMPT routing protocols, continuous transmission of data to sink occurs with no mobility support. On the other hand, transmission of similar information increases the load on forwarder/intermediate nodes, thereby increasing their energy consumption. These drawbacks motivate us to propose a routing protocol; CEMob, which is capable of avoiding redundant data transmissions with mobility support.

3.2 Basic Terminologies and Performance Parameters

Some basic terminologies and performance metrics used in this study are mentioned below:

- *Throughput:* Total number of successfully received packets at sink is called throughput.
- *Dynamic routing:* Type of routing in which route selection is done on the bases of destination and certain change in conditions.
- *Stability period:* Stability period is defined as a time duration from the start of a network till the death of the first node.
- *Residual energy:* Average total remaining energy of a network after each round is called residual energy.
- *Network lifetime:* Total time duration of a network operation, from the start of the network establishment till the death of the last node is called network lifetime.
- *Heterogeneous network:* A network, in which different initial energies are assigned to sensor nodes, is called heterogeneous network.
- *Number of alive nodes:* This measure gives the total number of nodes which are not depleted and still have residual energy to communicate.

- *Advanced nodes:* Sensor nodes which have more initial energy than that of normal nodes are called advanced nodes.

3.3 CEMob Protocol

Properties, network architecture and routing flow of CEMob is discussed in the following subsections.

3.3.1 Properties of CEMob

Following assumptions are taken for the proposed protocol:

- Every node in the network is on-body and fixed.
- There is only one coordinator (sink node) which is fixed at the center of the body and responsible for gathering the data from all sensor nodes. Sink has adequate hardware and software with constant power supply but batteries of sensor nodes is not rechargeable.
- Transmission range and transmission power of each sensor node is fixed.
- Location of all nodes is initially known to each node.
- The ultimate destination for each sensor node is sink node. Data transmission beyond the sink node is not allowed.
- The size of generated packet by each node is always fixed and each node transmits its generated data in its own time slot.

3.3.2 Network Architecture

Network architecture may be divided into two types: flat architecture and multi-tier architecture. In flat architecture, sensor nodes directly send their data to external network. In later case, data gathering is done using multiple nodes in the base tier and the sink at the second tier is responsible to link base tier with the external server at the third tier. Our proposed WBAN architecture is using multi-tier architecture in which nodes are affixed on the body of patient and sink is placed at the center of the body.
Two approaches are considered while designing a routing protocol for WBANs. One approach is the integration of routing functions with that of MAC layer. Whereas, the other choice is to propose a routing layer protocol such that link qualities are measured on the bases of selected parameters. Overall performance

of a network and several aspects like error-rates, throughput, bandwidth usage, transmission delay, availability, etc. We focused on the later approach to develop a new energy efficient routing protocol in which dynamic routing is used for data forwarding. In case of normal transmission, some nodes forward sensed data through intermediate nodes. Whenever, the sensed data type is emergency or the intermediate node is dead, node(s) establish(establishes) direct link with sink. As, we also consider body mobility, so, it is a better strategy to choose the next hop node by using dynamic routing.

3.3.3 Routing and Communication Flow

In order to preserve communication energy, CEMob exploits the threshold approach for data transmission. Every time node senses the information, it compares the current information with the stored information sensed earlier. Transmission of information occurs if variation is observed. This technique avoids transmission of same information again and again which results in less energy consumption of sensor nodes. As shown in the figure 3.1, eight sensor nodes are attached with the human body. Sink, that is affixed at the center of the body, is the destination for all nodes. However, CEMob protocol does not consider communication beyond the sink.

Both single-hop and multi-hop approaches are used to make the network more efficient in terms of energy consumption and quick transmission of sensed data. We have two types of data transmission: emergency data transmission and normal data transmission. In case of emergency data, all the nodes are supposed to establish direct link with sink. If data is normal and different from previously sensed data, then advanced nodes are supposed to use single-hop, whereas, other nodes use multi-hop transmission scheme. Figure 3.1 shows that, node 1, 2, 5 and 6 are advanced nodes which collect and forward data of normal nodes to the sink after aggregation. Node 3 and 7 forward their normal sensed data to node 6, whereas, node 4 and 8 send their normal data to node 5. In case of arms mobility as shown in figure 3.1, node 3 and 4 will forward their data to less distant advanced node. Different postures and corresponding routes for nodes are shown in the figure. Efficient selection of the next hop sensor node is necessary in case of arms' mobility. This dynamic routing strategy reduces the energy consumption as nodes choose less distant node for data forwarding. Communication flow diagram is shown in figure 3.2.

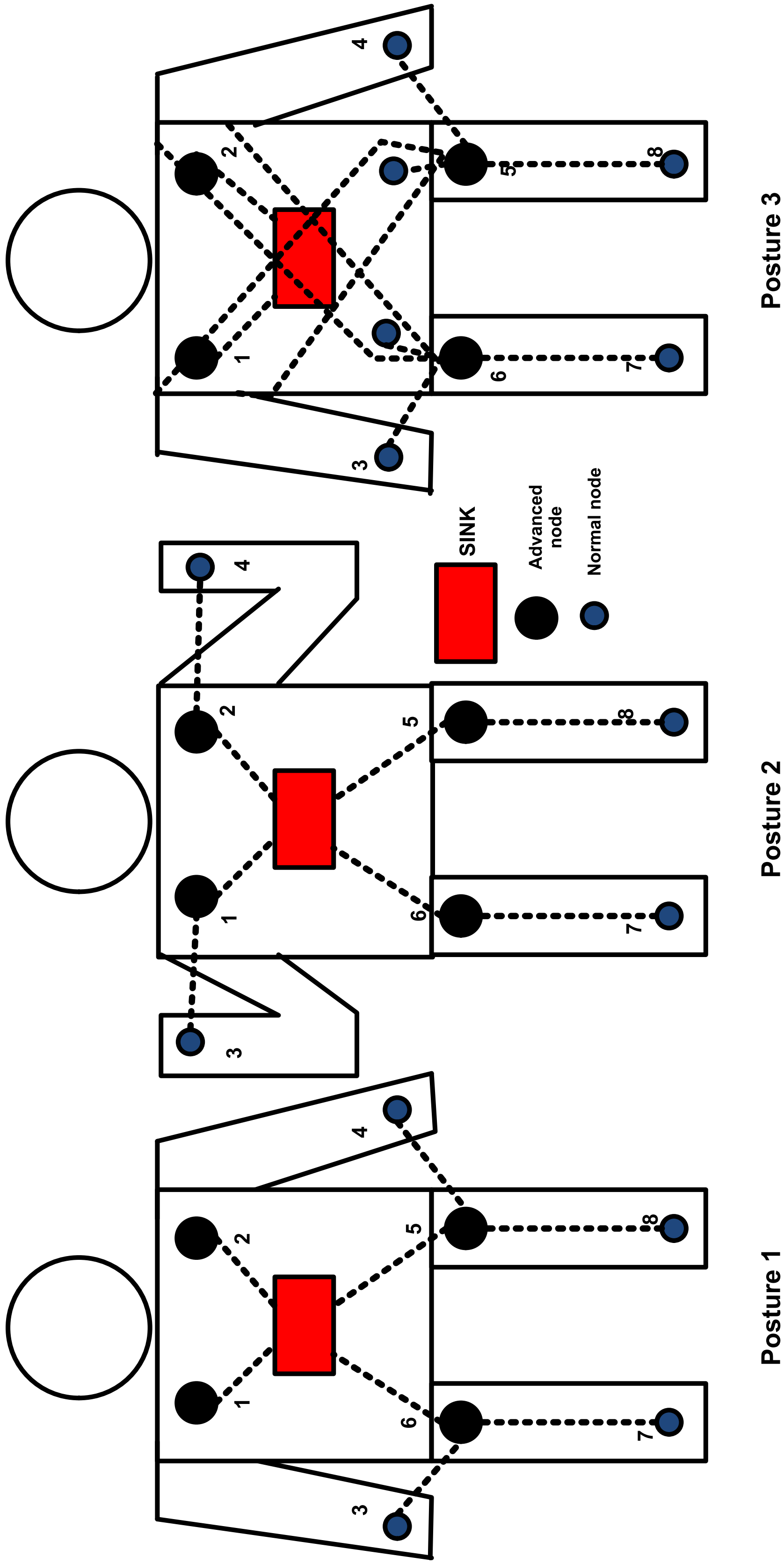

Figure 3.1: *Connections between nodes for different body postures*

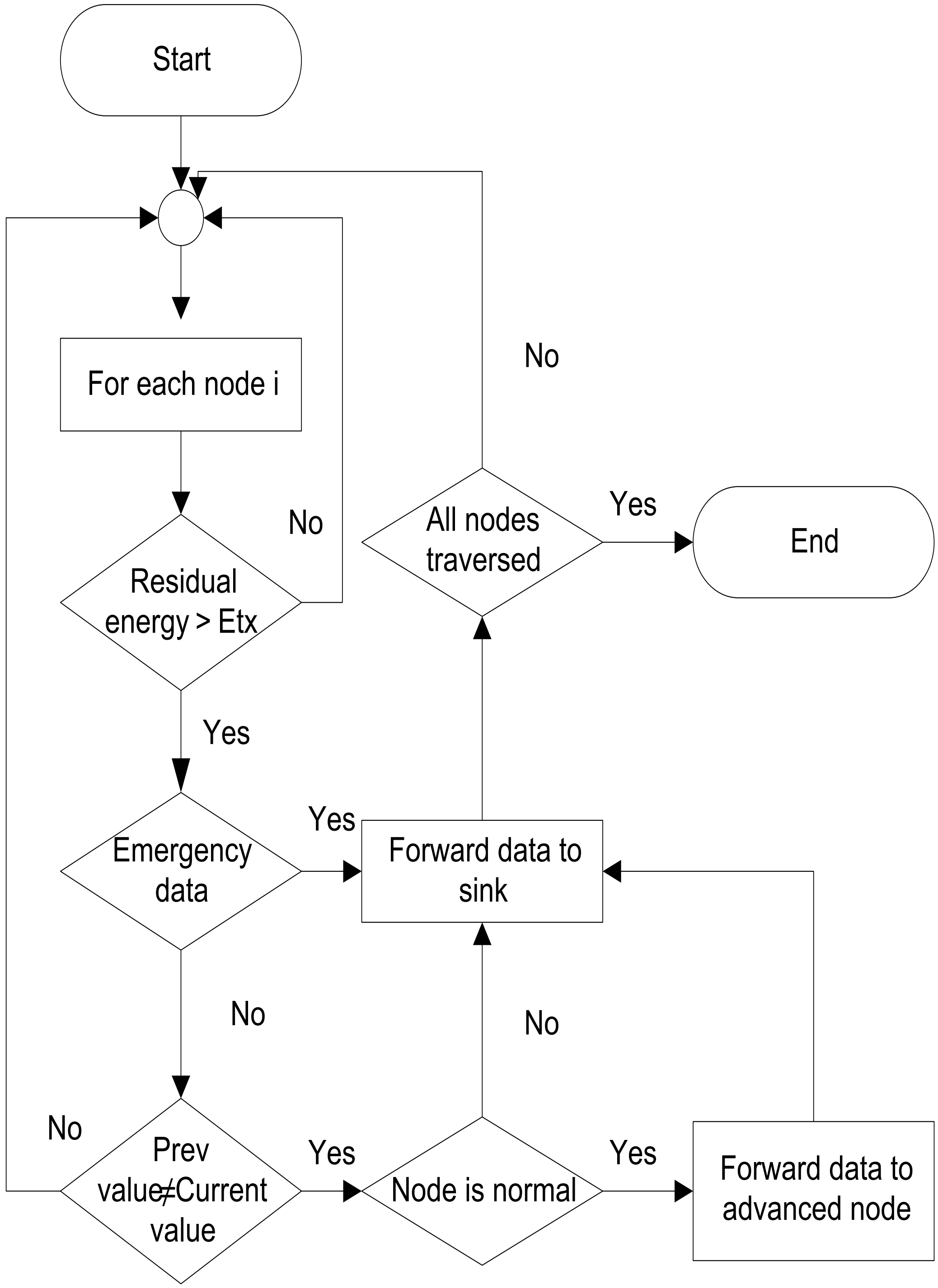

Figure 3.2: *Communication flow diagram*

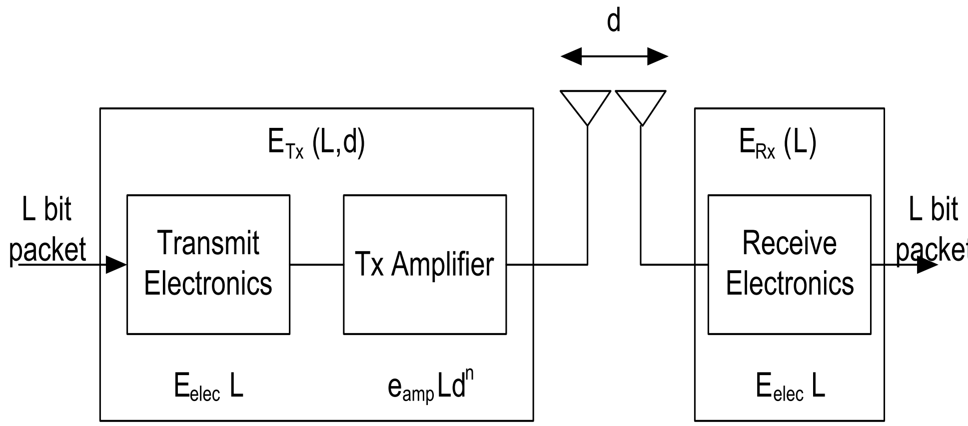

Figure 3.3: *First order radio model*

3.4 Energy Model

The first order radio model for WBANs, used in [2], is given below:

