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I, Swathi Motukupalli Ravindranath, hereby submit this original work as part of the requirements for the degree of Master of Science in Computer Science.

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Life time improvement of Wireless Body Area Networks using Clustered Voronoi Tessellation

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Life time improvement of Wireless Body Area Networks using Clustered Voronoi Tessellation

A Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Department of Electrical Engineering and Computing Systems, Of the College of Engineering and Applied Sciences

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Abstract

Research in the field of Wireless Body Area Networks has been increasing remarkably due to the advancement of technology in the field of wireless communication and micro-electronics. These miniaturized sensors are being widely used in various fields of health monitoring due to their capability of providing real-time data to the patients. One of the main challenges associated with 3-D WBANs is to do with the lifetime of a WBAN network. The stringent requirements of the sensors used in WBANs such as battery operated devices opens up a challenge to hoard as much energy as possible. A lot of the energy is lost while transmitting the data to the base station. Therefore, we have attempted to reduce the energy dissipation of sensors by grouping them into clusters. We have introduced a clustering algorithm based on the computational geometry concept of Voronoi Tessellation. We adopt the two phase structure of Low Energy Adaptive Cluster Hierarchy (LEACH) protocol and design an enhanced version of LEACH by incorporating Voronoi based clustering. This algorithm is defined by weighing the significance of prioritized nodes and 3-D positioning of the sensors on the body as well. The simulation results demonstrate that our algorithm does indeed increase the network lifetime as compared to its conventional LEACH protocol approach.
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Chapter 1: Introduction

1.1 Outline of Wireless Body Area Networks (WBAN)

In the recent years, wearable technology, which is most suitable for continuous health monitoring of patients, is revolutionizing into a more affordable health-care system. These minute sensors allow a patient to closely monitor his/her vitals and help provide feedback to maintain optimal communication by alerting the medical personnel in case of life-threatening situations. This kind of a system is referred to as Wireless Body Area Network (WBAN) that enables assimilation of minuscule, intelligent, and low power Sensor Nodes (SNs) strategically placed in, on or around the human body to sense and gather physiological information. Each SN should be capable of sensing and relaying vital information such as blood pressure, heart rate, glucose, physical activity, etc., to an access point such as a PDA (Personal Device Assistant) or a cell-phone. The data is refined by Base Station (BS) or the Coordinator. This is where all the processing of the information takes place after which, the data is sent through GPRS (General Packet Radio Service) or via satellite radio through the interweb to the health-care providers, physicians, pharmacists, emergency services, to your family and to everyone who is authorized to receive the data. A good example of the Body Area Network architecture used for medical applications is shown in
Fig 1.1. We also have some of the different types of commercially available sensors summarized later in Table 3.1.

A Sensor Node (SN) typically consists of six components namely:

- Sensing Unit,
- Radio transceiver,
- Memory and Storage Unit,
- Power Unit like a Battery,
- Processing Unit, and
- Analog-to-digital converter.
WBANs can also contain Actuators and Wireless Personal Device Assistants (PDA) inside of a WBAN network. While actuators are used as drug-delivery systems in a timely manner to inject prescribed drug into the body, the PDA or even a cell-phone acts as a Control Unit which collects all information and passes it on to the user or the Base Station. These SNs are used to sense or monitor changes inside the human body or the surrounding areas for chemical, biological, physical or physiological variations. After sensing the required data at SNs and collecting them at a coordinator, they may perform signal processing functions, i.e., filtration, amplification, digitization, feature extraction, etc. This processed data is then stored momentarily and forwarded to the gateway (BS) through the wireless link.

1.2 Characteristics and Features of WBAN

WBANs, which constitute a subset of Wireless Sensor Networks (WSNs) impersonate some of the characteristic features of WSNs. Similar to a WSN, each SN in WBAN is capable enough to sense, process and forward physiological information to a BS or Coordinator for diagnosis.

SNs can be either wearable on the body or implanted inside ones body. The SNs communicate with each other using short range wireless technology such as Bluetooth, ZigBee, or ultra wide band (UWB) [2]. The standard IEEE 802.15.6 is designed explicitly for WBANs and is further described in the next section.

1.2.1 Body Area Network Standard

IEEE 802.15.6 has a layered architecture, mostly constituting three Physical layers and a Medium Access Control (MAC) layer protocol. Each layer takes care of some part of the standard which is in turn responsible for providing services to the higher
layers. The logical links between the layers are defined by the interfaces present between them.

Since IEEE 802.15.6 has strict Quality of Service (QoS) and priorities to transfer the medical data to the medical server, a QoS enabled WLAN for the next hop is needed to preserve end-to-end QoS. However, IEEE 802.11e standard is widely used for WLAN. It is popular for networks in the hospital wards because it prioritizes the stations in the network [34].

**MAC Layer of IEEE 802.15.6**

Medium Access Control or MAC is a part of the Data Link Layer of the OSI reference model. This layer is directly responsible for transmitting data packets to and fro across the channel. The SNs transmit their data to their peers or to the coordinator using the MAC layer protocol.

Since energy efficiency is an important criteria in our work, it is very important that we consider the transmit medium and the protocol that the SNs use to communicate with one another. If the SNs send data at the same time to the Cluster Heads (CHs) or to the Coordinator, collision may occur and this will result in retransmission which means - wastage of energy to us [11]. A properly designed MAC protocol allows the node to access the channel in a way that collision is avoided which in turn saves energy and supports quality of service. Different MAC protocols are used for different kind of networks. There are two kinds of MAC protocols namely:

- **Contention based**

  In a Contention-based protocol, every node is allowed to access the shared carrier or the medium at any point in time. Each node senses the channel
to check for traffic before transmitting the data. CSMA/CA is a very good example of a contention-based protocol. It stands for Carrier Sense Multiple Access with Collision Avoidance. In this mode of communication, the CH could ask for permission from the Coordinator before sending packets to it.

- **Contention free**

  We use contention-free protocol, where the channel is divided into time slots and each node is allotted a particular time slot during which it is allowed to establish connection and transmit the data. This kind of MAC is preferred because it provides collision free communication as each node is informed in advance about each of its time slot. One good example is TDMA (or) Time Division Multiple Access. We use TDMA as a means of communication between SNs and the Coordinator.

### 1.2.2 Usage of WBAN

WBAN has a broad range of numerous applications in various domains including medical health monitoring, fitness management, sports, military, safety, security and entertainment. They are briefly discussed below:

- In field of medicine, WBANs can be used for managing diseases like diabetes by measuring blood sugar levels and controlling the amount of insulin injected accordingly. On similar grounds, it can also help the elderly people by tracking their medication intake and activity levels. Apart from that, it can also help patients suffering from Parkinson’s with frozen gait problem. It is also used for computer-assisted physical rehabilitation. In general, it is a very essential part of monitoring various kinds of patients.
• In sports, sensors worn on the body of athletes can be used by coaches or trainers to remotely monitor their physical condition during real games and training.

• For fitness, WBAN can be used by health enthusiasts who wish to track their fitness and improve their well-being.

• In armed forces, it can be extensively used by soldiers not only to get information on real time location, but it can also help soldiers while in battle fields or during extensive training.

• In security, it can be used for monitoring firefighters health involved in scanning for hazardous chemicals and smoke. Another usage would be for authorization e.g., using RFID tags (radio frequency identification), etc.

• In the entertainment domain, WBAN can be used for exchanging digital business cards, information transfer, etc.,

1.3 Issues encountered by WBAN

Even though there has been a lot of research in WBANs, there are many challenging issues which are yet to be addressed before WBANs are widely deployed in the market. Some of the important issues and challenges that are faced by this emerging technology are Advancement of Sensor Node in terms of weight, low-power consumptions and low-power operations, reliability and secure transfer of the patients data in real time, standardization, interoperability, better Quality of Service (QoS) and energy conservation.

