MASTER

Energy efficient topology formation for Bluetooth mesh networks using heterogeneous devices

Agnihotri, M.K.

Award date:
2015

Awarding institution:
Royal Institute of Technology

Link to publication
Energy efficient topology formation for Bluetooth mesh networks using heterogeneous devices

MOHIT KUMAR AGNIHOTRI

Master’s Degree Project
Stockholm, Sweden August 2015
Master Thesis

Energy efficient topology formation for Bluetooth mesh networks using heterogeneous devices

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Abstract

Internet of things (IoT) is the latest trend in our living spaces allowing machine to machine (M2M) communications at the extensive scale. To enable massive M2M communication and portable devices to run on limited power supplies for the extended duration of time, low-cost energy efficient wireless technologies are needed. Among the many competing technologies including Wi-Fi, Bluetooth has shown the potential to be one of the strong candidates to act as the connectivity solution for the IoT especially after the introduction of Bluetooth Low Energy (BLE). Nowadays BLE is one of the biggest players in the market of short-range wireless technologies. By 2020, nearly 30 billion BLE devices in the form of mobile phones, tablets, sports utilities, sensors, security systems and health monitors are expected to be shipped. This proliferation of low-cost devices may for the first time actualize the vision of IoT.

This thesis studies various mesh topology formation techniques that can be used to aid the development of large-scale networks in capillary networks focusing on BLE. In particular, the thesis focuses on how mesh networks can be established over BLE communications especially exploiting the heterogeneous characteristics of the devices. A novel algorithm is proposed called Topology Formation considering Role Suitability (TFRS) to maximize the network lifetime. The algorithm uses a newly introduced metric called role suitability metric (RSM) to assign the best role among master, relay and slave to a device. The RSM metric bases its decision on various device characteristics including, but not limited to, energy, mobility, and computational capability. We use the system-level simulation to evaluate the performance of the proposed algorithm against a reference under homogeneous deployment scenario consisting of heterogeneous devices.

Results show that the network lifetime can be improved significantly when the topology is formed considering the device characteristics for both master role selection and relay selection. TFRS can achieve moderate improvements ranging from 20% to 40% varying on the deployment characteristics over the reference case.
Acknowledgements

I would like to first thank my advisors, Cicek Cavdar, Francesco Militano and Roman Chirikov, and acknowledge the guidance, encouragement, knowledge, support, patience, and assistance imparted to me over last six months. Your efforts helped me to harness the raw skills and tools I brought into this experience and accomplish what I would not have otherwise been able to do.

I would also like to thank members of the WAN team, especially Yngve Selén, for providing an environment in which I felt welcomed and have been able to work side by side with such a talented research team.

I would like to thank my fellow students and friends for the technical help and moral support they offered me. In particular, I wish to thank, Anita Sajwan, Bhanu Teja Kotte, Biniam Gebregergs, Joanna Alexander, and Pratheeksha Ml.

Finally, I would like to thank my family. Dad and Mom, you have always encouraged me to expand my horizons and expressed confidence in me even when I felt it was unwarranted.
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### Acronyms

**AODV**  Ad hoc On-Demand Distance Vector. 28  

**BLE**  Bluetooth Low Energy. x, xiii, xv, 3, 6, 7, 18, 36, 38, 51–55, 87  

**BR**  Basic Rate. 11–15  

**BSF**  Bluetooth Scatternet Formation. 23, 35, 37, 39, 72  

**BSF-UED**  Bluetooth Scatternet Formation (BSF) with Unnecessary-Edges Deletion. 37  

**BTCP**  Bluetooth Topology Construction Protocol. 23  

**CDMA**  Code Division Multiple Access. 22  

**CH**  cluster head. 20, 22, 29  

**DSDV**  Destination-sequenced Distance-Vector. 28  

**DSR**  Dynamic Source Routing. 28  

**DWEHC**  Distributed Weight-based Energy-Efficient Hierarchical Clustering. 22  

**EDR**  Enhanced Data Rate. 11–15  

**FDMA**  Frequency Division Multiple Access. 14, 15  

**FHSS**  Frequency hopping spread spectrum. 14  

**HCI**  Host Controller Interface. 12  

**HEED**  Hybrid Energy Efficient Distributed. 22  

**IoT**  Internet of Things. 71  

**ISM**  Industrial, Scientific and Medical. 11, 12, 14  

**L2CAP**  Logical Link Control and Adaptation Protocol. 11  

**LE**  Low Energy. 11, 12, 14  

**LEACH**  Low Energy Adaptive Clustering Hierarchy. 20, 22  

**M2M**  Machine-to-Machine. 3, 4  

**MAC**  Media Access Control. 12
mAh  Milliampere-hour. 61, 62

OLSR  Optimized Link State Routing. 28

PAL  Protocol Adaptation Layer. 12

PHY  Physical. 12, 13, 15

QoS  Quality of Service. 4

RF  Radio Frequency. 13

RSM  role suitability metric. 35, 36, 40

Rx  Reception. 55

TDD  Time-Division Duplex. 14

TDMA  Time Division Multiple Access. 14, 15, 22

TFRS  Topology Formation considering Role Suitability. x, xiii–xv, 37, 40, 43, 46, 49, 63, 64, 67, 72, 85, 86

TORA  Temporally Ordered Routing Algorithm. 28

Tx  Transmission. 55

TxRx  Transmission/Reception. 53, 62

WCA  Weighted Clustering Algorithm. 22

WSN  wireless sensor networks. 3, 6, 20, 22, 29

ZRP  Zone Routing Protocol. 29
Chapter 1

Introduction

The Machine-to-Machine (M2M) communication implies the ability of machines to communicate without human intervention [1][2]. Lack of interaction places stringent requirement as there is no control during data communication and minimal servicing of the system at large, such as changing batteries. With emerging applications such as smart homes, smart cities, M2M traffic has seen an exponential increase in last few years. The M2M devices such as automatic meter readers are characterized by very low data rates, small data packets, and low mobility requirements but are expected to outnumber voice and data terminals significantly in the coming years. Allowing smoother transition, ETSIs (European Telecommunication Standards Institute) M2M Technical Committee has proposed a hybrid architecture whereby cellular-enabled gateways (GW) act as traffic aggregation and protocol translation points for their capillary networks. Capillary networks, in turn, are composed of a potentially high number of devices (e.g. sensors) equipped with short-range radio interfaces, such as IEEE 802.11, Bluetooth, ZigBee, etc. [3]. With a huge number of machines, efficient communication becomes a great challenge. Many techniques and protocols inspired from the existing work in the field of wireless sensor networks (WSN) have been investigated to improve energy efficiency in M2M capillary networks, such as resource management, data aggregation and clustering [4] [5]. This study focuses on the problem of topology formation and clustering in capillary networks maximizing network lifetime considering BLE as the connectivity technology between devices. This chapter introduces the area, the motivation of the work, research questions and contribution of the thesis.

1.1 Capillary Network - A Viable Option

The capillary network constitutes a multitude of communication methods where the main objective is to reduce the overhead on the core infrastructure and promote spectrum reuse or use of alternate spectrum. The capillary networks are specifically preferred for M2M type communication as they provide an efficient paradigm for connecting a large number of devices employing short-range communication technology. It enables the aggregation of non-3GPP technologies like Bluetooth, Wi-Fi, ZigBee, etc. allowing spectral reuse. A capillary network may comprise of homogeneous or heterogeneous devices, each using one or more short-range communication technology employing single or multiple hops for data communications. These networks are being considered as a prospective option for connecting the various devices in proximity. The figure 1.1 provides a bird-eye view of a possible capillary network architecture.

1.1.1 Unique Challenges for Capillary Network

The capillary networks must adhere to the requirements of reliability, latency and connectivity imposed by innovative use-cases outlined for the fifth generation of communication infrastructure [6]. Meeting these requirements especially in capillary networks is difficult owing to the atypical nature of devices.
It is envisioned that capillary networks would be used to enable M2M communication for the sensor type devices. These devices are characterized by limited power, compute and memory resources. Under these added constraints, the operational characteristic of the underlying short range radio technology used to enable the capillary network become critical to meet architectural needs. The technology must be able to minimize the delay, maximize networks operational lifetime while meeting the Quality of Service (QOS) requirements.

Irrespective of the enabling technology, the two aspects of which play a decisive role in delivering aforementioned requirements are: 1) How are the devices connected? Moreover, 2) How is the data transmitted over the multi-hop architecture? These can be classified as topology formation and routing aspects of the technology.

![End-to-end architecture for capillary networks](image)

**Figure 1.1:** End-to-end architecture for capillary networks [7]

### 1.2 Motivation

It is evident that the number of devices is growing, and user requirements are getting stringent. In order fulfil increasing demand, multiple technological solutions using Bluetooth, ZigBee, Wi-Fi etc. as the technology, have been proposed to solve connectivity and data aggregation and routing problems [8][9][10], each with idiosyncratic pros and cons. The viability of the proposed solutions depends on multiple factors including financial and technological.

A solution that is both technically feasible i.e. best in the performance and has a robust business case especially in terms of cost is most likely to dominate among many proposed solutions. An attempt has been made to understand the challenges considering the business case, along the technical limitations of the proposed solution(s) allowing us to better the technology and strengthen the business case.

**The Business Prospective:** the capillary networks poses new challenges to the service provider when compared to the conventional cellular network. It mostly due to the sheer number of devices, exceeding the elements in the current network by several orders of magnitude. While the number has been growing, a provider is still required to perform the three core functions i.e. deployment, management and maintenance of the network nodes.

On the other hand, the telecommunication industry has been witnessing negative trends in revenue. The gap between traffic carried by the network and the associated revenue is increasing[11]
(fig 1.2). This is an increasing concern as operators have indicated that continuing trend could threaten their ability to invest in essential capacity to provide next-generation communication services [12].

These challenges require innovative methods to simplify and reduce the associated cost for deployment, management and maintenance. Multiple solutions have been proposed to minimize the complexity of the network management aspects. It is recommended not to consider the nodes in a capillary network as individual nodes but economy of scale can be achieved by handling them in groups that use policies and managed parameters that are more abstract and also fewer in number [7]. Given the devices in the network are energy constrained, it is highly desired to increase the operational lifetime of the network. It would result in cost-efficient operation owing to replacing sensor batteries less frequently and reduced associated personal cost.

The Technical Prospective: among the various competing technologies for enabling capillary networks, BLE is one of the prime candidates to be a favoured technology. The inclination is driven by the wide acceptance of the technology, low cost and recent development in energy efficient operation enabling extended period of operation on a coin cell battery. The latest developments give it an edge, but the inherent design of the Bluetooth creates few challenges that must be overcome before BLE can be truly favoured.

The limitation arises from the Bluetooth communication topology that allows only direct i.e. single hop communication between a master and slave device. There is no direct communication between two slave devices. This means that although there is no theoretical limit to the number of Bluetooth devices that share a master, there is a limit to the number of these devices that can be actively involved in exchanging data with the master[14]. This limits communication capabilities in a star-like topology with the master at the centre.

The Bluetooth supports the possibility of having multiple masters for a slave device, thereby making it a relay. Using relay type functionality require a certain degree of topology creation and routing over it but the Bluetooth core specification denies any possibility of assuming these services from the Bluetooth protocol stack. As per the specification "Involvement in multiple networks (scatternet) does not necessarily imply any network routing capability or function in the Bluetooth device. The Bluetooth core protocols do not, and are not intended to offer such functionality, which is the responsibility of higher level protocols and is outside the scope of the Bluetooth core specifica-
In order to meet the requirements for increased network lifetime and the limitations of the Bluetooth technology, it is necessary to formulate efficient algorithms for topology creation and routing in order to achieve efficient multi-hop communication between the devices. The research community has extensively focused on developing algorithms for the efficient topology creation especially in the field of WSN while last decade has seen an increase in interest for Bluetooth based topology formation algorithms.

1.3 Scenario

The current study considers the home or office automation are the primary scenarios extending the vision of smart cities. It is also motivated by real-life use-cases and the undergoing work in Bluetooth SIG (mesh). The scenario is characterized by the homogeneous deployment of heterogeneous devices in an office or home space. These devices are categorised depending on the nature of energy supply i.e. connected, rechargeable and coin-cell battery. Example of such devices can be washing machine, mobile phone, temperature sensors, etc.

These devices are assumed to be homogeneously distributed since, in an office or home environment, most of the resources are planned to be easily accessible, for example, printers or coffee machines in a large office space. Also, owing to the symmetry in building design, sensors like temperature or pressure or security are also homogeneously distributed.

1.4 Research Question

The broad goals of the thesis can be further broken down into simpler, focused and quantifiable research questions.

The first question aims to identify the limiting characteristics or assumptions of the existing topology formation algorithms which impact the operations lifetime of the network. This question can be formulated as

“Q1: What are the limiting characteristics or assumptions of Bluetooth based topology formation algorithms for a deployment of heterogeneous devices?”

The second research question aims to uncover the prospective gain in the network’s operational lifetime by exploiting the heterogeneous nature of the devices.

“Q2: How much improvement in the network lifetime can be achieved for BLE mesh networks by exploiting heterogeneous device characteristics during topology formation?”

1.5 Solution Approach

The master thesis focuses on analysing the various factors which impact the operational lifetime of the capillary network using Bluetooth as the enabling technology and to develop a topology formation algorithm considering heterogeneous device characteristics to maximize the network lifetime as shown in table 1.1. The devices in the network are deemed to be heterogeneous, each having separate energy, compute and memory profile. The topology creation algorithms are reviewed to identify the current gaps and propose new algorithms or extensions to improve the network lifetime. For the scope of master thesis,
devices are characterised into following categories as given in table 1.1.

