

**ENERGY EFFICIENT LARGE SCALE TRACKING
SYSTEM USING SMARTPHONES**

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

COMPUTER NETWORKS

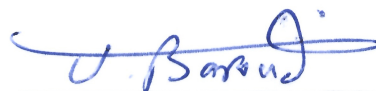
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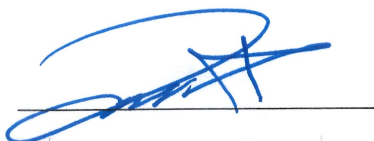
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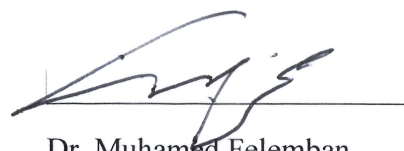
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*To my mom, dad and wife with love.
You are the co-authors of all my work.*

ACKNOWLEDGMENTS

Praise be to ALLAH, Lord of the Worlds, for guiding me and giving me health and strength to accomplish this thesis. I would like to express my great gratitude to my Advisor, Dr. Uthman Baroudi. I highly appreciate his support during the whole work of the thesis. Without his guidance and patience, I would not be able to finish this thesis. I also would like to thank other members of my thesis committee, Dr. Wisam Mesbah and Dr. Muhamed Felemban for their constructive support and encouragement. I sincerely thank King Fahd University of Petroleum and Minerals (KFUPM) for giving me the opportunity to study my masters degree and for providing financial support and excellent facilities. I would like to thank Dr. Mohammad Saad Al-Homoud, Dr. Salam Zummo and Dr. Ahmed Almulhem for providing me the opportunity to complete my thesis.

Special thanks to my parents and my wife. Your prayers and love are encouraging and helping me to reach my goals. I would like to say that: I genuinely appreciate your support and effort.

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LIST OF ABBREVIATIONS

AoA	Angle of Arrival
AP	Access Point
API	Application Programming Interface
BLE	Bluetooth Low Energy
SIG	Bluetooth Special Interest Group
CEET	Cooperative Energy-Efficient Tracking (The proposed system)
CH	Cluster Head
CONET	Cooperative Networking protocol
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Spectrum
GAMS	General Algebraic Modeling System
GPS	Global Positioning System
GNSS	Global Navigation Satellite System

HEED	Hybrid Energy-Efficient, Distributed clustering approach for ad hoc networks
ISM band	Industry Scientific Medical band
iOS	iPhone Operating System
LAN	Local Area Network
LLC	Least Cluster Change algorithm
LEACH	Lower Energy Adaptive Clustering Hierarchy
LEACH-M	LEACH Mobile
MIP	Mixed Integer Programming
OFDM	Orthogonal Frequency-Division Multiplexing
RN	Regular Node
RSSI	Received Signal Strength Indication
SC	Suppressed Carrier
SMS	Short Message System
TCH	Trivial Cluster Head (CH with no connected regular nodes)
TDMA	Time-Division Multiple Access
ToF	Time of Flight
TL-LEACH	Two-Level LEACH

QoS	Quality of Service
UWB	Ultrawide Bandwidth
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Networks
6LoWPAN	(IPv6) Low-power Wireless Personal Area Networks

THESIS ABSTRACT

NAME: Yousef Ahmed Ahmed Ali

TITLE OF STUDY: Energy Efficient Large Scale Tracking System using smartphones

MAJOR FIELD: Computer Networks

DATE OF DEGREE: Dec 2018

Using smartphones for tracking is motivated by the revolutionary technological advances and popularity of smartphones. Positioning and communication are among the main drainers of the phone battery. However, these two features are essential for any tracking system. In large crowds like Hajj, using cooperative approach between smartphones to report tracking data could achieve substantial energy saving. In this thesis, we proposed a cooperative approach that exploits the multiple communication interfaces (Cellular, WiFi and Bluetooth) in smartphones. Neighboring smartphones are cooperatively grouped to form a cluster. Cluster members communicate locally via Bluetooth which has low energy for communication. Cluster head uses the GPS, and WiFi or mobile data to report the tracking information for all members in the cluster which save energy for the rest members in the cluster.

The clustering is based on a cost function computed according to the smartphone history of cooperation. The thesis introduce a formulation of the power consumption used of tracking in our approach. The clustering construction problem is modeled as a mixed integer programming model and solved using GAMS (General Algebraic Modeling System). A mobile application is designed and implemented which applies all the functionality of the proposed solution. Through the design and implementation, we address all the technical issues that could affect the implementation feasibility of the system. The proposed system was evaluated through real experiments using the developed mobile application and through extensive simulation experiments using MATLAB. Both real experiments and simulation show substantial improvement in the energy efficiency when applying our system. Energy consumption is reduced by 55% when there are dense smartphones in the field.

ملخص الرسالة

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عنوان الرسالة: نظام تتبع ذو نطاق واسع واستخدام كفؤ للطاقة باستخدام أجهزة المحمول الذكية

التخصص: شبكات الحاسب الآلي

تاريخ الدرجة العلمية: ديسمبر ، 2018

التقدم التكنولوجي الكبير والانتشار الواسع للهواتف الذكية دفع لتطوير الكثير من الأنظمة التي تستخدم الهواتف الذكية في التتبع. الاتصالات وأنظمة تحديد المواقع تعد من أكثر ما يستهلك بطارية الهاتف، مع ذلك لا بد من استخدامهما في أي نظام تتبع. في الحشود الكبيرة مثل الحج ، يمكن أن يؤدي التعاون بين الهواتف الذكية في إرسال بيانات التتبع إلى تحسن كبير في حفظ طاقة بطاريات الهواتف. في هذه الرسالة اقترحنا نهجًا تعاونيًا يستغل واجهات الاتصال المتعددة في الهواتف الذكية (البلوتوث والواي فاي وبيانات الهاتف). يتم تجميع الهواتف الذكية المتجاورة لتشكيل مجموعة. يتواصل أعضاء المجموعة محليًا عبر البلوتوث الذي يستخدم طاقة منخفضة للاتصالات. يستخدم رأس المجموعة نظام تحديد المواقع مع الواي فاي أو بيانات الهاتف للإبلاغ عن معلومات التعقب لجميع الأعضاء في المجموعة ما يعني توفير الطاقة لبقية أعضاء المجموعة الذين يستخدمون فقط البلوتوث. يعتمد التجميع على دالة التكلفة المحسوبة وفقًا لتاريخ تعاون الهاتف مع بقية الهواتف الذكية. لقد درسنا استهلاك الطاقة المستخدم للتتبع في حلنا وقمنا بتصميم عملية بناء المجموعات كنموذج برمجي صحيح وحللهنا باستخدام برنامج جامز. لقد قمنا بتصميم وتنفيذ تطبيق هاتف ذكي يطبق جميع وظائف الحل المقترح. من خلال التصميم والتنفيذ ، قمنا بمعالجة جميع القضايا الفنية التي يمكن أن تؤثر على جدوى تنفيذ النظام. قمنا بتقييم النظام المقترح عبر تجارب حقيقية باستخدام تطبيق الهاتف المحمول المطور ومن خلال تجارب محاكاة شاملة باستخدام برنامج ماتيلا . تظهر كل من التجارب الحقيقية والمحاكاة تحسنًا كبيرًا في كفاءة الطاقة عند تطبيق نظامنا. انخفاض استهلاك الطاقة بنسبة 55٪ عند وجود عدد كبير (مائة فأكثر) من الهواتف الذكية قريبة من بعضها.

CHAPTER 1

INTRODUCTION

Mobile applications and services have become important in every aspect of our life due to the extraordinary technological advances and high popularity of smartphones. Internet communication and positioning services are among these essential services in recent smartphones. GPS[2] and WiFi[3] are the most prevalent technologies used for positioning and internet communication, respectively. Almost every recent smartphone is equipped with a WiFi and a positioning system. GPS and WiFi are preferable among other alternatives, GPS due to its high positioning accuracy comparing to other positioning systems[4], and WiFi due to its high bandwidth, flexibility, well-design and widespread infrastructure[5]. However, GPS and WiFi are known for high energy consumption. Continuous usage of WiFi and GPS would deplete the smartphone battery within few hours even if there are no other services running on the device [6, 7]. On the other hand, energy efficiency of smartphones is commonly considered as a major concern since they have restricted battery capacity due to the size and weight of the phone.

Using smartphones for monitoring large scale events like Hajj provides excellent potentiality for seamless and effective tracking. The need for real time tracking of people with special needs such as elderly and chronic patients, can be satisfied by smartphones. In such crowds and dense networks, there are more energy efficient solutions that can reduce substantial power consumption and still maintain acceptable QoS. For example, using short range communication in dense networks is more energy efficient. Several work in the literature proposed using a low-power communication interface as a secondary communication mean to save energy [8, 9, 10, 11, 12]. Bluetooth is an example of low-power and short-range communication technologies that is attached to almost Every smartphone in the market. Bluetooth popularity is due to its high security potentials, low power, low cost and small size ship [13].

In this thesis, we propose CEET an energy efficient solution for tracking large crowds using smartphones. CEET conserves the energy consumed by smartphones for positioning and communication based on cooperative mobile clustering. With large-scale events like Hajj, it is more likely to have dense smartphones in small areas which can be exploited to form clusters. Neighboring smartphones form a cluster and cooperatively perform the tracking task. Cluster members can share the task of positioning. Only one smartphone can perform the positioning task, instead of making each smartphone do the positioning operations individually. Smartphones are equipped with class 2 Bluetooth device transmitters which have 10 meters range approximately [14]. This assure a positioning accuracy with error

up to 10 meters in addition to the positioning error resulting from GPS which is around 8 meters in average[4]. This range of error is acceptable for many tracking applications. In addition to the energy saved from positioning, a significant amount of energy can be saved from communication. Cluster members reside within small areas, so communication within clusters can be done using short range radio interfaces that consumes low power such as Bluetooth. All communication within a cluster is done via Bluetooth. So cluster can be considered as a Bluetooth Personal Area Network. A cluster consists of one cluster head (CH) and regular cluster members. CH acts as a gateway between the cluster regular nodes and the WiFi access point. Besides, Bluetooth is used for all cluster configuration messages such as broadcasting and cluster construction . CHs are also carrying out the positioning process as illustrated in Figure 1.1. CEET does not require any modifications in the manufacturing equipment. Instead, any user, who is willing to participate, will have an application installed on his/her smartphone. This application, from the user point of view, is responsible of positioning and reporting the tracking information to the server. In addition to the mobile application, a server side application is responsible of processing the tracking information received from users.

1.1 Background

In this section we will give a background overview of technologies and protocols used in the thesis like smartphones, WiFi, Bluetooth and GPS.