• Selection and advancement of Sensor Nodes

As the SN will be implanted on to the human body, their size, form factor, and
compatibility with the human tissues are very crucial. This is the reason for motivation behind the search for new materials.

- **Quality of Service (QoS) and Reliability**
  For the success of a WBAN, QoS is an extremely critical factor. Equally important is the reliability of transmission in order to ensure that the sensed data is authentic, and is received by the Coordinator within a reasonable amount of time. Also, these should be processed so as to ensure guaranteed delivery of the data. The reliability of the network directly affects the quality of health-care provided by the medical personnel and in the worst case scenario; it can be dangerous if a critical event has gone undetected [33]. Thus, handling of QoS is a critical concern during the lifetime of a WBAN operation.

- **Energy Conservation**
  A very important constraint on SNs is the low power consumption requirement as they carry very limited and mostly irreplaceable power sources. Hence, even though regular networks aim to achieve high quality of service (QoS), sensor network protocols must focus primarily on power conservation.

- **Security and Reliability of WBAN**
  The data that is obtained by the SNs is highly sensitive and very confidential and should be encrypted while transmitted over the Internet. The user needs to be confident that the data obtained has not been tampered with and contains original data. The communication between SNs and the coordinator in a WBAN has the following characteristic features: Data confidentiality, Data authenticity and Data Integrity.
• Power Supply Issues

Since replacing batteries of the SNs is not always convenient and in some cases, nearly impossible, the search for innovative ways to recharge or replace the batteries is critical. Some recent research in this area includes solar powered batteries for SNs, energy harvesting methods and power transmission using evanescent waves, etc.

1.4 Thesis Chapter-Wise Organization

An important step in the development of a WBAN is the conservation of energy and maximizing of the lifetime of a WBAN. This can be attained by a detailed analysis of the network structure, scrutinizing different kinds of SNs used to form the network, trying out different routing methodologies used to route data packets to BS, examination of the protocols used in implementing the same, study of the most optimal placement of SNs on the human body, etc. Since SNs are used to collect very life-critical information, it is desired to make them as energy-efficient as possible. In this thesis, we will try to find an innovative routing methodology which reduces energy consumption of the SNs, thereby increasing the lifetime of the whole network. The rest of the document is organized in the following way:

Chapter 2

This chapter gives a detailed outline of current routing methodologies used in WBAN. It also considers Clustering techniques used in WSN, gives some background on the recent work that has taken place in the clustering field of WBAN. We end this chapter by introducing about how we built our system and how it is different from the previous works.
Chapter 3
In this chapter, we start by introducing our problem statement and then we describe some of the basic taxonomy required to understand the design of our approach namely, Convex Hull, Delaunay Triangulations, Voronoi Tessellations, 3D positioning of sensors. We then define our energy model based on which our WBAN is built. We include detail of all the phases used to build our algorithm. We explain the working of our Algorithm in brief by using flowcharts and its pseudo-code.

Chapter 4
This chapter explains the simulation parameters used and the test cases of our data set with results. We obtain results and draw graphs explaining how our algorithm has increased the lifetime of the WBAN network.

Chapter 5
This chapter covers the concluding remarks and probable future work that could focus on to fine tuning our current model.
Chapter 2: Background and Literature Survey

2.1 Current Routing Techniques used in WBAN

In Wireless Body Area Networks (WBANs), various types of Sensor Nodes (SNs) are placed on the human body and operate on very limited energy source. The information that is scanned by these nodes is processed and transmitted to the base station (BS). Since these nodes are send their data with limited amount of energy, one of the critical issues in the design of a WBAN is the design of underlying routing topologies. Many energy efficient protocols have been proposed for WBAN that ensure enhanced longevity of the network. [6] [13] [26].

Routing algorithms are an important component of the WBAN structure, as they enable us to build a mathematical structure that could optimize on energy consumption life time of a network, etc., by keeping track of the time it takes for the battery of an SN to run out of energy, and select the best route for the packet to traverse from the SN to the Coordinator. Although research on current routing technologies used in Wireless Body Area Networks (WBANs) is quite new and has recently started to pick pace, there are quite a few of them that have completely revolutionized this area. They are further discussed in this section.
2.1.1 One-hop routing [10]

The most simplistic form of routing is One-Hop or Direct Transmission of data from SNs to the BS or the coordinator. In such a WBAN, every SN transmits to the coordinator directly. The only reception that occurs is at the BS. This kind of communication is not only too expensive in terms of energy dissipation, but it also means that the nodes placed farthest away from the base station die prematurely in contrast to the nodes that are placed closer to it [3] as shown in Fig 2.2. This is because, due to the distance of the SNs from the BS, their battery drains pretty quickly and reduces the network’s lifetime [16].

2.1.2 Multi-hop Routing [10]

In a model called as MTE (Minimum Transmission Energy), a SN transmits to the coordinator by forwarding its data packet to another SN which is closer to the coordinator than itself. The latter either passes it on to the coordinator or to another
Figure 2.2: **Disadvantage of One-Hop Transmission** is that the nodes farthest from the coordinator such as the ones shown in Figure—die prematurely as opposed to those that are placed closer to the coordinator.
SN that is closer than itself. Therefore, the packets are transmitted from a farther node to another that is closer and further on until it reaches the coordinator as shown by Fig 2.3. A number of protocols employ this approach [28], [29]. To further increase the efficiency of this protocol, an optimization technique such as Data Aggregation has been added to it. However, even though these optimization techniques do improve the performance of Multi-Hop routing, it is still disadvantageous for the SNs that are strategically placed closer to the BS or the coordinator such as those in Fig 2.4. The nodes closer to the BS will have a higher volume of information reception from the SNs further away and also, to add to the fatigue, the overhead labor of performing optimization techniques on these data packets will add to the further dissemination of the energy costing the lifetime of such SNs.

In [7], routing topologies have been broadly classified into hierarchical/cluster based routing protocol and flat-routing based protocol. In flat-routing, every SN in
Figure 2.4: **Disadvantage of Multi-Hop Routing** is that the SNs placed closer to the coordinator such as those shown in Figure- die prematurely due to the overload of datapackets that are processed by them.

the WBAN is entrusted with the same role as the other, whereas in the latter, each SN may have different roles to play. In flat-routing topology, since there is no role play for any of the sensors, there would be chaos if they sent data packets without any predefined order. Hence, in this methodology the BS floods the network with a request and the SNs associated with the request transmit data, while others wait for their turn.

According to [6] [13], hierarchical and clustering based routing methodologies in WBAN can be classified as follows:

- Quality-of-Service (QoS) Aware Routing Protocol
- Temperature-Aware Routing Protocol
- Cluster-Based Routing Protocol
Postural-Based Routing Protocol

Cross-Layered Routing Protocol

2.1.3 Quality-of-Service (QoS) Aware Routing Protocol

Due to the complex support structure of WBANs which consist of voice/multimedia teleconferencing, web browsing, messaging and file transfers, etc., the associated communication channels and traffic patterns in mobile WBANs are more unpredictable. Hence all of these applications impose stringent and diversified Quality of Service (QoS) requirements. The Quality of Service aware routing protocols are based on specific types of QoS metrics that are present and hence have a QoS specific module for each type. Hence, this makes it complex to design them as coordination between different modules. Some of the protocols that are based out of this are: Reinforcement Learning based Routing Protocol with QoS Support (RL-QRP)[22], New QoS and Geographical Routing (LOCAL-MOR), Energy-Aware Peering Routing (EPR) [19], and more recently, QPRD and QPRR have been introduced [20].