<table>
<thead>
<tr>
<th>Device characteristic</th>
<th>Possible values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compute</td>
<td>High, Appliance, Sensor</td>
</tr>
<tr>
<td>Energy</td>
<td>Connected, Rechargeable battery, Coin cell battery</td>
</tr>
<tr>
<td>Memory</td>
<td>High, Appliance, Sensor</td>
</tr>
</tbody>
</table>

Table 1.1: Device characteristics

1.6 Research Methodology

The current study progressed in multiple phases: 1) background and literature survey, 2) system design, 3) algorithm implementation, 4) simulation and 5) result and analysis phase.

The background study phase is aimed to understand the details of the Bluetooth technology and related work in the field of topology formation. System design phase conceptualizes the detailed software architecture for the simulation environment which is used for comparative analysis of the proposed algorithm. In the final phase, data collected from the simulation are analysed to derive a conclusion. The figure 1.3 presents the step-by-step process followed in the study.

1.7 Outline of the Thesis Contributions

The thesis and its contributions to the mesh networking using Bluetooth are structured in three parts.

- The first part presents the background related to the Bluetooth technology, network lifetime and an extensive survey of the topology formation algorithms presenting the limitations and various assumptions which restrict the usage of the algorithms to specific cases. The review also provides insight into various shortcoming of the algorithms considering the heterogeneous nodes in a deployment.

- The second part presents the proposed topology formation algorithm with the role suitability. A detailed description of the algorithm, its limitations, and experimental setup is presented, allowing reproducibility and repeatability of the experiments.

- Finally the third part, presents the performance of the proposed algorithm compared to the reference. It is shown that network lifetime can be significantly increased by considering heterogeneous characteristics of devices during the topology formation.
Figure 1.3: Research methodology followed in the study
Chapter 2

Background Study

The chapter aims to provide a brief introduction of the Bluetooth technology, outlining the concepts and ideas relevant to the work. These concepts are further elaborated to gain an understanding of the operational structure and the perceived limitations of the technology. The reader is encouraged to visit [14] for the detailed descriptions of the Bluetooth fundamentals as the presented text provides very basic understanding and re-uses text and examples from the standard [14]. The section 2.2 introduces the network lifetime and the adopted definition for the work. Section 2.4 introduces existing work in the area of topology formation and later section 2.5 broadly introduces the routing techniques and the preferred methodology for the work. Finally the section 2.6 outlines the identified limitation and the defines the focus of the work.

2.1 Bluetooth Technology Review

Bluetooth is a short-range communication technology aiming to replace wires over small distances. It operates in 2.4 GHz range which is reserved for Industrial, Scientific and Medical (ISM) use. This free-rent policy allows endless technologies to operate in the spectrum, few to mention are Wi-Fi, ZigBee, microwave, etc. creating interference and requiring Bluetooth to be robust along with low power and low cost.

There are two types of Bluetooth devices: Basic Rate (BR) and Low Energy (LE). These devices include basic functionalities to perform device discovery, connection establishment and connection mechanism. These functionalities enable a Bluetooth device to detect neighbouring devices, connect and transfer data among them. The BR device may optionally have support for the Enhanced Data Rate (EDR), enabling faster data communication between the devices. A Bluetooth system is split into two logical entities, namely, host and controller.

Host: it is defined as a group of protocols for control and data multiplexing. It comprises of Logical Link Control and Adaptation Protocol (L2CAP) which is primarily responsible for multiplexing and de-multiplexing. Also, security and profiles are defined here enabling and dictating access to reusable device resources. It is possible to split the host application, the host, and the controller physically.

Controller: it is the radio module responsible for the reception and the transmission of packets. The Bluetooth specification [14] dictates that a Bluetooth device can have one primary and multiple secondary controllers. The primary controller is comprised of exactly one of BR/EDR or LE or combined BR/EDR and LE as the primary controller. In addition, there can be multiple secondary controllers including an 802.11 Protocol Adaptation Layer (PAL), 802.11 Media Access Control (MAC) and Physical (PHY), and optionally Host Controller Interface (HCI). Various possible valid combinations of Bluetooth host and controller are represented in figure 2.1.
2.1.1 Physical Layer Operation

Bluetooth operates in ISM band. Depending on the controller i.e. BR/EDR or LE, a device may use 80 or 40 channels spaced at 1 MHz or 2 MHz. The first channel starts at 2042 MHz and continues up to 2480 MHz. The lowest architectural layer in the Bluetooth system is the physical channel. A number of types of physical channels are defined which are characterized by the combination of a pseudo-random frequency hopping sequence, the specific slot timing of the transmissions, the access code and packet header encoding. These aspects, together with the range of the transmitters, define the signature of the physical channel.

Two devices that wish to communicate use a shared physical channel for this communication. To achieve this, their transceivers must be tuned to the same Radio Frequency (RF) at the same time, and they must be within a nominal range of each other. Given that the number of RF carriers is limited and that many Bluetooth devices could be operating independently within the same spatial and temporal area there is a strong likelihood of two independent Bluetooth devices having their transceivers tuned to the same RF carrier, resulting in a physical channel collision. To mitigate the unwanted effects of the collisions each transmission on a physical channel starts with an access code that is used as a correlation code by devices tuned to the physical channel. The access code is a property of the channel and is always present at the start of every transmitted packet.

Five Bluetooth physical channels are defined. Each is optimized and used for a different purpose.

- Basic and Adapted piconet channel: they are used for communication between connected devices and are associated with a specific piconet.
- Inquiry scan channel: it is used for discovering Bluetooth devices.
• Page scan channel: it is used for connecting Bluetooth devices.

• Synchronization scan channel: it is used by devices to obtain timing and frequency information about the Connectionless Slave Broadcast physical link or to recover the current piconet clock.

A Bluetooth device can only use one of these physical channels at any given time. To support multiple concurrent operations, the device uses time-division multiplexing between the channels. In this way, a Bluetooth device can appear to operate simultaneously in several piconets, as well as to be discoverable and connectable.

The Bluetooth system provides a point-to-point (figure 2.2(a)) or a point-to-multipoint connection (figure 2.2(b)). One Bluetooth device acts as the master of the piconet, whereas the other device(s) act as a slave(s). Piconets that have common devices are called scatternet (figure 2.2(c)). Each piconet has a single master. However, slaves can participate in different piconets on a time-division multiplex basis. Also, a master in one piconet can be a slave in other piconets.

![Diagram of Piconets](image)

Figure 2.2: Piconet with a single slave operation (a) a multi-slave operation (b) and a scatternet operation (c)[14]

### 2.1.2 Bluetooth BR/EDR Operation

The BR / EDR radio PHY uses a shaped, binary frequency modulation to minimize transceiver complexity. During typical operation, a physical radio channel is shared by a group of devices that are synchronized to a common clock and frequency hopping pattern. One device provides the synchronization reference and is known as the master. All other devices synchronized to a master's clock and frequency hopping pattern are known as slaves. A group of devices synchronized in this fashion forms a piconet. This is the fundamental form of communication in the Bluetooth BR/EDR wireless technology.

Devices in a piconet use a specific frequency hopping pattern, which is algorithmically determined by certain fields in the Bluetooth address and clock of the master. The basic hopping pattern is a pseudo-random ordering of the 79 frequencies, separated by 1 MHz, in the ISM band. The hopping pattern can be adapted to exclude a portion of the frequencies that are used by interfering devices. The adaptive hopping technique improves co-existence with static (non-hopping) ISM systems when they are co-located. Frequency hopping takes place between the transmission or reception of packets. Bluetooth technology provides the effect of full duplex transmission through the use of a Time-Division Duplex (TDD) scheme.

Typically within a physical channel, a link is formed between a master device and slave devices. Exceptions to this include inquiry and page scan physical channels, which have no associated physical link. The link provides bi-directional packet transport between the master and slave devices, except in the case
of a connectionless slave broadcast physical link. In that case, the link provides a unidirectional packet transport from the master to a potentially unlimited number of slaves. Since a physical channel could include multiple slave devices, there are restrictions on which devices may form a physical link. There is a link between each slave and the master. The physical links are not formed directly between the slaves in a piconet.

2.1.3 Bluetooth LE Operation

The LE system employs a frequency hopping transceiver to combat interference and fading and provides many Frequency Hopping Spread Spectrum (FHSS) carriers. The radio operation uses a shaped, binary frequency modulation to minimize transceiver complexity. It employs two multiple access schemes: Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). Forty (40) physical channels, separated by 2 MHz, are used in the FDMA scheme. Three (3) are used as advertising channels, and 37 are used as data channels. A TDMA based polling scheme is used in which one device transmits a packet at a predetermined time, and a corresponding device responds with a packet after a predetermined interval. The physical channel is sub-divided into time units known as events. Data is transmitted between LE devices in packets that are positioned at events.

There are two types of events: Advertising and Connection events. Devices that transmit advertising packets on the advertising PHY channels are referred to as advertisers. Devices that receive advertising packets on the advertising channels without the intention to connect are called scanners. Transmissions on the advertising PHY channels occur in advertising events. At the start of each advertising event, the advertiser sends an advertising packet corresponding to the advertising event type. Depending on the kind of advertising packet, the scanner may make a request to the advertiser. LE devices may fulfil the entire communication in the case of unidirectional or broadcast type between two or more devices using advertising events.

They may also use advertising events to establish pair-wise bidirectional communication between two or more devices using data channels. Devices that need to form a connection to another device listen for connectable advertising packets. Such devices are referred to as initiators. If the advertiser is using a connectable advertising event, an initiator may make a connection request using the same advertising PHY channel on which it received the connectable advertising packet. The advertising event is ended, and connection events begin if the advertiser receives and accepts the request for a connection be initiated. Once a connection is established, the initiator becomes the master device in what is referred to as a piconet, and the advertising device becomes the slave device. Connection events are used to send data packets between the master and slave devices. Within a connection event, the master and slave alternate sending data packets using the same data PHY channel. The master initiates the beginning of each connection event and can end each connection event at any time [14].

2.1.4 Bluetooth Topology

2.1.4.1 BR/EDR Topology

Anytime a link is created using the BR/EDR controller it is within the context of a piconet. A piconet consists of two or more devices that occupy the same BR/EDR physical channel. The terms master and slave are only used when describing these roles in a piconet.

A number of independent piconets may exist nearby. Each piconet has a different physical channel (that is a different master device and an independent timing and hopping sequence). A Bluetooth device may participate concurrently in two or more piconets. It does this on a time-division multiplexing basis.
2.2. NETWORK LIFETIME

A Bluetooth device can never be a master of more than one piconet. (Since in BR/EDR the piconet is defined by synchronization to the master's Bluetooth clock it is impossible to be the master of two or more piconets.) A Bluetooth device may be a slave in many independent piconets. A Bluetooth device that is a member of two or more piconets is said to be involved in a scatternet. Involvement in a scatternet does not necessarily imply any network routing capability or function in the Bluetooth device.

![Bluetooth BR/EDR topology](image)

Figure 2.3: Bluetooth BR/EDR topology[14]

In Figure 2.3 an example topology is shown that demonstrates a number of the architectural features described below. Device A is a master in a piconet (represented by the shaded area) with devices B, C, D and E as slaves. Three other piconets are shown: a) one piconet with device F as master and devices E, G and H as slaves, b) one piconet with device D as master and device J as slave, and c) one piconet with device M as master and device E as a slave and many devices N as slaves.

2.1.4.2 LE Topology

In Figure 2.4 an example topology is shown that demonstrates a number of the LE architectural features. Device A is a master in a piconet (represented by the shaded area) with devices B and C as slaves. Unlike BR/EDR slaves, LE slaves do not share a common physical channel with the master. Each slave communicates on a separate physical channel with the master. One other piconet is shown with device F as master and device G as a slave. Device K is in a scatternet. Device K is master of device L, and slave of device M. Device O is also in a scatternet. Device O is the slave of device P and the slave of device Q.

2.2 Network Lifetime

The lifetime for a battery-powered device can be defined as the duration of time for which it can operate before degrading its battery to a point where it can’t perform basic functionalities. The definition can be extended to a network, where the network’s lifetime is dependent on the devices participating in the network and can be defined as the duration of time during which the network can provide the expected functionality to the participating devices. It is very closely linked to the devices in the network and their energy characteristic like energy source type and dissipation rate.

In the literature, there are numerous articles which address the problem of network lifetime in the context of the topic being addressed and propose various methods to estimate it. These definitions are
analysed in the purview of the current work and most suitable is chosen as the preferred method of lifetime calculation in current work.

- Single failure: the network lifetime is defined as the duration of the time until the first device in the network fails. For a given topology with $N$ device and $T_n$ as lifetime of a device, it can be given as:

$$\text{Lifetime} = \min_{n \in N} T_n$$ (2.1)

The definition was used in the work [15] with slight modification where the sink node was excluded to indicate an infinite power supply. The metric suffers from the limitation that it is very basic and doesn't consider the cases where due to the network redundancy, required functionality is still available. The metric can only be successfully used if the network considers all nodes with equal importance and are critical to delivering the necessary functionality [16].

- m-of-n failures: the definition extends the first device failure to incorporate for the possible redundancies in the network. It defines the lifetime as the duration of time before $m$ devices in the network runs out of energy.