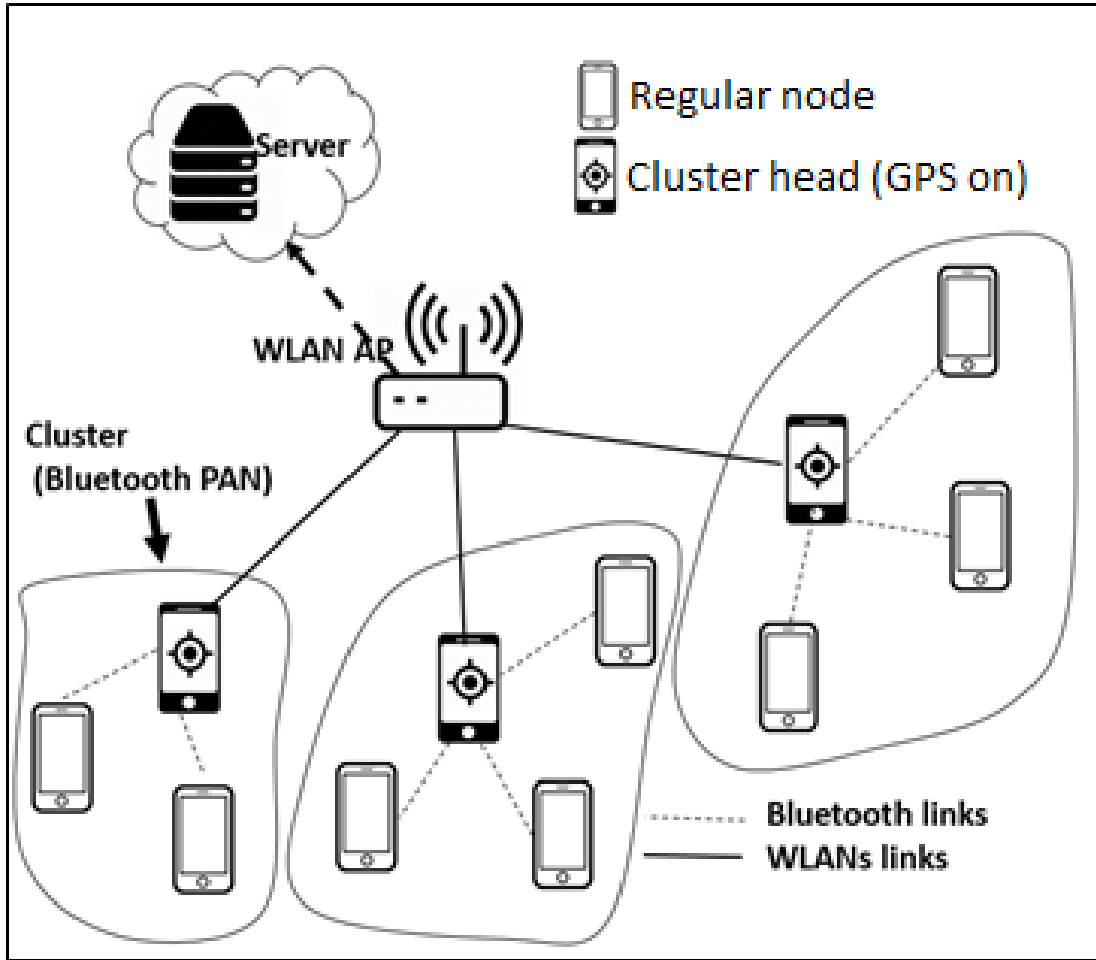


Figure 1.1: Overview of CEET system components

1.1.1 Smartphones

Smartphones are mobile phones equipped with advanced operating systems. Smartphones provide many features and functions of computers such as internet communications, web browsing, multimedia and gaming, in addition to typical phone functionality like voice calls and SMS, and many other advanced technologies like touch screen, GPS and mobile applications. The term of smartphone goes to the early nineties of the last century when IBM introduced its smartphone prototype Angler [15], However, smartphones recently refer to mobile phones with

touch screen and equipped with recent sophisticated technologies. These smartphones emerge in 2007 when apple introduces its smartphone iPhone. At that time Android was growing operating system. Google Android and Apple iOS are the most dominating operating systems in the market. Android had 88% of the market share of smartphones sales in the second quarter of 2018. While Apple iOS has 11.9% and rest operating systems only have less than 0.1% of the market shares[16].

1.1.2 Wi-Fi

Wireless Fidelity (Wi-Fi) is a wireless networking technology based on the IEEE 802.11 standards for Wireless Local Area Networks (WLANs). WiFi is a trademark of the Wi-Fi Alliance. Wi-Fi is mostly deployed as a star topology in the infrastructure mode. One device (called an access point) acts as a router for other devices. It is usually set up for short-distance networks like home and organization networks. Wi-Fi is highly preferable wireless technology due to its easy implementation, ubiquitous and cheap deployment, high bandwidth and wide geographical coverage. Wi-Fi has several versions with different specifications such as radio ranges, bands and bandwidth. Table 1.1 summarizes the main characteristics of 802.11 standards[17]. 802.11 standards family was first introduced in 1997, and the number of standards is still growing as new specifications are actively developed.

Standard	Band (GHz)	Bandwidthm (MHz)	Modulation scheme	Maximum data rate
802.11	2.4	20	DSSS,FHSS	2 Mb/s
802.11b	2.4	20	DSSS	3 Mb/s
802.11a	5	40	OFDM	4 Mb/s
802.11g	2.4	20	DSSS, OFDM	5 Mb/s
802.11n	2.4, 5	20, 40	OFDM	600 Mb/s
802.11ad	60	2160	SC, OFDM	6.76 Gb/s
802.11ac	5	40, 80, 160	OFDM	6.93 Gb/s

Table 1.1: 802.11 standard specifications

1.1.3 Bluetooth

Bluetooth is a short range wireless communication technology operates in the unlicensed ISM band (Industry Scientific Medical band) at 2.4 to 2.485GHz. Bluetooth was introduced in 1994 by Ericson then standardized by IEEE in 2002 as IEEE 802.15.1. Bluetooth Special Interest Group (SIG) manages the Bluetooth specifications development as IEEE stops maintaining the standard. Bluetooth is widely used in everyday applications for portable, moving and fixed devices such as smartphones, wireless headsets, beacons and PCs. Bluetooth popularity is due to its high security potentials, low power, low cost and small size ship. Bluetooth used Frequency Hopping Spread Spectrum (FHSS) to mitigate the collision of other wireless signals in the same frequency band. Bluetooth signal ranges vary depending on the class of Bluetooth transmitter which are divided to three classes. Class one has the highest transmit power and longest range. Table 1.2 shows the Bluetooth transmitter classes. Smartphones use Bluetooth transmitter devices of class two, thus, we will consider the communication range and transmitting power of class 2 for the rest of the thesis since our approach is based on smartphones.

Class	Maximum transmit power	Communication range
Class 1	100 mW	100 meters
Class 2	2.5 mW	10 meters
Class 3	1 mW	< 10 meters

Table 1.2: Bluetooth device transmitter classes

Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a subset of the version 4 of the Bluetooth specifications. It has new protocol suit as an alternative to the classic Bluetooth. BLE is aimed to reduce the transmission power while still reach similar range as the classic Bluetooth. Bluetooth Low Energy devices can be divided into two roles; central and peripheral. A peripheral usually has data that is needed by other devices while a central typically uses the information received from a peripheral to accomplish some task. Peripherals make their presence known by advertising/broadcasting their information. Centrals, on the other hand, are able to scan for peripheral advertisements that might have data they are interested in. When a central discovers a peripheral, the central can request to connect with the device and gain access to the peripherals data.

1.1.4 Smartphones positioning

The current advancements in smartphones in positioning and communication give a great motivation to use smartphones in tracking systems. There are different positioning technologies that can be used nowadays by smartphones for positioning. The quality of positioning in these techniques differs in terms of positioning accuracy, response time and energy consumption. The level of positioning accuracy

and response time can be determined according to the application requirements. However, techniques that provide high level of positioning accuracy like GPS require generally higher power consumption. The following is a background overview of the main positioning technologies.

GPS

The Global Positioning System (GPS) is a world wide satellite system that provides free positioning and time information services for civilian uses any time and anywhere in the world. GPS was initially a project sponsored by united states department of defense and currently operated by US Air force [18]. The GPS system is composed of three main components: Satellites, GPS ground segments (aka control stations) and GPS receivers. Control stations keep updating satellites with their positions and checking their clocks. First GPS satellite was launched in 1978 and currently there are 31 working satellites in orbit. This assures the availability of adequate number of satellites for a receiver to determine its location based on Trilateration. GPS receiver needs at least four satellite on sight to determine its position. GPS receiver doesn't need to send any data to the satellite, the other way around, GPS satellite sends signals containing its position and a time stamp indicates the signal leaving time. Signals travel in the speed of light, thus, GPS receiver can compute its distance from the satellite based on the time difference between transmitting and receiving the signal [18].

WiFi positioning techniques

A number of positioning technologies have been developed to overcome the shortcomings of GPS. Wi-Fi and cellular based positioning systems are the most viable alternatives to GPS. The widespread and cheap Wi-Fi interface cards, besides the affordable positioning accuracy provided by some Wi-Fi techniques, are good inducement to favor Wi-Fi positioning to other alternatives. In Wi-Fi positioning systems, fixed Wi-Fi access points (APs) are used for positioning. Wi-Fi -access points are extensively deployed everywhere in urban areas. Hence, Wi-Fi APs signals are usually overlapped which create a natural reference system for positioning. There is a significant research related to Wi-Fi positioning and several techniques have been developed to exploit Wi-Fi access points in positioning. These techniques can be classified into four main categories [19].

- **RSSI based techniques**

These set of techniques measure the received signal strength from multiple access points and used them to compute the position through trilateration and a propagation model [20, 21, 22]. This class of techniques is easy to deploy since values of RSSI (Received Signal Strength Indication) can be computed easily in nowadays smartphones applications. On the other hand, RSSI depend on the changing environment besides the target position which may cause accuracy problem due to the inadequate modeling of changing environment.

- **Fingerprinting based techniques**

These set of techniques rely on the idea of recording of RSSIs from specific locations to all access points in range and store them in a database. Then if a target passes by the same location, it will have the same fingerprint recorded in the database so we can determine the position [23, 24, 25]. This class of techniques provide high positioning accuracy. However it requires an expensive recording operation and the recorded fingerprints might become an accurate values if the environment changes (e.g. the furniture moved).

- **Triangulation based techniques**

in this approach, mobile measures the Angle of Arrival (AoA) between the mobile and multiple-antenna access points, and then apply triangulation for positioning [26, 27] . These kind of systems that used triangulation can provide very accurate positioning but these systems are difficult to deploy because they require modification in the deployed hardware. For example in some systems it is necessary to have at least eight antennas in each Wi-Fi access point.

- **Time based techniques**

it measures the time that it takes for the signal to travel from Wi-Fi access point to the target mobile [28, 29]. This class of positioning techniques require a hardware modification to enhance the coarse time of flight estimates. Moreover, the positioning accuracy provided by such techniques is low even with the hardware modifications. Some algorithms [30, 31] proposed enhancements to obtain finer Time of Flight (ToF) using joint estimation of

AoA and ToF but that requires all access points to be synchronized which is difficult to apply.

1.2 Problem statement

The technological advances in smartphones have brought promising potentials to tracking systems. GPS and WiFi are widely used technologies in recent smartphones for positioning and communication, respectively. However, both GPS and WiFi have serious energy problem [6, 7]. For large scale tracking systems, where tracked people are supposed to move in groups, the continuous usage of the individual smartphones GPS and WiFi is not an energy efficient solution. This motivate us to propose a cooperative approach between smartphones for tracking with goal of increasing energy efficiency. The proposed approach exploits the coexistence of multiple communication interfaces (WiFi and Bluetooth) in recent smartphones. Neighboring smartphones are cooperatively grouped to form a cluster. A cluster is a network of one dynamically selected cluster head and regular members that communicate locally via Bluetooth. The cluster head is responsible of positioning and sharing positioning information with the rest of cluster members. It, also, acts as a gateway between the cluster regular members and the server. We present a clustering approach according to the available energy and the energy cost.

In this thesis we address the theoretical and technical aspects to implement this system. Our thesis will address the following research questions:

What is the impact of the proposed solution on increasing the energy efficiency?

What are the factors that have impact on the energy efficiency when applying our approach?

What is the optimal cluster size? What is its impact on energy efficiency?

How often the cluster head rotation should be for better performance?

What is the impact of the proposed solution on network stability?

Does the proposed solution guarantee a fair energy saving for all smartphones participating in the system?

From technical point of view:

There are set of features that is essential to implement the proposed system in real smartphones such as automatic pairing and connecting between smartphones and automatic enabling and disabling WiFi and GPS services. Moreover, there are security standards that are enforced by smartphones manufacturers that could be barriers to implement the proposed system. Therefore, we try in this thesis to answer these question:

Is the proposed solution feasible to be implemented in real smartphones?

What are the features that are essential to apply the proposed system and are they applicable in smartphones?

What are the technical and industrial barriers that could rise when implementing the system?

What are the system requirements (software and hardware) to implement the system?

1.3 Thesis Contribution

The main objective of this thesis is to design and implement an energy efficient tracking system using smartphones. This main objective has been achieved through the development of CEET mobile application and a server side application to store and visualize the tracking information collected from CEET apps.

Besides the main objective we can identify the following contributions:

- Propose an energy efficient clustering protocol for smartphones to cooperatively achieve tracking by sharing smartphones GPS and long range communication services. We extend the energy saving gained from reducing the communication power proposed in [12] to be for both communication and positioning.
- Introduce an analysis for the power consumption, identify the saving energy method, and evaluate the proposed solution in terms of energy saving, fairness and stability of the network and compare it to other solutions through extensive simulations.
- Model the clustering problem as a mixed integer programming problem and solve it using GAMS to get the optimal cluster construction.
- Study the feasibility of the implementing the proposed system in real smartphones. We address the technical issues that can rise when implementing such systems in real mobile apps like security including auto Bluetooth pairing, auto connection, automatic enabling, and disabling location services.

1.4 Organization of Thesis

The rest of the thesis is organized as follows. Chapter 2 provides an overview of the previous work related to reducing power consumption for tracking, wireless clustering and the multiple radio interfaces. Chapter 3 covers our proposed solution and the problem formulation and assumptions. In chapter 4 and 5 we discuss the design and implementation issues of the proposed system in real smartphones. We address the feasibility of the solution and discuss the obstacles and barriers that could raise when implementing the system in real smartphones. Performance evaluation of the proposed system is conducted in chapter 6, through extensive simulations and real experiments. Chapter 7 is left for conclusion and future directions.