2.1.4 Postural-Movement-Based Routing Protocols

This protocol is built on the basis of LOS (Line of Sight Transmission). LOS is when a SN can send a packet to another with the least amount of propagation loss on the body. If the LOS between the nodes is lost, it then transmits via a relay node which is in the LOS of the receiver node. So, when the receiving node is within the LOS, the transmitting SN will send the data directly, else the transmitting SN will make use of a relay node to send the packet thereby saving on the propagation loss. The protocols that are based on the Postural-Moment of the body are:
• On-Body Store and Flood Routing protocol (OBSFR),
• Opportunistic Routing-Based protocol,
• Probabilistic Routing (PRPLC),
• DTN-Routing Dynamic-Postural Partitioning protocol (DVRPLC),
• Energy-Efficient Thermal-Power Aware-Routing protocol (ETPA)

2.1.5 Temperature-Aware-Routing Protocol

Temperature Aware protocol is relevant to those networks that consist of in-vivo SNs. For such SNs, due to the radio signals generated, electric and magnetic fields lead to rise in temperature and affect the power consumption of the node’s circuitry [32]. The purpose of Temperature Aware protocols is to keep the SN’s temperature below a certain level so as to slow the rate of increase in temperature to prevent it from harming the host.

TARA (Thermal-Aware Routing Algorithm) is one of the first protocols to consider temperature as a metric of routing methodology. This protocol states that the two major sources of heat are antenna radiation and power dissipation of the circuit. Since all the SNs may not be equipped with a temperature sensor within them, the temperature is measured by observing the sensor activities. The other prominent routing-based protocols introduced in this domain are:

• Least Temperature Rise (LTR) [5]. It deals with reducing the amount of heat produced in bio-medical sensor networks, power consumption and end-to-end delay.

Similarly, the more recent protocols introduced in this domain are:
• ALTR - Adaptive Least Temperature Rise (2006),
• LTRT - Least Total Route Temperature (2007),
• HPT - Hot-spot Preventing Routing (2008),
• RAIN - Routing Algorithm for Homogeneous Network and without-ID Sensor Nodes (2008),
• TSHR - Thermal-Aware-Smallest Hop Routing (2009), and

2.1.6 Cross-Layered Routing-Based Protocol

Cross-Layered Routing protocol takes care of the two most critical concerns in WBAN which is energy efficiency and load balancing. Hence, a collaboration between MAC layer and the Network layer is necessary. These protocols address and try to solve the issue by introducing a cross-layer of both network and MAC layers at same-time to improve the overall-performance of the Wireless Body Network (WBAN). In this protocol, both the layers are informed about the overhead-communication of the neighbouring SNs. Under such circumstances, in order to balance the energy consumption, the SN chooses SN that is currently less consumed power as compared to its peers for the next-hop communication, leading to a balance in the network. The protocols designed based out of this methodology are:

• WASP - Wireless-Autonomous Spanning Tree Protocol,
• CICADA,
• TICOSS - Timezone Coordinated Sleeping Scheduling,
2.1.7 Clustering-based Hierarchical Model

In this kind of hierarchical approach, a network can be broken into several groups as shown in Figure 2.5. Based on pre-specified criterion, the SNs are assembled into clusters and for each Cluster, a Cluster Head (CH) is elected. The responsibility of the CH lies in routing the data from the cluster to other CHs or directly to the BS. The clusters are either static or dynamic depending on the protocol. Data hops from one SN to another. However, because it moves from one layer to another, it moves faster than in the multi-hop representation. Furthermore, the overhead time and the latency is comparatively on the lower side as the data does not travel via as many SNs as in a multi-hop model. In clustering, optimization is an inherent quality which results in a more planned and systematic topology. We will talk more about Clustering in the next section.

- Biocomm and Biocomm-D
2.2 Wireless-Sensor-Network clustering Review

Hierarchical-clustering based techniques are used in various routing methodologies due to a lot of advantages.

Among the numerous advantages offered by Hierarchical-clustering based techniques, a few of them which increase the network lifetime are as follows: It is easy to widen the scalability factor of the network and reduce the energy consumption of a network. Definition of Network lifetime is stated as the time passed till the first (or the last SN) in the network has drained out of its battery power. These type of models are also employed effectively in networks which incorporate One-to-Many, Many-to-One or One-to-All communication protocols because data aggregation and load balancing are best supported by Clustering Algorithms.

In each type of clustering, a few selected SNs are elected to execute the role of a CH. These CHs group the SNs into non-overlapping clusters. Data that is sensed by these SNs is passed on to the CH. The CHs aggregate the data, then transmit it to the BS.

Most of the clustering algorithms are differentiated depending on their criterion used for Clustering. There are many noteworthy algorithms that are based upon this ideology and we will discuss a few of the important ones namely, LEACH (Low-Energy Adaptive Clustering Hierarchy), TEEN (Threshold-sensitive Energy Efficient sensor Network protocol), APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network protocol), and HEED (Hybrid Energy-Efficient Distributed clustering).
2.2.1 LEACH: Low-Energy Adaptive Clustering Hierarchy

LEACH designed by Heinzelman et al [16] has been extensively used as an inspiration for many more clustering algorithms that have introduced after it. The main characteristic feature of LEACH is that it selects CHs by rotation, so that the energy intensive role is equally executed by all the nodes in the network. The working of the LEACH algorithm is repeated for a number of rounds, where each round of LEACH has two phases namely, Set-up Phase and Steady-State Phase [16]. In the set-up phase, the CHs are selected and the clusters are formed, while in the steady-state phase, data is delivered to the BS. Their working in detail is as given below:

Phase: Set-up

During the set-up phase, the SNs elect themselves to be CHs for a particular round based on a certain probabilities. The election process has many factors under consideration such as the percentage of CHs currently chosen and the number of times each SN has been elected a CH till now. In the beginning of this phase, every SN selects a fraction random number between 0 and 1. If the selected number falls below a certain threshold, it is then elected as the CH for that particular round. The value of the Threshold is calculated using equation 2.1.

\[
T(n) = \begin{cases} 
\frac{P}{1 - P(rmod\frac{1}{p})}, & \text{if } n \in G. \\
0, & \text{otherwise.} 
\end{cases}
\]  

(2.1)

where \(T(n)\) is the Threshold calculated using the above formula

\(P\) is the desired percentage of the CHs.
$r$ is the current round in progress

$G$ is the set of nodes that have not yet been elected as CHs for $\frac{1}{p}$ rounds.

According to this formula, every node will get a chance of becoming a CH within the following $\frac{1}{p}$ rounds [16]. After the CHs are chosen, a notification is called the advertisement message to all the other nodes in the network using the CSMA protocol. Each SNs calculates the RSSI (Received Signal Strength Indicator) value of the broadcast signal and joins the CH with the highest RSSI value.

**Phase: Steady-State**

After the Clusters are formed and the network is organized, the SNs are now ready to send their data packets to their respective CHs by using the TDMA schedule chart that is created by each individual CH. The SNs send their packets during their allocated time slot. After receiving all data, the CH data aggregation step which compresses the data into a single composite signal [16]. The steady-state phase comes to an end with the transmission of the combined data packet from CHs to the base station, after which the next round begins.