The definition is better considering the single failure, but it lacks accuracy as pointed out by Dietrich and Dressler. Consider the case when $m' < m$ nodes at strategic positions (perhaps around the base station) fail and the remaining nodes now have no possibility of transmitting any data to the sink. Then the network should not be considered alive, but the metric does not recognize this until another $m - m'$ nodes have failed [16].

- Clustered m-of-n failures: it was first introduced by Hellman and Colagrosso in [17]. The nodes are divided into two groups namely critical and non-critical based upon the role they play in the network operations. The definition allows for $k$ out of $m$ failures in the non-critical and no failure in the critical category. This definition improves on the aspect of treating all devices equally but still has limitation discussed for “m-of-n failures”.

The current work focuses on heterogeneous devices forming a fully connected mesh network and usage of Bluetooth as the technology allows easy classification of the device into critical and non-critical.
2.2. NETWORK LIFETIME

With these assumptions, "clustered m-of-n failures" is the best-suited method for estimating network lifetime. The devices acting as "Master" and "Relay" are classified as critical, and all the slaves are non-critical devices. In the adopted definition, it is allowed to have "$K$ of $K$" failure in the non-critical cluster, while "0 of $M$" are allowed in the critical cluster. The first failure in the critical cluster defines the lifetime of the network.

For a network with $N$ devices, $M$ critical and $K$ non-critical, the network lifetime can be given by equation 2.2.

$$
\text{Lifetime} = \min_{m \in M} T_m
$$

(2.2)

2.2.1 Factors Affecting Network Lifetime

Given the definition of the lifetime, it is important to understand the various topological, routing and technology factors which impact the energy dissipation and thereby affecting the network lifetime.

Under the purview of Bluetooth as the technology, it is important to consider following aspects to obtain maximal network lifetime. In the current thesis, we focus on the problem of device role selection while topology adaptation and routing are mentioned for the completeness. We consider heterogeneous devices in the network and aim to use their characteristics to formulate rules for assigning roles to the devices.

1. Device Role Selection: in the BLE scatternet, we have three kinds of devices as earlier outlined i.e. master, relay, and slave. It is recommended to assign these roles based on the device characteristics as master and relay nodes are used to enable inter and intra-piconet communication. Any algorithm which uses device characteristic based metric to assign these roles must be preferred over random role assignment. For example, it is optimal to assign "master" role to a device with maximum energy. The node with second highest energy should be assigned the "relay" role.

   In the figure 2.5, an example of random and characteristics based role selections is provided. The topology as depicted in figure 2.5b must be preferred over 2.5a as it allows a device with the maximum capability to be chosen as a master.

2. Topology Adaptation: as the network become operational, the energy at various nodes is consumed. The master and the relay nodes are worst affected owing to extra responsibility of relaying the traffic. Therefore, it is beneficial to alternate the role of the master and relay among several nodes. Thus, it is important for a topology formation algorithm to have a maintenance phase where options for
suitable master and relays can be periodically evaluated, and role can be switched if deemed necessary.

For example, let us assume two piconets with $M1$ and $M2$ as the master and $R1$, $R2$ and $R3$ as possible relays between them. Initially, all of them have 100% energy, and $R1$ is chosen as the relay. The rate of energy dissipation for a slave is 1 unit/sec and for a relay is 3 unit/sec while all the masters are connected to mains. The resulting topology is presented in figure 2.6. Let’s assume there are two algorithms, one with maintenance phase and one without, the network lifetime can be given by the following graphs in the figure 2.7. It is evident that existence of maintenance phase in the algorithm enhances the network lifetime by switching the nodes in master or relay roles.

3. **Routing Algorithm:** this plays a significant role as all inter-piconet communication must be routed. The routing algorithm generally performs two steps i.e. route discovery and packet forwarding along the discovered route. The methodology utilized to achieve these fundamental operations impact the network lifetime of the network.

### 2.3 Network Residual Energy

This is the measure of the total energy in the network at any point in time. It is calculated by summing over the residual energy of all the nodes in a deployment. The metric can be used to estimate the impact of the routing algorithm on the underlying topology. Failure of the critical device marks the end of the network lifetime, comparison of the residual energy at that instant allows us to determine if a routing hot-spot is responsible for the failure of the critical node or not.

### 2.4 Topology Formation Algorithm(s)

The problem of topology formation has been extensively studied in the field of WSN. A WSN consists of spatially distributed nodes, communicating using wireless methodologies. They are required to operate autonomously without human intervention. Given the sensors have limited resources, it is important to design an algorithm which consider these limiting characteristics.

#### 2.4.1 WSN Topology Formation Algorithm(s)

In WSN, for the efficient data aggregation and network management, nodes are divided into groups called clusters, and the process is termed as clustering. Each cluster has a designated cluster head (CH) which
2.4. TOPOLOGY FORMATION ALGORITHM(S)

Figure 2.7: Network lifetime with and without relay maintenance
handles scheduling activities and communication in the cluster. Following are few of the prominent clustering protocols.

- **Low Energy Adaptive Clustering Hierarchy (LEACH)** [18]: the algorithm aims to distribute the energy consumption evenly across the network. The network is divided into clusters formed by randomly elected CHs. The protocol operates in four distinct phases: 1) advertisement 2) cluster setup 3) schedule creation and 4) data transmission. The energy drain for the cluster head is limited by randomizing the CH.

  The main advantages of the algorithm are: 1) load is equally shared among the cluster heads. 2) Usage of TDMA with Code Division Multiple Access (CDMA) minimizes collisions and interference from nearby clusters. However, there are few disadvantages. 1) load balancing relies only on the probability of election without the consideration of the initial energy of the nodes. 2) Frequent election of CH brings overhead and may diminish the gain in energy consumption. 3) CHs are randomly elected.

- **Hybrid Energy Efficient Distributed (HEED)** [19]: it is a distributed algorithm where cluster heads are elected based on the residual energy and communication cost avoiding random selection of CHs. The algorithm executes in three phases: initialization, repetition, and finalization phase.

  The probability for a node to be elevated to the role of CH if it has the highest energy and minimum inter-piconet communication cost. The algorithm supports the possibility of heterogeneous nodes as it accounts for the initial energy, and it can vary for each node.

  The main advantages of the algorithm are: 1) better load balancing by using multiple parameters for CH election. 2) multi-communication over single hop, allowing energy conservation. However, there are few limitations. 1) Performing of clustering for each round of operation imposes significant overhead. 2) CH near the sink suffer from hot-spot phenomena and tend to die earlier than the rest of the network.

- **Distributed Weight-based Energy-Efficient Hierarchical Clustering (DWEHC)** [20]: the algorithm aims to improve upon the HEED by optimizing the cluster size and intra-cluster topology using location information. The algorithm operates alike HEED, but unlike LEACH and HEED, it creates multi-level topology for intra-cluster communication. The cluster is organised into multiple levels, and child node use either direct or indirect communication involving multiple intermediate nodes to reach the cluster head.

  The algorithm outperforms HEED considering the energy consumption in intra-cluster communication and the clustering process take a definitive amount of time irrespective of network size.

- **Weighted Clustering Algorithm (WCA)** [21]: The algorithm aims to determine a stable topology and re-invoked only if the re-configuration is unavoidable. The algorithm considers several system parameters while deciding the cluster head. Few to mention including, but not limited to, are energy, ideal node degree, transmission power, link capacity, etc. Based upon the application requirements, few or all of these metrics can be used to determine the suitable cluster head.

  The main advantage comes from the flexibility of changing weights associated with the metrics.

### 2.4.2 Bluetooth based Topology Formation Algorithm(s)

Topology formation in Bluetooth can be considered as the subset of the WSN topology formation problem with limitations arising from the technology. The Bluetooth standard allows the creation of scatternets by involving one or more device in more than one network. These interconnected piconets, also known as scatternets form the communication topology as it allows communication over multiple hops. The process can be divided into piconet formation, and interconnection steps and an algorithm which does these is termed as BSF algorithm. These algorithms have been divided into multiple categories based on
the ideology of operation and structure of final scatternet. The algorithms can be divided into following broad categories.

- **Centralized**: these BSF algorithms assume that there is a central node with full visibility of the network. The central node can be a device in the network or a remote server. Salonidis, Bhagwat, Tassiulas, et al. in [22] proposed a BSF formation topology which first collects the neighbour information with an inquiry procedure. Once the data is collected, a coordinator node is chosen and the rest of the node await instruction from the coordinator node.

The algorithm named Bluetooth Topology Construction Protocol (BTCP) [22] assumes that all the devices are within range of each other, and the number of devices in the network is restricted to 36 as the default scheme works for a number of nodes less than or equal to 36. A larger number of nodes may lead to a topology that is not a fully connected scatternet. The algorithm is able to use the sophisticated mathematical tools to optimize the topology for multiple variables due to the existence of a central node and can easily outperform decentralized algorithms. The major weakness of the algorithm lies in the fact that it is non-scalable since it is centralized while it generates fully connected topology and is capable of assigning roles to the devices.

In Lin, Tseng, and Chang in [23] described a ring topology for scatternet structure. A ring is created by piconets connected my slave-salve bridges. Each master is allowed to have slaves outside the bridge. The two main characteristics of the algorithm are: Usage of Bluetooth park mode and centralized operations. These make the algorithm non-scalable and park method introduces relatively long message delays.

- **Single-Hop**: these algorithms assume that all nodes are in radio range of each other and direct communication between all the devices is possible. The assumed structure exhibits the characteristic of a completely connected graph and thereby known graph-topologies can be used to connect the devices.

In [24], Dapurdar proposed used of cube structure in 2 and 3-D for creating scatternet. The author argues that these structures provide higher connectivity, lower diameter, less node contention, multiple paths between any two nodes, inbuilt routing, easy inter-piconet scheduling and the ability to reconfigure for dynamic environments. The algorithm relies on the random inquiry and scan procedures for the role selection.

In [25], Song, Li, Wang, et al. introduced the dbBlue algorithm which used famous De Bruijn graphs to form the backbone. The structure enjoys nice routing property that the diameter of the graph is $O(\log n)$ and we can find a path with at most $O(\log n)$ hops for every pair of nodes without any routing table. Moreover, the network congestion is at most $O(\frac{\log n}{n})$, assuming that a unit of total traffic demand is equally distributed among all pair of nodes. The algorithm is capable to locally update the structure dBBlue using at most $O(\log n)$ communications when a node joins or leaves the network. Similarly to [24], the algorithm assumes the existence of random leader.

The basic drawback of single-hop algorithms is that they assume that every node is in the radio range of the others which is a limiting assumption as it’s scarcely true in reality, thereby restricting the use of these algorithms to very specific scenarios.

- **Tree-based**: These algorithms utilize the fact that a connected graph contains a spanning tree and the algorithms in this category utilize various ways to construct tree-like backbone for the final scatternet. The Spanning tree has been the preferred choice of the many algorithms for implementing the backbone as it guarantees connectivity and additional links can be added to increase robustness.

In [26], Wang, Stojmenovic, and Li proposed a tree-based algorithm which assumes single-hop network. The algorithm does not require knowledge of the device position as it operates on the virtual position selected and communicated by the device during the initiation phase. The algorithm TSF [27] is similar to the first algorithm.
The algorithms start by assuming single node in the tree and during the discovery phase they acquire information about the neighbouring devices. The neighbouring device information coupled with the set of rules is used to build scatternet. Later these scatternet or piconets are merged to obtain the final topology.

Zaruba, Basagni, and Chlamtac in [28] proposed BlueTree algorithm for the multi-hop network lifting the assumption of radio vicinity of the nodes. The algorithm start at the designated root node also referred as "Blue Root". The root captures all of it is neighbours as slaves. The root then assigns it is a slave to act as masters and captures their neighbours. The process is repeated until all the nodes in the network are enslaved. The algorithm suffers from two major drawbacks: 1) No leader selection algorithm 2) The degree of a piconet is not limited to 7. The main advantage of the tree-based algorithm is simplicity of the design, but the tree structure have weak fault-tolerance and high susceptibility for a node to become network bottleneck.

- **Mesh-based:** this category of the algorithms solve the main drawback of the Tree-based algorithm by forming mesh-like structure, thereby adding multiple routes. These algorithms assume that the devices acquire neighbour information during the discovery process. Few of the famous algorithms in the category are BlueStars [29], BlueMesh[30], BlueMIS[31] and BSF-UED[32].

The BlueStars[29] algorithm operates in three phases: 1) Discovery phase 2) Piconet formation and 3) Interconnection of piconet leading to scatternet formation. The discovery phase handles collecting neighbour information in symmetric manner i.e. if \( v \) is informed about \( u \), \( u \) must also know about \( v \). Based upon the information collected in the discovery phase, each node decide the most suitable role for itself i.e. Master or Slave based upon the set of rules encoded in each node. This phase starts simultaneously at multiple nodes and ends with the formation of scattered piconets. The final phase concerns the selection of gateway devices to connect multiple piconets so that the resulting BlueConstellation is connected. By using the information gathered during the BlueStars formation phase, each master selects some of its slaves to be gateways to neighbouring piconets. The selection of the gateways is performed so that the obtained scatternet is connected. The comparative performance presented showed that due to the simplicity of its operations BlueStars[29] is the fastest protocol for scatternet formation. The main disadvantage of the algorithm is that it produces scatternets with an unbounded, possibly large number of slaves per piconet, which imposes the use of potentially inefficient Bluetooth operations.