Transmission energy of each node is calculated as,

if d $>d_o$,

$$E_{tx}(L,d) = E_{elec} * L + L * (e_{amp}(n) * d^n), \tag{3.1}$$

or if d $<d_o$,

$$E_{tx}(L,d) = E_{elec} * L + L * (e_{fs}(n) * d^n). \tag{3.2}$$

Whereas, transmission energy for intermediate node is,

$$E_{tx}(L,d) = ((E_{elec} + E_{DA}) * L) + (e_{amp} * L * d^n). \tag{3.3}$$

Equation for reception energy is:

$$E_{rx}(L) = E_{elec} * L. \tag{3.4}$$

Here, E_{tx} and E_{rx} are transmitting and receiving energies of each node, respectively, which transmits or receive L bits at a distance d. E_{elec} is the energy, which dissipates to run the circuitry of transmitter and receiver. n is the path loss exponent and d_o is the reference distance. e_{amp} and e_{fs} are characteristics of transmitter amplifier. Whereas, E_{DA} is the energy consumed in data aggregation. Used values for these parameters are given in table 3.1.

Parameter	Value
Number of nodes	8
Sink's position	At the center of the body
Initial energy	Advanced node: 0.3 J Normal node: 0.2 J
Packet size	4000 bits
E_{elec}	50 nJ/bit
e_{fs}	10 pJ/bit/m^2
e_{amp}	0.0013 pJ/bit/m^4
E_{DA}	5 nj/bit

Table 3.1: *Simulation parameters*

3.5 Simulation Results and Discussions

Simulations are conducted in MATLAB by considering parameters given in table 3.1. Eight sensors nodes are deployed at fixed positions on a human body of height 1.6 meters and width 0.8 meters. Sink node is placed at the center of the body. Exact positions of all nodes are shown in table 3.2. We consider a heterogeneous network such that the normal nodes are initially equipped with 0.2 J, whereas, each advanced node is equipped with 0.3 J. For evaluation purpose, CEMob is compared with two existing routing protocols; ATTEMPT and RE-ATTEMPT. Results are averaged over five independent runs and each run performs 5500 rounds of monitoring.

Node no.	x-axis (m)	y-axis (m)
1	0.4	1.5
2	0.2	1.3
3	0.7	0.6
4	0.2	0.6
5	0.3	0.5
6	0.6	0.5
7	0.6	0.3
8	0.3	0.3

Table 3.2: *Coordinates of deployed nodes on human body*

3.5.1 Stability Period and Network Lifetime

Figure 3.4 shows that stability period and network lifetime of CEMob is greater than that of ATTEMPT and RE-ATTEMPT. This is due to the fact that continuous transmissions are avoided in proposed protocol which results in less energy consumption and increases stability period. Also, load distribution is well balanced in CEMob and multi-hop transmission scheme preserve the energy of distant nodes. This approach also helps in increasing the total network lifetime. In ATTEMPT and RE-ATTEMPT, nodes die quickly because of single-hop and continuous transmissions. The stability period of ATTEMPT and RE-ATTEMPT is 478 and 569 rounds, respectively. Whereas, the first node dies at 3230th round in the proposed protocol. So CEMob, has *81%* and *84%* more stability period than RE-ATTEMPT and ATTEMPT, respectively.

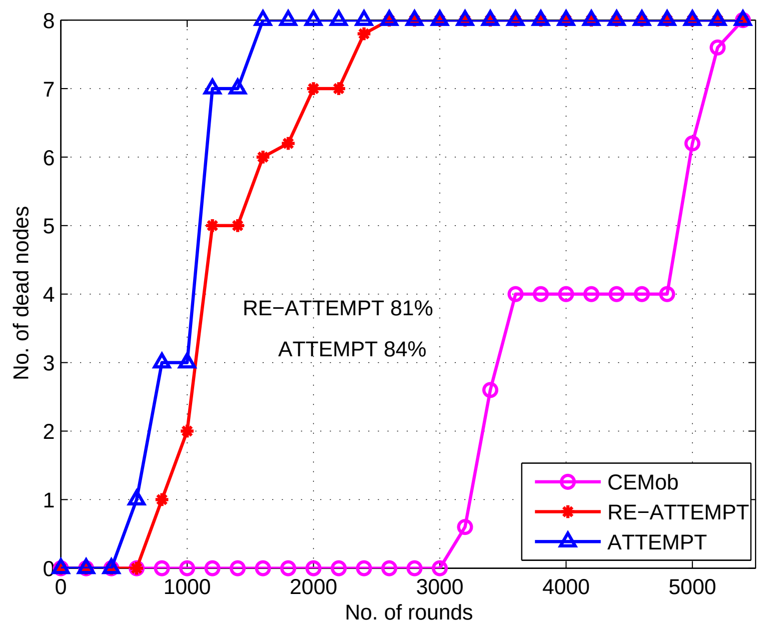

Figure 3.4: *Stability period and network lifetime comparison*

3.5.2 Residual Energy of WBAN

As mentioned before, CEMob only transmits data when the currently sensed data differs from previously sensed and stored data. This approach produces a slow decrease in average residual energy of the network as the rounds proceed, thereby, increasing the network lifetime. It is shown in figure 3.5, that CEMob has 71% and 55% more network lifetime than that of ATTEMPT and RE-ATTEMPT, respectively.

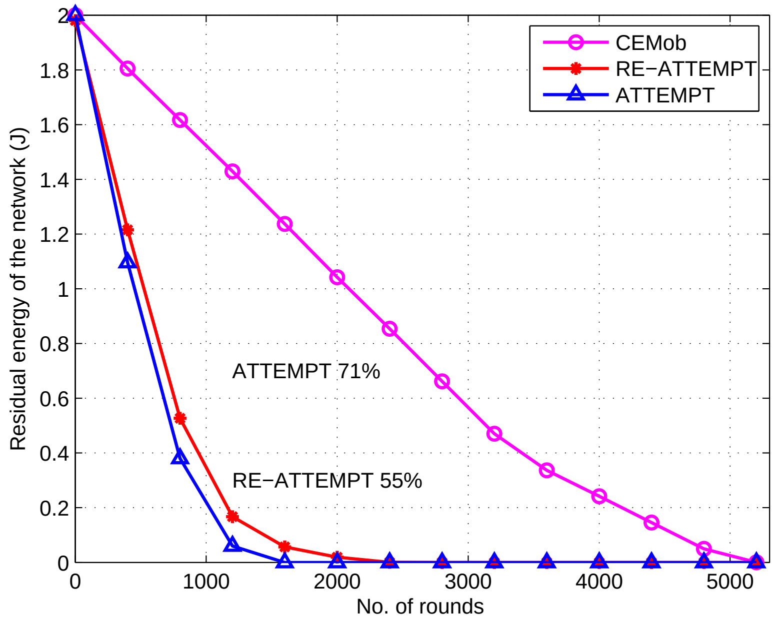

Figure 3.5: *Residual energy comparison*

3.5.3 Network Throughput

As the network lifetime of CEMob is more than ATTEMPT and RE-ATTEMPT routing protocol, therefore, the sink will receive data packets for longer duration in case of CEMob. It is obvious from the figure 3.6 that the total number of packets received at the sink for CEMob is less than that of RE-ATTEMPT because of non-continuous transmission. However, it is still equal to that of ATTEMPT till 800th round. We utilize uniform random model for packet drop calculation, in which probability of packet drop is set as 0.4.

Parameter	**CEMob**	**ATTEMPT**	**RE-ATTEMPT**
Stability period	High	Low	Low
Network lifetime	High	Low	Low
Energy consumption	Low	High	High
Throughput	High	Low	Low
Network type	Heterogeneous	Heterogeneous	Heterogeneous
Mobility	Yes	No	No

Table 3.3: *Performance comparison*

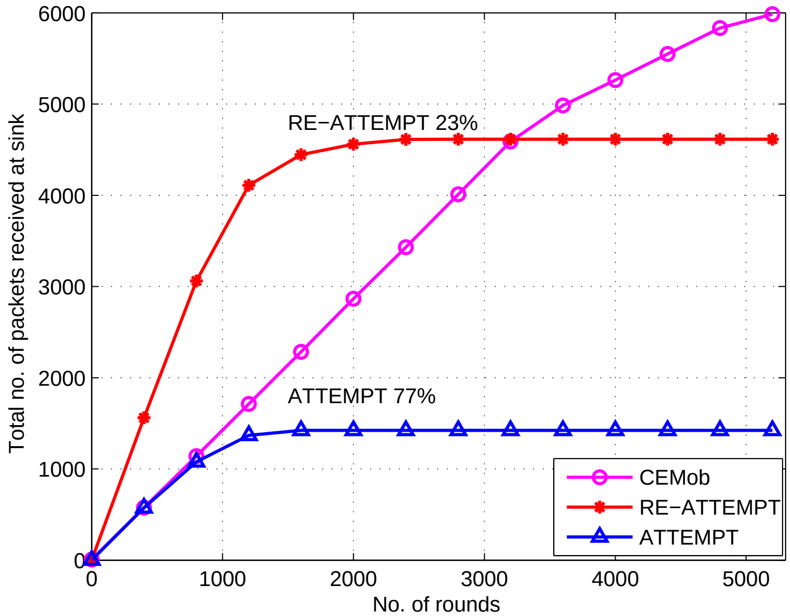

Figure 3.6: *Network throughput comparison*

Chapter 4

Co-CEStat Protocol

4.1 Motivation of Co-CEStat

In previously designed protocol, CEMob, we propose a solution to make a network more energy efficient by utilizing non-continuous transmissions and multi-hop approach to preserve the energy of distant nodes. Furthermore, we introduce the static version of CEMob, RE-CEStat, in which next-hop node is selected on the basis of residual energy of next-hop node. RE-CEStat also avoids redundant transmissions to preserve energy of nodes. Reliable delivery of data is also of great importance in WBANs. As, link between two nodes may be effected by channel impairments, therefore, a protocol is required which may ensure reliability of the network by providing redundant links for data transmissions. Conventional cooperation approach is one of the techniques to increase the overall network throughput by utilizing more than one link for the same data transmission. For this purpose, we propose a conventional cooperation protocol, Co-CEStat that utilizes cooperation between nodes to enhance the network performance.

4.2 Basic Terminologies and Performance Parameters

Some major terminologies and performance metrics are defined below:

- *Throughput:* Total number of packets successfully received at the sink is called throughput.
- *Stability period:* In applications such as body area network,stability period is usually defined as a time interval between the start of a network and the time at which the first node dies.
- *Residual energy:* Average total energy of a network after each round is called residual energy.
- *Network lifetime:* Total time duration of a network operation, from the start of the network establishment till the death of the last node is called network lifetime.
- *Heterogeneous network:* A network in which different initial energies are assigned to sensor nodes is called heterogeneous network.
- *Data aggregation:* Forwarding nodes process the raw data received by other nodes and send the aggregate value to the sink.
- *Number of alive nodes:* This measure gives the total number of nodes which are not depleted and still have residual energy to communicate.

- *Advanced nodes:* Sensor nodes which have more initial energy than that of normal nodes are called advanced nodes.