There are different modifications to LEACH that have been proposed over time. Some of the notable ones are:

- **TL-LEACH** [23] - Two Level hierarchy for LEACH which uses a relay node for transmitting data packets from CHs to the Base Station,

- **E-LEACH** [36] or Energy LEACH which takes into account Residual Energy of every SN,

- **M-LEACH** [30] or the Multihop-LEACH selects the optimal path for transmitting from CH to the Base Station via other CHs,
• LEACH-C [27] which is the Centralized version of LEACH. It disperses the CHs throughout the network, and

• LEACH-FL [31] - It is an improvement on LEACH Protocol of Wireless Sensor Networks Using Fuzzy Logic,

There are a lot of others as well such as W-LEACH, T-LEACH, etc.,

2.2.2 TEEN Protocol and APTEEN Protocol

TEEN and APTEEN, introduced by Manjeshwar and Agrawal, are both hierarchical protocols that stand for Threshold-sensitive Energy Efficient sensor Network protocol (TEEN) [24] and Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network protocol (APTEEN) [25]. Since these two are hierarchical based protocols, they work in clusters. The closest of the nodes form clusters and this process is repeated until all the SNs are grouped together. The SNs sense the medium continuously. But data is transmitted reactively only if a certain criterion is met. At the beginning of each round, there are two threshold values that are broadcasted by the CH to its member SNs. They are called Hard Threshold ($H_T$) and Soft Threshold ($S_T$). Hard threshold is the minimum threshold used to trigger a SN to transmit its data to the CH which means that only if the sensed attribute is beyond the Hard Threshold, and if the range is greater than or equal to the Soft Threshold, the SN will transmit to the CH. This reduces the redundant transmissions and hence saves energy. The Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) is an extension to TEEN and it uses same architecture as the latter. It is a hybrid protocol that is adaptive combines proactive and reactive approaches according to the needs of an application.
2.2.3 HEED - Hybrid Energy-Efficient Distributed clustering

Hybrid Energy-Efficient Distributed clustering or HEED [37], introduced by Younis and Fahmy, is a multi-hop clustering algorithm which is different from LEACH by the manner in which it elects the CH. The algorithm aims to prolong the network lifetime and hence the CH is elected based on hybrid combination of two parameters of residual energy of each node and inter cluster communication cost and this improves energy efficiency thereby increasing the lifetime of the network. The probability that a SN is elected as a CH is given by the relation:

$$CH_{prob} = CH_{prob} \times \frac{E_{residual}}{E_{max}}$$  \hspace{1cm} (2.2)

Where $E_{residual}$ is the current Energy of every SN and $E_{max}$ is the reference maximum Energy which is the same for all the nodes in the system. The SNs go through several iterations until the CH is elected. If there are several candidate CHs, the node with the lowest inter-cluster cost is elected as the CH. The data aggregation part is similar to that of LEACH.

2.3 WBAN: Wireless Body Area Network Clustering Review

2.3.1 LEACH: Low-Energy Adaptive Clustering Hierarchy in WBAN: Wireless Body Area Network

In [38], a slightly modified LEACH protocol has been proposed based on WBAN networks. The only difference is the inclusion of priority nodes in the probability function of LEACH. Priority SNs are those whose data is valued more as in compared to other SNs present on the body. For example, the SNs sensing the ECG, EMG and
the glucose data is given higher priority and hence, the probability of them becoming CHs is reduced. However, if the issue is still not resolved, almost-dying SNs are spared from becoming the CHs while they are healthier SNs present to do the job, i.e., they do not consider Residual Energy of the SNs for selection of CH, thereby reducing the network lifetime.

### 2.3.2 Anybody: a self-organization protocol for body area networks

AnyBody [35] is a cluster-based self organizing data gathering protocol. It uses the same Steady-State phase as LEACH and similar to LEACH, it selects the CHs at regular time intervals. However, unlike LEACH, where it is assumed that all the SNs are within the range of the Coordinator, Anybody uses density-based cluster Head selection method. Anybody protocol follow the following steps [35]:

- neighbor discovery,
- density calculation,
- cluster-Head construction,
- setting up of the backbone, and
- setting up of the routing path.

Initially the algorithm starts off with the one-hop neighbors being discovered by transmitting a $Hello_1$ message during the beginning of the time frame. In the second time frame, a second $Hello_2$ message is sent to find the two-hop neighbors. Next, each node calculates its density based on its two-hop neighborhood information and shares the density information with its neighbor nodes by broadcasting a $Hello_3$ message.
In the third step, the CHs are chosen with the highest density. During the next step, the pathway from CH to CH is determined with the help of gateway nodes. Finally, gradient_setup messages are sent out by the Coordinator to all the CHs and the CHs resend it to confirm that they are all connected amongst each other. Now, that the clusters are formed and well connected, the data aggregation and transmission is initiated.

The disadvantage of this protocol would be its overhead in forming clusters as there are a lot of packets traversing to-and-fro in the WBAN. For a network consisting of 100 nodes, the overhead transmission of messages to form clusters that include, \( \text{Hello}_1, 2, 3 \) messages, join messages gradient_setup messages come up to nearly 500 [35]. This would deplete the minuscule SNs of their energy.

### 2.3.3 HIT - Hybrid Indirect Transmission Protocol

Similar to LEACH, HIT (Hybrid Indirect Transmission) is broken into two rounds which include the Set up phase and a Steady State phase. The two characteristic features of HIT are that unlike LEACH, the nodes transmit indirectly to the Coordinator, i.e., via multi-hop transmission. It also allows multiple, parallel and indirect transmissions across multiple, adjacent clusters with collision avoidance. The details of the HIT protocol are as follows: Initially, one or more CHs are elected and then new clusters are formed by the status information after it is flooded by the CHs. After cluster formation, upstream and downstream relationships for each cluster are formed due to which multiple routes are figured out within each cluster from the SNs to the CHs. should not be in contact with at the same time. Lastly, the SNs transmit the sensed data to the CH through upstream neighbors using TDMA schedule [18].
2.3.4 Voronoi in WBAN - Our Work

From our literature review, we notice that not many clustering algorithms, apart from the ones mentioned above have been considered in WBAN. Hence, in the next chapter, we introduce a Clustering Algorithm based on Voronoi Diagrams and Residual Energy. The CHs are chosen by considering the Residual Energy of the SNs and the clusters are formed around the CHs by using the geometrical concept of Voronoi Diagrams as explained in the next chapters.
Chapter 3: Approach to Our Design

In this chapter, we introduce a new of the clustering algorithm which could increase lifetime of wireless Body Area Networks (WBAN). We provide steps for our clustering approach and also indicate how our algorithm can be used within the LEACH structure to enhance Sensor Nodes’ (SNs) life span in a WBAN. We also provide rationale behind our algorithm’s design and illustrate how it works on a human body sample data points.

We employ a cluster based hierarchical topology where each SN transmits its data packets to its respective Cluster Head (CH) instead of sending it directly to the Base Station (BS). The CH in turn aggregates the data received from its member SNs and then forwards aggregated data to the BS using CSMA/CA algorithm of the IEEE 802.15.6 protocol.

3.1 Preliminaries

This section explains the geometrical properties used in the design of our algorithm. A detailed explanation of each of the terminologies is given here.
3.1.1 Convex Hull

It is a fundamental concept in computational geometry. The definition of a convex hull in the Euclidean space is as follows:

A subset \( S \) of the plane is called convex iff for any pair of points \( p, q \in S \) the line segment \( pq \) is completely contained in \( S \). The convex hull of a set \( S \) is the smallest convex set that contains \( S \).

In simple words, the convex hull of \( S \) is the smallest convex polygon that contains all the points of the vector \( S \).

Convex hull algorithm is used in many fields such as computer graphics, pattern matching, etc.,. Additionally, Voronoi tessellations and Delaunay triangulations can also be deduced using the convex hull algorithm.

3.1.2 Delaunay Triangulation

Delaunay triangulation is used in many spheres of science such as in optimization techniques like meshing, terrain mapping, etc.,. It’s algorithm subdivides a plane into triangles whose vertices represent the points of the plane. The definition of diving a plane into Delaunay triangles can be given as:

Three points \( s_i, s_j, s_k \in S \) are the vertices of a Delaunay triangle iff there is a circle passing through \( s_i, s_j, s_k \) so that all the other points from the
set $S$ lie outside the circle. This circle is known as the circumcircle defined by the points $s_i, s_j, s_k$.