The BlueMesh[30] algorithm solved the problem of unbounded piconet by limiting the number of slaves while still guaranteeing the connectivity. Unlike the BlueStars, this algorithm relies on the two-hop information acquired by round device discovery phase. Under the assumption of Unit Disk Graph, if a master has more than seven neighbours, it chooses up to seven slaves among them so that it can reach all the others via the chosen ones. Such coverage is always possible with up to five slaves.

Initially the node \( a \) which has the larger Id among the neighbours starts the procedure and creates a set \( S_p(a) \) which consists of neighbours of \( a \) with lower identifier than \( a \) and larger neighbours of \( a \) that are not masters. Followed by this, \( a \) creates the maximal independent set from \( S_p(a) \), denoted by \( S'(a) \) and it can contain maximum of 5 nodes under the Unit Disk Graph assumption. All the nodes in \( S'(a) \) are slaved by \( a \) and procedure stops. This procedure is repeated at all the nodes who have been contacted by their higher id neighbours but are not selected as slaves. This procedure creates a set of piconets. A pair of piconet is called neighbours if they can be interconnected through a gateway slave or through a pair of intermediate gateways. The algorithm shows weaknesses on the worst-case number of slave roles a node can assume especially considering dense networks.

The BlueMIS[31] algorithm aimed to simplify the scatternet formation procedure in BlueMesh[30] by re-formulating the slave selection problem as the maximal independent set problem, and reduces the process to two iterations. In the first iteration, every node creates a piconet with itself as a master node. In the second iterations, following a clustering based approach, each node estimates
whether or not its piconet is needed for the overall connectivity. If not, it deletes its piconet. In BlueMIS I, each node passes greedily by its neighbours in order from the smallest neighbour to the largest neighbour, with respect to the identifier of nodes. A node \( u \) adds a neighbour \( v \) to \( S(u) \) if \( v \) is not neighbour to any node in \( S(u) \). A node \( v \) in \( S(u) \) is considered as a slave of \( u \) if \( u \) is not in \( S(v) \) or if \( u \) is in \( S(v) \) and the identifier of \( v \) is smaller than that of \( u \). BlueMIS I has \( O(1) \) time complexity i.e. the execution of the algorithm does not depend on the number of nodes. The main disadvantage of BlueMIS I is the large number of piconets (masters) in the formed scatternets. BlueMIS II improves the efficiency of the scatternets by simple rules, but the lack of implementation details leads to different possible implementations. Depending upon the implementation, BlueMIS II either suffers from a long execution time or from piconets with a large number of slaves depending on the implementation used.

The BSF-UED[32] algorithm provides guaranteed connectivity with degree constrained piconet with deterministic execution time. The algorithm operates in two steps: 1) piconet construction 2) piconets interconnection. The piconet construction phase generates a set of disjoint outdegree-limited piconets such that every node is either master or slave in exactly one piconet. All nodes have unique comparable identifiers, and, therefore, some nodes are local maxima. This property is used to initiate a wave-like process whereby larger nodes successively attempt to capture smaller neighbours. Nodes cannot be captured twice nor capture other nodes once they are themselves, slaves. To limit the outdegree, a number of delegation rules are defined by which nodes can control the number of slaves they capture and delegate excesses (if any) to other neighbours. The delegation is feasible under the Unit Disk Graph assumption. The second phase interconnects the disjoint piconets formed in Phase 1 to form the output scatternet. This phase uses the maximal independent set technique as detailed in BlueMIS[31] to connect the piconets. This allows the graph to be connected while additional rules are observed to maintain degree constraint after the formation of scatternet.

The table 2.1 and 2.2 presents the summary of the reviewed algorithms. In the current work, BSF-UED proposed by Jedda, Casteigs, Jourdan, et al. is chosen as the reference algorithm. The algorithm creates topologies that are fully connected, degree constraint in a time bounded fashion. Also, the algorithm introduces the definitive procedure for node delegation, making it a prime choice over the others.

2.5 Routing

The topology formation algorithms provide the basic infrastructure which can be used by the routing algorithms to enable multi-hop communication. These protocols are required to be implemented at the application layer as Bluetooth does not provide them inherently. Numerous routing protocols for ad-hoc and mesh networks have been proposed over the last decade, but most of these were designed for the either fixed networks or Wi-Fi based wireless networks. These protocols have been adapted to be used in the Bluetooth scatternet.

The routing protocols for the ad-hoc network can be classified into following broad categories.

1. Proactive In this category of the routing protocols, each node maintains path information to every other node in the network before the packet transmission. The routing data is usually kept in a table like structure. These tables are periodically updated and/or if the network topology changes. The difference between these protocols exists in the way the routing information is updated, and the type of information kept at each routing table. Examples of these protocol are Optimized Link State Routing (OLSR) [39], Destination-Sequential Distance-Vector (DSDV) [40].

The protocols use "discovery" and "control" messages to gather the network information and then disseminate it throughout the aforementioned network. Each node uses this information to com-
pute next hop destinations for all nodes in the network. Also, periodic flooding of topology data is done to ensure that the database does not remain unsynchronized for extended periods of time. Keeping routes to all destinations up-to-date, even if they are not used, is a disadvantage concerning the usage of bandwidth and network resources. These protocols do not scale in the frequency of topology change. Therefore, the proactive strategy is appropriate for a low mobility network. The behaviour is preferable when low latency is the primary concern and where bandwidth and energy resources permit such behaviour.

2. Reactive This category of protocols seek to set up routes between the pair on-demand after the transmission request arrives. If a node wants to initiate communication with a node to which it has no route, the routing protocol will try to establish such a route. The route remains valid till destination is achieved or until the route is no longer needed. Few of the prominent on-demand routing protocols are: Dynamic Source Routing (DSR) [41], Ad hoc On-Demand Distance Vector (AODV) [42] and Temporally Ordered Routing Algorithm (TORA) [43].

When a transmission is intended, the protocol initiates the probe to discover the route to the requested destination. The protocol may use a special message or flooding to discover the route. This is not optimal in terms of bandwidth utilization, but they scale well in the frequency of topology change. This strategy helps in minimizing the resources used for maintaining unused routes. The reactive protocols perform poorly when subjected to constant bit rate traffic as they need to determine the route for every transmission event, thereby increasing the probability of buffer overflow assuming a finite number of buffers. The reactive protocols can be further classified into Source and Hop-by-Hop routed. In source routed, the source determines the exact path to the destination while all the intermediate node acts as relay forwarding the message on the pre-decided route. In hop-by-hop routing, the message is forwarded to the next best node who is in turn responsible for routing the packet using local routing information.

3. Hybrid These protocols aims to achieve the balance between the reactive and proactive approach.
<table>
<thead>
<tr>
<th>BSF Algorithm</th>
<th>Role Selection Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BlueTREE [28]</td>
<td>Designated Node called Blue root.</td>
</tr>
<tr>
<td>Enhanced BlueTree [33]</td>
<td>Designated Node called Blue root; Also, set of nodes called init nodes which are manually selected, initiate the algorithm.</td>
</tr>
<tr>
<td>TSF [34]</td>
<td>Manually designated root node which initiates the procedure.</td>
</tr>
<tr>
<td>BlueHRT [35]</td>
<td>Manually designated leader which controls the topology creation.</td>
</tr>
<tr>
<td>BlueSTAR [36]</td>
<td>Introduces the metric named 'Weight' which is used to identify the suitability of a device for a role. No specifics for calculation of the metric and its impact on the network is identified.</td>
</tr>
<tr>
<td>SHAPER [37]</td>
<td>No role assignment procedure exist. Rely on Bluetooth procedure for role assignment.</td>
</tr>
<tr>
<td>BlueMIS [31]</td>
<td>Introduces the concept of keys which are used to determine between master and slave roles. No definition or description for the computation of key is provided.</td>
</tr>
<tr>
<td>HMT [38]</td>
<td>Manually designated root node which initiates the procedure.</td>
</tr>
</tbody>
</table>

Table 2.2: Review of device role selection methodologies
These start in a proactive manner where a route table is built, and route information is stored. The routes in the table are marked valid for a certain duration of time, and any transmission after the expiry of validity period requires path discovery like in a reactive protocol. Each time a transmission is done, the validity timer for the route is reset. The Zone Routing Protocol (ZRP) [44] is an example of Hybrid routing.

In the current work, we have chosen to use a proactive protocol for routing the traffic over the generated topology. The reason stems from the fact that the protocols are easy to design and aims to minimize the routing delay. Given the network lifetime metric considers the first critical failure, the routing protocol assumes discovered routes are valid for the entire duration of a lifetime.

2.6 Research Gap(s)

The existing topology formation algorithms formulated for WSN or Bluetooth have unique gaps when considering them for topology formation in the Bluetooth-based network. The key findings are summarized below.

1. WSN algorithms exploit the idea of clustering, but most of them have a random CH selection. All the inter-cluster communication happen directly between the CHs without any gateway node. This type of communication is not preferred in Bluetooth owing to technology limitations.

2. Bluetooth based topology formation algorithm considers the network to comprise of homogeneous nodes, thereby system or device parameters are not utilized for the role assignment in the network.

3. Maintenance phase is absent in all the reviewed algorithm implying that the algorithms are efficient considering a snapshot of the ad-hoc network.

In the current work, we have focused on introducing the role assignment to the devices participating in the network considering the device and system parameters. The idea is motivated by the existing work in WSN but adapted to be used with Bluetooth technology. The introduction of the maintenance phase to maintain optimal topology over time is a candidate for the future work.
Chapter 3

Problem Statement

The current chapter defines the problem of topology formation and routing in Bluetooth based capillary networks. For the simplicity, we present a logical view of the problem, outlining the various parameters assumed to be available as inputs, the objective function and expected output.

3.1 Logical View of Problem

The problem of network lifetime is formulated as the function of the input parameters and set of topology formation algorithm. The input in the form of device position and characteristics is fed to the algorithms, and the output topology is subjected to the traffic, which is routed to estimate the network lifetime and residual energy.

The framework is used to describe the basic process used to perform the comparative analysis of the chosen metric for the reference and proposed algorithm. The framework is defined as a sequential collection of the basic design block, which are triggered by an input and produce an output as a response to the trigger. A design block can have multiple designated input and output ports which are connected to the blocks to form a process. An example of the design block with single input marked in yellow and output port marked in red is depicted in the figure 3.1.

The current framework expects device characteristics and traffic profiles as the basic input parameters. The first phase i.e. topology formation utilizes the characteristics parameter. These are fed to both the reference and the proposed algorithm to generate topologies, later called as the reference and the proposed topology respectively. The second phase i.e. routing uses these generated topologies along with the device traffic profiles as the input. Based upon the source and destination pairs described by the traffic profile, the data is routed, and logs are generated capturing the data packets and device current energy. In the final phase, generated logs are fed to the log processing unit which identifies the first failure of a critical device and determines the effective network lifetime for the topology. A detailed depiction of the process is presented in figure 3.2.

Figure 3.1: Block design for Topology formation and routing framework
3.2 Input Parameters & Explanation

To evaluate the effectiveness of the proposed algorithm, a set of algorithms are designed, each aiming to provide quantitative support for the expected results. The input parameters of the problem are categorized into three broad categories based on their functionality in the proposed algorithm.

1. Algorithmic parameters: these impact the operation of the algorithm like master or gateway selection and have an impact on the final topology generated. In the current study, we have the following algorithmic parameters:

   • Master role selection: this parameter identifies which metric is used for the master role selection in phase 1 of the algorithm. The algorithm as described (refer chapter 4 section 4.2) can use one of the following methods:
     - Reference: masters are selected based on the assigned unique random id.
     - $RSM_E$: masters are chosen depending on the type of energy sources and its relative value (in case of battery type)
     - $RSM_{EN}$: masters are chosen depending on the type of energy sources, its relative value (in case of battery type) and the number of neighbours for a device.

   • Gateway selection: this determines the set of rule(s) followed to select devices to act as a gateway between two piconets. There are three possible set of rule(s) for selecting a device:
     - Reference: the gateways are selected based upon the priority of the interconnect rule followed by the piconet capacity. In case of identical parameters, ties are broken randomly.
     - Reference with energy: the gateways are selected based upon the priority of the interconnect rule followed by the device energy. It is mandated to have piconet capacity $\geq 1$ for the selected device.
     - Energy: the gateways are chosen entirely upon the device energy followed by the interconnect rule.

   • Interconnect prioritization rule: this defines how the interconnects are prioritized. The algorithm can have two different prioritization rules as described below:
     - Reference: in this, 3 hops is preferred over 2 hops and among two hops, master-salve is prioritized over common slave interconnect. Refer chapter 4 section 4.4 for details.
3.3. OBJECTIVE

- Proposed: in this, 2 hops is preferred over 3 hops and among two hops, common slave type is prioritized over master-slave type interconnect. Refer chapter 4 section 4.4.1.2 for details.

2. Device parameters: these impact the scenarios begin evaluated in terms of device characteristics. The parameters are described below:

  - Cartesian coordinates: these determine the location of a device in a 2-D plane. It is chosen randomly from a uniform distribution.
  - Energy characteristics: defines the energy source for a device and is chosen randomly for a device with the constraint of maintaining the device-type density. The allowed values are:
    - Main-connected: the unlimited supply of energy.
    - Rechargeable battery: high capacity replenishable energy source and with a probability for recharging.
    - Coin cell battery: low capacity depletable energy source and without a probability for recharging.
  - Compute characteristics: defines the compute capabilities of a device. The algorithm mandate that coin-cell energy source type device can have only medium or low compute type.
  - Memory characteristics: defines the storage capacity for a device. The algorithm mandate that coin-cell energy source type device can have only medium or low memory capacity.
  - Battery size: it determines the size of the battery for a device in constraints to the energy type a priori assumed.
  - Battery level: it determines the current charge level of the battery.