4.3 Co-CEStat: The Proposed Protocol

Co-CEStat is using multi-tier architecture in which nodes and sink are affixed on the human body. Co-CEStat aims to achieve energy efficiency by utilizing cooperation between nodes for data forwarding. Co-CEStat is discussed in detail in the following subsections.

4.3.1 Properties of Co-CEStat

Proposed protocol has following properties:

- Every node in the network is fixed.
- There is only one coordinator (sink node) which is fixed at the center of the body and responsible for gathering the data from all sensor nodes. Sink has adequate hardware and software with constant power supply but batteries of sensor nodes is not rechargeable.
- Transmission range and transmission power of each sensor node is fixed.
- Location of all the nodes is initially known to each sensor node.
- The main destination for each sensor node is sink node. Data transmission beyond the sink node is not considered.
- The size of generated packet by each node is always fixed and each node transmits its generated data in its own time slot.

4.3.2 Network Topology

Figure 4.1 shows the network topology of Co-CEStat compared with NoRE-CEStat routing protocol. Eight sensor nodes are attached with the human body. Sink, that is affixed at the center of the body, is responsible for collecting and forwarding data of all the sensor nodes to external server. However, communication beyond sink is not considered for this protocol. Coordinates of sensor nodes deployed on human body are shown in table 4.1. Network is heterogeneous in terms of initial energies of nodes and there are two types of nodes: Advanced nodes and normal nodes. Advanced nodes have more initial energy than that of normal nodes. In figure 4.1, nodes 1, 4, 5 and 8 are normal nodes, whereas, nodes 2, 3, 6 and 7 are advanced nodes. In NoRE-CEStat, forwarder node is selected on the basis of residual energy. Whereas, in Co-CEStat , cooperative nodes are fixed and allow source nodes to utilize more than one link at a time for data transmission. To differentiate cooperative routing protocol with non-cooperative protocols, we use *No* with each protocol's name throughout the discussion.

Node no.	x-axis (m)	y-axis (m)
1	0.4	1.5
2	0.6	1.2
3	0.2	1.2
4	0.7	0.8
5	0.1	0.8
6	0.5	0.5
7	0.2	0.5
8	0.2	0.2

Table 4.1: *Coordinates of nodes deployed on human body*

4.3.3 Routing and Communication Flow

Co-CEStat is cooperation based protocol in which there are four advanced nodes which are serving as cooperative nodes. By using cooperation, normal nodes are allowed to forward more packets through cooperating nodes in each round. Each link has its own capacity and every node receives a flow which cannot exceed the total capacity of the link. Outgoing and incoming flow for each node must be equal to satisfy the flow network restriction, except when it is a normal source node, which has more outgoing flow, or sink, which has just incoming flow. Link between cooperative node and sink is high capacity link as it carries regular packets along with forwarded packets. Normal source nodes multi-cast data simultaneously on two links to avoid information loss.
To minimize energy consumption, Co-CEStat makes use of threshold approach for data transmission. Every time the information is sensed, threshold is compared. If threshold value is crossed, sensed data is considered to be emergency data and is directly sent to sink. Otherwise, the current information is matched with stored information which is sensed earlier. Transmission of information occurs if variation is observed. This technique avoids transmissions of the same information which

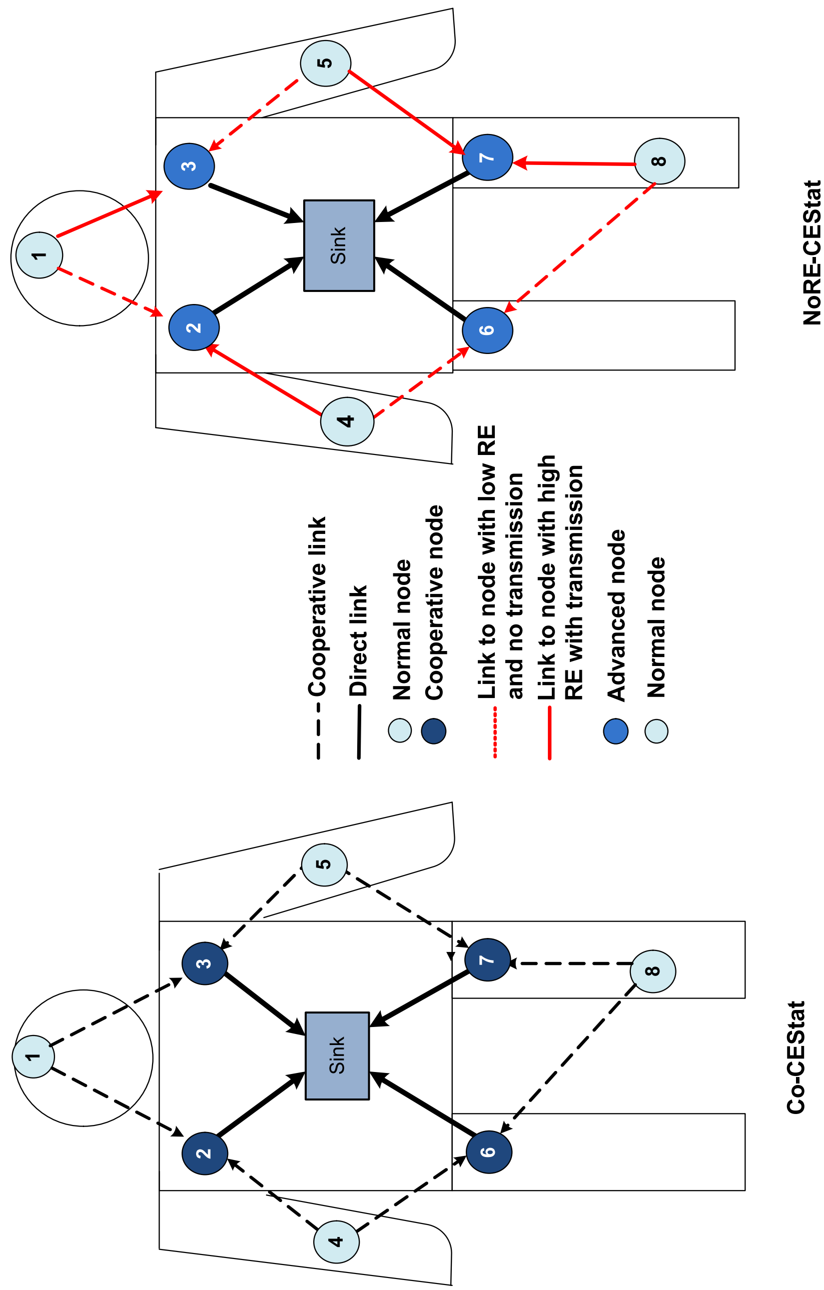

Figure 4.1: *Nodes' deployment on human body*

results in less energy consumption of sensor nodes. Whenever,the sensed data is emergency or the cooperative nodes are dead, node(s) establish(establishes) direct link with sink. If the data is normal and it is different from previously sensed value, than cooperative nodes are supposed to use single-hop communication, whereas, normal nodes utilize cooperative routing. Node 1, 4, 5, and 8 forward their normal sensed data to sink through their corresponding cooperative nodes. Node 2, 3, 6 and 7 are cooperative nodes which collect and forward data of normal nodes with their own sensed data to the sink after aggregation. This dynamic routing strategy reduces the energy consumption as nodes choose less distant node for data forwarding. Energy consumption for transmission of data from a node i to another node j is proportional to distance d_{ij}^n between two nodes. n is the path loss exponent and depends on the transmission environment.
Transmission energy depends on whether the node directly transmits data to sink or transmits cooperatively using neighbouring nodes as relays. Transmission and reception energy of each node is calculated with the help of energy model discussed in the following section.

4.4 Energy Model

According to first order radio energy model [2], transmission energy of sensor node at distance, d $>d_o$ is ,

$$E_{tx}(L,d) = E_{elec} * L + L * (e_{amp} * d^n), \tag{4.1}$$

and for d $<d_o$ is,

$$E_{tx}(L,d) = E_{elec} * L + L * (e_{fs} * d^n). \tag{4.2}$$

Whereas, transmission energy for intermediate node is,

$$E_{tx}(L,d) = ((E_{elec} + EDA) * L) + (e_{amp} * L * d^n). \tag{4.3}$$

Equation for reception energy of all sensor nodes is:

$$E_{rx}(L) = E_{elec} * L. \tag{4.4}$$

Here, E_{tx} and E_{rx} are transmitting and receiving energies of each node, respectively, which transmits or receive L bits at a distance d. E_{elec} is the energy, which dissipates to run the circuitry of transmitter and receiver. n is the path loss exponent and d_o is the reference distance. e_{amp} and e_{fs} are characteristics of transmitter amplifier. Whereas, EDA is the energy consumed in data aggregation

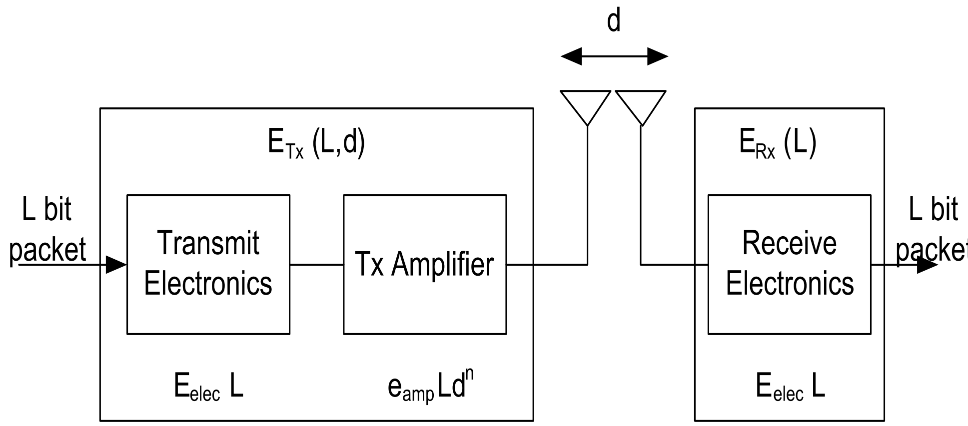

Figure 4.2: *First order radio model*

by intermediate or forwarder nodes. Used values for these parameters are given in table 4.2. Figure 4.2 explains the radio energy model.

4.5 Simulation Results and Discussions

In order to validate the proposed idea, simulations are conducted in MATLAB. Performance of the proposed Co-CEStat is compared with non-cooperative NoRE-CEStat and NoRE-ATTEMPT routing protocols. The aim of this evaluation is to observe the effects of cooperative routing in Co-CEStat. Different performance parameters are compared and discussed in the following subsections. Simulation parameters are presented in table 4.2. Results are averaged over five independent runs and each run performs 5500 rounds of monitoring. To differentiate cooperative routing protocol with non-cooperative protocols, we use *No* with each protocol's name in simulated plots and discussions.

Parameter	Value
Number of nodes	8
Initial energy	Advanced node: 0.3 J
	Normal node: 0.1 J
Packet size	1000 bits
Data generation rate	4000 bits
E_{elec}	50 nJ/bit
e_{fs}	10 pJ/bit/m^2
e_{amp}	0.0013 pJ/bit/m^4

Table 4.2: *Simulation parameters*

4.5.1 Stability Period and Network Lifetime

Figure 4.3 shows the stability period and network lifetime of all the compared protocols. It is clear from the results that stability periods for Co-CEStat and NoRE-CEStat are almost same and greater than NoRe-ATTEMPT. As NoRE-ATTEMPT transmits information continuously, more energy is consumed by each node in each round. Increased Stability period of Co-CEStat and NoRE-CEStat is because of non-continuous data transmission. Data is transmitted only if some difference is found between current and previously transmitted data.

4.5.2 Residual Energy of a Network

Figure 4.4 shows the residual energy per round of all the analyzed protocols. Networks are equipped with two types of sensor nodes in terms of initial energy. There are normal nodes with initial energy equal to 0.1 joules, whereas, advanced nodes have 0.3 joules as initial energy. Initial total energy of all protocols is kept same i.e. 1.6 Joules. It is observed from compared results of four protocols that non-continuous transmission in Co-CEStat and NoRe-CEStat causes greater residual energy per round. Another reason for more residual energy is that multi-hop transmission is utilized for each distant node in Co-CEStat and NoRe-CEStat.