Figure 3.2: Delaunay Triangulation over an unequal terrain
(reprinted from [9])

The most common methodology used for generating the triangulation is to employ “The Divide and Conquer” algorithm by Guibas and Stolfi [15]. The algorithm first calculates the convex hull of the points. After the points are arranged in the increasing order of their respective x-axis, the space is successively divided into halves until every created subset contains no more than three points. The subsets can now be triangulated and merged to give the most optimal Delaunay triangulation.

Such a scheme is most commonly used to model a piece of terrain and draw its topographic map. Such maps are used to predict the height of a point on the terrain that has not been measured yet [9].

3.1.3 The Voronoi Tessellation

The Voronoi diagram is a versatile geometrical structure used to divide a plane into convex polygons with finite length of segments. A Voronoi tessellation around a
point $s_i \in S$ is formed when you divide the space around the point $s_i$ into zones in such a way that, every point in the zone containing $s_i$ is closest to $s_i$ than any other point present in the vector $S$, i.e., each point $p \in S$ is assigned a set of vector points that are closer to itself than to any other point in $S$. It is widely used in various scientific fields such as design of roads, tall structures, telecommunication networks, terrain modeling, neural networks, etc. It can also be used to map the nearest location of a gas station, or a restaurant, etc.

The definition of Voronoi function is as follows:

Let $P = p_1, p_2, ..., p_n$ be a set of $n$ distinct points in the plane; these points are the sites. We define the Voronoi diagram of $P$ as the subdivision of the plane into $n$ cells, one for each site in $P$, with the property that a point $q$ lies in the cell corresponding to a site $p_i$ if and only if $dist(q, p_i) < dist(q, p_j)$ for each $p_j \in P$ with $j \neq i$. 

Figure 3.3: Delaunay Triangles on a set of random points [12]
Different methods used to compute Voronoi Diagrams

There are various methods used to compute Voronoi tessellations. Since it works on the distance metric, the basic formula used to calculate the distance between each of the two points for 2 – D Voronoi computation is:

\[ \text{dist}(a, b) = \sqrt{(a_x - b_x)^2 + (a_y - b_y)^2} \]  

(3.1)

where \( \text{dist}(a, b) \) denotes the Euclidean distance between two points \( a \) and \( b \).

One of the famous algorithms used to draw 2 – D Voronoi diagrams is called Sweepline algorithm where two lines namely \textit{sweepline} and the \textit{beachline}, both move through the plane containing the points as the algorithm progresses. \textit{Sweepline} is a straight line that sweeps across the plane while incorporating all the points. For 3-D, Voronoi polygons can also be deduced from Delaunay triangles. On the Delaunay triangles formed, perpendicular bisectors are drawn across every edge of
the triangles. The bisectors and their intersections form the edges and vertices of the Voronoi Tessellations respectively.

The complexity of the $2-D$ Voronoi diagram is linear. For $n$ sites, there are $n$ faces, at most $2n - 5$ vertices and at most $3n - 6$ edges [9]. However, our algorithm utilizes Voronoi diagrams in both $2-D$ and in $3-D$. Figure-3.5 illustrates an example of $3-D$ Voronoi polyhedrons formed around a random set of uniform data in MATLAB.

![3D Voronoi Region](image)

Figure 3.5: An example plot of $3-D$ Voronoi polyhedrons formed around a random set of uniform data points

### 3.1.4 3-D Positioning System

Sensors relaying vital information are placed at fixed locations on the human body. Hence, the requirement for determining the most accurate position of the sensors need to be defined. Unquestionably, positioning of the sensors in WBAN remains to be the most important issue that affects the life time of a network. Hence, the requirement for determining the most accurate position of the SNs has not been emphasized in this
thesis. We have tried to incorporate a reliable 3D topology model in our algorithm [14] [39].

The 3–D system that is used to model our data-set follows—a X Y Z coordinate system. X Y coordinates represent the front and the sagittal plane of the body. The third Z coordinate is used to capture the depth of the SN inside the human body frame.

In this model, the distance between two sensors \( A(x_a, y_a, z_a) \), \( B(x_b, y_b, z_b) \) is calculated using the relation:

\[
d = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2 + (z_b - z_a)^2}
\]  

(3.2)

### 3.2 The Dataset

A WBAN structure can be made of a myriad of SNs depending on the end user application. A number of tiny wireless SNs are placed on or inside the human body to create a WBAN. Here, we introduce one such probable Wireless BAN structure composed of physiological SNs that are either wearable or implanted.

The standardization of WBAN by IEEE 802.16.5 protocol has specified that up to 64 SNs can be placed to constitute a WBAN’s network topology consisting of only one Hub [4]. However, one or more WBANs can co-exist in a network hence that would mean a WBAN can support upto 256 SNs [21]. We have considered 25 for convenience. However, the network can be scaled to required number as well. The uses of some of the most common SNs has been mentioned in Table 3.1 and Figure-3.6 shows the approximate position of SNs considered on the human body.
Table 3.1: Common use of sensors in WBAN

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Function of each sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>Obtaining acceleration on each spatial axis of three-dimensional space</td>
</tr>
<tr>
<td>Artificial cochlear implant</td>
<td>Converting voice signal into electric pulse and sending it to implanted electrodes in ears, generating auditory sensation by stimulating acoustic nerves.</td>
</tr>
<tr>
<td>Artificial retina</td>
<td>Receiving pictures captured by external camera and converting them to electric pulse signals, which are used to stimulate optic nerves to generate visual sensations.</td>
</tr>
<tr>
<td>Blood-pressure sensor</td>
<td>Measuring the peak pressure of systolic and the minimum pressure of diastolic.</td>
</tr>
<tr>
<td>Blood oxygen saturation sensor</td>
<td>Measuring blood oxygen saturation by absorption ratio of red and infrared light passing through a thin part of body.</td>
</tr>
<tr>
<td>Carbon dioxide sensor</td>
<td>Measuring the content of carbon dioxide from mixed gas by infrared technique.</td>
</tr>
<tr>
<td>ECG (electrocardiogram)</td>
<td>Sensor for monitoring heart activity</td>
</tr>
<tr>
<td>EMG (electromyography)</td>
<td>Sensor for monitoring brain electrical activity</td>
</tr>
<tr>
<td>EEG (electroencephalography)</td>
<td>Sensor for monitoring Electrical activity</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>Measuring angular velocity of rotating object according to principle of angular momentum conservation.</td>
</tr>
<tr>
<td>Humidity sensor</td>
<td>Measuring humidity according to the changes of resistivity and capacitance caused by humidity changes.</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>Measuring pressure value according to the piezoelectric effect of dielectric medium</td>
</tr>
<tr>
<td>Respiration sensor</td>
<td>Obtaining respiration parameters indirectly by detecting the expansion and contraction of chest or abdomen.</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>Measuring temperature according to the changes of materials physical properties</td>
</tr>
<tr>
<td>Tilt sensor</td>
<td>Monitoring trunk position</td>
</tr>
<tr>
<td>Visual sensor</td>
<td>Capturing features of subject, including length, count, location, and area.</td>
</tr>
</tbody>
</table>
Figure 3.6: Approximate placement of sensors on a Human frame
Figure 3.7: The radio model followed by LEACH that is adapted into our algorithm

Table 3.2: The characteristics of our Energy Model

<table>
<thead>
<tr>
<th>Components used</th>
<th>Energy Dissipated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter and Receiver</td>
<td>50 nJ/bit</td>
</tr>
<tr>
<td>Transmitter Amplifier</td>
<td>100 pJ/bit/m²</td>
</tr>
</tbody>
</table>
3.2.1 Energy model

We have adopted a simplistic energy model that is being used by the LEACH algorithm in [16]. In this model, the transmitter and the receiver consume 50 $nJ/bit$ energy and the transmitter amplifier dissipates 100 $pJ/bit/m^2$ to reach an acceptable normalized Signal to Noise ratio ($\frac{E_b}{N_0}$) which is useful for comparing the Bit Error Rate (BER) for different modulation schemes (see Figure- 3.7 and Table 3.2).