3.3 Objective

The aim of the proposed algorithm is to maximize network lifetime which is defined in chapter 2 section 2.2.

3.4 Output Parameter

The algorithmic performance of the proposed versus reference algorithm is measured in terms of network lifetime and residual network energy.
Chapter 4

Topology Formation considering Role Suitability (TFRS)

The chapter introduces the proposed topology formation algorithm exploiting the idea of utilizing device characteristics to make an informed decision on the preferred role for a device. This is important in the heterogeneous deployments where not each device has same capabilities in terms of power, compute and memory. It is followed by a description of the chosen reference BSF algorithm outlining the reasons for the choice. Finally, an elaborate description of the algorithm is presented. An algorithm is viewed as a series of steps, called phases which must be performed one after the other to achieve the desired result. Each of these phases is complimented with a detailed analysis of perceived limitations of the current algorithm and methods which could be used to overcome them.

4.1 Role Suitability Metric (RSM)

It has been already pointed out that in a heterogeneous deployment not all devices are same. They can differ in various characteristics, few of them are outlined in table 4.1. The existence of such differentiation implies that certain devices in the network are better suited for a role while other are not. The literature review has already revealed that most of the current state of the art topology formation algorithm either do not consider device characteristic thereby essentially treating network as homogeneous deployment or weakly introduce the notion, but do not define a formal method for the computing role preference for the device. A quick summary of the reviewed algorithms is presented in the table 2.2.

<table>
<thead>
<tr>
<th>Device Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
</tr>
<tr>
<td>Compute capability</td>
</tr>
<tr>
<td>Memory capacity</td>
</tr>
<tr>
<td>Traffic</td>
</tr>
</tbody>
</table>

Table 4.1: Device characteristics

We define a new metric called the "role suitability metric (RSM)" which aims to encapsulate the idiosyncratic feature of a device into a one single numerical value which can be used by the algorithms to assign roles to the devices in a network. Few of the possible, such characteristics and their impact on the preferred role is described in table 4.2, for example, low mobility device is suitable for master role while
<table>
<thead>
<tr>
<th>Device Characteristic</th>
<th>Explanation</th>
<th>Role Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>It identifies the current energy level at the device. The valid range of value can vary between 0-100%</td>
<td>Higher value is more suitable for master, followed by relay/bridge and lastly slave.</td>
</tr>
<tr>
<td>Mobility</td>
<td>It identifies the probability of a device to stay in a given piconet at any instant of time. This is expressed in terms of probability and can vary between 0-1.</td>
<td>Higher mobility is suitable for the slave role followed by relay and master.</td>
</tr>
<tr>
<td>Traffic Class</td>
<td>It is used to identify the generic nature of the traffic generated from the device. It can be classified as half-duplex UL, half-duplex DL and Full-duplex.</td>
<td>It can be used to identify potential load in a piconet and can be used to effectively distribute the load among various possible piconets.</td>
</tr>
<tr>
<td>Power Class</td>
<td>It is used to identify supported power class for a device. The Bluetooth standard currently defines 3 power class i.e. 1, 2 and 3 differentiated by the output power. Device with power class 1 can operate in all the power ranges.</td>
<td>Lower the power class, device is preferred for master role as it can communicate at all power level. The preference is followed by relay and slave.</td>
</tr>
<tr>
<td>Memory</td>
<td>It identifies the memory available at the device.</td>
<td>Higher the memory, master role is preferred, followed by relay and slave.</td>
</tr>
<tr>
<td>Compute Capability</td>
<td>It identifies the processing power available at the device.</td>
<td>Higher the compute ability, master role is preferred, followed by relay and slave.</td>
</tr>
</tbody>
</table>

Table 4.2: Description of device characteristic that can be used to derive role metric

A low energy device is suitable for slave role. The metric is derived as a weighted sum of various characteristics of a device which may be considered relevant for the operation or has an impact on the performance of the network. In a BLE mesh network, this can be used to evaluate the aptness of a node to perform a certain role. The roles are identified as master, relay or slave. The RSM is computed locally for each node and is the weighted sum of device characteristic, including, but not limited to energy, compute power, mobility, etc.

The metric can be generalized for a device having $C \subseteq \{c_1, c_2, \ldots c_n\}$ as a set of $n$ characteristics and each associated with weight $W \subseteq \{w_1, w_2, \ldots w_n\}$. The RSM value for such a device is calculated as a function of these characteristic and associated weights as defined in equation 4.1.

$$RSM = f(C, W)$$

where $f$ is a generic function

(4.1)

For example, considering power, compute, memory and number of neighbours as the device characteristic, denoted by $c_1, c_2, c_3$ and $c_4$ and $w_1, w_2, w_3$ and $w_4$ their associated weights, the RSM value can be calculated as in equation 4.2 employing summation as the function.

$$RSM = \sum_{i=1}^{4} c_i * w_i$$

(4.2)

In the current work, we have used energy and number of neighbours for a device as the parameters to calculate the RSM value. Based upon the characteristic used to compute RSM, it is differently named. The equations 4.3 and 4.4 are used to compute values based upon energy ($RSM_E$) and neighbour ($RSM_{EN}$) characteristics which are later utilized in the proposed algorithm. The energy level for a device can vary between $1 - 100\%$ while the capacity of a rechargeable battery is ten times greater than a coin-cell. The differentiation of the device based on the energy is depicted in figure 4.1. Using the equation 4.3, a connected device is given RSM value of 200 while variation between 1-99 is possible for rechargeable and 1-10 for the coin-cell type.
\[ RSM_E = \begin{cases} 
200 & \text{if Source} = \text{Mains Supply} \\
0.1 \times \text{EnergyLevel} & \text{if Source} = \text{Rechargeable} \\
0.1 \times \text{EnergyLevel} & \text{if Source} = \text{Coin-Cell} 
\end{cases} \]

\[ RSM_{EN} = \begin{cases} 
200 + N \times W & \text{if Source} = \text{Mains Supply} \\
0.1 \times \text{EnergyLevel} & \text{if Source} = \text{Rechargeable} \\
0.1 \times \text{EnergyLevel} & \text{if Source} = \text{Coin-Cell} 
\end{cases} \]

where \( W \) is the associated weight and \( N \) is the number of neighbours for a device. The impact of the neighbours is considered only for the mains connected devices as they have an infinite supply of power and can easily accommodate a larger number of slaves.

![Relative energy of devices](image)

**Figure 4.1: Relative energy of devices**

### 4.2 Proposed Algorithm

From the findings of the literature review, we propose a new algorithm, hereby named as TFRS. For the comparison purpose, BSF with Unnecessary-Edges Deletion (BSF-UED) algorithm proposed by Jedda, Jourdan, and Mouftah in [45] was chosen to be the reference algorithm. The unique characteristics of the algorithm which include guaranteed **connectivity**, **out-degree limitation** and **finite convergence time** along with a definitive mechanism for node-delegation made it a prime choice over others. The ability of node delegation is important as it allow to control the topology at node and piconet and can be used in future to assign specific nodes to determined piconets. The algorithm makes following assumptions on the graph formed by the device. 1) The input graph is assumed to be unit disk graph. 2) Nodes are static, and mobility of nodes is not considered.

The algorithm assumes that each node has a unique, comparable and constant identifier and the graph formed by the devices exhibits Unit Disk Graph characteristics. The operation of the algorithm can be divided into two phases: 1) piconet construction and 2) piconet interconnection.

### 4.3 Piconet Construction in Reference Algorithm

This phase aims to generate a set of disconnected piconets. The operation starts in a distributed manner with each node identifying their neighbours via BLE scanning procedure. A neighbour is defined as a node which is in the unit radius of the device and can effectively communicate. After the discovery
round, each node is aware of the neighbours and their unique identifiers. Given the unique and comparable property of identifiers, some node must be local maxima based on the unique identifiers. The device identified as the local maxima initiates the algorithm and starts to capture nodes.

The current state of the node(u) denoted by state(u) = \{none, master, slave\} and the state of an edge between node(u) and node(v), denoted by c(u, v) = \{white, black, silver, green, red, blue\}. The meaning for the colours is defined as below.

- black: u captured v i.e. u is the master of v.
- silver: u tried to capture v, but another node already captured v.
- green: u was captured as a slave by another node. Thus, it abandoned capturing v.
- red: u delegated the capture of v to another node w such that ID_u > ID_w > ID_v.
- blue: u delegated to v the capture of a common node w such that ID_u > ID_v > ID_w.

Each node can be captured by its larger neighbours, but a node can be enslaved only once by its larger neighbour. If the node was not captured, then it will consider all its neighbours such that ID_u > ID_{neigh} as potential preys and will try to enslave them. Each node can capture a maximum of \(\varphi(u)\) neighbours which is the capacity of the node and initially set of 7. Whenever a slave is added to the piconet, the capacity of the master is decremented by 1. This is required to fulfil the degree-limited constraint for the BSF algorithms.

In case, if a node has more than seven neighbours i.e. the maximum capacity of a node, delegation is performed. A node(v) with highest identifier among the potential preys is chosen to be delegated along with the common neighbours between node(u) and node(v) until the number of preys are less or equal to the node capacity. The process is continued until all the devices are captured and part of a piconet. The figure 4.2 depicts the results obtained after phase 1 operation. For a detailed step-by-step example reader is encouraged to read [45].

**4.3.1 Limitation(s) of the Reference Algorithm**

The major limitation for the phase 1 of the algorithm stems from the fact that selection of the master depends upon the random unique id assigned to the devices. The identifier is either allocated randomly or derived from the device's mac address to maintain the uniqueness and comparable property. This approach is sufficient for the homogeneous deployment, but not suitable for heterogeneous deployments.
In a piconet, master are the devices which are required to perform additional tasks like routing the packets among slave nodes and thus consume resources like energy faster than slave nodes while require more compute and memory capabilities. The random assignment of the unique identifier cannot ensure that an optimal device is chosen as a master, thereby limiting the network lifetime for a piconet.

### 4.3.2 Piconet construction in TFRS

The problem can be alleviated by optimizing the algorithm to compute RSM and use it as a comparison metric while deciding the local maxima and thus the initiating node. It is possible for two devices to have same RSM value and ties are broken by considering the unique identifier value. The pseudo code used for comparing devices with RSM and unique identifiers is described in algorithm 3.

Let us reconsider the graph presented in the figure 4.2a, with following extra information about the device characteristic.

1. Device 2 & 5: energy source: connected; compute and memory capability: high; unique id: same as device number
2. Device 3,4 & 6: energy source: rechargeable(99%); compute and memory capability: medium; unique id: same as device number
3. Device 1,7 & 8: energy source: coin-cell battery(99%); compute and memory capability: low; unique id: same as device number

It is evident that device 2 and 5 are best suited for the master role. Using the algorithm 1 and 2, characteristics based metric can be derived for each device (considering three as the weight for each neighbour) as represented in table 4.3. Using these metrics along with the unique identifier, devices with better capabilities are chosen as master. The piconet generated using TFRS algorithm after optimized role selection are depicted in figure 4.3. It is expected to experience increased or similar network lifetime for any piconet formed using $RSM_E$ or $RSM_{EN}$ as the metric.

<table>
<thead>
<tr>
<th>Device id</th>
<th>$RSM_E$</th>
<th>$RSM_{EN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>212</td>
</tr>
<tr>
<td>3</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>206</td>
</tr>
<tr>
<td>6</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4.3: RSM & RSMN Metric for the devices

### 4.4 Piconet Interconnection in Reference Algorithm

This phase of the algorithm aims to connect the piconets created in the initial phase of the algorithm. Each of these piconets is treated as a meta-node, and the algorithm tries to connect these meta-nodes to each other creating a mesh-like network. The two piconets $P(u)$ and $P(v)$ with masters $u$ and $v$ respectively,
Figure 4.3: Optimized piconet with RSM or RSMN

Algorithm 1 Role specific metric computation

1: procedure RSMComputation\((u)\) \(\triangleright\) Node \(u\)
2: \(U_E \leftarrow\) EnergSrc\((\text{Node}_u)\) \(\triangleright\) EnergSrc():Energy Source for Node \(U\)
3: if \(U_E ==\) CONNECTED then
4: \(RSM_U = 200\)
5: return \(RSM_U\)
6: else if \(U_E ==\) RECHARGEABLE then
7: \(RSM_U =\) EnergyLevel\((u)\) \(\triangleright\) EnergyLevel(): returns current battery level
8: return \(RSM_U\)
9: else
10: \(RSM_U = 0.1 \ast\) EnergyLevel\((u)\)
11: return \(RSM_U\)
12: end if
13: end procedure

are considered neighbours if they can be interconnected through a interconnect. In Bluetooth, scatternet can be formed by using three types of interconnect. These are termed as one-hop, two-hop and three-hop interconnect and differ in the ways slaves of the piconet are utilized to for a scatternet. These are described below and depicted in the figure 4.4.

1. One hop interconnect: two piconets, let’s say \(P(u)\) and \(P(v)\) where \(u\) and \(v\) are the piconet masters are connected via an edge between \(u\) and \(v\).

2. Two hop interconnect: two piconets, let’s say \(P(u)\) and \(P(v)\) where \(u\) and \(v\) are the piconet masters, and have a common slave \(s\).

3. Three hop interconnect: two piconets, let’s say \(P(u)\) and \(P(v)\) where \(u\) and \(v\) are the piconet masters, and have \(s_u\) and \(s_v\) as slaves. Link is formed by \(s_u\) capturing \(s_v\) as its slave or vice-versa.