4.5.3 Network Throughput

Communication is mediated by two different links in terms of bit rates. In Co-CEStat, links between cooperative nodes and sink are high data rate links, whereas, links between source nodes and cooperative nodes have low data rates. Nodes which transmit data through cooperative nodes are allowed to transmit more packets per round than nodes using non-cooperative or direct communication. It is clear from figure 4.5 that Co-CEStat achieves 51% and 52% more throughput due to cooperative routing than that of NoRe-CEStat and NoRe-ATTEMPT, respectively. We also assume that the link failure may occur and there is a chance of packet loss due to bad link condition. For simulations, we assume the probability of link failure equal to 0.3. Overall performance comparison of the compared protocols is given in table 4.3.

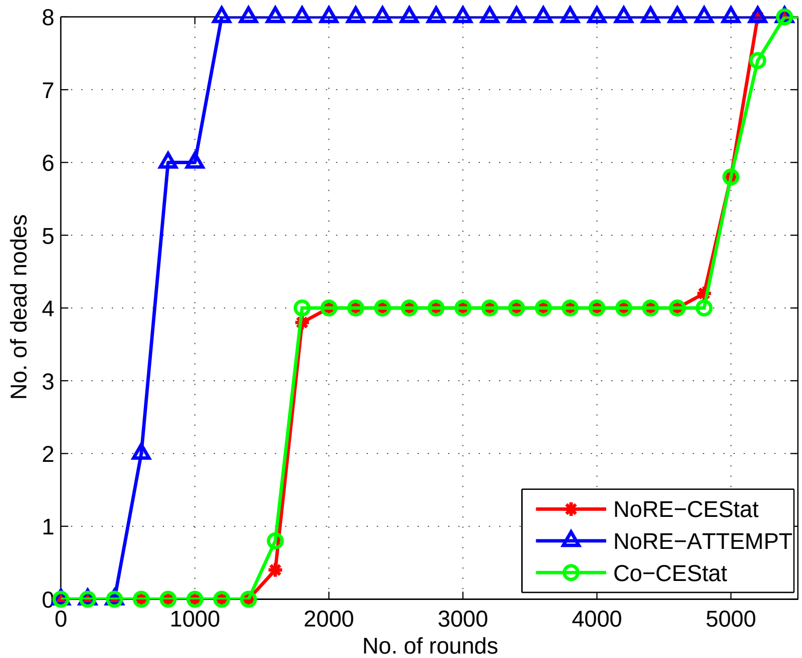

Figure 4.3: *Stability period and network lifetime comparison*

Parameters	Co-CEStat	RE-CEStat	RE-ATTEMPT
Stability period	High	High	Low
Network lifetime	High	High	Low
Throughput	Higher	High	Low
Cooperation	Yes	No	No
Network type	Heterogeneous	Heterogeneous	Heterogenous

Table 4.3: *Performance comparison*

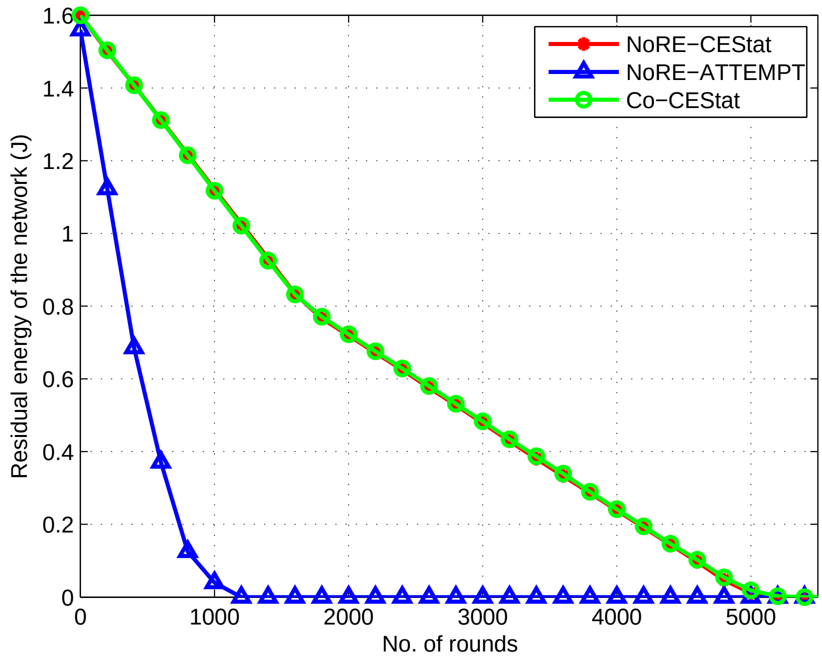

Figure 4.4: *Residual energy per round comparison*

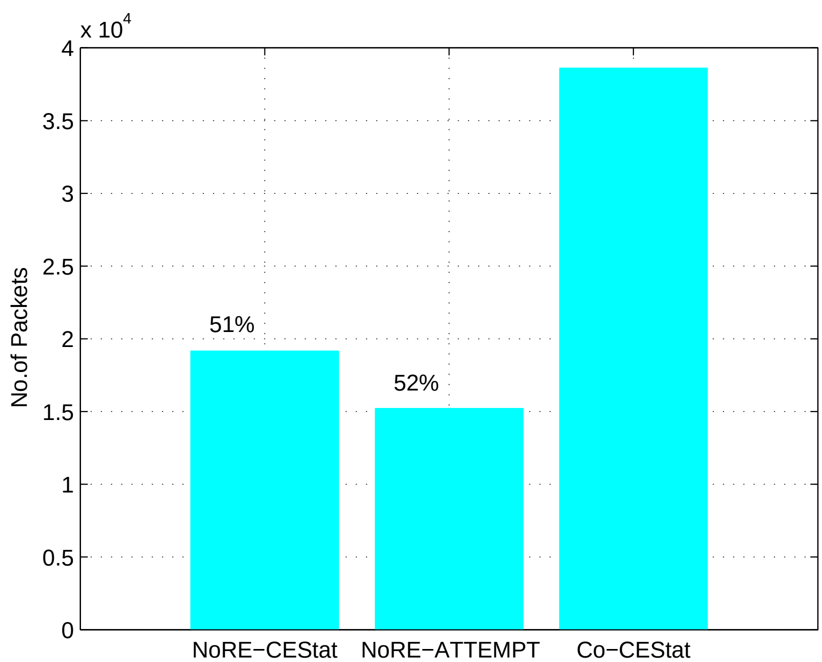

Figure 4.5: *Throughput comparison of compared protocols*

Chapter 5

Reliable and Energy Efficient Incremental Cooperative Communication for WBANs

5.1 Motivation

In WBANs, low energy consumption of sensor nodes with reliable and quick delivery of data is of special concern. Direct link between transmitter and receiver is appropriate to deliver data from source to destination in WBANs. However, links between nodes may experience path-loss due to fading or noise in both Line-of-Sight (LOS) and Non-LOS (NLOS) scenarios. Less SNR at any particular time, causes packet drop at sink due to more BER than certain threshold. Therefore, an efficient and reliable topology for WBAN is required which may ensure greater throughput with less energy consumption of sensor nodes. Conventional cooperative communication proves to be more reliable by providing cooperative links along with direct link for the transmission of same information. To reduce the energy consumed by cooperative nodes in conventional cooperation, incremental cooperation approach is used in the literature to wisely utilize the merits of both direct and cooperative links. This type of cooperative communication increases the EE of WBAN. Major objectives behind this research are: (i) to study the effects of incremental relay-based cooperation with different number of cooperative relays/nodes, (ii) to improve the EE of conventional cooperative scheme by using incremental cooperative scheme and (iii) to implement incremental cooperation schemes in WBAN's protocols to improve the overall network PER and EE.

5.2 Basic Terminologies and Performance Parameters

Some basic terminologies and performance metrics that are used in this research are mentioned below:

- *Path loss:* Reduction in the power of signal as it propagates through the channel is called path loss.
- *Fading:* Degradation of a signal on propagation paths is called fading. Energy absorption, reflection, diffraction, shadowing by body, and body posture may cause fading.
- *Shadowing:* Variation in path loss, due to movement of body parts or environment, around the mean is called shadowing.
- *PER:* Number of successfully received packets divided by the total number of packets transmitted is called PER.
- *EE:* The way of managing and restraining the growth of energy consumption is called energy efficiency.

- *BER:* Number of erroneous bits divided by the total number of received bits is called BER.
- *Diversity:* Antenna diversity or space diversity, is a wireless diversity schemes that uses two or more antennas to improve the quality and reliability of a wireless link.
- *SNR:* It is defined as the ratio of signal power to the noise power, often expressed in decibels.
- *Stability period:* In WBAN, stability period is usually defined as a time interval between the start of a network and the time at which the first node dies.
- *Residual energy:* Average total remaining energy per second of a network is called residual energy of a network.
- *Network lifetime:* Total time duration of a network operation, from the start of the network establishment till the death of the last node is called network lifetime.
- *Throughput:* Total number of successfully received packets per unit time at the sink is called throughput.
- *Heterogeneous network:* A network in which different initial energies are assigned to sensor nodes is called heterogeneous network.
- *Advanced nodes:* Sensor nodes which have more initial energy than that of normal nodes are called advanced nodes.

5.3 System Model

We consider a WBAN which consists of on-body sensor nodes which are supposed to transmit their sensed data to coordinator/sink attached with the body. Ultimate destination for each node is sink and it is assumed that sink has a constant power supply with no energy constraint. We propose a three-stage cooperation protocol for WBAN and compare its analytical and simulation results with the contemporary schemes. As the distances between sensor nodes in WBAN is small, so it is assumed that all the nodes are within the transmission range of each other. Communication is considered to be half-duplex. Fig. 5.1 explains the system model of proposed scheme.
Our proposed WBAN scheme consists of four communication phases. There are three potential relays R_1, R_2 and R_3 available for a source node. Proposed scheme

has a three stage ARQ mechanism as shown in figure 5.1. In the first phase of cooperation, the source transmits the data packet to the destination, and all three relays overhear this packet. If the destination node decodes the packet successfully in the first phase, it sends a short feedback in the form of positive ACKnowledgement (ACK 1) which indicates that there is no need of relaying. However, if the destination node fails to decode the data packet correctly, a Negative ACKnowledgement (NACK 1) is sent which is also heard by all relays. After this, three stage relaying process is invoked. If relay R_1 has received and decoded the data packet correctly in the first phase, it forwards that packet to the destination during the second phase. If packet is decoded successfully at destination, it transmits back ACK (ACK 2), and hence, the first stage of cooperative relaying becomes successful. Otherwise, destination node sends NACK (NACK 2), implying the need for second stage of cooperative relaying. Upon overhearing NACK 2, relay R_2 forwards the data packet, which is received correctly in the first phase, to the destination in the third phase. If the destination node is able to decode the packet successfully, it sends back ACK 3, otherwise it sends NACK 3, which indicates the failure of second stage of cooperation as well. It may be noted that, even if R1 does not transmit in the second phase (due to decoding failure at R_1), R_2 can forward the packet to the destination in the third phase, if it had received the packet correctly in the first phase. Same is the case with third relay R_3, if R_2 is unable to decode the packet in the first phase or destination fails to decode and receive the packet correctly from R_2, R_3 is responsible to transmit that data packet to the destination. If the destination node is able to decode the packet successfully, the success of third stage of relaying is occurred otherwise the packet is considered dropped. Figure 5.1 shows the incremental cooperative communication model for three stage relaying. In the next section, we present expressions for the PER and

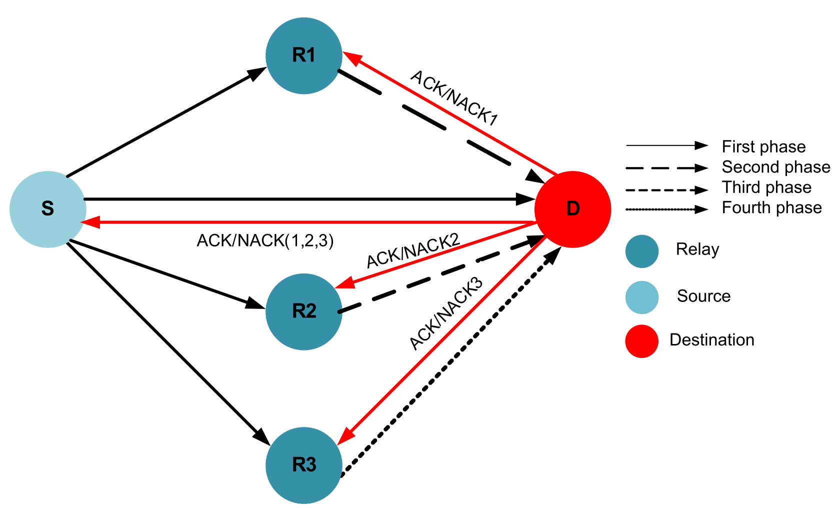

Figure 5.1: *3-stage incremental cooperative communication*

EE for the three stage relaying scheme and to explain signal propagation. Expressions for single and two stage relaying communication schemes may be seen in [8]. Our derived expressions are mostly dependent on distance between sensor nodes.