CHAPTER 2

RELATED WORK

In this chapter we review the work related to reducing the energy used by tracking systems. Our work focuses on reducing the energy used for both communication and positioning since they are the main pillars in any tracking system. The survey provides a short review of the techniques used to reduce the positioning power in general. Then we survey the cooperation approaches for wireless communication and positioning . Since our approach exploits coexistence of multiple radio communication interfaces, we reviewed the work addressing the multiple interfaces in wireless communication.

A significant amount research in the literature has been carried out to reduce the power consumption of positioning while can still provide a good level of accuracy. For instance, one of the common approaches to overcome the high energy consumption by GPS is to duty cycle GPS by making GPS operates in lower rate to save energy. However, Duty-cycling of GPS trade-off the energy efficiency for positioning accuracy. Duty cycling is a good solution to save energy where the

high accuracy is not requirement for the application. EnTracked [32] is an example of systems that follow a duty cycling approach but it can still guarantee a good quality of service for positioning in terms of accuracy by using the velocity measured by the accelerometer to schedule the next GPS update. EnTracked is a smart technique in terms of energy efficiency and positioning accuracy but it doesn't take into account cases when GPS is not available.

Micro-Blog [33] explores the accuracy and energy consumption of positioning techniques GSM, GPS and Wi-Fi. The proposed algorithm can choose adaptively the low energy method if it meets the application requirement. A probabilistic model is proposed in [34] to choose dynamically among positioning techniques according to the application positioning accuracy requirements. A model also proposed to determine the satisfactory accuracy for particular applications such as social networking and search applications.

RAPS is proposed in [7] which is a rate adaptive GPS based positioning for smartphones to overcome the shortcomings of GPS especially the high power consumption and the lack of accuracy in indoor environments. It uses a number of techniques to determine when to switch on the GPS only if the positioning uncertainty exceeds the threshold. It uses Bluetooth communication to minimize the positioning uncertainty. Also, it utilizes the cell tower-RSS to determine locations when GPS signals are unavailable.

The proposed solutions above are not adapting the cooperation between smartphones. They are proposed for single device working alone for positioning. More-

over, these approaches require modification on the manufacturing specifications of the devices. In the following section we survey the cooperative techniques for both communication and positioning.

2.1 Cooperative wireless networks

The concept of cooperation between nodes has been extensively studied in the domain of wireless networks. Network nodes cooperate to increase the performance of the network and overcome many wireless network constraints. For example, Cooperation between wireless nodes can increase network throughput [35, 36, 37], reduce latency, extending the network coverage [38, 39, 40] balance the load [41, 42], enhance the QoS and assure energy efficiency.

In [43] authors present a cooperative video distribution system to reduce the power used in real time video streaming and enhance the delivery efficiency. In the system model, a base station is selected to transmit the video stream to other mobile devices. Two low-complexity approximation algorithms were proposed to select an energy efficient flow.

In domain of positioning, many cooperation schemes in wireless mobile networks have been proposed to increase the positioning accuracy or reduce the power consumption. For example, Sammarco et al. [44] propose a client server based approach for cooperative positioning. In this approach mobile phones cooperate to retrieve their position using cell ID and signal strength. Smartphone uses its Bluetooth interface to ask its neighbors their signal strength and cell ID and send

it to the server which has a database storing signal strength values and estimate the position and send it back to the mobile phone. In [45] authors studied estimation theories for cooperative localization using Ultrawide Bandwidth (UWB) wireless networks. They proposed ranging models exploiting the nanoseconds delays in UWB networks which provides aa accurate positioning to the centimeter level. They also proposed a novel algorithm called SPAWN which reduce the communication messages and increase the localization accuracy and robustness by computing a net-factor graph, and a fit messaging schedule. Authors in [46] propose a cooperative approach for localization based on smartphones. They used Bluetooth and WiFi links to overcome the problem of indoor positioning where GNSS signals are missing or weak. They discuss and analyze the localization accuracy and finally they developed an application implementing their approach. The approach focuses in the indoor localization and evaluates accuracy of positioning specially when there is more than one wall between the outdoor anchor node and the node indoor.

In [47], authors introduce a comprehensive study of the theoretical and practical aspects of the cooperative localization. They categorized cooperative localization into two categories: spatial and temporal cooperative localization. Spatial cooperative localization occurs between spatially neighboring nodes while temporal cooperation obtains the location information from the positioning history of the node itself. They also categorized the spatial localization into distributed and centralized algorithms. They argue that centralized algorithms achieve higher

positioning accuracy while distributed algorithms require lower communication overhead.

2.2 Wireless network clustering

Clustering of wireless devices has been widely investigated by the research community with different objectives.

The lowest-ID algorithm proposed in [48] was the first clustering algorithm proposed for wireless networks. In this approach each node has a unique ID which is used for cluster head selection. Nodes with highest ID (in contrary to its name the lowest ID) is more likely to be selected as a cluster head than nodes with lower IDs. The problem with this approach is the selection of the same nodes as a cluster head in every round even if the nodes are mobile. This leads to unfair power consumption.

In the Highest-Degree clustering algorithm proposed in [49], nodes are selected as cluster heads according to their degree. Nodes with higher degree have more probability to be selected. The node degree is determined according to the number of 1-hop neighboring nodes. The more 1-hop neighboring nodes the higher the degree. As a result, this approach reduces the number of clusters. One of the problem of this algorithm is that it is very sensitive to node mobility. A few nodes movement would change the nodes degree leading to ripple impact.

Least Cluster Change (LCC) clustering algorithm [50] is an improvement of the Lowest-ID algorithm. It follows the same paradigm in the cluster construction.

However, the re-clustering process is done in response to some certain events rather than periodically. Cluster reformation occurs when node disconnects, or clusters overlap. Since the reformation of clusters does not happen periodically, this leads to unbalanced in power consumption if the events that trigger the cluster reformation do not happen for long periods.

Max-Min [51] is the first clustering algorithm that considers multi-hop clustering. Cluster members are not necessarily have direct communication links (1-hop) to the cluster heads which leads to more stable networks. The previous algorithms have a general purpose. Many clustering algorithms have been proposed to adapt different scenarios that require different considerations such as load balancing or energy efficiency.

Clustering is widely used especially in wireless sensor networks to reduce the power consumption of sensor nodes. A variety of clustering algorithms have been proposed in the literature to address the energy efficiency problem. Energy efficiency is essential for wireless sensor due to their limited batteries.

LEACH [52] is one of the earliest and well known algorithms for saving energy for wireless sensor networks. In LEACH cluster heads gathers data from regular nodes and aggregates it then send it to the sink. To balance the load among cluster nodes, the cluster head role is rotated periodically based on a priority values randomly generated and assigned to each member in the cluster. However, the randomization to rotate the cluster head cant assure fairness in load balancing among cluster nodes especially with mobile networks which were not considered

in the protocol design.

Another variation of LEACH was introduced in [53] called TL-LEACH. Authors proposed a hierarchical approach with three layers. First layer consists of the regular nodes while second layer for cluster heads that aggregate data from regular nodes. Nodes with higher battery levels are selected for the third layer, and they act as relays between the cluster head and the sink. This algorithm outperforms the original LEACH in terms of the energy saving.

An enhancement to TL-LEACH algorithm has been proposed in [54] to improve the energy efficiency. Authors proposed a centralized optimization model for selecting the third layer nodes (called in their paper grid heads). The fuzzy c-means algorithm is used to minimize the overall distance between nodes and their cluster head and subsequently increase the communication energy efficiency.

An enhancement to LEACH has been proposed in [55] to support multi-hop clustering and reduce the power consumption. Authors have added new rules for CH selection and rotation and they proposed multi-hop model based in leveling and generic routing.

Most of the above algorithms do not consider nodes mobility after clustering. Clustering of mobile nodes has posed new challenges in terms of connectivity and energy efficiency. A number of clustering protocols have been proposed to support nodes mobility. One of the earliest protocols that support nodes mobility is LEACH-M protocol [56] which is a modified version of LEACH that supports node mobility. The protocol proposed a membership declaration to confirm the

enrolment of sensor nodes in specific cluster. If a sensor node did not receive a request from its cluster head during two consecutive frames, it would assume that it has moved out of the cluster head communication range. Then the node will broadcast a request to join a new cluster. LEACH-M protocol increases the packet delivery rate but it increase the control messages overhead.

In [57], an enhancement to the LEACH-M protocol is proposed. For the selection of the cluster head, they argue that it is better to choose a node with less mobility relative to its neighbors. The node with minimum mobility in a group is more likely to be chosen as a cluster head. A cluster based routing CBR-Mobile protocol for mobile sensor nodes has been proposed in [58]. The CBR-Mobile is an adaptive TDMA scheduling protocol that can reassign time slot adaptively according to the mobility and traffic conditions in the network. CBR-Mobile is a cross layer protocol where the cluster based routing cooperates with the MAC layer to support the node mobility. CBR-Mobile can improve the packet delivery ratio but with the cost of increasing the control messages overhead.

HEED [59] uses a vector of metrics for choosing CH such as residual energy and within cluster communication cost. The cluster head role is not randomly rotated like LEACH but according to battery level of each node which assures a longer lifetime for the network. However, HEED considers prolonging the network lifetime and overlook the fairness among nodes which make it more suitable for scenarios of group networking where the whole network nodes share the same task.

CONET [12] is an energy efficient distributed clustering protocol for mobile de-

vices with multiple communication interfaces. Inter clusters communication are performed via Bluetooth and cluster heads represent gateways between the cluster members and the WiFi access point. Only CH enables its WiFi which saves energy for rest of the cluster members. Selection of the cluster head depends on the bandwidth requirements and the energy saving ratio. To force fairness and load balancing every regular node sets a timer when joining a cluster. RN disconnects from the cluster when the timer expires. An extension to CONET has been introduced in [60] proposing three cost metrics for clustering: the residual energy, WiFi physical data rate and number of mobile stations expected to cooperate.

In this thesis we propose an enhancement to CONET clustering algorithm to increase the energy efficiency. Moreover, our solution gains more energy saving by reducing the use of GPS in addition to the WiFi proposed in the original CONET.

2.3 Multiple radio communications

The coexistence of multiple radio interfaces in mobile devices motivates the use of heterogeneous wireless technologies to achieve different goals. Systems in such heterogeneous environment can exploit the advantages and overcome the shortcomings of different radio interfaces. In the literature several works have been proposed to exploit the coexistence of multiple radio interfaces to achieve many goals such as energy efficiency, interference mitigation, increasing data throughput, reducing the latency, network discovery, and the recovery of connection loss. Authors in [61] proposed a combination of WLAN and the short range 802.15.4

protocol. However, in this work roles are allocated statically to each radio interface. All communications are assigned to WiFi interface while the chip CC2420 is reserved only for control messages. Another combination of 802.11 WLAN and the low power 802.15.4 has been proposed in [62]. Authors have proposed a bulk communication approach to save energy. The idea is to reduce the time spent by high power WLAN interface in idle mode and switch off instead. The WLAN interface keeps switched off till a certain amount of data is buffered then the WLAN interface is used to send the bulk data while the low power radio interface is used for waking up handshake and control messages. Coolspots [10] is one of the earliest protocols that exploits the coexistence of multiple radios. They proposed using Bluetooth when it is available and can satisfy the bandwidth requirements otherwise it switches to use the WiFi interface.

Authors in [63] proposed an approach for Voice over IP in smartphones exploiting the multiple radio interfaces. They used Bluetooth as a secondary channel to wake up the WiFi interface.

In [64] authors proposed a wireless sensor nodes that combine three radio interfaces, WiFi, Bluetooth and 6LoWPAN to reduce the energy consumption and the latency and increase the overall robustness of the system. They proposed a dynamic mechanism to adeptly select the appropriate radio interface depending on the application requirements and the operating conditions.

Another combination of WiFi and 6LoWPAN is proposed in [8] to enhance the connectivity and reduce the wireless communication interference. They proposed a

cognitive algorithm to select the appropriate radio interface using interface priority table created and updated periodically by the algorithm.

Many approaches have been proposed for selecting the radio Interface in Heterogeneous Wireless Networks. In [65] proposed a probabilistic approach for selecting the network interface. they considered metric like the price charged and the QoS to select the appropriate interface.