The reference algorithm initiates the interconnection phase by constructing the gateway table at each master. Each entry of it comprises of following elements:

- \(v\): the master of the neighbouring piconet.
- \(s_v\): the gateway of piconet \(P(v)\) (can be equivalent to \(v\))
- \(u\): the master of the current piconet.
- \(s_u\): the gateway of piconet \(P(u)\) (can be equivalent to \(u\))
Algorithm 2 RSM with neighbour Computation

1: procedure RSMNComputation($u, w$) ▷ Node $u$, weight per neighbour
2: \[ U_N \leftarrow \text{Neighbours}(\text{Node}_u) \] ▷ Neighbours(): Returns the neighbours for node $u$
3: \[ U_E \leftarrow \text{EnergSrc}(\text{Node}_u) \] ▷ EnergSrc(): Energy Source for Node $U$
4: if $U_E \rightleftharpoons \text{CONNECTED}$ then
5: \[ RSM_U = w \ast U_N + RSM(u) \]
6: return $RSM_U$
7: else
8: return $RSM(u)$
9: end if
10: end procedure

Algorithm 3 Node comparison with RSM

1: procedure NodeCompare($u, v$) ▷ Node $u$ and Node $v$
2: \[ U_{rsm} \leftarrow RSM(\text{Node}_u) \]
3: \[ V_{rsm} \leftarrow RSM(\text{Node}_v) \]
4: if $U_{rsm} > V_{rsm}$ then ▷ Node $U$ is better suited for master role
5: return Node $U$
6: else if $U_{rsm} < V_{rsm}$ then ▷ Node $V$ is better suited for master role
7: return Node $V$
8: else
9: \[ U_{id} \leftarrow \text{ID}(\text{Node}_u) \]
10: \[ V_{id} \leftarrow \text{ID}(\text{Node}_v) \]
11: if $U_{id} > V_{id}$ then ▷ Node $U$ is better suited for master role
12: return Node $U$
13: else if $U_{id} < V_{id}$ ▷ Node $V$ is better suited for master role
14: return Node $V$
15: end if
16: end if
17: end procedure

- $\varphi(s_u)$: the piconet capacity of gateway $s_u$.
- $I$: interconnect rule; refer 4.4
- role: $M$, if $s_u$ becomes master to $s_v$, else $S$.

The gateway table can have multiple entries for a piconet neighbour differing in the interconnect rule and the gateway(s). These entries are prioritized on the basis of the interconnect rule and ties are broken based on the piconet capacity of the gateway device. The algorithm for each piconet $P(u)$ constructs a maximal independent set of its larger piconet neighbours. The construction is done on the fly as each time a piconet $P(u)$ interconnects to a larger neighbour piconet $P(v)$, it does not interconnect with any neighbour piconet $P(w)$ that shares the same entry in both $P(u)$ and $P(v)$ and has a larger identifier than both [45].

### 4.4.1 Limitation(s) of Reference Algorithm

The main limitations for the second phase lies in the selection and prioritization of the available gateways between neighbouring piconet. The current method uses interconnect rule followed by the piconet capacity for prioritization of the gateways. Each of these aspects is discussed below.
### 4.4.1.1 Gateway Prioritization

The gateways are the critical nodes in the Bluetooth scatternet. They enable inter-piconet communication, and their failure may lead to a disconnected network unable to provide desired functionality thereby limiting the effective network lifetime. It is of paramount importance to choose an optimal gateway node among the available options to increase the viability of the thus formed network.

The current algorithm does not base gateway selection upon the suitability of the device, continuing the notion of a homogeneous network. This leads to sub-optimal selections of the gateways in a heterogeneous deployment, thereby limiting the network lifetime to sub-optimal values.

**Gateway prioritization in TFRS** in order to adapt the solution for the heterogeneous devices, we propose two different gateway prioritization based solution. Both of these solution requires extension of the gateway table with a new parameters called *GatewayEnergyAvg*, *GatewayEnergyMin*.

1. *GatewayEnergyAvg*: it is defined as the average of the current energy for the participating gateways.
Table 4.4: Set of interconnect rules

\[
\text{GatewayEnergyAvg} = \frac{\text{Energy}(s_u) + \text{Energy}(s_v)}{2}
\]  

2. GatewayEnergyMin: it is defined as the minimum of the participating gateways energies 4.6.

\[
\text{GatewayEnergyAvg} = \min(\text{Energy}(s_u), \text{Energy}(s_v))
\]

The proposed solutions define a new method for the gateway prioritization using the existing and newly added fields. The solutions are termed as "Reference with Energy" and "Energy" based prioritization.

**Reference with energy**: the solution extends the prioritization offered by the algorithm to include energy for breaking the ties among many suitable gateways. Also, the prioritization on the basis of the piconet capacity is dropped, although ensuring each participating gateways has at least one as the piconet capacity. In case of two gateways having exactly same parameters, ties are broken based on the unique identifier, where a device with a higher value is chosen.

The rationale for walking away from the piconet capacity based prioritization is that it does not provide any valuable device or network related characteristic. Any value more than one is equally good for the consideration. Thus, only the device with piconet capacity \( \geq 1 \) are considered as gateways. The detailed comparison procedure is described in algorithm 4. The proposed solution keeps all the essential aspects of the reference algorithm while improving the gateway selection and is thereby expected to perform better in average case or equal in worst case when considering the network lifetime of the formed topology.

**Energy**: the solution can be viewed as the new approach where only energy is used as the primary criteria for prioritizing the gateways while minimum piconet capacity \( \geq 1 \) is required for a gateway to be considered as a prospective gateway. The comparison procedure is described in algorithm 5. The topology created using energy based prioritization rule is expected to outperform both reference and reference with energy.

The figure 4.6 summarizes the impact of the prioritization on the selection of the gateway between the piconets. The orange line indicates the preferred edge for the interconnect. The algorithm chooses one of the preferred edges randomly.
Algorithm 4 Gateway selection using Reference with Energy

1: procedure ReferenceWithEnergy($Gw_1$, $Gw_2$) \quad \triangleright \text{Gateway Table entry}
2: \quad GwRule_1 = Rule(GW_1) \quad \triangleright \text{Rule(): returns the interconnect rule for the gateway entry}
3: \quad GwRule_2 = Rule(GW_2)
4: \quad GwCap_1 = Capacity(GW_1) \quad \triangleright \text{Capacity(): returns the piconet capacity for the gateway entry}
5: \quad GwCap_2 = Capacity(GW_2)
6: \quad GwEnergy_1 = Energy(GW_1) \quad \triangleright \text{Energy(): returns the energy profile for the gateway entry}
7: \quad GwEnergy_2 = Energy(GW_2)
8: \quad \text{if } (GwRule_1 \rightarrow GwRule_2 = 0) \text{ AND } (GwCap_1 \rightarrow GwCap_2 = 0) \text{ then}
9: \quad \quad \text{if } (GwEnergy_1 \rightarrow GwEnergy_2) \text{ then}
10: \quad \quad \quad \text{return Gateway } Gw_1
11: \quad \else
12: \quad \quad \text{return Gateway } Gw_2
13: \quad \end{if}
14: \quad \text{else if } (GwRule_1 \rightarrow GwRule_2 = 0) \text{ then}
15: \quad \quad \text{if } (GwCap_1 \rightarrow GwCap_2) \text{ then}
16: \quad \quad \quad \text{return Gateway } Gw_1
17: \quad \else
18: \quad \quad \text{return Gateway } Gw_2
19: \quad \end{if}
20: \quad \text{else}
21: \quad \quad \text{if } (GwRule_1 \rightarrow GwRule_2) \text{ then}
22: \quad \quad \quad \text{return Gateway } Gw_1
23: \quad \else
24: \quad \quad \text{return Gateway } Gw_2
25: \quad \end{if}
26: \quad \end{procedure}

4.4.1.2 Interconnect Rule(s) in Reference Algorithm

the second limitation of the phase 2 stems from the defined prioritization of the interconnect rules. The current algorithm prefers a three-hop over a two-hop interconnect. Also, among the various possibilities, the rule favours two-hop interconnect where a slave acquires the master over both masters acquiring a common slave. The specific reason for the choices made is unclear from the reference text but considering the delay aspect of the formed topology, the decision are unfavourable for the following reasons.

1. More hops imply more delay and higher energy consumption.
2. When a master acts as a slave in another piconet, all the slaves for the given master cannot communicate. This hampers the intra-piconet communication and adds to the delay.

In the study [46], a comparison of the delay performance of the various interconnect possibilities was performed. The results of the study indicate that two-hop common slave performed over the master-slave gateway and thus it was concluded that a common slave over master-slave gateway would be a preferred choice for connecting the Bluetooth piconets.

Interconnect Rule(s) in TFRS  

based upon the results from the study [46] and objective to minimize the number of hops, a new set of interconnect rules were defined. These are illustrated in the table 4.5. TFRS proposes interconnect rules preferring two-hop over the three-hop interconnect while ensuring all the two-hop interconnects are common slave based. The use of these interconnect rules along with the gateway prioritizations are expected to result in increased network lifetime.
Algorithm 5 Gateway selection using energy

1: procedure Energy($Gw_1, Gw_2$) \hspace{1cm} \triangleright Gateway Table entry
2: \hspace{1cm} $GwEnergy_1 = \text{Energy}(GW_1)$ \hspace{1cm} \triangleright Energy(): returns the energy profile for the gateway entry
3: \hspace{1cm} $GwEnergy_2 = \text{Energy}(GW_2)$
4: \hspace{1cm} if ($GwEnergy_1 > GwEnergy_2$) then
5: \hspace{2cm} return Gateway $Gw_1$
6: \hspace{2cm} else
7: \hspace{3cm} return Gateway $Gw_2$
8: \hspace{1cm} end if
9: end procedure

Figure 4.6: Impact of prioritization rule on gateway selection; link colours are red=node was delegated, green=higher degree node was enslaved and yellow=preferred interconnect link
<table>
<thead>
<tr>
<th>Interconnection Rule</th>
<th>Illustration</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-rule 1a</td>
<td><img src="image1" alt="Illustration" /></td>
<td>$v$ captures $s_u$</td>
</tr>
<tr>
<td>I-rule 1b</td>
<td><img src="image2" alt="Illustration" /></td>
<td>$v$ captures $s$</td>
</tr>
<tr>
<td>I-rule 1c</td>
<td><img src="image3" alt="Illustration" /></td>
<td>$u$ captures $s_v$</td>
</tr>
<tr>
<td>I-rule 2</td>
<td><img src="image4" alt="Illustration" /></td>
<td>$s_u$ captures $s_v$</td>
</tr>
<tr>
<td>I-rule 3</td>
<td><img src="image5" alt="Illustration" /></td>
<td>$v$ captures $u$</td>
</tr>
</tbody>
</table>

Table 4.5: Set of interconnect rules as defined in TFRS
Chapter 5

Methodology

The current chapter introduces the high-level description of the system used in the study. It provides a logical understanding of the working of the simulator and various sub-modules. The later part of the chapter is focused on the experimental settings.

5.1 System Design

It provides the highest level of the abstraction and all the experiments are performed in the context of the system. The simulator implements the described system, and it consists of the BLE device(s) and transmission manager. The figure 5.1 presents the high-level view of the model.

![Figure 5.1: BLE mesh system design](image)

5.1.1 BLE Device

The current work considers network deployment with heterogeneous devices which may have varying characteristics. Few of the possible characteristics are listed in the table 4.1. For the simplicity, the study is restricted to consider only energy, compute and memory characteristics of a device. These are further classified into possible broad categories based on the devices encountered in home or office based surroundings.
1. Energy
   - Mains powered: they have unlimited access to the power and are always ON. An example of such a device is a coffee machine in an office and washing machine, dishwasher, etc. in the home.
   - Rechargeable: these devices have larger battery when compared to the coin-cell battery with a probability of replenishment. Examples include smartphones, tablets, etc. In the current study, the likelihood of replenishment of the rechargeable devices is set to 0. This is done to have deterministic results.
   - Coin cell battery: these operate on minimum power and include temperature, pressure, light sensors, etc. as potential examples.

2. Compute & Memory Capabilities
   - High: these devices have a relatively high amount of compute power and can support complex operations. Examples include smartphones, tablets, etc.
   - Middle: these devices have limited compute capability limiting to very basic operations. An example of such a device is a coffee machine in an office and washing machine, dishwasher, etc. in the home.
   - Low: these devices have almost no compute capability. They collect and forward the raw data to the central server for the processing. Example include temperature, pressure, light sensors, etc.

5.1.1.1 BLE Device Design

A BLE device is made up of multiple modules: characteristics, middleware, and transmission/reception module. These modules provide unique services and are together responsible for the successful operation of the device. The figure 5.2 depicts these modules.

![BLE Device Design](image)

Figure 5.2: BLE device design overview

- Middleware module: it is responsible for enabling the mesh based topology creation and routing the data between the devices. It houses two important sub-modules namely routing and topology module as depicted in figure 5.3b.
5.1. SYSTEM DESIGN

- Topology sub-module: the module houses the scatternet formation algorithm which is responsible for creating a mesh network by forming piconets and later connecting them. The module may have more than one algorithm for this purpose or may use multiple algorithms for various phases for mesh formation.
- Routing sub-module: this modules is responsible for enabling transmission of data among the devices connected to same or different piconets. The modules leverage the mesh network created by the topology sub-modules to determine the path(s) between the devices and transmit data using discovered routes.