5.4 Analysis of 3-Stage Incremental Cooperative Communication

In this section, we derive expressions for calculating PER for three-stage incremental relaying. We also analyze the overall energy consumption for our proposed cooperative scheme. It is assumed that link between two nodes in WBAN is affected by path loss, shadowing and Additive White Gaussian Noise (AWGN). According to [3], the path loss model for WBAN, which is dependant on distance d between communicating nodes, is based on the Friis formula in free space and is described as:

$$PL(d) = PL(d_o) + 10nlog\frac{d}{d_o}, \tag{5.1}$$

where $PL(d_o)$ is the path loss in dB at a reference distance d_o and n is the path loss exponent. Path loss due to distance may vary with the body movement and certain changes in surrounding environment. It may differ from its mean value and this phenomena is called shadowing. Shadowing may also occur in static body. By considering the factor of shadowing, the total path loss may be given as:

$$PL = PL(d) + X_\sigma. \tag{5.2}$$

Here X_σ is a shadowing factor in dB which is a Gaussian-distributed random variable with zero mean and a standard deviation, σ. According to channel model for WBAN given in [3], SNR at the receiver end is computed as:

$$\gamma(dB) = P_T - PL - P_N \tag{5.3}$$

where P_T is the transmit power and P_N is the noise power for all nodes.

5.4.1 PER analysis

For three-stage incremental relaying, it is assumed that there are three potential relays, R_1, R_2 and R_3 available to cooperate with the source. Let PER_{SR_1}, PER_{SR_2}, PER_{SR_3}, PER_{R_1D}, PER_{R_2D} and PER_{R_3D} represent the probability of error of source-to-relay (R_1) ($S - R_1$), source-to-relay (R_2) ($S - R_2$), source-to-relay (R_3), ($S - R_3$), R_1-to-destination ($R_1 - D$), R_2-to-destination ($R_2 - D$) and R_3-to-destination ($R_3 - D$) links, respectively.

The three-stage relaying process fails if one of the following events occur:
(i) the four links, $S-D$, $S-R_1$, $S-R_2$ and $S-R_3$ fail,
(ii) $S-D$, $S-R_2$ and $S-R_3$ links fail, $S-R_1$ link is error free, R_1 decodes and forwards but R_1-D link fails;
(iii) direct communication, $S-R_1$ and $S-R_3$ links fail, R_3 decodes and forwards the data packet, but R_3-D link fails,
(iv) $S-D$, $S-R_1$ and $S-R_3$ links fail while $S-R_2$ link is error free, R_2 decodes and forwards but fails due to error in R_2-D link,
(v) $S-D$, $S-R_1$, $S-R_2$ and $S-R_3$ links fail, whereas, R_1-D, R_2-D and R_3-D links are in error,
(vi) $S-D$ and $S-R_3$ link fail, $S-R_1$ and $S-R_2$ links are in error free, but R_1-D and $S-R_2$ links fail,
(vii) $S-D$ and $S-R_1$ links fail, $S-R_2$ and $S-R_3$ links are error free, R_2 and R_3 decode and forward the packet but R_2-D and R_3-D link fail,
(viii) $S-D$ and $S-R_2$ links fail, $S-R_1$ and$S-R_3$ links are error free, R_1 and R_3 decode and forward the packet but R_1-D and R_3-D links fail.
Hence, the PER for the three-stage relaying scheme is given as:

$$\begin{aligned}
&PER_{CC}^{(3)} = \\
&PER_{SD}PER_{SR_1}PER_{SR_2}PER_{SR_3} \\
&+ PER_{SD}(1-PER_{SR_1})PER_{SR_2}PER_{SR_3}PER_{R_1D} \\
&+ PER_{SD}PER_{SR_1}(1-PER_{SR_2})PER_{SR_3}PER_{R_2D} \\
&+ PER_{SD}PER_{SR_1}PER_{SR_2}(1-PER_{SR_3})PER_{R_3D} \\
&+ PER_{SD}(1-PER_{SR_1})(1-PER_{SR_2})(1-PER_{SR_3})PER_{R_1D}PER_{R_2D}PER_{R_3D} \\
&+ PER_{SD}(1-PER_{SR_1})(1-PER_{SR_2})PER_{SR_3}PER_{R_1D}PER_{R_2D}PER_{R_3D} \\
&+ PER_{SD}PER_{SR_1}(1-PER_{SR_2})(1-PER_{SR_3})PER_{R_1D}PER_{R_3D} \\
&+ PER_{SD}(1-PER_{SR_1})PER_{SR_2}(1-PER_{SR_3})PER_{R_1D}PER_{R_3D}
\end{aligned} \tag{5.4}$$

5.4.2 EE Analysis

we analyze EE for three-stage incremental cooperation according to energy model given in [20]. This model considers the energy required to run the circuitry of transmitter and receiver for both data and ACK/NACK packets. The total energy consumed in the transmission of a data packet is computed below for three stage relaying process.

$$
\begin{aligned}
&EE^{(3)}_{CC,DATA} = \\
&[(E_{TX_{elec}} + 4E_{RX_{elec}} + \frac{P_T}{R})(1 - PER_{SD}) \\
&+ (2E_{TX_{elec}} + 5E_{RX_{elec}} + 2\frac{P_T}{R})PER_{SD}(1 - PER_{SR_1}) \\
&+ (2E_{TX_{elec}} + 5E_{RX_{elec}} + 2\frac{P_T}{R})PER_{SD}PER_{SR_1}(1 - PER_{SR_2}) \\
&+ (2E_{TX_{elec}} + 5E_{RX_{elec}} + 2\frac{P_T}{R})PER_{SD}PER_{SR_1}PER_{SR_2}(1 - PER_{SR_3}) \\
&+ (2E_{TX_{elec}} + 5E_{RX_{elec}} + 2\frac{P_T}{R})PER_{SD}(1 - PER_{SR_1})PER_{R_1D}PER_{SR_2}(1 - PER_{SR_3}) \\
&+ (3E_{TX_{elec}} + 6E_{RX_{elec}} + 3\frac{P_T}{R})PER_{SD}(1 - PER_{SR_1})PER_{R_1D}(1 - PER_{SR_2})PER_{R_2D}PER_{SR_3} \\
&+ (4E_{TX_{elec}} + 7E_{RX_{elec}} + 4\frac{P_T}{R})PER_{SD}(1 - PER_{SR_1})PER_{R_1D}(1 - PER_{SR_2})PER_{R_2D}(1 - PER_{SR_3}) \\
&+ (E_{TX_{elec}} + 4E_{RX_{elec}} + \frac{P_T}{R})PER_{SD}PER_{SR_1}PER_{SR_2}PER_{SR_3}](L + H).
\end{aligned}
\tag{5.5}
$$

Where, L is the packet size and H is overhead size in bits. $E_{TX_{elec}}$ and $E_{RX_{elec}}$ are the energies required for transmitter and receiver electronics in transmitting and receiving one bit, respectively. R is the data rate.

We find the total energy consumption of all the events in which packet transmission is successful:

(i) The probability of successful direct transmission is $(1-PER_{SD})$. Three relays overhear the packet which consumes receiving energy, $(E_{TX_{elec}} + 4E_{RX_{elec}} + \frac{P_T}{R})$.

(ii) The direct link (S-D) fails and R_1 correctly receives and decodes the message from source. R_1 forwards the packet to the destination with probability $PER_{SD}(1 - PER_{SR_1})$ which results in total energy consumption per bit of $(2E_{TX_{elec}} + 5E_{RX_{elec}} + 2\frac{P_T}{R})$.

(iii) In case $S-D$ and $S-R_1$ links fail and $S-R_2$ link is error free. The energy consumption is same as in (ii).

(iv) In case $S-D$, $S-R_1$ and $S-R_2$ links fail and $S-R_3$ link is error free. The energy consumption is same as in (ii).

(v) $S-D$ link fails, $S-R_1$ link error free, and R_1 decodes and forwards the message to the destination. $S-R_2$ and R_1-D links fail and $S-R_3$ link is error free. The probability of this event is $PER_{SD}(1-PER_{SR_1})PER_{R_1D}PER_{SR_2}(1-PER_{SR_3})$ and energy consumption per bit is same as in (ii).

(vi) The $S-D$ link fails, $S-R_1$ and $S-R_2$ links are error free, and R_1-D, R_2-D and $S-R_3$ links are in error with total probability of $PER_{SD}(1-PER_{SR_1})PER_{R_1D}(1-PER_{SR_2})PER_{R_2D}PER_{SR_3}$. The energy consumption per bit is $(3E_{TX_{elec}} + 6E_{RX_{elec}} + 3\frac{P_T}{R})$.

(vii) Direct link fails, $S-R_1$, $S-R_2$ and $S-R_3$ are error free links, whereas, R_1-D and R_2-D links are in error with the total probability of $PER_{SD}(1-PER_{SR_1})PER_{R_1D}(1-PER_{SR_2})PER_{R_2D}(1-PER_{SR_3})$. Energy consumption per bit is $(4E_{TX_{elec}} + 7E_{RX_{elec}} + 4\frac{P_T}{R})$.

(viii) All four links from source to destination and relays fail with probability $PER_{SD}PER_{SR_1}PER_{SR_2}PER_{SR_3}$. The energy consumption per bit for this event is $(E_{TX_{elec}} + 4E_{RX_{elec}} + \frac{P_T}{R})$. Total energy consumption also includes the energy involved in the transmission of ACK/NACK packets and is computed as follows:

$$\begin{aligned}
&EE^{(3)}_{CC,ACK/NACK} = [(E_{TX_{elec}} + 4E_{RX_{elec}} + \frac{P_T}{R}) \\
&+ (E_{TX_{elec}} + 4E_{RX_{elec}} + \frac{P_T}{R})PER_{SD}(1 - PER_{SR_1}) \\
&+ (E_{TX_{elec}} + 3E_{RX_{elec}} + \frac{P_T}{R})PER_{SD}(1 - PER_{SR_1})(1 - PER_{SR_2})PER_{R_1D} \\
&+ (E_{TX_{elec}} + 3E_{RX_{elec}} + \frac{P_T}{R})PER_{SD}PER_{SR_1}(1 - PER_{SR_2}) \\
&+ (E_{TX_{elec}} + 3E_{RX_{elec}} + \frac{P_T}{R})PER_{SD}PER_{SR_1}(PER_{SR_2})(1 - PER_{SR_3}) \\
&+ (E_{TX_{elec}} + 3E_{RX_{elec}} + \frac{P_T}{R})PER_{SD}(1 - PER_{SR_2})PER_{SR_1}PER_{R_2D}(1 - PER_{SR_3})](A + H)
\end{aligned} \tag{5.6}$$

Where A is the size of ACK/NACK in bits. Energy consumption is same for the transmission and reception of both ACK and NACK. The first term in (6) shows the energy consumption involved in the transmission of ACK/NACK by the destination in the first phase. (1-PER_{SD}) is the probability of ACK and NACK is transmitted with probability PER_{SD}. In second phase, either ACK or NACK is transmitted for the the packet decoded and forwarded by R_1 to destination, this happens with probability PER_{SD} (1-PER_{SR_1}). The second term in eq. 5.6 represents the energy consumption associated with second phase. In the third phase, R_2 forwards the packet, which is followed by another sequence of ACK/NACK transmissions. ACK/NACK is transmitted if R_2 decodes and forwards the packet to the destination. This may happen because of the following reasons: (i) failure of direct communication, one-stage relaying, $S - R_2$ link becoming error free and (ii) failure of $S - D$ and $S - R_1$ links, $S - R_2$ link becoming error free. In the fourth and last phase, ACK/NACK is transmitted if R_3 decodes and forwards the packet to the destination. This may happen because of the following mentioned reasons: (i) failure of $S - D$, $S - R_1$ and $S - R_2$, $S - R_3$ link is error free and (ii) failure of $S - D$ and $S - R_1$, success of $S - R_2$, failure of $R_2 - D$ link and $S - R_3$ link is error free. Therefore, the EE of three-stage incremental cooperative communication is computed as follows:

$$\eta^{(3)}_{CC} = \frac{(1 - PER^3_{CC})xL}{E^3_{CC} + EE^{(3)}_{CC,ACK/NACK}}. \tag{5.7}$$

Where x=$(E_{TX_{elec}}$+$4E_{RX_{elec}}$+$\frac{P_T}{R})$.