Mathematical expression for the dissipation of energy by the Transmitter to transmit a $k$-bit message by a distance $d$ using the above mentioned energy model is:

$$E_{Tx}(k, d) = E_{Tx} - e_{elec}(k) + E_{Tx} - a_{mp}(k, d)$$  \hspace{1cm} (3.3)

or

$$E_{Tx}(k, d) = E_{elec}(k) * k + \epsilon_{amp} * k * d^2$$  \hspace{1cm} (3.4)

where $d$ is the distance between the transmitter (SN under consideration) and the receiver (coordinator).

Similarly, the expression for dissipation of energy by the Receiver during reception for the same $k$-bit message coming from a distance $d$ is:

$$E_{Rx}(k) = E_{Rx} - e_{elec}(k)$$  \hspace{1cm} (3.5)

or

$$E_{Rx}(k) = E_{elec} * k$$  \hspace{1cm} (3.6)

There are two different relations used for calculation of energy dissipation depending on the distance $d$. If distance between the sensor and the coordinator is less than the threshold value $d_0$, we use free space model with $E_{fs} = 10 \times 0.00000000000$. Otherwise, we use the multi-path fading channel where $E_{mp} = 0.0013 \times 0.000000000001$.

$d_0$ can be calculated as $d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}}$.  

37
This implies that, if the CH transmits a packet for a distance of \( d \) to reach the coordinator up the energy consumption by the CH and the Coordinator can be calculated as follows:

\[
E_{TX}(k,d) = E_{elec} * k + \epsilon_{fs} * k * d^2, d < d_0 \tag{3.7}
\]

or

\[
E_{TX}(k,d) = E_{elec} * k + \epsilon_{mp} * k * d^4, d > d_0 \tag{3.8}
\]

\[
E_{Rx}(k) = E_{elec} * k \tag{3.9}
\]

**Assumptions**

- Size of the data packet = 4000 bits.
- The coordinator is assumed to be a high energy node.
- The size of the message sent by the member SNs to their CH as well as the size of the aggregated message sent by the CH to the BS is of the same size; namely 4000 bits.
- The sensors in the frame sense the environment at a fixed rate and keep sending data regularly to the coordinator at a constant rate.
- All the sensors can communicate with each other. The CH and Member SNs are time-stamped for every SN in the network.
- The nodes are stationary and homogeneous with same initial energy.
- The SNs follow peer-to-peer communication.
- All CH communicate with the coordinator using One-Hop transmission.
• All member SNs communicate with their respective CH using One-Hop.

• All SNs are aware of their location and their neighbor’s position.

3.3 The Algorithm

The reason behind using clustering algorithms is mainly to minimize energy consumption throughout the network. In clustering, the sensors form groups amongst themselves, known as clusters and elect their respective CH. The flow of data is now from SN → Cluster Head → Coordinator. When compared with other routing protocols, clustering has unparallel advantage in terms of scalability and energy consumption.

In our algorithm, the CHs are chosen and the SNs group themselves into clusters around the chosen CHs. This process is repeated as per Voronoi polygons that are formed around the CHs for every round. In addition, the CHs also compress the data that is collected from their respective member SNs, and the aggregated data-packets is now transmitted to the coordinator. The CHs are selected based on their Residual Energy. The top 5 sensors with the most Residual Energy are chosen as the next round CHs. By this method, we ensure that only the most SNs are chosen for the role of CH. Figure– 3.8 is a flow chart that describes in brief the two phases: CH selection and Data aggregation process of our algorithm.

The human frame of reference is of size 200 * 200 cm (cite reference). The number of SNs we have used for our simulation is 25. Two positions or coordinates have been considered in and hence performed simulations with the coordinator at the center of the human body frame and at the usual position (the approximate coordinates of a trouser’s pocket). Furthermore, energy of all the nodes have been initiated set to
Table 3.3: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of the Frame</td>
<td>(2m \times 2m)</td>
</tr>
<tr>
<td>Number of Sensors</td>
<td>25</td>
</tr>
<tr>
<td>Coordinates of the base station</td>
<td>((116, 100))</td>
</tr>
<tr>
<td>Initial Energy of the sensors</td>
<td>0.5 (J)</td>
</tr>
<tr>
<td>Number of iterations/rounds</td>
<td>2500</td>
</tr>
<tr>
<td>Size of the data packet</td>
<td>4000 (bits)</td>
</tr>
<tr>
<td>Data aggregation energy</td>
<td>(E_{DA} = 50nJ/\text{bit})</td>
</tr>
<tr>
<td>Energy consumption of free space</td>
<td>0.1 (pJ/\text{bit}/m^2)</td>
</tr>
<tr>
<td>Energy consumption for multi-path loss</td>
<td>0.13 (pJ/\text{bit}/m^4)</td>
</tr>
</tbody>
</table>

0.5\(J\). As given Table 3.3, in the data packets have been assumed to be of size 4000 bits.

### 3.3.1 Phase: Clustering

Being a CH drains a sensor’s battery to a great extent. The random CH selection of LEACH can throw the energy off balance, therefore leading to an early death of SNs. To assist uniform distribution of energy consumption and hence the same residual energy throughout the network, we take into consideration Residual Energy for election of CHs. Our main goal is to make sure that, the sensors that are already dying don’t get picked as a CH when there are more energetic nodes that can do the job. The elected CHs now broadcast themselves to their member SNs in the WBAN.

Additionally, the BS determines, a-priori, an optimal number of CHs to be present at every-single round. This depends on the number of alive SNs in the network.
3.3.2 Phase: Data Transmission and Aggregation

We know that, receiving a message is not a low cost operation. Hence, we not only need to minimize the transmit distances, but also the number of transmit and receive operations for each message. Hence, data aggregation is an important step in the transmission phase. Now, all the SNs are hierarchically structured and linked to their CHs. The next step is data transmission. There are two kinds of transmissions that take place here. Firstly, the SNs send their packets to their respective CH for aggregation. Later, the CHs transmit the condensed data over to the BS for processing. Each of the member SNs use Time Division Multiple Access protocol to send data packets to their respective CH as defined by the CH. In TDMA, each member sensor is allotted a particular time slot by the CH to transmit the data in a given channel. This means that during a particular time slot, when one SN is transmitting, all the other SNs can turn off their radio to conserve energy.

Additionally, the size of the data packet transmitted is 4000 bits. A point to note is that, the size of the message that nodes send to their CHs as well as the size of the aggregated message that a CH sends to the BS is considered to be the same.

3.3.3 Working of the Algorithm

This section describes the working of our algorithm on a higher level.

Step 1:

We start by plotting the data points. Figure– 3.9 illustrates the data-set on a hypothetical human body frame (Also see Figure– 3.10).
We select first five CHs from the dataset for the initial round. The CHs are chosen based on their ability to create perfect clusters which means each cluster should ideally contain five member SNs (See Figure- 3.11).

Step 2:

We draw Delaunay Triangles over the set of CHs that are chosen (See Figure- 3.12). By joining the perpendicular bisectors drawn on every edge of the triangles, we get our Voronoi polygons for the current set of CHs (See Figure- 3.13). Figure–3.14 portrays a hypothetical creation of clusters that are formed by the Voronoi polygons. The polygons or the clusters are not measured to scale.

Step 3:

In this step, the data aggregation and data transmission takes place. Here, the member SNs first transmit data packets during their respective time slots to the CHs. The CHs aggregate the data and send the aggregated data to the Coordinator. This is end of ROUND 1.