None of the above studies investigate the power used in smartphones. The study in [66] investigate and evaluate the common intuition that the Bluetooth has lower power consumption than WiFi in smartphones. They examine the power consumption and bandwidth for both WiFi and Bluetooth in different settings. They also compare the power consumption in the idle mode for the both interfaces. They identify many scenarios that WiFi outperforms Bluetooth in terms of power efficiency. They conclude that the power saving mode is working effectively in all smartphones tested in their experiment in the WiFi infrastructure mode. Thus, the battery is hardly drained when the smartphone is connected to the WiFi access point but not communicating. They suggest that using WiFi is better in situations that require high data rates. While in situation with low data rates it is more energy efficient to use Bluetooth. In regards to our system, the data rate is low since only health information and location are needed to send periodically which account for few bytes per seconds. Thus, our initial hypothesis that Bluetooth is more energy efficient for our system don't contradict with this study.

CHAPTER 3

CEET PROTOCOL

In this chapter, we introduce CEET in detail. First we illustrate the design and operations of CEET. Then we define the parameters and power consumption formulation.

Before we go through the protocol specifications, we should present the following assumptions about smartphones and the network. Smartphones are referred to as nodes for the rest of the paper.

- All smartphones are equipped with Bluetooth, WLAN/mobile data and GPS.
- Each node has an access to the Internet either through a WLAN access point or through cellular networks.
- Participants often move which means our clustering algorithm should assure seamless hand off from one cluster to another.
- All smartphones have the same Bluetooth range.

3.1 CEET operations

Algorithm 1 is a pseudo code that represent the clustering operations proposed in CEET.

The following section presents an illustrated examples of CEET operations.

3.1.1 Cluster head advertisement

When a node is booted up, it announces itself as a cluster head and it broadcasts information about itself like the available bandwidth, current cost, location information, ID and network address. Initially, we consider the reciprocal value of the smartphone battery level as the clustering cost value. Since the node is just booted up, it has no regular nodes connected to it. It is called a trivial cluster head in this case. It waits for receiving join requests and checking for neighboring CHs, simultaneously.

Non-trivial cluster heads (cluster heads that have connected regular nodes within the cluster) announce their CH timer instead of clustering cost. CHs with higher timers are more likely to be chosen by other nodes because it assures that nodes spend more time as regular nodes, thus, save more energy. CH stops advertising when it has the maximum allowed number of RNs.

Nodes Advertise their resources through Bluetooth and they keep broadcasting as long as they are cluster heads. Once a node is admitted as a regular node to a cluster, it stops advertising and starts to forward its tracking information through Bluetooth to the cluster head.

Algorithm 1: The clustering algorithm

Data: S_{ch} is set of neighboring CHs
 S_{bch} is set of bruned CHs
 CH_{time} is the time a node should serve as a CH when selected

```
1 while battery is not drained do
2   Become a CH;
3   broadcast data;
4   if join request received then
5     if have enough bandwidth then
6       if RNs in the cluster = 0 then
7         | Set CH timer= $CH_{time}$ ;
8       end
9       send accept;
10    else
11      | send reject;
12    end
13  end
14  if RNs exist in the cluster then
15    | Set CH timer = 0 Continue
16  else
17    forall CHs in  $S_{ch}$  do
18       $CH_{best}$  = CH with highest CH timer in  $S_{ch}$  then the lowest cost
19      if timers are equal;
20      send a join request to  $CH_{best}$  ;
21      if receive an accept then
22        become a RN ;
23        set RN timer ;
24        while CH timer is not expired CHi is reachable bandwidth
25          is satisfied do
26            | continue as RN
27          end
28        else
29          | move  $CH_{best}$  to  $S_{bch}$ 
30        end
31    end
32  end
33 end
```

3.1.2 Cluster Head Selection

If a CH has no RNs in the cluster (trivial CH), neither receives a join request, it tries to find a neighboring CH to connect to. It selects CH with highest CH timer provided that it has sufficient bandwidth. Choosing a CH with higher timer assures that the node can stay a longer time as a RN therefore reduce the number of hand offs and increase the energy efficiency. If there is no nearby CHs, node selects next trivial CH with the lowest clustering cost. If a node selects a CH, it sends a join request. If it is accepted, it becomes a regular node in the cluster. If it receives a reject or not receiving an acceptance, it tries to join the next CH following the same procedure. It keeps its role as CH as long as it does not receive an acceptance message.

CH checks always number of RNs in its cluster. If there is at least one node, it keeps its role as a CH. If it receives a join request, it accepts the join request as long as it has sufficient bandwidth and the number of connected nodes is less than the maximum allowed number of slaves in piconet. If a trivial cluster head receives a join request and accepts it, it set a timer to define the time it will serve as a cluster head. It accepts join requests as long as it is in the cluster head role.

Figure 3.1 gives an illustrative example for cluster head advertisement. In this example we assumed that four nodes have booted up simultaneously. In the initial state, all nodes are cluster head nodes and they all advertise their resources along with their clustering cost at the same time (battery level). All nodes are listening to packets of other nodes while advertise their packets. Advertisement messages

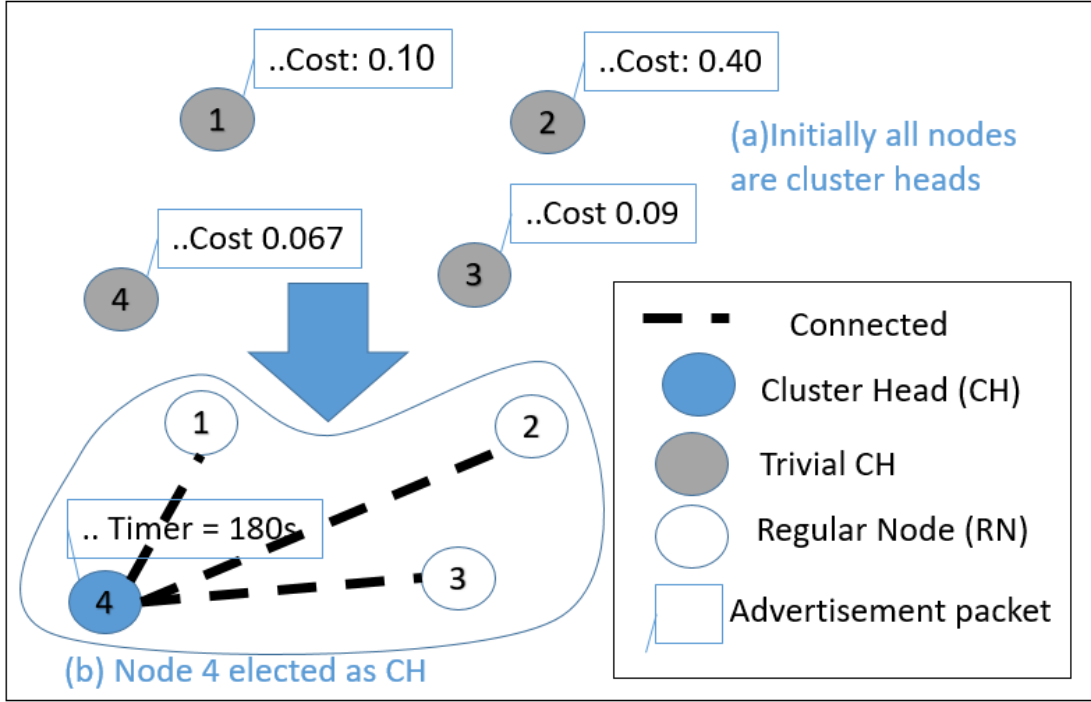


Figure 3.1: An illustrative example of CEET initial clustering

are transmitted through Bluetooth and all nodes are within the Bluetooth range of each other, so each node can listen to all advertising packets of all other nodes in the example. Since Node 4 has the lowest cost, other nodes send join request to Node 4. Node 4 sends an acceptance acknowledgment for nodes assuming that it has a sufficient bandwidth to serve them all. Nodes other than Node 4 change their role to regular node and stop advertising. Node 4 continues advertising but it advertises its CH timer instead of the clustering cost.

Figure 3.2 shows an example of a node selecting a cluster head from two neighboring CHs. Node 1 can hear both node 4 and node 6 advertisements. Since node 4 has the lowest cost, node 1 chooses to join 4. Node 4 accepts the join request assuming it has enough bandwidth.

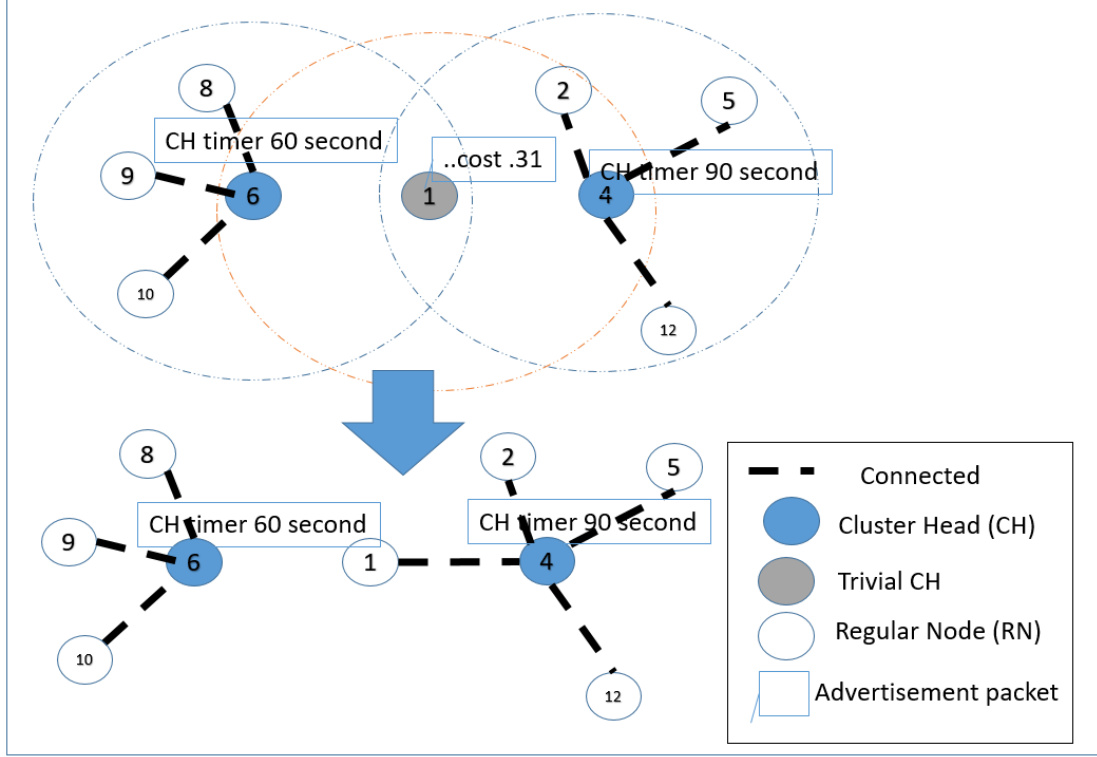


Figure 3.2: Example of cluster head selection based on the remaining CH timer

3.1.3 Role switching

To balance the energy saving among all nodes in the network, it is important to rotate the CH role routinely among all nodes. When a node (trivial cluster head) is selected as a cluster head, it starts a timer for a predefined period. Later we will study the effect of this timer on fairness and stability of the network. When the timer expires, it disconnects from all connected regular nodes in its cluster as shown in Figure 3.3. All nodes after disconnecting from the cluster starts looking for the next cluster head. Either they connect to an existed cluster or elect one of them to be a cluster head. Unless a node is admitted to a new cluster, it changes its role to be a trivial CH.