5.5 Simulation Analysis of PER and EE for 3-Stage Incremental Cooperative Communication

In this section, we present performance evaluation of our proposed WBAN, which is compared with existing schemes, in terms of PER and EE . All results are obtained from the expressions presented in section 5.4. Simulation parameters are

Table 5.1: *Simulation parameters*

Parameter	Value
Packet size	500 bits
Overhead	80 bits
ACK/NACK	64 bits
Transmission power	-12 dBm
Data rate	2 Mbps
$E_{TX_{elec}}$	50 nJ/bit
$E_{RX_{elec}}$	50 nJ/bit

Table 5.2: *Channel model parameters*

Parameters	NLOS	LOS
d_o (cm)	10	10
PL(d_o)(dB)	48.4	35.2
n	5.9	3.11
X_σ	5	6.1

given in tables 5.1 and 5.2. We only consider the case of on-body sensor nodes as we further implement these models in on-body WBAN protocols.

5.5.1 PER

PER is plotted against distance to see the effect of various distances between source and destination, r_{sd}. For cooperative communication, distance between source and relay, r_{sr}, and relay and destination, r_{rd}, are kept half of the distance between source and destination. Figure 5.2 and 5.4 show PER for on-body LOS and NLOS, direct and cooperative communication schemes. It is observed from the figure 5.2 and 5.4 that PER for direct communication is higher than the PER for cooperative communication. When direct link is not reliable enough for efficient transmission, cooperative communication proves to be better solution by providing redundant links for packet transmission. It is seen from the figures that path loss increases with the increase in distance. Therefore for larger distance, direct communication has more PER. Thus, for increased hop length between source and destination, cooperative communication is useful. It is obvious from the plots that two relay communication is better than single relay communication, same is the case for three relay communication which is better than single and double relay communication. When the first and second stage of relaying fails, relay R_3 provides an extra redundant link to the destination and enhances network reliability. It is also shown that PER of LOS communication is less than NLOS communication due to more path loss in NLOS communication. Therefore, LOS communication offers less PER for longer hop lengths between source and destination.

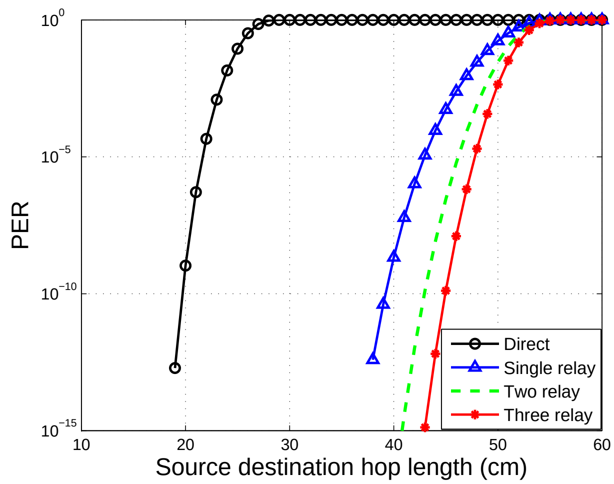

Figure 5.2: *PER for on-body NLOS communication*

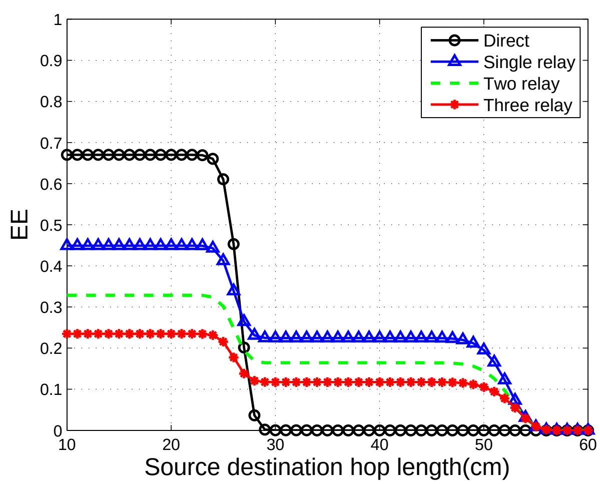

Figure 5.3: *EE for on-body NLOS communication*

5.5.2 EE

EE of direct and incremental cooperative communication schemes are observed in figure 5.3 and 5.5. Series of experiments are performed in [6] to find the best distance between source and relay and between relay and destination. The hop lengths of $S-R$ and $R-D$ links are selected to be 0.5 times the distance between the source and the destination. Figure 5.3 and 5.5 show the results for the EE of on-body NLOS and LOS scenarios, respectively. EE is plotted against $S-D$ hop length, r_{sd}, for direct and cooperative communication schemes. It is concluded from the results that increased distance between source and destination, r_{sd}, decreases EE considerably. For lower distances, direct transmission proves to be more energy efficient than cooperative transmissions. When the hop length, r_{sd}, exceeds certain threshold, cooperative communication turns out to be more energy efficient than direct communication. Although, cooperative communication improves reliability as it has lower PER, its EE is significantly affected because of increased energy consumption due to additional transmissions and decoding by the relays. When r_{sd} is above the threshold, the PER of direct communication is so high that its EE is significantly affected. As the PER of three relay communication is lowest than the other two relaying schemes, so it has lowest EE due to more energy consumption by relays.

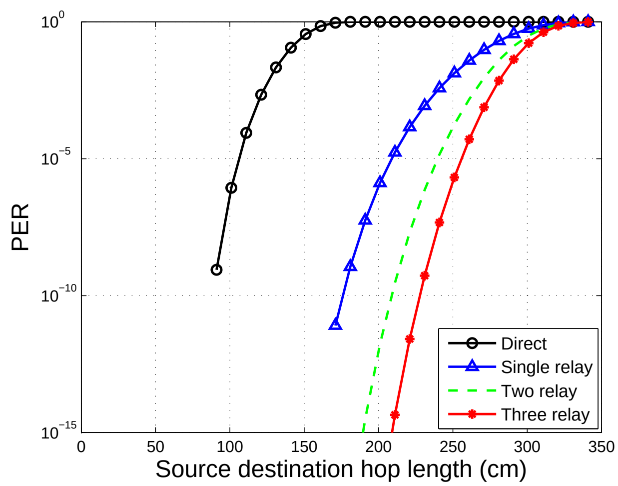

Figure 5.4: *PER for on-body LOS communication*

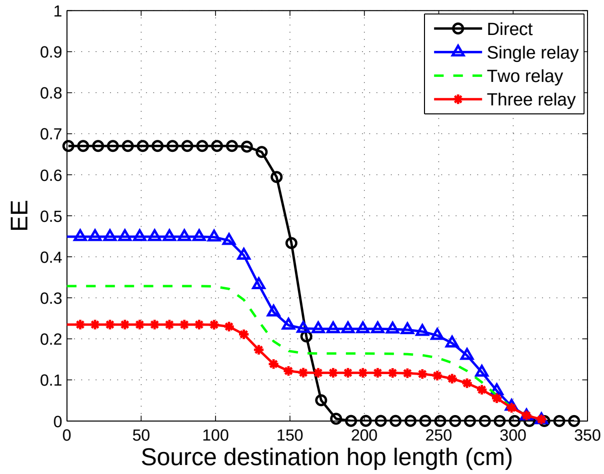

Figure 5.5: *EE for on-body LOS communication*

5.6 Incremental Cooperative Routing Protocols for WBANs

We consider two incremental cooperative communication schemes, discussed in the previous sections. We design two network layer protocols for WBANs and implement two and three-relay incremental cooperation in them to analyze and compare their performance. Firstly, we study the effect of two-stage incremental cooperation in InCo-CEStat protocol. To study the effects of three-stage incremental cooperation, we design EInCo-CEStat protocol and compare its results with the InCo-CEStat. EE, PER, throughput and stability period for all three protocols are observed. We also compare EInCo-CEStat with a conventional co-operation protocol; Co-CEStat.

We consider four phase incremental relay-based cooperation in EInCo-CEStat by using three potential relays for each source node. In the first phase, the source transmits data to sink, which is overheard by its three potential relays, R_1, R_2 and R_3. If the destination/sink is able to detect the packet correctly in this phase, it sends back an ACK, and relays just remain idle. If NACK is received from sink at source node, it indicates that data packet is dropped due to high BER and data forwarding from R_1 is needed. If R_1 successfully detects the data packet in the first phase, it forwards the data packet to the destination (sink) in the second phase. If data packet is received with acceptable BER at the sink, the second phase of cooperation is successfully completed. However, if sink fails to detect the packet sent by R_1, R_2 is supposed to forward the packet to sink which was correctly received in the first phase. If the sink again fails to receive the packet from R_2 due to high BER, failure of the third phase occurs. Finally, the last phase of communication occurs between R_3 and sink. System model for InCo-CEStat is also the same with two relay cooperative communication. Therefore, InCo-CEStat consists of three communication phases accordingly.

Figure 5.6 shows the topology of InCo-CEStat and EInCo-CEStat protocols for comparison. Two heterogeneous networks consisting of eight sensor nodes are shown in figure 5.6. There are four normal source nodes (S), four cooperative nodes (R), and a sink node (D). Cooperative nodes also have their own sensed data to be transmitted along with data to be forwarded. In the proposed protocols, it is assumed that sink limits all nodes to transmit only in their own reserved time slots. Collision avoidance and network coordination is essential to maintain QoS in WBANs. Further, half-duplex communication is assumed, and all the nodes are within the transmission range of each other.

All nodes transmit on different links and are independent of each other. Time Division Multiple Access (TDMA) scheme is utilized and channel is accessed by nodes in different time slots.

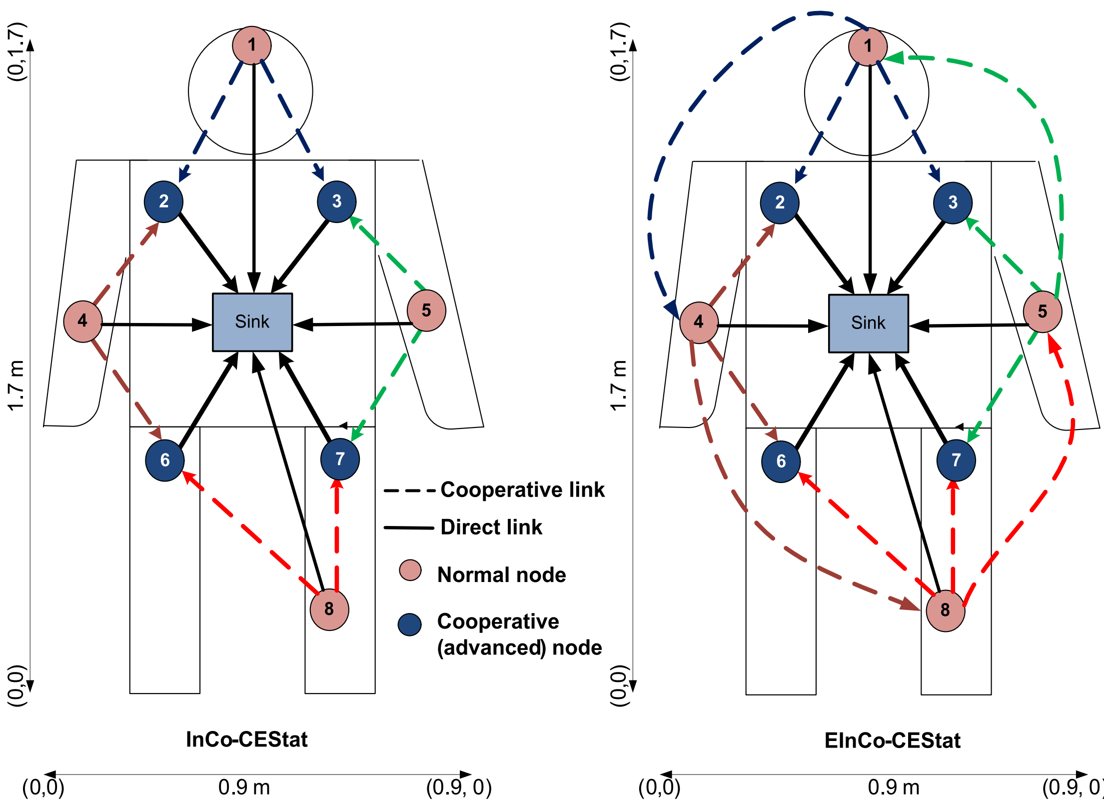

Figure 5.6: *Network topology of InCo-CEStat and EInCo-CEStat*

5.7 Simulation Results and Discussions

We compare the performance of incremental relay-based cooperation implemented in InCo-CEStat and EInCo-CEStat; with conventional cooperative protocol, Co-CEStat. We assume network area of $0.9m \times 1.7m$, where on body nodes are