- Transmission/Reception (TxRx) module: it is depicted in figure 5.3c and is responsible for the sending and receiving the data messages to or from other devices. The module interface with the transmission manager to fulfill required functionality.
- Characteristics module: this is responsible for the defining the unique feature of a device. It encompasses various sub-modules. Each of these modules is responsible for a particular device characteristic like energy, mobility, radio, etc. It also acts as an interface to other module providing access to these characteristics. The figure 5.3a depicts the overview of characteristics module.
For example, the energy module defines the type of power source, current level of power (if on battery supply); traffic module identifies the device address, average uplink and downlink traffic rates and mobility module defines whether a device is static or mobile. The characteristic information is available to the topology and routing block via middleware interface and can be used by the algorithms to make intelligent decisions.

![Characteristics Module Design Overview](image1)

![Middleware Module Design Overview](image2)

![TxRX Module Design Overview](image3)

Figure 5.3: Modular view of BLE characteristics module

5.1.2 Transmission Manager

It is responsible for providing communication infrastructure between BLE device(s). The basic procedures like scanning, advertisement, neighbour discovery, etc. are supported by the transmission manager. This can be considered as a mathematical model for the radio channel and is capable of supporting emulation of basic channel characteristic. It is possible to configure the transmission manager to account
for the radio interference created by nearby device and collision due to simultaneous transmissions on the same physical channel.

The figure 5.4 presents the details of the transmission manager. To account for the channel propagation parameters between two BLE devices, the transmission manager provides multiple queues, each emulating for one or more channel propagation parameter(s).

In the current study, we have chosen to use the transparent mode configuration for transmission of the data between two BLE devices. It is done to simplify the study and to make the model deterministic as the collision and interference are modeled as probabilistic phenomena.

5.1.3 Channel Capacity Model

It is assumed to have an infinite capacity channel between the device free from collision and interference. Any packet transmitted is received at the destination without fail under the assumption of device reachability.

5.1.4 Power Model

Each device consumes a certain level of power for its basic operations. In the current study, we have classified all operations into two broad categories: 1) reception and 2) transmission. Any other energy dissipation is attributed to the idle current loss, required to keep the device operational.

For the current study, we assume that approximately 0.1 \( \text{mJ} \) of energy is consumed at each transmission and reception event. Furthermore, 1 \( \mu \text{A} \) of idle current flows in the circuit when the device is neither transmitting or receiving. At any point in time to determine the operational status of a device, it is required to account for the current power during the operation and adjust it after each successful transmission or reception event. While it is easy to account energy loss for the Transmission (Tx) or Reception (Rx) event, adjusting the idle current is relatively tedious as its continuous phenomena.

To model currently available energy, we have decided to piggy-back the idle current energy losses at every transmission event. The decision stems from the fact that uplink data transmission frequency is pre-known (assuming periodic reporting) while reception is mostly sporadic. It is also assumed that each transmission and reception event take infinitesimally small amount of time. The idle current losses are calculated for the entire period (time difference between two transmission events). These losses with the transmission energy loss are detected to account both for the event and idle current loss. The residual energy of the device is updated in accordance to equation 5.1. The figure 5.5 depicts the energy adjustments for the BLE device.
IdleEnergy = 1μA * 3Volts * T where T is the transmission period

$TxE = RxE = 0.1mJ$ where $TxE$ & $RxE$ is transmission and reception energy cost

$CurrEne_T = \begin{cases} 
  CurrEne_{T-1} - IdE - TxE & \text{if Event = Transmission} \\
  CurrEne_{T-1} - RxE & \text{if Event = Reception}
\end{cases}$

$DeviceStatus = \begin{cases} 
  Alive, & \text{if CurrentPower} > 0 \\
  Dead,  & \text{if CurrentPower} <= 0
\end{cases}$

### 5.1.5 Routing Model

It defines the routing methodology used in the simulator. The current simulation environment uses a minimal proactive routing assuming that routes are valid for entire network lifetime. At the start of the simulation, control packets are used by the piconet masters to discover the routes to the desired destination. The control packets are flooded through the network to discover all the possible routes. At the destination, each copy of control packet via different path is acknowledged, and the response message is generated for the initiator. This process establishes the set of known routes between a source and destination pair. The algorithm always prefers a route with minimum hops among the various possible routes. When more than one route has same hop count, the first discovered route is used to transmit the packet.

For a graph as depicted in figure 5.6a, if a Source "S" is required to send packets to destination "D", the control messages are flooded, and they arrive at destination via different routes, as depicted in figure 5.6b. In the response, the destination generates the control message and delivers to the initiator using the reverse route. At the end of the process, both the source and the destination have learned all possible routes among the pair. Hereafter the route with minimum hops is chosen for the communication. In the current example, route "S → 1 → 3 → D" is preferred as it was first discovered and has same or lesser number of hops when compared to other routes.

### 5.1.6 Traffic Model

It is used to describe the flow of the data among the devices connected in the network. It is utmost important to have fair traffic model i.e. it must ensure the comparability of the algorithms. To maintain the fairness, the current traffic model ensures an equal amount of data is generated from each device formed.
irrespective of the algorithm and number of devices in the network.

In the current traffic model, a triplet of (Source, Destination, Rate) identifying the traffic flow. Endpoints are chosen such that no sensor node acts as the sink.

### 5.2 Experiment Design

to perform the experiments, the simulator was provided by a telecommunication company. The base and extended topology formation along with routing algorithms were implemented in tool using Java© as the programming language. The experiment design consists of multiple parameters. A few of these parameters are constant for the entire study while others vary for each experiment.

The following parameters remain constant for the duration the study. This is required to be able to compare the data obtained from the various experiment.

1. Traffic Model: this defines the communication between the devices and the piconets.
2. Transmission Model: this defines how are the packets transmitted from a source to destination and what factors influence the successful or unsuccessful delivery of the packet.
3. Routing Model: it defines the routing methodology used in the simulator.

The following parameters are varied for each resulting in the multiple data set. These data set are later mathematically analysed to derive meaningful conclusions.

1. Device Density: this is used to determine the density of the a particular class of the device in a deployment.
2. Device Deployment: the cartesian coordinate of a device.
3. Device Count: number of devices in the deployment
4. Topology Formation Algorithm: the algorithm used to generate the scatternet.

The step-by-step process for the experiment is described in figure 5.7 as a flow chart.
Figure 5.7: Flow chart for experiment design
Chapter 6

Performance Evaluation and Results

In this section, we analyse the performance of proposed algorithm compared with the reference case where master and gateway role selection is not based on device characteristics and not energy aware. The simulation set-up and the parameters are described in the following sections together with the results. The final section outlines the perceived limitations of the simulator which may have minor effects on the results but does not change the drawn conclusions.

6.1 System Parameters

In the simulations, we have assumed channel capacity, power routing and model as described in the sections 5.1.3, 5.1.4, 5.1.5 and 5.1.6 respectively. A homogeneous deployment is created where all the heterogeneous devices are distributed over an area of 30 x 30 meters. We consider three different type of deployments each varying in the density of the coin-cell type devices. Type 1 has 30%; Type 2 has 50%, and Type 3 has 70% of the total number of the device as coin-cell. In addition, deployment density can vary from 35 to 75 devices. The deployments forming connected graph are considered for simulation.

It is assumed that a device can effectively communicate within the radius of 10 meters and all the devices in the communication range are considered neighbours. Each device generates 1 packet per second for a priori known device, called as the destination. It is mandated that a sensor type device is not chosen as the destination. For the battery-powered devices, capacity is assumed to be 2500 Milliampere-hour (mAh) for rechargeable and 250 mAh for the coin-cell while mains connected devices have infinite energy capacity. The initial battery percentage for the rechargeable device can vary from 50% to 99% while coin-cell devices have fixed value of 99%. For transmission and reception of a packet with 20 bytes, energy equivalent to 100 μA H is consumed. In the study, transmission rate is limited to 1 packet every 10 seconds for each device.

The results presented are averaged over 100 iterations and depicted with 95% confidence bars. Each iteration is characterized by the unique deployment of devices with randomly selected source and destination pairs. The analysis is performed for different coin-cell percentage varying from 30% to 70%, varying the number of devices from 35 to 75. For each of the deployment setup, each device is assigned different characteristics and spatial location in the simulation area under the constraints of homogeneous distribution. Summary of system parameters is presented in table 6.1.

6.2 Simulation Results

The simulations were designed to study the impact of the system parameters under various deployment conditions. The system parameter consists of device characteristics, transmission and reception range, traffic rate and the channel conditions. The deployments are characterized by the variation in the number
Table 6.1: Summary of system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-ordinates</td>
<td>Random value from Homogeneous distribution</td>
</tr>
<tr>
<td>Device Energy Class</td>
<td>Connected, Rechargeable, and Coin-cell</td>
</tr>
<tr>
<td>Battery Size</td>
<td>250 mAh for Coin-cell and 2500 mAh for Rechargeable</td>
</tr>
<tr>
<td>Battery level</td>
<td>1-99%</td>
</tr>
<tr>
<td>Deployment Area</td>
<td>30 x 30 m</td>
</tr>
<tr>
<td>Tx/Rx Range</td>
<td>10 m</td>
</tr>
<tr>
<td>No of Devices in Deployment</td>
<td>[35,45,55,65,75]</td>
</tr>
<tr>
<td>Device type Density (M,R,C)</td>
<td>[35%,35%,30%], [25%,35%,50%], [15%,15%,70%]</td>
</tr>
<tr>
<td>Traffic Rate</td>
<td>1 packet/sec</td>
</tr>
<tr>
<td>Channel Model</td>
<td>Lossless, collision and interference free</td>
</tr>
</tbody>
</table>

of device and density of coin-cell devices. Each simulation can assume one of the possible values from 30, 40, 50, 60, 70 for the possible number of devices in the deployment area, and 30, 50, 70 % of the devices can be the coin-cell type. The deployment ensures homogeneous placement for different kind of devices i.e. connected, rechargeable and coin-cell.

6.2.1 TFRS versus Reference algorithm

The analysis aims to observe the effect of TFRS algorithm on the network lifetime when compared to the reference algorithm. The TFRS employs both master and gateway selection strategies to maximize the network lifetime. It is expected that combined effect of role with gateway selection will have a perceivable positive impact with increased network lifetime. For the simulations, pairs of master and gateway selection strategies were made. The pairs constituted as (master selection, gateway selection): 1) MS-Ref, GS-Ref 2) MS-E, GS-E and 3) MS-EN, GS-E.

The graphs in figure 6.1 depict the observed network lifetime for various device deployments varying in the number of total devices and the density of coin-cell devices with error bar indicating confidence level of 95%. The results indicate two distinct outcomes.

1. Role based master and gateway selection algorithms conclusively perform better than the reference algorithm. The observation is in-line with the expectation.

2. Using neighbour information along with energy does not result in the extended network lifetime, which is against the expectation. Upon further analysis, the simulation results are in line with the rationality. The inclusion of the neighbour information in the master selection allows formation of a denser piconets. This leads to a lower number of piconets but increases the traffic to be handled by each master and associated gateway nodes, leading to faster decay of battery powered nodes. The performance metric monitors the failure of the first critical device; thereby we observe a decrease in network lifetime.

It must be noted that when the device when the device number is high, 75, MS-E performs better. For the lower number, 35, it is hard to comment which algorithm performs better due to the
6.2. SIMULATION RESULTS

![Graphs showing network lifetime variations](image)

*Figure 6.1: Observed network lifetime for TFRS algorithm*

variations as depicted with the error bars.

6.2.2 Impact of Master Role Selection

Taking a step further and analysing the individual impact of the master selection, the analysis aims to study the effect of master role selection strategy on the network lifetime. The simulation alternates between the three possible master selection (MS) strategies i.e. MS-Ref, MS-E (energy) and MS-EN (energy with neighbour information) while for gateway selection (GS), GS-Ref (reference) algorithm is used. It is expected to observe an increased network lifetime for the topology established with optimized role determination strategies like MS-E and MS-EN.

The graphs in figure 6.2 depict the observed network lifetime for various device deployments varying in the number of total devices and the density of coin-cell devices with error bar indicating confidence level of 95%. For more graphs refer to appendix A. Given the information presented in figure 6.2, it can be seen that optimized master role selection results in the marginally improved network lifetime affirming the superiority of the role selection strategy. On a careful analysis of the various master determination strategies, it is observed that MS-E always perform better or equal, while the relationship between MS-Ref and MS-EN cannot be deterministically established.

This observation can be attributed to the fact that master selection aims to optimize the master role while the network lifetime is dependent both on master and gateway nodes. After the application of the selection algorithm, the probability of finding a low-power device as the gateway is higher for MS-E and
MS-EN over MS-Ref, as the devices with better capacity are hand-picked to act as masters. Also, MS-EN aims to lower the number of piconets by forming dense piconets and thus creating higher amount of traffic to be carried over the gateway.

### 6.2.3 Impact of Gateway Selection

On the similar lines, the current analysis aims to study the impact of proposed gateway selection strategies on the network lifetime. The simulation alternates between the three possible gateway selection(GS) strategies i.e. GS-Ref, GS-Ref+E (reference with energy) and GS-E (energy) while for master selection (MS), MS-Ref (reference) algorithm is used. It is expected to observe an increased network lifetime by the usage of optimized gateway selection strategies irrespective of the master role determination strategy employed.