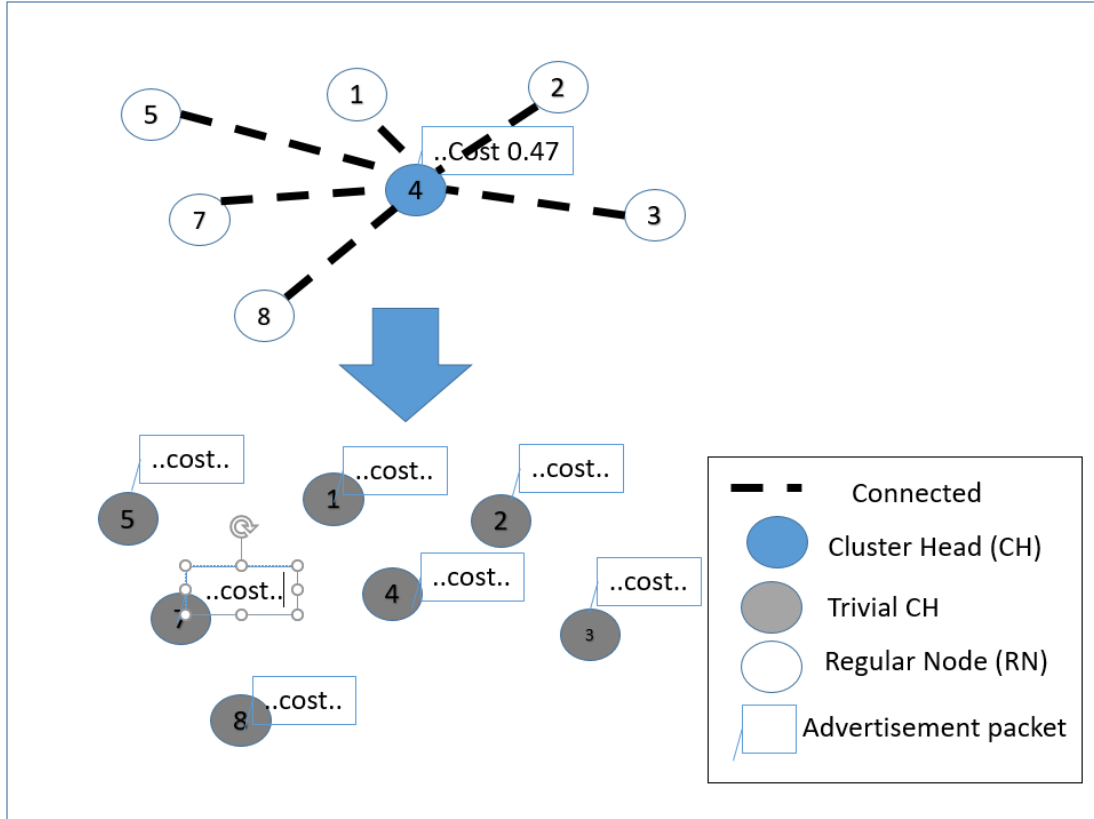


Figure 3.3: Example of a cluster head timer expired

3.1.4 Connection loss

Besides the RN timer expiration, there are other reasons to disconnect from a cluster such as connection loss. The cluster head may become unreachable due to its mobility or the mobility of the regular node itself. If a regular node becomes outside the Bluetooth communication range of the cluster head, it hands off and start the procedure of finding next cluster head. The connection loss may also occur due to the failure of the cluster head itself such as switching off the Bluetooth or switching off the smartphone itself.

3.1.5 Bandwidth Requirements

The data rate in our application is constant. Smartphones collect small amount of data from health sensors and report it periodically (i.e. 30 seconds). This corresponds to small number of bytes per second which can be satisfied by the cluster head all the time. However, our clustering algorithm can be general and serves other applications not only ours. So in our algorithm we consider a variable data rate. Thus, as the data rate is changing over time, the bandwidth requirements of all regular nodes should be satisfied all the time by the cluster head. A regular nodes is disconnected from the cluster if the cluster head can not serve its bandwidth.

3.2 Power Consumption Formulation

Our goal is to minimize the energy used by smartphones for tracking purpose. The energy saving should be fair for all participating smartphones. To achieve that we propose a clustering algorithm to share the task of localization and communication among nodes within every cluster. The goal of our clustering algorithm is to find the optimal selection of the cluster head and normal members for each cluster, with goal of minimizing tracking energy. Thus, we use the tracking power as the cost function. It should be equal for all participating smartphones as much as possible.

Assume that we have a smartphone that starts to cooperate at time 0, its role as a cluster head or a regular member can be determined depending on usage history

of its resources. To compute the cost of node (i) at time (t), we should consider the energy consumption history of node (i). For that we use the cumulative amount of energy used by the node since its participation. The cost of node (i) at time (t) is the cumulative power from time 0 to time (t) divided by the expected power used to achieve the task in the traditional way (GPS and WiFi) for the same period. Therefore, we can define $cost_i(t)$ as follows:

$$cost_i(t) = \frac{P_i^{CEET}}{P_i^{trd}} \quad (3.1)$$

where P_i^{CEET} represents the power consumption by node (i) when running CEET protocol and P_i^{trd} represents the expected power that would be used by node (i) through the traditional way for positioning and communication. In the traditional approach, the power needed is the GPS power and WiFi power. Therefore, P_i^{trd} can be defined as follows:

$$P_i^{trd} = P_i^W + P_i^G \quad (3.2)$$

where P_i^w represents WiFi power to transmit local data (r_i) of node (i) and P_i^G represents GPS of node (i). we can define both P_i^W as follows:

$$P_i^W = P_i^{W_A} \frac{r_i}{R_i^w} + P_i^{W_I} (1 - \frac{r_i}{R_i^w}) \quad (3.3)$$

Similarly we can define the Bluetooth power (P_i^B) to transmit r_i as follows:

$$P_i^B = P_i^{B_A} \cdot \frac{r_i}{R_i^B} + P_i^{B_I} (1 - \frac{r_i}{R_i^B}) \quad (3.4)$$

$P_i^{W_A}$ and $P_i^{B_A}$ represent WiFi and Bluetooth power of node i when they are active (i.e. transmitting). R_i^W denotes the maximum transmission rate for the WiFi interface, while $P_i^{W_I}$ and $P_i^{B_I}$ represent both, respectively, when they are idle (listening but not sending or receiving).

The following equation represents the cumulative energy:

$$E_i^{new} = E_i^{old} + P_i^{CEET} \quad (3.5)$$

P_i^{CEET} depends on the current role of the node whether it is a regular node or a cluster head. If node i current role is RN, then P_i^{CEET} is equal to P_i^B where P_i^B denotes the Bluetooth power to forward node i local data to its cluster head. If node (i) is a cluster head, then current P_i^{CEET} can be defined as follows:

$$P_i^{CEET} = P_i^W + P_i^G + P_i^B + \sum_{\substack{j=1 \\ i \neq j}}^n X_{ij} \cdot P_j^{Frwd} \quad (3.6)$$

$$X_{ij} = \begin{cases} 1 & \text{if node j is connected to CH i} \\ 0 & \text{otherwise} \end{cases} \quad (3.7)$$

P_j^{frwd} represents the power needed by CH i to forward data of node j which is a regular node in the same cluster. The following equation defines the P_j^{frwd} :

$$P_j^{frwd} = \frac{r_j}{R_i^B} (P_i^{B_A} - P_i^{B_I}) + \frac{r_j}{R_i^W} (P_i^{W_A} - P_i^{W_I}) \quad (3.8)$$

R_i^B and R_i^W represent the maximum transmission rate for Bluetooth and WiFi of

node i. $r_j R_i^B$ represents the power consumed by CH i to receive data from node j through Bluetooth. Since we add the power to receive the data of node j we should subtract idle Bluetooth idle power for the time to receive the same amount of data which is represented by $r_j \cdot R_i^B$. Therefore, the expression $\frac{r_j}{R_i^B}(P_i^{B_A} - P_i^{B_I})$ represents the actual CH (i) power to receive data from node (j) through Bluetooth. Similarly $\frac{r_j}{R_i^W}(P_i^{W_A} - P_i^{W_I})$ is the CH i WiFi power to forward same data.

3.3 Problem Modeling

To model this problem as an optimization problem, let's first define the following terms:

Let $S = 1..N$ be the set of nodes (smartphones).

C_i denotes the clustering cost for node (i) which is defined in equation 3.1.

$FreeBW_i$ is the available bandwidth.

k is the maximum number of regular nodes in a cluster (Bluetooth slaves in a piconet)

D_{ij} indicates if node i and j are within the Bluetooth range of each other.

$$D_{ij} = \begin{cases} 1 & \text{if nodes i, j can reach each other} \\ 0 & \text{otherwise} \end{cases}$$

Then, we define our binary decision variables.

$$X_{ij} = \begin{cases} 1 & \text{if node } j \text{ is connected to CH } i \\ 0 & \text{otherwise} \end{cases}$$

$$Y_i = \begin{cases} 1 & \text{if node } i \text{ is a cluster head node} \\ 0 & \text{otherwise} \end{cases}$$

The goal of our optimization model is to reduce the tracking power consumption for all nodes in the network. Therefore, we choose to the objective function to be the total power consumption of the whole network as our objective function. The output of the optimization model is an optimal construction of cluster in terms of power consumption, specifying the CH for each cluster. The optimal solution will tend to reduce the number of nodes that are not connected to any cluster. We can model our problem as follows.

$$\text{Min} \sum_{i=1}^n \sum_{\substack{j=1 \\ i \neq j}}^n X_{ij} \cdot (P_j^B + P_j^{fwd}) + \sum_{i=1}^n Y_i \cdot (P_i^W + P_i^G + P_i^B) \quad (3.9a)$$

Subject to:

$$X_{ij} \cdot C_i \leq C_j \quad \forall (i, j) \in S, i \neq j \quad (3.9b)$$

$$\sum_{i=1}^n X_{ij} + Y_j = 1 \quad \forall (i, j) \in S, i \neq j \quad (3.9c)$$

$$\sum_{i=1}^n X_{ij} \leq 1 \quad \forall (i, j) \in S, i \neq j \quad (3.9d)$$

$$\sum_{j=1}^n X_{ij} \leq k \quad \forall (i, j) \in S, i \neq j \quad (3.9e)$$

$$\sum_{j=1}^n X_{ij} \cdot r_j \leq FreeBW_i \quad \forall (i, j) \in S, i \neq j \quad (3.9f)$$

$$X_{ij} \leq D_{ij} \quad \forall (i, j) \in S, i \neq j \quad (3.9g)$$

The objective function (3.9a) aims at minimizing the total consumption power for the whole network. The first term of the equation represents the tracking power for a node in a regular node (RN) role. It takes into account the power of the node itself to send its data to the CH via Bluetooth and the power needed by its CH to forward its data. The GPS power is neglected since RN switch off their GPS. The second term of the equation defines the tracking power of the node in CH role. It consists of GPS power, WiFi power to transmit local data rate and the power of Bluetooth. Power to forward data of other RNs in the cluster, are computed in the first term.

Equations from (3.9b) to (3.9g) represent the problem constraints. Equation (3.9b) guarantees that a cluster head can only admit new members with higher cost to assure that a CH can only serve nodes that had shared their resources before, hence, enhance fairness in energy saving for all nodes. While equation (3.9c)

ensures that all nodes are either a CH or a regular node. Equation (3.9d) ensures that every node is connected to one CH at most. The node should not be connected to more than one CH or it should be a CH itself. Equation (3.9e) specifies the maximum number of nodes in a cluster, since the cluster is a Bluetooth local area network (piconet) which is limited to one master and seven slaves. Equation (3.9f) is the bandwidth requirement. CH must satisfy the bandwidth requirements of all nodes in its cluster and it can't accept new RN if it doesn't have sufficient bandwidth to serve it. Finally, constraint (3.9g) assures that every cluster head is reachable by all nodes in its cluster.

CHAPTER 4

CEET APPLICATION DESIGN

In this chapter we define the system architecture and its components. We define the components interfaces, behavior and connections. This chapter illustrates in detail the architecture of both the mobile application and the server-side application. We identify here the technologies to be used in our system, data architectures and system layering etc..