Table 5.3: *Coordinates of nodes deployed on human body*

Node no.	x-axis	y-axis
1	0.45	1.6
2	0.2	1.5
3	0.7	1.5
4	0.1	0.85
5	0.8	0.85
6	0.2	0.5
7	0.7	0.5
8	0.7	0.3

deployed at fixed positions as shown in table 5.3 and sink is placed at the center of the body i.e., $0.4m \times 0.8m$. Co-CEStat and InCo-CEStat use two relays for each normal source node, whereas, EInCo-CEStat uses three relays. Topology of InCo-CEStat and EInCo-CEStat is shown in figure 5.6 and topology of Co-CEStat is already shown in previous chapter. Table 5.4 shows the simulation parameters considered for all three schemes. Rest of the simulation parameters are same as

Table 5.4: *Simulation parameters for WBAN protocols*

Parameter	Value
Number of nodes	8
Number of sink	1
Initial energy	Cooperative node: 0.3 J Normal node: 0.15 J
Offered load	10,000 bits/node
Average wait time [38]	4 seconds/packet
BER threshold	0.5

given in table 5.1 and 5.2.

5.7.1 Stability Period and Network Lifetime

Stability period and network lifetime of compared protocols is shown in Figure 5.7. It is observed from the figure that Co-CEStat has less stability period than

InCo-CEStat and EInCo-CEStat because in Co-CEStat, cooperative nodes always forward data irrespective of channel conditions. Each cooperative node forwards data of two other nodes along with its own sensed data which causes extra energy consumption. InCo-CEStat and EInCo-CEStat prove to be more stable with greater network lifetime because incremental relaying adapts to channel conditions and cooperative nodes forward the data only when it is needed. However, EInCo-CEStat has less stability period than InCoCEStat. This is due to extra energy consumption by third node which acts as a relay when two-stage cooperative relaying is unsuccessful. Third relay node, which is invoked for forwarding data in fourth phase, is always a normal source node having less residual energy than cooperative nodes. As this node forwards the data along with its own sensed data and has less initial energy, therefore, it dies earlier than other nodes. EInCo-CESTat has 24% less stability period than that of InCo-CEStat and 17% more stable than Co-CEStat.

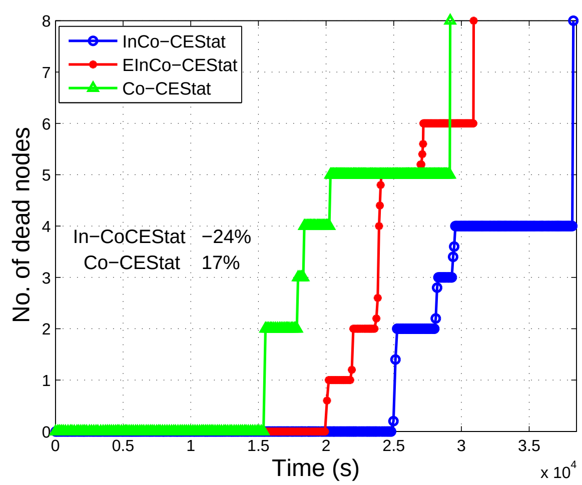

Figure 5.7: *Stability period and network lifetime*

5.7.2 Throughput and Packet Drop Rate

Figure 5.8 and 5.9 show results for total number of packets received at sink successfully and the number of packets dropped due to higher BER than certain pre-defined threshold, respectively. It is observed from the figure 5.9 that EInCo-CEStat has highest overall throughput. This is due to availability of more links for packet transmission, in case of failure of direct link. InCo-CEStat has two cooperative nodes, whereas, EInCo-CEStat has three cooperative nodes to forward data of normal nodes. Higher throughput is achieved by increasing diversity order in EInCo-CEStat at the cost of EE. During network lifetime, Co-CEStat has highest throughput due to reception of three copies of transmitted data at sink, whereas, incremental relaying allows the reception of single copy of data at a time. Availability of three redundant links and longer network lifetime in EInCoCEStat, causes highest overall network throughput. EInCo-CEStat has 5% and 12% more throughput than Co-CEStat and InCo-CEStat, respectively.

Packet drop rate of EInCo-CEStat is also less than that of InCo-CEStat, as shown in figure 5.9. In case, the direct communication between source and sink fails, there are three more communication links available to forward the data to the sink. Whereas, InCo-CEStat completes its relaying in three phases and has two more redundant links after the failure of direct link. This behaviour supports the simulation results shown in figure 5.2 and 5.4. Packet drop rate of Co-CEStat is also greater than incremental cooperative communication protocols. More number of transmissions leads to more number of link failures and more packet drops.

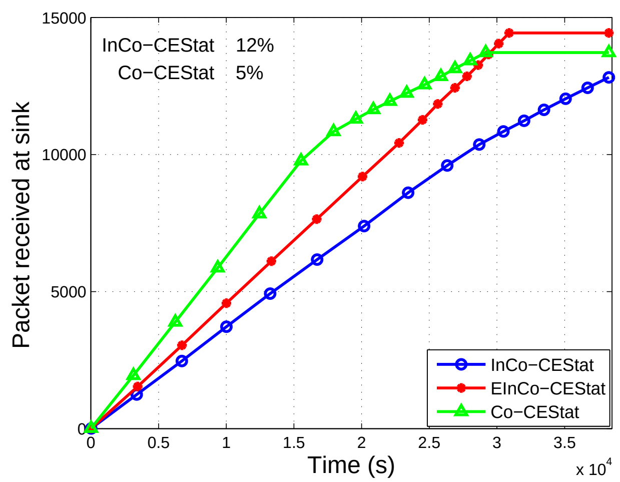

Figure 5.8: *Number of packets received successfully at sink*

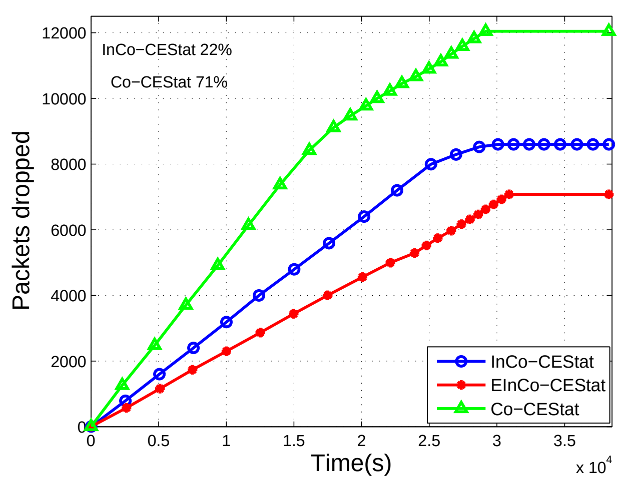

Figure 5.9: *Number of packets dropped*

5.7.3 Residual Energy of WBAN

Residual energy of all three compared WBANs is evaluated in figure 5.10. EE of Co-CEStat is improved by using incremental cooperation in InCo-CEStat and EInCo-CEStat. It is shown previously in figure 5.3 and 5.5 that 2-relay incremental cooperation is more energy efficient than 3-relay incremental cooperation. Figure 5.10 supports the results in figure 5.3 and 5.5. In order to reduce PER and to achieve higher diversity order, three cooperative links are used in EInCo-CEStat which consumes more transmission and reception energy than InCo-CEStat with two cooperative links. However, EInCo-CEStat is still more energy efficient than Co-CEStat. Therefore, EInCo-CEStat and Co-CEStat have increased throughput at the cost of increased energy consumption. In Co-CEStat, cooperative nodes always forward the data and consume energy even when it is not needed. So, it is seen from the figure 5.9 that at any instant of time, InCo-CEStat has highest residual energy which leads to highest network lifetime. Incremental relaying saves the channel resources, however, extra energy is consumed in redundant transmissions.

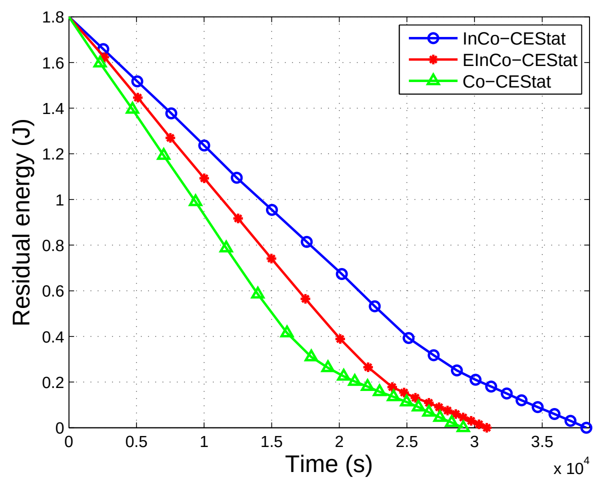

Figure 5.10: *Residual energy of network*

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In this thesis, four network layer protocols are proposed for WBANs. The first proposed protocol, CEMob, is an energy efficient routing protocol for WBANs which exploits both single-hop and multi-hop communications in heterogeneous network. It avoids transmission of similar information to preserve energy of communicating nodes. Moreover, effects of body mobility, on communication between nodes, are also observed in this work. Performance comparison of CEMob with two existing routing protocols; ATTEMPT and RE-ATTEMPT, shows that CEMob's performance is superior in terms of energy efficiency. CEMob has 23% and 77% more stability period than ATTEMPT and RE-ATTEMPT, respectively. Second protocol, Co-CEStat, is a cooperative routing protocol for WBANs. Purpose of this research is to exploit cooperative routing in heterogenous network to enhance WBAN's performance in terms of throughput. By avoiding repeated data transmission, Co-CEStat achieves greater stability period. Whereas, use of cooperative routing increases the overall network throughput due to availability of more than one link for transmission of same data. Simulation results of Co-CEStat are compared with already designed routing protocols; RE-ATTEMPT and RE-CEStat. Performance comparison shows that Co-CEStat has 51% and 52% higher throughput than RE-CEStat and RE-ATTEMPT, respectively. Thirdly, we proposed two incremental cooperative communication protocols; InCo-CEStat and EInCo-CEStat, to enhance the performance of Co-CEStat protocol. These protocols utilize incremental cooperation to improve energy efficiency and PER of Co-CEStat in the presence of AWGN and fading channel. Network throughput is enhanced by propagating independent signal through different paths. Whereas, energy efficiency is improved by utilizing incremental relay-based cooperation which saves channel resources by ensuring that relaying process is adaptable to channel conditions. Simulation results show that InCo-CEStat is 17% more energy efficient than Co-CEStat, whereas, EInCo-CEStat has 12% and 5% more throughput than InCo-CEStat and Co-CEStat, respectively. This type of cooperative transmission improves number of successful packets received at sink and achieves higher energy savings than Co-CEStat.

6.2 Future Work

In future, we aim to analyze and deal with multiple BANs along with mobile sink concept in our work. Research is being done in WSNs to achieve higher energy savings and greater network lifetime with sink mobility [39-42]. We want to implement such sink mobility in our WBAN protocols in future. Our focus will also be on secure and reliable delivery of information for critical data of WBAN [32]. For this purpose, we are required to study and analyze different QoS requirements, bandwidth limitations and other challenges to design an efficient routing protocol as in [43-45]. Our goal is to implement these features in our WBANs protocols.

Chapter 7

References

[1] IEEE standard for local and metropolitan area networks - Part 15.6. Wireless Body Area Networks, 29 February 2012.