The graphs in figure 6.2 depict the observed network lifetime for various device deployments varying in number of total devices and the density of coin-cell devices with error bar indicating confidence level of 95%. For more graphs refer to appendix B. Based upon the information depicted in the figures 6.3, we can observe a monotonic increase in the network lifetime as the gateway selection algorithm is varied from GS-Ref to GS-E. The observation is in-line to with the expectations. It must be pointed out that the GS-E provides much higher improvement in the observed network lifetime when compared to GS-Ref+E while GS-Ref+E provides marginally better performance than GS-Ref. It is attributed to the fact
6.2. SIMULATION RESULTS

Figure 6.3: Observed network lifetime using GS-Ref, GS-Ref+E & GS-E as gateway, MS-Ref as master selection algorithm

that GS-Ref+E springs into action when multiple choices exist based upon the pre-defined interconnect prioritization rules, and ties are broken by GS-Ref+E using energy as the determining parameter. When there are no ties to be broken, GS-Ref+E performs exactly as GS-Ref.

6.2.4 Impact of Device-Type Ratio

The simulation aims to uncover any relationship between the performance of an algorithm and the device densities. To derive this, data from all the above simulations was utilized to performance comparison analysis between the achieved network lifetime by an algorithm under specific device-type densities.

The simulation results presented in 6.4 are in-line with the expectations. Following conclusions can be derived:

1. With the increase in the coin-cell density, the network lifetime decreases.

2. No significant variation is observed in network lifetime using reference algorithm. This results from the random selection of the role for the devices.

3. TFRS performs best for the type 1 deployment, while a moderate difference is observed for type 2 and type 3 deployments.
6.2.5 Impact of Device Density

The simulations aim to study the relation between the observed network lifetime and the number of devices in a deployment. It is expected that network lifetime would decrease with the increasing number of devices owing to increased traffic flowing through the bridges.

The simulation result suggests that with the increase in the device density with coin-cell ratio > 50%, the network lifetime decreases. The following facts support the observation. When the number of coin-cell in the network is smaller, the trend can’t be identified as proposed algorithm at-times is able to find optimal path consisting of only connected devices, thereby, resulting in very high network lifetime. The reason for the observed decrease in the network lifetime (coin-cell > 50%) can be attributed to following reasons.

1. Routing: the model employed doesn’t consider the existence of the multiple paths to a destination, neither it accounts for the goodness of a path. All the traffic is routed using a minimum hop route determined at the start without any consideration for load balancing when the multiple route exists.

2. Sinks: it is mandated to have either connected or rechargeable device as a destination. With the increase in the number of nodes, the total traffic per destination increases thereby exhausting the associated resources faster.
Figure 6.5: Impact of device density on network lifetime

Given the routing model and sink selection, it becomes evident that with the increase in the number of devices, the traffic load on the chosen bridges increases, resulting in decreased network lifetime. The observation is true until the ratio of coin-cell is considerably higher when compared to other devices. As the number of coin-cell decreases, it is possible to have higher network lifetime.

6.3 Limitation(s) of Experiment(s)

Like all the studies, there are certain limitation(s) on the simulation setup and the conclusions derived must be considered in the light of them.

1. Distributed simulation: the algorithm requires to be simulated as an autonomous distributed procedure, but the simulator design restricts it. Instead, the simulation was performed in sequential event-based approach where each device would evaluate entry conditions for the initiation of the distributed algorithm. The sequential flow of the algorithm resulted in a behavioural deviation from a real type deployment where the distributed processing would imply balanced piconet sizes. Currently, only after the master with highest id has enslaved all possible slaves, lower id master can proceed (even if they are local maxima). The limitation doesn’t have a significant impact on the drawn conclusion as it only affects the density of piconets which are in close vicinity of each other. The issue was not addressed in the study as it was a limitation from the simulator and required a significant amount of changes in the simulator.
2. Actual vs. effective battery: the algorithm does not consider the frequency of the traffic generated from a device, thereby considering the effective energy same as the actual energy. This may lead to incorrect role assignment when a device with higher energy is preferred as master or gateway without the consideration of the rate of energy dissipation. The limitation leads to lower observed network lifetime. As a work around, the current study assumes identical traffic rates from each device. Under this assumption, both actual and effective battery are same.

3. Restricted modelling of rechargeable devices: the simulation setup assumes replenishment possibility for the rechargeable device is zero, which is restrictive. In a real-world scenario, where rechargeable device represents devices like smartphones, tablets, etc., the likelihood of recharging is much higher. This limits observed performance gains when employing characteristics based role assignment for both masters and gateways. The limitation like above leads to lower observed network lifetime than actual. The decision not to model was due to the complexity of incorporating a probabilistic model for the recharging in the simulation. Also, it doesn’t have any adverse impact on the conclusions, as uplifting the limitation would strengthen the results.

4. Strict performance metric: the metric used for determination of the network lifetime does not account for the possible existence of alternate routes between a source and destination pair. It assumes failure of a single critical node leads the network parted and, therefore, limits the lifetime to the first failure. In the real-world, given the mesh type topology, there might exist alternate routes and thus perceived network lifetime may be greater than the one observed from the simulations. The limitation leads to lower observed network lifetime, and metric to incorporate check of the existence of multiple routes will result in increased lifetime. The issue wasn’t considered in the current study due the limitations of the simulator and the complexity of the task.
Chapter 7

Summary & Outlook

The chapter discusses the results observed from the simulations, drawing the meaningful conclusion and their impact on the field of the study. It also provides an overview of the study with definitive, substantiated arguments for the research question(s), each of which is answered in the study. Finally, suggestions are made for next steps considered as future work in regards to the current study. The proposed suggestions are aimed to uplift certain assumption from the study and explore new idea(s) which were developed during the study.

7.1 Discussion

The study explores the idea of using the heterogeneous device characteristics to make intelligent decisions while formation of the network topology which include both piconet master selection and determination of most suitable device to act as a gateway between piconets by proposing a novel topology formation algorithm.

The literature review done in the study indicates that most of the current topology formation algorithms considers the network with homogeneous nodes. Under this assumption, no emphasis is put on the determination of the suitability of a device for the assigned role.

The study assumes that a network constitutes of heterogeneous devices each having unique characteristics and the network forms a connected graph. The assumption on the connectivity of the network graph is required to ensure formation of connected topology. Under these assumptions, we have defined role suitability metric which is capable of encapsulating device specific characteristics into a numerical value which can be later used to evaluate the adequacy of a device for a certain role in a network. Considering Bluetooth as the technology, roles are restricted to \{master, gateway and slave\}. The metric is not limited by the number of characteristics or the roles as it is defined in a generic way where a user has the flexibility to adapt the characteristics, their associated weights and the function which determines the relation between them. The weights need to be determined carefully for each device characteristic depending on the priority of optimization. In this study, we did not focus on how to merge multiple characteristics and left it as a future work.

We have defined two metrics based upon the above idea, named as $RSM_E$ and $RSM_{EN}$. The former uses current energy state of the device to determine the suitability while the later employs both current energy state and device neighbour information for computing suitability. Both of these metrics are used for making decisions for selecting master and gateways.

Based on the literature survey, the current state of the art algorithm named BSF-UED was selected as the reference and a novel algorithm called TFRS is proposed based on this reference exploiting the het-
ergonomic characteristics of the devices. The impact of the proposed algorithm was measured in terms of increased network lifetime which is the effective time before a critical element in the network fails. The proposed algorithm exhibits higher network lifetime.

The following conclusions can be drawn from the results.

1. TFRS performs better than the reference algorithm considering energy as the suitability metric for homogeneous deployments.

2. Simulations indicate that improvement from 20% to 40% is observed against the reference algorithm in the network lifetime with TFRS under homogeneous deployment conditions. Further, to achieve statistical confidence, a higher number of simulation iterations are desired.

3. It is important to employ both master and gateway selection to achieve maximum performance. Usage of one in the absence of other doesn’t provide significant benefits over the reference algorithm.

4. Denser piconets may lead to decreased lifetime owing to increased load on the master and associated gateway nodes. This happens, especially when the percentage of coin-cell type sensors is more than 50%.

Finally, looking back on the proposed research questions, the answers can be summarised as below.

1. **Q1: What are the limiting characteristics or assumptions of Bluetooth based topology formation algorithms for a deployment of heterogeneous devices?**
   - All of the algorithms do not consider the heterogeneity in consideration assuming all the device to be of homogeneous type. In the wireless sensors networks, there are certain algorithms which consider heterogeneous device, but they consider only Cluster head based inter-cluster communication. This approach is not preferred in BLE.

2. **Q2: How much improvement in the network lifetime can be achieved for BLE mesh networks by exploiting heterogeneous device characteristics during topology formation?**
   - The network lifetime can be improved by 20% to 40% under homogeneous deployment by exploiting the heterogeneous characteristics of the devices.

### 7.2 Future Work

The study was limited by certain assumptions, limitations and practicalities which confined the scope of the study. The proposed future work aims to lift these and extend these idea(s) for a wider applicability.

- Incorporation of adaptation phase: literature review has confirmed that most of the studies do not have an adaptation phase to maintain optimality of the topology. The future work can focus on the determining efficient methods aiming to have an adaptive topology. These kinds of procedure are especially important to rotate the assigned roles among the devices to share the load and increase observed network lifetime. Currently, all the use cases have predictable traffic, but in future if this assumption is not true, it would be interesting to explore adaptive methods to maintain efficient topology.

The study could focus on multiple topological aspects, few of which are mentioned below.

1. **Shared gateway role:** the study can focus on developing an efficient algorithm or procedure which can ensure that any point in time, the most suitable device is selected as a gateway between piconets. This would require periodic assertion of the assigned role and substitution (if required).
2. Node delegation: the study can focus on using the dynamic node information like traffic generation and reception frequency, frequently contacted node, etc. to determine the optimal piconet for a device when more than one membership is possible.

- Extension of role specific metrics: in the simulations performed, only two of the available characteristics were used for determining the suitability of a device for a given role. The future study could focus on establishing the relationship between various device characteristics and network lifetime and thereafter employing them to identify the role suitability.

- Evaluation metrics: the network lifetime metric used is very restrictive and doesn't account for the existence of the multiple path between a source and destination pair. It would be interesting to extend the metric to account for the multiple paths.

- Delay metric: the work can be extended to incorporate "Delay" metric. The changes in the algorithm impact the final topology and thus the path traversed by a packet to reach from source to destination. The delay incurred is, therefore, dependent on the number of hop in the path, devices and their characteristics, thereby an important metric for the evaluation of the algorithm.

- Simulator: it would be interesting to evaluate above discussed idea on a parallel simulator where all devices can operate simultaneously, representing real life simulation unlike in a sequential event-based simulator.
Glossary

**De Bruijn graphs**  A De Bruijn graph is a directed graph with $d^n$ nodes labelled by $n$-tuples over a $d$-character alphabet (denoted by juxtaposition). The edges are defined to be ordered pairs of the form $((\alpha_1...\alpha_n), (\alpha_2...\alpha_n\alpha_{n+1}))$ where $\alpha_{n+1}$ is any character in the alphabet. [47], 23

**Unit Disk Graph**  In geometric graph theory, a unit disk graph is the intersection graph of a family of unit disks in the Euclidean plane. That is, it is a graph with one vertex for each disk, and with an edge between two vertices whenever the corresponding disks have non-empty intersection. 25, 26, 38
Bibliography


Appendices
Appendix A

Impact of Master Selection on Network lifetime
Figure A.1: Impact of Master Selection on Network lifetime - A
Figure A.2: Impact of Master Selection on Network lifetime - B
Appendix B

Impact of Gateway Selection on Network lifetime
Figure B.1: Impact of Gateway Selection on Network lifetime - A
Figure B.2: Impact of Gateway Selection on Network lifetime - B
Appendix C

Impact of Algorithms on Network lifetime
Figure C.1: Impact of TFRS on Network lifetime - A
Figure C.2: Impact of TFRS on Network lifetime - B
Appendix D

Device Survey

D.1 Rechargeable Battery Capacity

<table>
<thead>
<tr>
<th>Device</th>
<th>Capacity (mAh)</th>
<th>Device</th>
<th>Capacity (mAh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy S5</td>
<td>2800</td>
<td>Galaxy Note 3</td>
<td>3200</td>
</tr>
<tr>
<td>HTC One</td>
<td>2600</td>
<td>Lumia 1520</td>
<td>3400</td>
</tr>
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<td>1570</td>
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<td>2100</td>
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<td>Moto X</td>
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<td>2070</td>
<td>iPhone 5</td>
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</tr>
<tr>
<td>LG G2</td>
<td>3000</td>
<td>iPhone 4s</td>
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<tr>
<td>Lenovo K3</td>
<td>2900</td>
<td>iPhone 5s</td>
<td>1570</td>
</tr>
<tr>
<td>Dell Venue 8</td>
<td>7000</td>
<td>iPhone 6</td>
<td>1810</td>
</tr>
</tbody>
</table>

Table D.1: Survey of rechargeable devices battery capacity

D.2 Coin Cell Battery Capacity

<table>
<thead>
<tr>
<th>Device</th>
<th>Capacity (mAh)</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimote</td>
<td>1000</td>
<td>CR2477</td>
</tr>
<tr>
<td>Gimbal</td>
<td>225</td>
<td>CR2032</td>
</tr>
<tr>
<td>BlueSense</td>
<td>620</td>
<td>CR2450</td>
</tr>
<tr>
<td>kontakt io</td>
<td>1000</td>
<td>CR2477</td>
</tr>
</tbody>
</table>

Table D.2: Survey of BLE devices battery capacity