4.1 Use Case Diagrams

The Use Case Model defines the main functions of the proposed application and describes the interactions between users (human or devices) and the system. Use cases are units of the proposed system with focus on the users not the system itself. A case study may include sub-case studies, or it could be extension for another case study. For example, in our application the log in and sign up in the system are different case studies. In use case modeling, use cases are units of meaningful work that is performed by actors. Actors are the users of the system

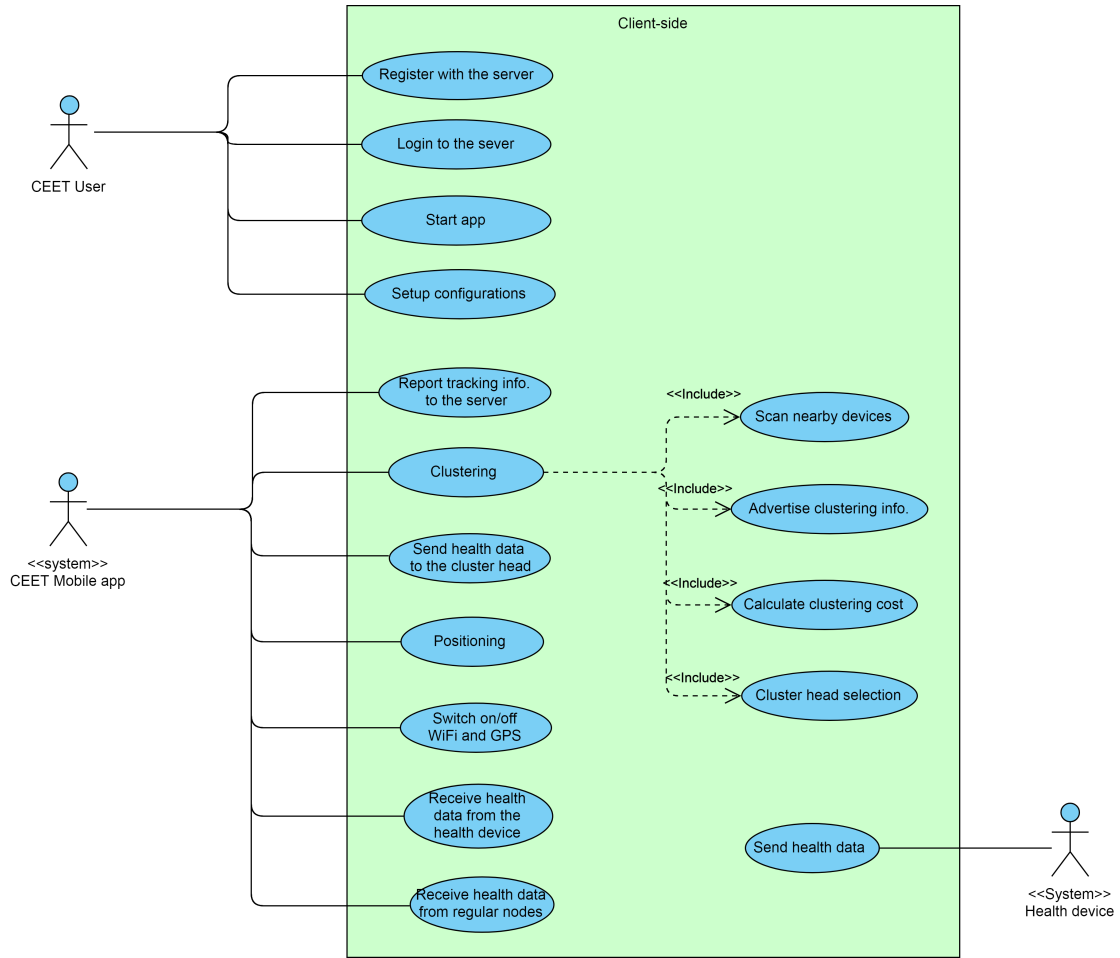


Figure 4.1: Use case diagram for the CEET mobile application

and they could be either humans or systems. In our system we can identify three type of actors in the client side (the mobile application) and two actors in the server side. Actors in the client side are:

- CEET application user (human)
- CEET mobile application (system)
- Health device (sytem)

In the server side, we can identify the following two actors:

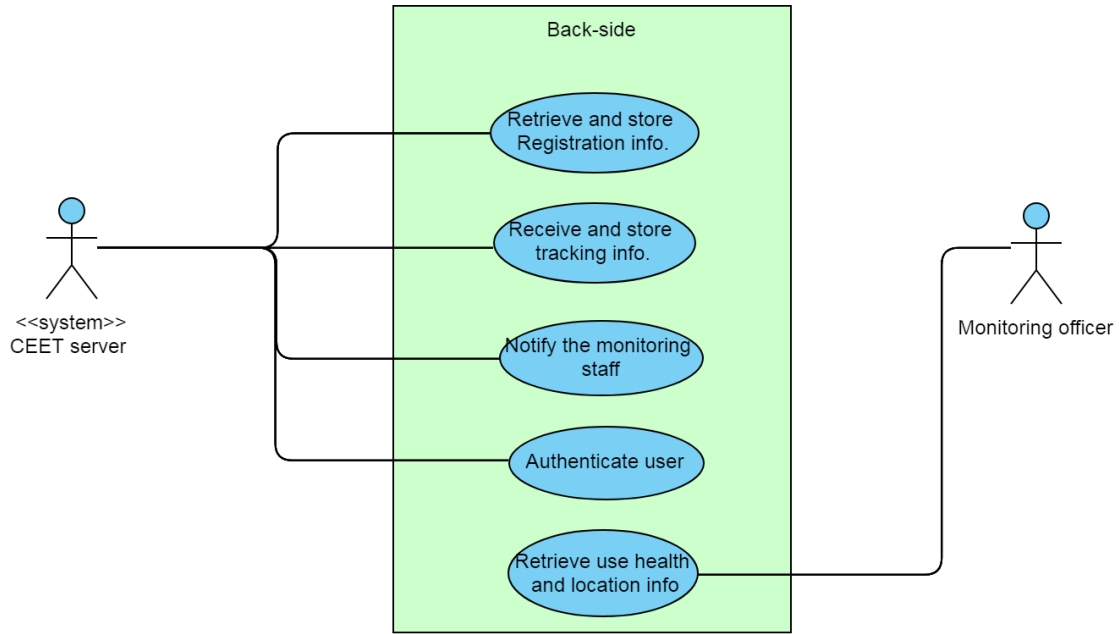


Figure 4.2: Use case diagram for CEET server

- Monitoring officer (human)
- CEET server (system)

The class diagram in 4.3 represents the CEET application main classes and their relationships.

4.2 Implementation Technologies

4.2.1 Platform

Android application can be implemented using many programming languages like Java, C++, C#(XAMARIN), Java script (like React Native) and Kotlin. Google in its Android development environment supports many programming languages: Java, C++ and Kotlin. In our thesis project we chose to work in Java as the

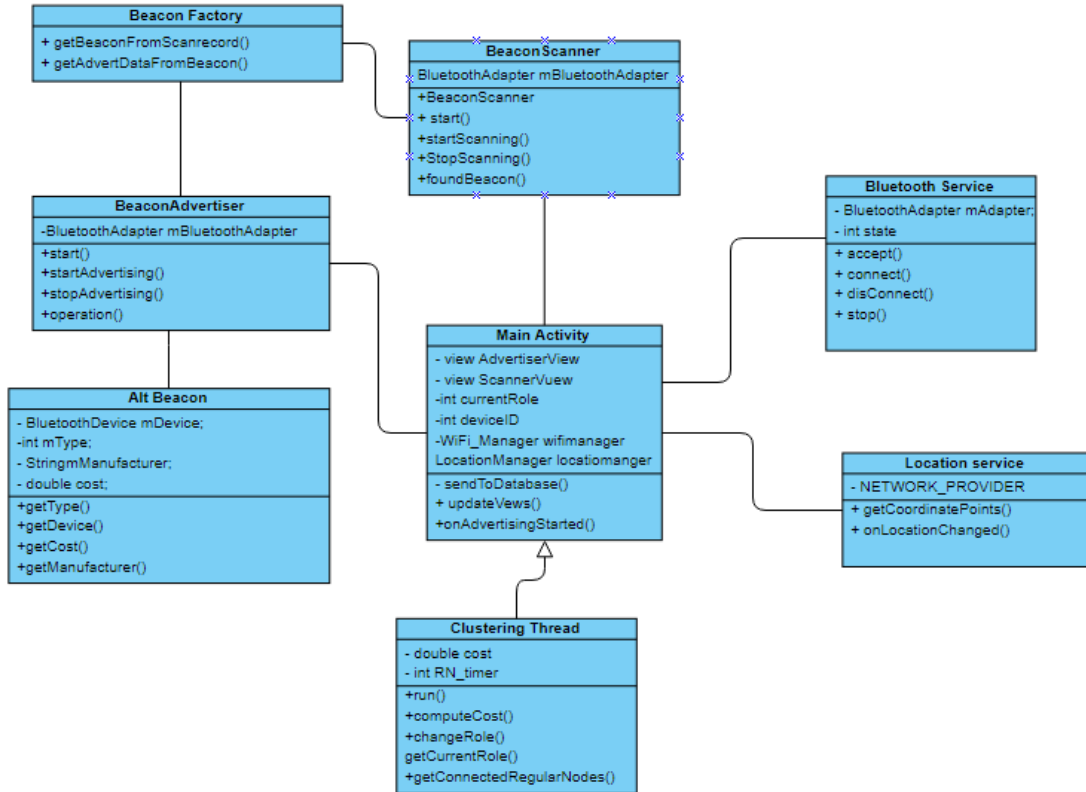


Figure 4.3: CEET mobile application class diagram

development language for many reasons:

- Java has a complete and strong core features like multi-threading and automatic memory management. These features are maintained regularly by Oracle.
- Java has huge community, so lot of open source code, support, tools, libraries and frameworks can be found easily which makes the application development much easier.
- Java is secure, and it protects against many threats because nothing is executed outside the JVM.

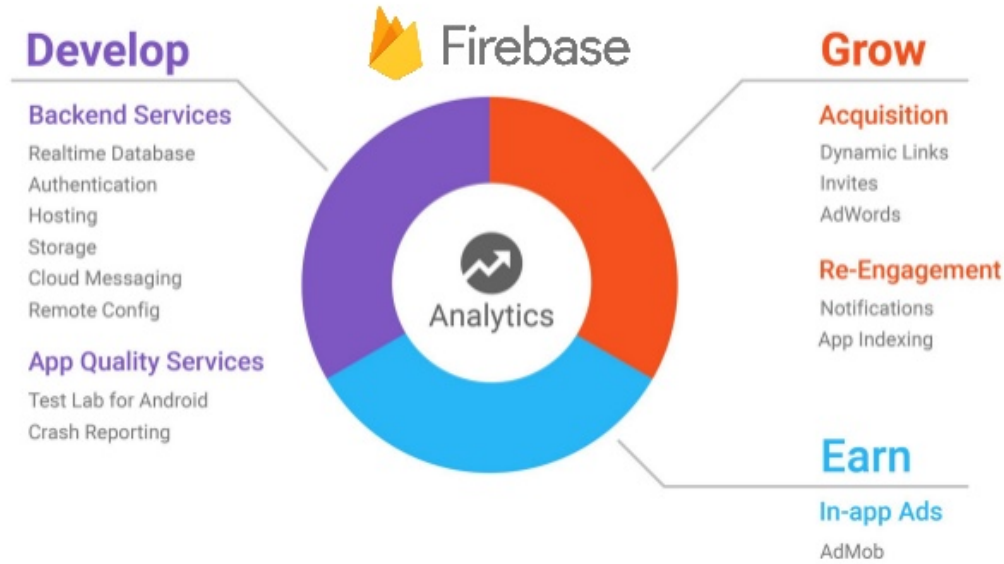


Figure 4.4: Firebase Analytics

4.2.2 Database

Firebase is a development platform for mobile and web applications. It was created by Firebase company in 2011 then Acquired by Google in 2014. At the moment, it provides 18 products and services used by more than a million apps. The key services offered by Firebase are storage, real time database and authentication [67].

Firebase products provide tools, services and platforms in three different domains: development, earning and growing. Developers can get set of cloud services and tools to develop applications with high quality, grow their businesses and earn money. Figure 5.12 (adapted from [68]) shows the main products and services provided by Firebase classified into the three aforementioned domains.

We used the real time database and authentications services provided by Google Firebase to implement our application. The real time database is es-

essential to our application since our application requires real time monitoring and notifications so officials can have an immediate acts in case of emergency. While the authentication services are essentials to know what tracking data are belonged to whom.

Firebase Real-time Database is a cloud-hosted, document-oriented and NoSQL database. It uses JSON format to store data and it synchronize with clients in real time. Firebase real time database provides many capabilities which can be summarize by follow:

- Real time: clients can be notified with data changes in real time in scale of milliseconds. This qualify the program for real time monitoring which is the case in our application.
- No need for server application to access the database client devices can access directly the database.
- Working on offline mode, data is stored in locals to assure availability even when the device is not connected to the internet. Once the device is connected data is synchronized.

Authentication and Security Rules in Firebase

The firebase real time database is stored in the cloud so the need for security mechanism to protect data while stored and transmitted is essential. Firebase defines security rules language to determine who can access data for writing and reading. The rules written in JSON format which is the same format data stored

in the database. Along with the Firebase security rules Firebase provides Firebase Authentication services that can be used easily by developer to authenticate users to apps. Firebase Authentication provides UIs and libraries to implement log in and log up methods. Security rules with authentication services are used to determine who has access, with what privileges and on what data. Our application provides write only privileges to users smartphone to report their tracking information. A full privilege access is given to the system admin and to the monitoring staff. Firebase support three rules for authentication and security:

- Read: defines who can read the data.
- Write: defines who can modify the data in the database.
- Validate: defines the correct form that can be accepted.

4.2.3 Beacon Advertisement

Bluetooth Beacons are devices that use Bluetooth low-energy (BLE) to broadcast wireless signals so nearby devices can listen to these signals and act accordingly. Recent smartphones apply the concept of Beacons which allows their Bluetooth transmitter to broadcast and receive beacon signals. There are many standards and protocols for advertising beacons. For the implementation of CEET application we have adapted the AltBeacon standard which is an open source specifications proposed by Radius. AltBeacon has been chosen because it enables developers to have their own UUID and easily modify the PDU parameters. according to the application requirements.