[2] N. Javaid, and A. Ahmad, "RE-ATTEMPT: Energy-Efficient Routing Protocol for Wireless Body Area Sensor Networks", *International Journal of Distributed Sensor Networks*, vol. 2014, article ID 464010, 9 pages, 2014.

[3] W. Shaoqing , N.Jingnan, "Energy efficiency optimization of cooperative communication in wireless sensor networks", *EURASIP Journal on Wireless Communications and Networking*, pp. 162-326, 2010.

[4] K.Y. Yazdandoost, K. Sayrafian-Pour, "Channel model for body area network (BAN)", IEEE P802.15-08-0780-09-0006.

[5] J.M Dricot, S. Van Roy, G. Ferrari, F Horli1, P De Doncker, "Impact of the environment and the topology on the performance of hierarchical body area networks". *EURASIP Journal on Wireless Communications and Networking* vol. 2011, no. 122, pp. 1-17, 2011.

[6] AK. Sadek, W. Yu, KJ. Liu, "On the energy efficiency of cooperative communications in wireless sensor networks", *ACM Transactions on Sensor Networks (TOSN)*, vol. 6, no. 1, 5 pages, 2009.

[7] N. Javaid, Z. Abbas, and M.S.Fareed, "M-ATTEMPT: A New Energy-Efficient Routing Protocol for Wireless Body Area Sensor Networks", *The 4th International Conference on Ambient Systems, Networks and Technologies*, vol. 19, pp. 224-231, 2013.

[8] K. S. Deepak and A. V. Babu, "Improving energy efficiency of incremental relay based cooperative communications in Wireless Body Area Networks", *International Journal of Communication*, doi: 10.1002/dac.2641, 2013.

[9] S. Gonzalez, A. Vasilakos, H. Cao, and V. C. Leung, "Body Area Networks: A Survey", *Mobile Networks and Applications*, vol. 16, no. 3, pp. 171–193, 2011.

[10] S. Akram, N. Javaid, A. Tauqir, A. Rao, and S. N. Mohammad, "THE-FAME: THreshold Based Energy-Efficient FAtigue MEasurement for Wireless Body Area Sensor Networks Using Multiple Sinks", *Eighth International Conference on Broadband and Wireless Computing, Communication and Applications*, 2013.

[11] Q. Nadeem, N. Javaid, S. N. Mohammad, M. Y. Khan, S. Sarfraz, and M. Gull, "SIMPLE: Stable Increased-throughput Multi-hop Protocol for Link Efficiency in Wireless Body Area Networks", *Eighth International Confer-*

ence on Broadband, Wireless Computing, Communication and Applications, 2013.

[12] N. A. Pantazis, S. A. Nikolidakis, and D. D. Vergados, "Energy-Efficient Routing protocols in Wireless Sensor networks:A Survey", *IEEE Communications Sureveys and Tutorials*, vol. 15, no. 2, pp. 551–591, 2013.

[13] M.Zhang and A.Sawchuk, "Human Daily Activity Recognition with Sparse Representation", *IEEE journal of Biomedical and Health Informatics*, vol. 17, no. 3, pp. 553–560, 2013.

[14] M. Maalej, S. Cherif and H. Besbes, "QoS and Energy Aware Cooperative Routing Protocol for Wildfire Monitoring Wireless Sensor Networks", *The ScientificWorld Journal* vol. 2013, Article ID 437926, 11 pages, 2013.

[15] A.S Ibrahim, Z. Han and K.J. Ray Liu, "Distributed Energy-Efficient Cooperative Routing in Wireless Networks", *IEEE Transaction on Wireless Communications*, vol. 7, no. 10, pp. 3930–3941, 2008.

[16] A. kailas and M. A. Ingram, "Opportunistic Large Array-Based Cooperative Transmission Techniques for Long-Term Body Implants", *the 11th International Symposium on Wireless Personal Multimedia Communications* , 2008.

[17] J. W. Jung and M. A. Ingram, "Residual-energy-activated cooperative transmission (REACT) to avoid the energy hole", *Proceedings of the IEEE International Conference on Communications Workshops*, pp. 1-5, 2010.

[18] S. Ivanov and D. Botvich, "Cooperative Wireless Sensor Enviroments Supporting Body Area Networks", *IEEE transactions on Consumer Electronics*, vol 58, no.2, pp. 284–292, 2012.

[19] B Braem, B Latre , I Moerman, C Blondia, E Reusens, W Joseph, L Martens, P Demeester, "The need for cooperation and relaying in short-range high path loss sensor networks", *Proceedings of IEEE Conference on Sensor Technologies and Applications*, Valencia, Spain, pp. 566-571, 2007.

[20] E Reusens, W Joseph, B Latr , B Braem, G Vermeeren , E Tanghe, L Martens, I Moerman , C Blondia, "Characterization of on-body communication channel and energy efficient topology design for wireless body area networks", *IEEE Transactions on Information Technology in Biomedicine* vol. 13, no. 6, pp. 933-945, 2009.

[21] Chen Y, Teo J, Lai JCY, Gunawan E, Low KS, Soh CB, Rapajic PB, "Cooperative communications in ultra-wideband wireless body area networks:

channel modeling and system diversity analysis", *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 1, pp. 5-16, 2009.

[22] Yu R, Zhang Y, Gao R. "Mobile device aided cooperative transmission for body area networks", *Proceedings of ACM International Conference on Body Area Networks*, Corfu Island, Greece, pp. 65-70, 2010.

[23] JM Gorce , C Goursaud, G Villemaud ,R DErrico , L Ouvry , "Opportunistic relaying protocols for human monitoring in BAN", *Proceedings of IEEE Conference on Personal, Indoor and Mobile Radio Communications*, Tokyo, Japan, pp. 732-736, 2009.

[24] GE Arrobo, RD Gitlin, " Improving the reliability of wireless body area networks", *Proceedings of IEEE Conference on Engineering in Medicine and Biology Society*, Boston, Massachusetts, USA, pp. 2192-2195, 2011.

[25] GE Arrobo , RD Gitlin, "New approaches to reliable wireless body area networks", *Proceedings of IEEE Conference on Microwaves, Communications*, Antennas and Electronics Systems, Tel Aviv, Israel, pp. 1-6, 2011.

[26] P Ferrand , M Maman, C Goursaud, JM Gorce , L Ouvry. "Performance evaluation of direct and cooperative transmissions in body area networks", *Annals of Telecommunications*, vol. 66, no. 3, pp. 213-228, 2011.

[27] X Huang , H Shan , X Shen, " On energy efficiency of cooperative communications in wireless body area networks", *Proceedings of IEEE Conference on Wireless Communications and Networking Conference*, Quintana Roo, Mexico, pp. 1097-1101, 2011.

[28] A K. SADEK, W. Yu and K.J. Ray Liu, "On the Energy Efficiency of Cooperative Communications in Wireless Sensor Networks", *ACM Transactions on Sensor Networks*, vol. 6, no. 1, article 5, 2009.

[29] H. A. Sabti, and D. V. Thiel, "Node Position Effect on Link Reliability for Body Centric Wireless Network Running Applications", *IEEE Sensors Journal*, vol. 14, no. 8, pp. 2687–2691, 2014.

[30] F. A.-Ntim, and K. E. Newman, "Lifetime estimation of wireless body area sensor networks using probabilistic analysis", *Wireless Personal Communications*, vol. 68, no. 4, pp. 1745–1759, 2013.

[31] S. Ivanov, C. Foley, S. Balasubramaniam, and D. Botvich, "Virtual groups for patient WBAN monitoring in medical environments", *IEEE Transactions on Biomedical Engineering*, vol. 59, no.11, pp. 3238–3246, 2012.

[32] S. K. Chen, T. Kao, "A reliable Transmission protocol for ZigBee-Based Wireless Patient Monitoring", *IEEE Transaction of Information technology in Biomedicine*, vol. 16, no. 1, pp. 6–16, 2012.

[33] Q Shen, W Zhuang, "Energy efficient scheduling for delay constrained communication in wireless body area networks", *Proceedings of IEEE GlobeCom*, California, USA, pp. 280-285, 2012.

[34] M Al Ameen , N Ullah , MS Chowdhury , SMR Islam ,K Kwak, "A power efficient MAC protocol for wireless body area networks". *EURASIP Journal on Wireless Communications and Networking*, DOI:10.1186/1687-1499-2012-33.

[35] S Dumanli , S Gormus , IJ Craddock, "Energy efficient body area networking for mHealth applications", *Proceedings of Medical Information and Communication Technology (ISMICT)*, La Jolla, USA, pp. 1-4, 2012.

[36] P.K Chong and D. Kim, "Surface-Level Path Loss Modeling for Sensor Networks in Flat and Irregular Terrain", *Proceedings of the ACM Transactions on Sensor Networks*, vol. 9, no. 2, article no. 15, 2013.

[37] T. S. Rappaport, "Wireless Communications: Principles and Practice",(2nd Edition)

[38] M.-H. Zayani, V. Gauthier, and D. Zeghlache, A joint model for IEEE 802.15.4 physical and medium access control layers, in *Proceedings of the 7th International Wireless Communications and Mobile Computing Conference (IWCMC '11)*, Istanbul, Turkey, 2011.

[39] Y. Yun, and Y. Xia, "Maximizing the Lifetime of Wireless Sensor Networks with Mobile Sink in Delay-Tolerant Applications", *IEEE Transactions on Mobile Computing*, vol. 9, no. 9, pp. 1308–1318, 2010.

[40] X. Li, J. Yang, and A. Nayak, "Localized Geographic Routing to a Mobile Sink with Guaranteed Delivery in Sensor Networks"*IEEE Journal on Selected Areas in Communications*, vol. 30, no. 9, pp. 1719–1729, 2012.

[41] B. Behdani, J. C. Smith, and Y. Xia, "The lifetime maximization problem in wireless sensor networks with a mobile sink: mixed-integer programming formulations and algorithms", *IIE Transactions*, 2013.

[42] H. El-Sayed, A. Mellouk, L. George, S. Zeadally, "Quality of service models for heterogeneous networks: overview and challenges", *Annals of telecommunications*, vol. 63, no. 11–12, pp. 639–668, 2008.

[43] P. Ballarini, L. Mokdad, and Q. Monnet, "Modeling tools for detecting DoS attacks in WSNs", *Journal of Security and Communication Networks*, vol. 6, no. 4, pp. 420–436, 2013.

[44] J. Ben-Othman, L. Mokdad, and B. Yahya, "An Energy Efficient Priority-Based QoS MAC Protocol for Wireless Sensor Networks", *International Conference on Communication*, pp. 1–6, 2011.

[45] J. Ben-Othman, and L. Mokdad, "Enhancing data security in ad hoc networks based on multipath routing", *Journal of Parrallel and Distributed Computing*, vol. 70, no. 3, pp. 309–316, 2010.

Chapter 8

List of Publications

1. S. Ahmed, N. Javaid, S. Yousaf, et al., "Co-LAEEBA: Cooperative Link Aware and Energy Efficient protocol for Wireless Body Area Networks", accepted in Computers in Human Behavior (in press), 2014 (IF=2.2).

2. S. Yousaf, et al., "CEMob: Critical Data Transmission in Emergency with Mobility Support in WBANs", The 28th IEEE International Conference on Advanced Information Networking and Applications (AINA-2014), Victoria, Canada, 2014. (Chapter 3 in thesis)

3. M. Akbar, N. Javaid, S. Yousaf, et al., "TRP: Tunneling Routing Protocol for WSNs", The 28th IEEE International Conference on Advanced Information Networking and Applications (AINA), Victoria, Canada, 2014.

4. S. Yousaf, et al., "Co-CEStat: Cooperative Critical Data Transmission in Emergency in Static Wireless Body Area Network", The 9th IEEE International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA'14), Guangzhou, China, 2014. (Chapter 4 in thesis)

5. S. Yousaf, et al., "Incremental Relay-based Co-CEStat Protocol for Wireless Body Area Networks", The 9th IEEE International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA'14), Guangzhou, China, 2014. (Chapter 5 in thesis)

6. S. Yousaf, et al., "Reliable and Energy Efficient Incremental Cooperative Communication for WBANs", submitted in IEEE ICC (International Conference on Communcation) SAC-Communications for E-Health, 2015. (Chapter 5 in thesis)

7. S. Yousaf, N. Javaid, et al., "Incremental Cooperative Communication for Improving Reliability in WBANs", submitted in IEEE transactions on Mobile Computing. (IF=2.9) (Chapter 5 in thesis)