Step 4:

After the CHs transmit the data to the sink SN, Calculate Residual Energy of all the SNs. The SNs that were previously CHs usually will have lower energy than the rest of the network as data aggregation does dissipate quite some energy. If we arrange all the SNs based on their descending order of Residual Energy, the SNs which were CHs in the previous round will ideally contain the least energy amongst the rest of the SNs. Hence, our algorithm chooses the next Five CHs from the pool of SNs, with the maximum residual energy.
Step 5:

Repeat Step 2, 3 and 4 till at least one SNs die.
3.3.4 The Pseudocode

Algorithm 1: Pseudo code for Clustering Algorithm

Data: frame of reference \((x, y, z) = (200, 200, 30);\)
set coordinates of sensor points \(S(i);\)
sink(x,y) = (center of the frame);
Initialize \(E0, ETX, ERX, EDA, d0;\)
Initialize number of rounds \(r;\) Initialize nodes \(n = 25;\)
Initialize \(j = 5\) as we consider \(j = \sqrt{n};\)

while \(i < \text{nodes}\) do
    Plot the sensor nodes \(S(i);\)
end

while \(\text{round} == 1\) do
    set coordinates of \(CHS(j);\)
    Plot the \(CHS(j);\)
end
End first Iteration

while \(r < 2500\) do
    while \(i < \text{nodes} n\) do
        if \(S(i) < 0\) then
            increment \(\text{deadNodes}\) counter;
            \(j = \text{round}(\sqrt{\text{AliveNodes}});\)
        end
        voronoin(\(CHS);\)
    while \(j < 5\) do
        (distance from CHS to its member nodes);
        \(d(i, j) = \sqrt{(CHS(j).x - S(i).x)^2 + (CHS(j).y - S(i).y)^2};\)
        for each \(i\), select \(\text{MIN}(d(i, j));\)
        (distance from CHS to the sink node);
        \(\text{dist}(i, j) = \sqrt{(CHS(j).x - \text{sink}.x)^2 + (CHS(j).y - \text{sink}.y)^2};\)
        \(S(j).E = S(j).E - \text{Energy dissipation based on dist}(i, j);\)
        \(S(i).E = S(i).E - \text{Energy dissipation based on d}(i, j);\)
    end
    find \(\text{MaxEnergy}(\text{all nodes} n);\)
    \(\text{newCHS} = \max5(\text{MaxEnergy});\)
    \(\text{CHS} = \text{newCHS};\)
end
Increment \(r\) by 1;
REPEAT till \(r = 2500\)
Figure 3.8: The flowchart of our Cluster Head Selection Algorithm
Figure 3.9: Sensors placed on a hypothetical Human Outline

Figure 3.10: Hypothetical plot of sensors
Figure 3.11: Step1: The selection of CHs for determining of Voronoi polygons

Figure 3.12: Step2: Plot depicting the Delaunay Triangles formed on the CHs
Figure 3.13: Step2: Plot showing the Voronoi Polygons formed by joining the perpendicular bisectors of Delaunay Triangles
Figure 3.14: The complete clusters formed by the Voronoi Polygons
The increase in the usage of Wireless Sensors in the field of health monitoring has paved way for WBANs which are now becoming an in-dispensable mechanism in the health-care system. It helps in monitoring a person’s vitals and other important bodily signals of a wide variety of patients such as old aged people, people suffering from disabilities or athletes as they provide complete freedom of movement and unattended monitoring along with reporting of the real time information back to the medical personnel periodically.

Clustering is a conventional topology used in optimization of routing Sensors to increase the Sensor-Netowrk’s life-time. Similarly, Voronoi cell based WSNs on randomly deployed SNs which form CHs with a possibility of $p$ have been used in [8]. There has been quite a bit of research in using Voronoi diagrams for WSNs. For example, Voronoi diagrams have also been used in deploying sensor nodes in a mobile Sensor Network [17]. In WBAN also, we have employed Voronoi cell based Clustering where CHs are formed based on their Residual Energy. The non-CH nodes or the normal nodes join the cluster of the closest CH to form a Voronoi Tessellation.

This chapter is divided into 2-D simulations setup and 3-D simulations setup. We run simulations for 25 SNs and 64 SNs in 2-D till all the SNs get exhausted (dead) and discuss the network lifetime of each setup under consideration. We also perform
comparisons of the lifetime of our proposed WBAN network with LEACH and Multi-Hop networks in 2-D and plot graphs to show the same. The energy model used in all of the simulations performed below is the same and has been tabulated in Table 3.7)

4.1 Clustering in 2-D

Simulation of our proposed algorithm is performed in MATLAB. For our first simulation, a set of 25 nodes have been deployed. We have also run simulations on a WBAN consisting of 64 nodes as specified by IEEE 802.15.6, that in the presence of a single hub, there can be up to 64 nodes present in a WBAN.

4.1.1 SETUP-1: With 24 Sensor Nodes

We have used 25 SNs. Their coordinates and the relevance of each SN is explained in Table 4.1. We have used 25 SNs in this particular setup as we found 25 most apt sensors that could be placed on a human body at any point of time. However, we have also run simulations on the standard number of SNs that can be placed in a WBAN stated by IEEE 802.15.6 [4]. Figure- 4.1 shows the placement of SNs in MATLAB. Initial CHs are chosen by keeping in mind their connectivity to the Coordinator and their ability to make perfect clusters. For this particular setup, the coordinates chosen are shown in Figure- 4.2.

After the Cluster Head Selection, Data aggregation phase occurs. In this phase, each member SN join their respective cluster and transmit data packets to their CH. The CH in turn aggregates the information and delivers the aggregated packet to the Coordinator. In this phase, the energy dissipation is calculated at the end of each round. The Residual Energy now plays an important role in the selection of next set
of CHs for Round-2. The CHs that contain the most Residual energy amongst all the sensor nodes are elected as the CHs for Round-2. Figure- 4.3 shows the remnants of energy that is left over in each sensor after Round-1.

The numbers represented by each SN in Figure- 4.2 gives us the number of the CH to which that particular SN is transmitting. The number of the CH itself is changed to 26 to keep a track of all the CHs in every round. For example, in Figure- 4.2, SNs numbered 12 mean that they all transmit to Node Number 12 which is their CH. However, nomenclature of Node Number 12 is changed to 26 to avoid ambiguity.

Similarly, for every consecutive round, Residual Energy is calculated using the equation [3.6] and [3.7]. For the next round, the CHs are as shown in Figure- 4.4.

The maximum number of Rounds (rmax) is taken to be 2000. The death of the first node occurs at Round-764 as shown in the graph 4.7 and 4.5. After all the nodes die, the simulation ends when all the SNs turn red like in Figure- 4.6.

**Network Lifetime**

As illustrated in plot 4.7, the blue line denotes the number of nodes that survive in each round after communicating with the CHs or the Coordinator respectively. As the number of rounds increase, the nodes slowly start to exhaust themselves. This graph gives us the death of each node Vs the total number of rounds it took for all the nodes to die giving us an idea of the lifetime of the network. Our simulation shows us that all the nodes lasted till \textbf{round=1015}, after which SNs started to die slowly and gradually. Finally, all the energies of all the SNs went to Zero at \textbf{Round=1788} which is nearly 1800 rounds. Thus, this improved algorithm provides us better results than LEACH and Direct-Transmission where the energy of the nodes dissipates quicker than in our algorithm.
Figure 4.1: 2-D placement of 25 SNs on the 2m X 2m human body frame
4.1.2 SETUP-2: With 64 Sensor Nodes

As stated by the IEEE 802.15.6 standard for WBANs, we have also incorporated 64 SNs into our WBAN model to check performance of the network. Figure- 4.8 shows us the plots of the SNs in our model. The coordinates of the points are randomly chosen. The network lifetime of this simulated setup of WBAN is similar to the previous setup in which 25 SNs were placed. The network lifetime of this network is
Figure 4.3: Residual Energy after Round-1
Figure 4.4: Next Round of CHs formed by using Voronoi Tessellations
Figure 4.5: The node that died at Round = 1015
Figure 4.6: Simulation in MATLAB when all the SNs die, i.e., when the energy of all the SNs equals to 0
Figure 4.7: Number of Rounds Vs. SNs. The plot that shows the network lifetime of SETUP-1
shown in the graph 4.9. In the given plot, we see that all the nodes start to die at \textbf{round = 962}. All of them perish at \textbf{Round=1820} as compared to SETUP-1 in the network which only lasted till \textbf{Round=1788}.