Table 4.1: AltBeacon packet structure

Field Name	Description	Accepted Values
Advertisement length	Length of the data field	0x1B
Advertisement type	Define data structure specified by the manufacturer	0xFF
MFG ID	Manufacturer identifier.	Compatible with the Bluetooth SIG assigned numbers database
BEACON CODE	AltBeacon advertisement code	0xBEAC
BEACON ID	Beacon device identifier	Specified by the manufacturer
REFERENCE RSSI	Received signal strength	0 to -127
MFG RESERVED	To be used by the manufacturer	0x00 to 0xFF

Figure 4.5 shows the Altbeacon advertising PDU. It contains 1-byte field identify the data field length, followed by the company identifier followed by 24 bytes of advertising data.

There are also other standards that can be used as alternatives to AltBeacon. The following are the most used standards:

- **iBeacon:** [69] is the Apples version of BLE beacon which are meant originally for iOS devices. However, it is compatible with Android but native for iOS devices. The broadcast packets is up to 47 bytes in length and the data part of the packet is 2-39 bytes and it contains four main components, UUID, major, minor and TX power.
- **Eddystone:** [70] is the Google's version of the BLE beacons and it support four types of broadcast packets:
 - Eddystone-URL: it has only one field: URL. The size of the field is depending on the length of the URL.
 - Eddystone-UID it works similarly for Apple's iBeacon.

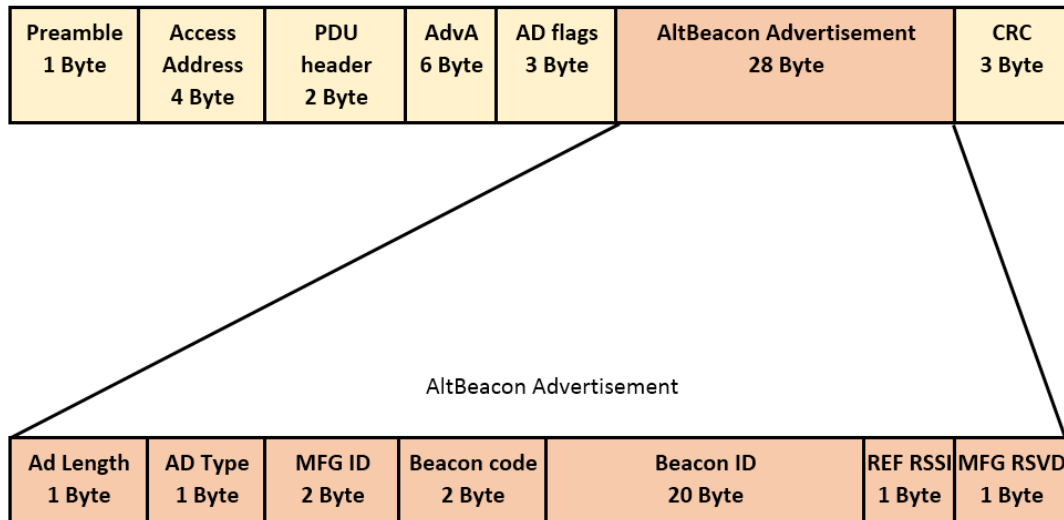


Figure 4.5: BLE advertising PDU

- Eddystone-TLM allows to send telemetry data along with the UID.
- Eddystone-EID: similar to Eddystone-UID with more security option.

CHAPTER 5

CEET APPLICATION IMPLEMENTATION

CEET must fulfill the following requirements:

- The system must assure a positioning accuracy so users can be located to small areas.
- Continuous real time reporting of the sensed information from users along with their locations.
- Simultaneous tracking of large number of users.
- Efficiency of energy consumption to conserve the battery.
- Automatic enabling of Bluetooth in the start of the application.
- Automatic enabling and disabling of WiFi interface and location services including GPS.

- All clustering operations should run in the background and not interfere with any system functions

5.1 Android Location Services

Android smartphone systems provide different types of positioning services that can be determined based on the application requirements. The following aspects of location services has direct effect power consumption and on the positioning quality.

- **Accuracy:** how accurate is the gathered location. Higher accuracy requires higher power consumption. Android developer guide defines four level of location accuracy. Developer can set the level of accuracy the application requires using `setPriority()` method. Table specify the argument values that can be passed to this method
- **Latency:** How long it takes to gather the location information. In general, less latency requires more power consumption. For setting the latency time Android defines the function `setMaxWaitTime()` which specify how quick the location information should be retrieved. The value passed to this function should be several times larger than the value used in `setinterval()` mentioned in last section.
- **Frequency:** How frequently location information is calculated. Higher frequency means more power consumption. Location frequency in Android

Table 5.1: Positioning power levels in Android systems

Value	Accuracy	Battery use	Description
HIGH ACCURACY	High	Very high	Uses GPS, cell and Wi-Fi, besides variety of sensors
BALANCED ACCURACY	Accurate	Balanced	It uses Wi-Fi and cell and rarely GPS.
PRIORITY LOW_POWER	Coarse accuracy (city level)	Low	Usually uses cell towers and avoid using GPS and WiFi
PRIORITY NO_POWER	NA	No power	Get location from other apps.

can be set up using two methods `setInterval()` and `setFastestInterval()`. `setInterval()` set the interval of location computing for the current app while `setFastestInterval` specifies the interval of delivering location information from other apps.

5.2 Bluetooth Pairing

One of the main issues when applying automatic connections between devices is the Bluetooth pairing. There are security considerations forced by Bluetooth specifications to maintain high security standards for Bluetooth devices. These security standards Bluetooth pairing is the process of establishing a secure connection between two Bluetooth devices. The pairing between devices is established in the following stages:

Stage one: all messages sent during this stage are not encrypted. This stage starts when a Bluetooth device sends a pairing request to another Bluetooth device. The two devices then exchange the information required to establish a secure connection including I/O capabilities and authentication and bonding re-

quirements.

Stage two: once the pairing information has been exchanged between the two devices in stage one, devices start to exchange keys to establish a secure connection. They generate a temporary key using one of the pairing methods explained below in this section. Both devices exchange rand and confirm values to verify that both are using the same key. The temporary key is used to establish a short-term key that is used to encrypt the connection.

Stage three: this stage is only used if bonding requirements were exchanged in stage one. If two devices are bonded, they can encrypt their connection without exchanging any secret keys as the keys are already stored in both devices. Instead, only an enabling encryption request would be sent.

5.2.1 Bluetooth Pairing Methods

Bluetooth Low Energy support four association methods

- **Just work:** in this method the temporary key is set to 0. This method is secure against passive attacks and insecure against active attacks.
- **Passkey entry:** the temporary key in this method is six digits number. This method is more secure than the previous one and it can protect against passive attacks and a number of active attacks.
- **Out of band:** this method allows flexibility for developer to define their own pairing approach so security depends on the protection capability of the used approach.

- **Numeric comparison:** protects against passive and active attacks.

One of the requirements in our application is auto Bluetooth pairing, since it is not practical to ask the user to enter a key whenever wants to connect to other devices. Therefore, the connection method **Just work** must be applied in our application.

5.2.2 Automatic Bluetooth pairing

CEET approach requires automatic Bluetooth pairing without the user being notified. No need to ask the user to enter the PIN for pairing. Android provides a `setPin()` function to allow developers to programmatically enter the PIN code in the developing time. When a node needs to join a cluster it initiates a pairing call and it used a predefined PIN as a pass key.

```
BroadcastReceiver broadcastReceiver = new BroadcastReceiver() {  
    @Override  
    public void onReceive(Context context, Intent intent) {  
        String BLE_PIN = "1234";  
        String action = intent.getAction();  
        if (BluetoothDevice.ACTION_PAIRING_REQUEST.equals(action))  
        {  
            BluetoothDevice bluetoothDevice = intent.getParcelableExtra(BluetoothDevice.EXTRA_DEVICE);  
            bluetoothDevice.setPin(BLE_PIN.getBytes());  
            Log.e(TAG, msg: "Auto-entering pin: " + BLE_PIN);  
            bluetoothDevice.createBond();  
            Log.e(TAG, msg: "pin entered and request sent...");  
        }  
    }  
};
```

Figure 5.1: Android code for auto Bluetooth Pairing

5.3 System Permissions

Every Android mobile application has a manifest file at the root of the code structure. This file is stored as an xml file and it has the name `AndroidManifest.xml`.

Application specifications are described in this file like the android version, build tools etc. Among other things the permissions of the application should be declared on this file. Android applications must request permission to access some sensitive system features like location services and internet access. Some features in our application require explicit permission contest and approval weather in the installation phase or on the running time. The following are the features that need permission approval in our application:

- Automatic enabling and disabling WiFi interface since it is a main feature in our specifications to save energy.
- Enabling location services programmatically.
- Access to fine and coarse location service.
- Access to Bluetooth administration services.
- To calculate the cost function used in the clustering process we need to maintain continuous monitoring of the battery level.

Each permission in Android is labeled by a unique label so it can be identified by the label. Figure 5.2 is a snap shot of the permissions declaration in the manifest file of our application.

```

<uses-permission android:name="android.permission.ACCESS_WIFI_STATE" />
<uses-permission android:name="android.permission.CHANGE_WIFI_STATE" />
<uses-permission android:name="android.permission.WAKE_LOCK" />
<uses-permission android:name="android.permission.BLUETOOTH" />
<uses-permission android:name="android.permission.BLUETOOTH_ADMIN" />
<uses-permission android:name="android.permission.ACCESS_FINE_LOCATION" />
<uses-permission android:name="android.permission.ACCESS_COARSE_LOCATION" />
<uses-permission android:name="android.permission.ACTION_BATTERY_CHANGED" />

```

Figure 5.2: System permissions declaration in the manifest file

5.3.1 Automatic enabling and disabling of location services

Some system features require only declaration on the manifest file to be used by the application like accessing Android WiFi manager. While some features require granting the access permission on the runtime, besides the declaration on the manifest file. These features require user interaction to approve the permission. Enabling Bluetooth and location services are examples of such features. Figure 5.3 shows an example of GPS enabling request on the run time. Figure 5.4 shows a sample code for a request to enable the location services from the user. The permission on runtime may be tolerated in our application with some services like enabling Bluetooth because Bluetooth only needed to be enabled when starting the application and it will be enabled during the whole time of the application lifetime. However, this may become an issue for services that require enabling and disabling frequently during the clustering process. It is not practical to ask the user enabling or disabling the GPS manually every time the device is selected as a cluster head or switch to a regular node. On the other hand, enabling and disabling the GPS is a core feature in our approach to save energy. Therefore, a

full automatic access for enabling and disabling location services is a must for our approach to achieve its goal of saving energy.

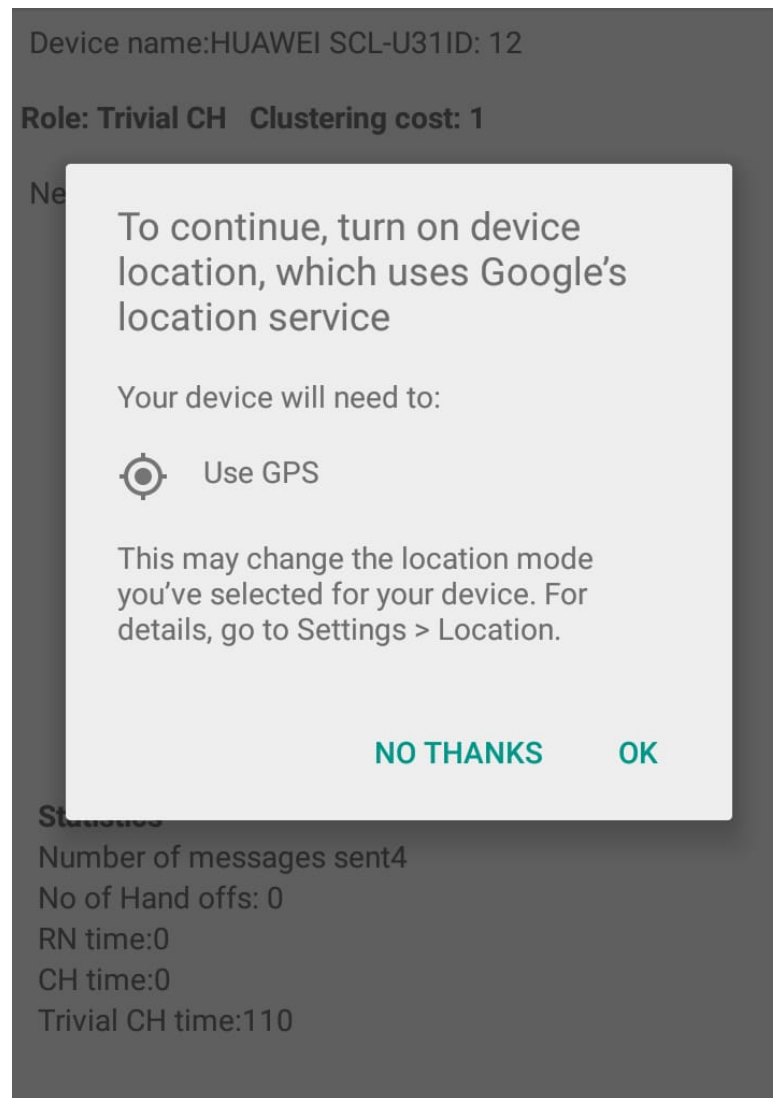


Figure 5.3: GPS enabling request on the run time

To alleviate this problem, the application will ask user permission only when starting the application. The location services will be enabled all the time. However, Android provides different levels of positioning accuracy that can be triggered automatically without user explicit interaction. These parameters are explained in detail in section 5.1. So no need to disable and enable the GPS on the runtime.