Even though the difference is not much, it can be inferred that as the population of the network rises, or as the redundant SNs in the network are increased, the network lifetime also increases.
Figure 4.9: The network lifetime plot of 64 Sensor Nodes for SETUP-2
4.1.3 Performance Metrics for Comparison

We have compared our algorithm with LEACH and Direct Transmission routing protocol which are the most common protocols used today. In One-Hop transmission, all the SNs directly transmit to the Coordinator. There is no relaying of information through any other nodes in between. The graph 4.10 gives us an idea of the lifetime of a network that incorporates One-Hop protocol. Figure- shows that all the nodes die by the time they reach the 1000th round. Low Energy Adaptive Clustering Hierarchy:LEACH on the other hand, is a Cluster based routing protocol that randomizes the rotation of CHs for every round based on their energy and previous CH selection to give a fair chance to all the SNs in the CH election. Even though LEACH does achieve reduction in energy dissipation and extends the lifetime of the network considerably, it does not meet up to the lifespan of our algorithm. Figure- 4.11 gives us a graph of Rounds Vs Alive node using LEACH clustering Algorithm. From the graph, we can deduce that the network may approximately last up to 1300 rounds which is comparatively lower than what our algorithm offers.

4.2 Clustering Simulations in 3-D

This is a fairly new concept. From our Literature Survey, we know that Voronoi based clustering in 3-D has not been done before and we have introduced 3-D based Voronoi Clustering in WBAN for the following reasons: firstly, WBANs provide the freedom of movement for the patient. It gives a patient the freedom to move around in a 3-D space. Moreover, the sensors that are placed inside the human body for instance, Retina-implants, knee-implants, Kidney monitoring sensors [1], some of the cancer detecting sensors etc., go considerably deep into the z-axis. We have
approximately considered the depth of these sensors on the human frame in 3-D and performed our simulations for standing and sitting positions to start with. This work can be extended to simple slow movements as well.

4.2.1 SETUP-3: 25 Sensors placed in a standing position

We have 3 axis in a 3-D WBAN network. The X-axis and Y-axis represent the frontal plane and the Saggital plane respectively. The Z-axis refers to the transversal plane as shown in Figure- 4.14 and we have considered the depth of a person to be the Z-axis which is limited to 30cm for an average person.
Figure 4.11: The network lifetime graph of Rounds Vs. Number of Alive Nodes for the conventional LEACH protocol.
Algorithm Steps

- The sensors are plotted using MATLAB. Refer Figure- 4.15a and Figure- 4.17b for the position of sensors from different angles.

- Convex Hull is drawn and the Delaunay Triangles are formed out of the coordinates provided. See Figure- 4.12, it shows the delaunay triangles formed on the coordinates of the SNs. Each triangle is represented by a color.

- Voronoi tessellations or polyhedrons are connected from the bisectors of the delaunay triangles formed. Refer Figure- 4.13. In this Figure-, we see that the Voronoi polyhedrons are formed out of the CHs elected in Round 1.

- After the clusters are formed, data aggregation takes place by every CH. Subsequently, the aggregated data is sent to the Coordinator for further processing.

- Now, similar to the 2-D algorithm, Residual energy is calculated for every SN, and a new set of CHs are chosen for the next round.

- This process is repeated until all the nodes die.

We have simulated two such human body postures namely, standing and sitting.

Standing Model of WBAN

Figure- 4.15a shows the sensors plotted in the 3-D plane. The network lifetime of this model is shown in Figure- 4.16.
Figure 4.12: The delaunay Triangulation formed on the data points of the SNs given in 3-D

Sitting Model of WBAN

Figure- 4.17b shows the SNs of a human frame in the sitting position plotted in the 3-D plane. The network lifetime of this model is shown in Figure- 4.18. All the nodes die at Round=1819.

Thus it can be concluded that the lifetime of the network in the sitting posture is slightly longer due to the fact that the SNs are closer together because of the crunching of the lower abdomen. As the lifetime of the network has not drastically changed over 2-D and 3-D models, the consistency of the algorithm is proved.
Figure 4.13: The Voronoi tessellations formed over the initial set of CHs
Figure 4.14: Three planes of motion for a Human body [41]
(a) Deployment of SNs in a 3-D model  
(b) Deployment of sensors from view of the Y-axis

Figure 4.15: Plotting of the coordinates in standing posture (3-D) from two different angles

Figure 4.16: The network lifetime graph of Rounds Vs. Number of Alive Nodes for a 3-D human model of the WBAN
Figure 4.17: Plotting of the coordinates in sitting posture 3-D from two different angles

Figure 4.18: The network lifetime graph of Rounds Vs. Number of Alive Nodes for a sitting human model of the WBAN in 3-D
Chapter 5: Conclusion & Future work

We conducted an analysis using LEACH on WBAN and proposed an improved and a simpler geometrical based clustering algorithm applicable to WBAN. We utilized few geometrical concepts namely Convex Hull, Delaunay Triangulations, Voronoi Tessellations and by using these concepts we have written an algorithm that could cluster data points on the human body to effectively get sensed data packets and transmit it across the Coordinator. In 2-D networks, we found that the average lifetime of the network comes up to 1700 - 1800 rounds depending on the number of sensors contained in WBAN. We infer from our experiments that the more the number of redundant SNs in a network, there is an increase in the lifetime of the network as well. In 3-D models, we have noticed not much of a change in the lifetime as compared to 2-D models however, they fare slightly better in terms of network lifetime as compared to their 2-D counterparts. Weighed against LEACH and Direct or One-Hop transmission, our algorithm performs 1.3 times better than LEACH and 1.8 times better than Direct transmission protocol. In conclusion, our improved algorithm reduces energy consumption and prolongs effective lifetime of the entire network better than conventional protocols like LEACH and One-Hop Transmission.
Table 5.1: Number of Alive nodes Vs Rounds for all three protocols

<table>
<thead>
<tr>
<th>Rounds</th>
<th>0</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>1800</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Transmission</td>
<td>25</td>
<td>24</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LEACH</td>
<td>25</td>
<td>25</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Voronoi - LEACH</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>18</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

5.1 Future Work

Though we have obtained encouraging results and tested for both 2D and 3D data points, there are a lot of open areas where the work can be extended.

- We simulated our work in MATLAB, to take it one step ahead, the same work can be replicated in a test bed to acquire results from an actual system.

- We can increase the network size beyond 64 sensors.

- We can possibly use TDMA scheduling protocol throughout the network. The primary reason being, CSMA wastes energy in an energy-constrained network. This also prevents collisions of data packets, little overhead at higher efficiency.

- We could utilize TDMA or contention-free protocols, sensors can save energy by turning off their transmitters and receivers during their time slots.

- We have observed that our algorithm works well for basic slow movements of the body such as standing, sitting, etc. The algorithm may be extrapolated for fast movement such as walking, running and different movements of the body in a fast pace by tweaking the clustering algorithm to check for continuous changes of the position of the SN in the network.
• Different type of data aggregation methods can reduce the size of the data packet, thereby reducing the energy dissipation of the CHs.
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