Instead, we can only change the power and accuracy parameters during the run time. When the device is selected as a cluster head only change the level of accuracy to be high. Whereas the accuracy level changed to no power mode when the node is selected as a regular node.

```

if (Build.VERSION.SDK_INT >= Build.VERSION_CODES.M) {
    //we need to get user to grant access to the ACCESS_COARSE_LOCATION, beacon scanning requires this
    if (this.checkSelfPermission(Manifest.permission.ACCESS_COARSE_LOCATION) != PackageManager.PERMISSION_GRANTED) {
        // so if its not granted yet, we do need the request it
        final AlertDialog.Builder builder = new AlertDialog.Builder(this);
        builder.setTitle("This app needs location access");
        builder.setMessage("Please grant location access so this app can detect beacons.");
        builder.setPositiveButton(android.R.string.ok, null);
        builder.setOnDismissListener(new DialogInterface.OnDismissListener() {
            @Override
            public void onDismiss(DialogInterface dialog) {
                requestPermissions(new String[]{Manifest.permission.ACCESS_COARSE_LOCATION}, PERMISSION_REQUEST_COARSE_LOCATION );
            }
        });
        builder.show();
    }
}

```

Figure 5.4: Permission request on the runtime

5.4 clustering operations

This section illustrates the implementation of clustering operations on the CEET application developed for Android smartphones. The clustering process in the CEET application applies the clustering algorithm illustrated in chapter 3. Smartphones in CH or trivial CH roles broadcast an advertisement packet periodically. The advertisement packet consists of information that is used in the clustering process. As illustrated in section 4.2.3, we have adopted the Altbeacon advertisement standard. The information needed for clustering and communication have been encapsulated in the Beacon ID field as shown in Figure 5.6. Figure shows the java code for the advertisement packet.

Message Type field identifies type of the message. This field have one of the

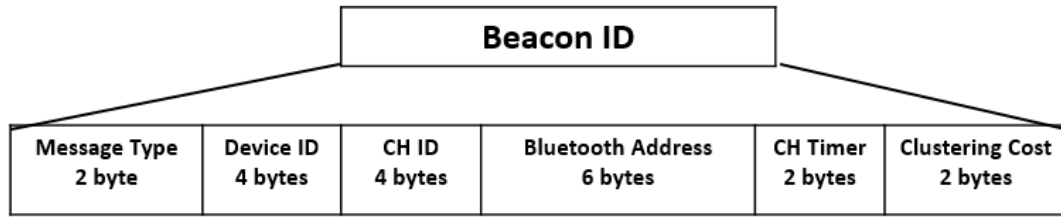


Figure 5.5: Beacon advertisement packet architecture

```

public AltBeacon(BluetoothDevice device, String manufacturer, String beaconCode, int BEAC_TYPE,
    int Message_type, int Device_ID, int ClusterHeadID, String Bluetooth_address, int clusteringCost, int CH_timer) {
    this.mDevice = device;
    this.mType = Message_type;
    this.mManufacturer = manufacturer;
    this.mBeaconCode = beaconCode;
    this.mBluetooth_address = Bluetooth_address;
    this.mId2 = clusteringCost;
    this.mId3 = ClusterHeadID;
    this.Device_ID = Device_ID;
    this.mRefRSSI = BEAC_TYPE;
    this.BEACON_TYPE = BEAC_TYPE;
    this.cost = clusteringCost;
    this.mManufacturerReserved = Device_ID;
    this.CH_timer = CH_timer;
    this.CH_ID = ClusterHeadID;
}

```

Figure 5.6: Java code for the advertisement packet architecture

following values:

- ADVERTISE if the value of message type is advertise, it indicates that this packet is broadcast by a trivial cluster head.
- CH_ADVERTISE indicates that the packet is an advertisement of a non-trivial CH.
- JOIN_REQUEST this message is sent by a node to request to join a cluster.
- REPLY_ACCEPT sent by a CH to notify acceptance.
- REPLY_REJECT sent by a CH to notify rejection to join the cluster.
- DISCONNECT_NOTIFY sent by a CH to give notice to connected regular

```

public interface MESSAGE_TYPE {
    public static final int Advertise = 0;
    public static final int CH_Advertise = 1;
    public static final int JOIN_REQUEST = 2;
    public static final int REPLY_ACCEPT = 3;
    public static final int REPLY_REJECT = 4;
    public static final int ACCEPT_ACK = 5;
    public static final int DISCONNECT_NOTIFY = 6;
    public static final int DISCONNECT_ACK = 7;
}

```

Figure 5.7: Advertisement packet types

nodes that the Cluster head will stop serving as a cluster head and disconnect from all connected nodes.

Device ID identifies the ID of the smartphone that send this packet. CH ID if this packet is a join request, CH ID contain the ID of the cluster head that it would like to join.

Bluetooth Address contains the Bluetooth address of the smartphone that send this packet. This address is used to establish pairing and connection.

CH Timer determines the remaining time of a CH to serve as CH before turning to trivial CH. The value of this field is zero if the node is a trivial CH.

Clustering cost determines the cost of clustering for the advertiser based on its history of cooperation.

Non-trivial cluster heads announce their CH timer besides clustering cost. CHs with higher timers are more likely to be chosen by other nodes because it assures that nodes spend more time as regular nodes, thus, save more energy. CH stops advertising when it has the maximum allowed number of RNs. Trivial CH set

their CH timer to zero therefore won't be selected to join by other nodes unless there is no a CH in the field. If there are two or more cluster head in the field with the same timer values, nodes select CH with least cost value.

5.5 Database Implementation

All tracking information collected from users smartphones are stored in a cloud database (Google Firebase). Android studio provides Firebase support and provides integrated tools to handle the communication with the Firebase database. Figure 5.8 shows the steps to integrate the CEET application to the firebase on the server.

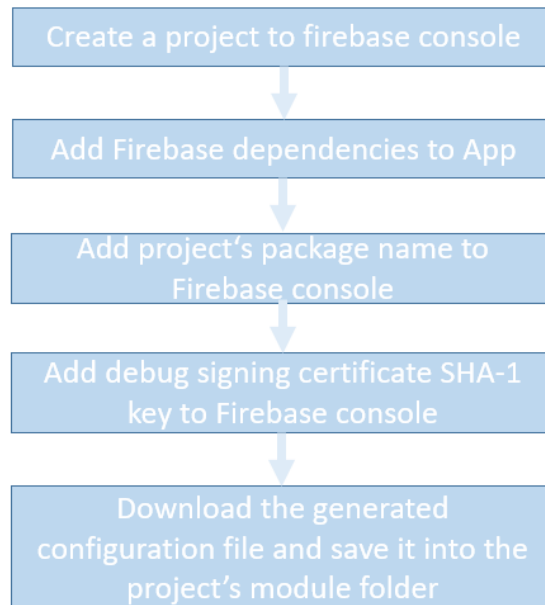


Figure 5.8: Database Integration to Android Firebase Console

To implement the communication between CEET application and Firebase database, Firebase libraries have been added to the Gradle file of the CEET ap-

plication, then a reference to the Firebase database has been creates to enable reading and writing to the Firebase database. Figure 5.9 shows the steps how to configure the communication between the application and the database.

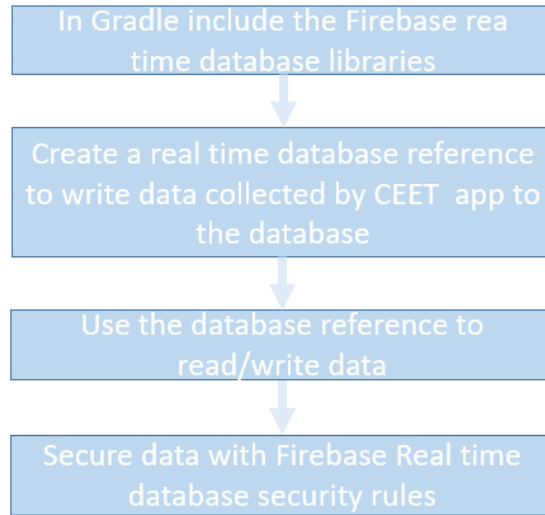


Figure 5.9: Communication between Firebase Database and CEET Application

User Authentication

The authentication configuration in CEET system is done through Google Firebase website Figure 5.10 shows the procedure to enable the authentication methods to access the Firebase database . Users are authenticated by their email and password. After installing the application, users are required to register their information once. They should register their names, emails and passwords. Firebase Authentication system will grant a user ID. This ID is used to authenticate the user in all attempts to access the database for reading or writing.

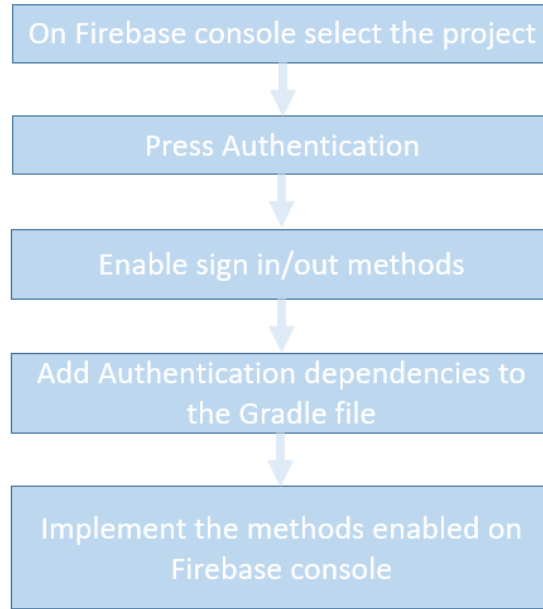


Figure 5.10: Firebase Google Authentication

5.6 Activities

Activity in android mobile application is an interface component that provides application users a view can interact with. Generally, mobile applications consist of more than one activity. The main activity usually is the first to be launched when the application is booted up. For example, in our application CEET the main activity is the first to be launched for already registered and logged in users. If the app is not registered yet, the log in activity it will be firstly launched. Activity can launch other activities, so users can navigate through activities to perform different actions.

Once an activity calls another activity, the current activity stopped but it is preserved in the back stack. The called activity is sent the foreground of the screen and it takes the user focus. When user go back to the previous activity,

the current activity is destroyed while the previous activity shows again in the foreground and resume.

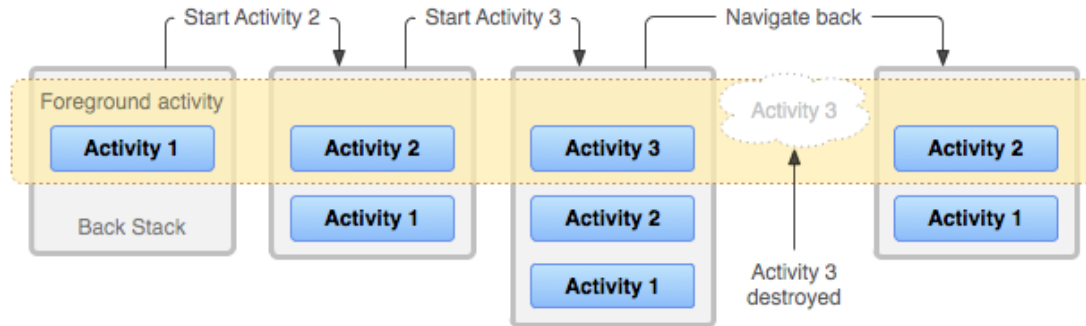


Figure 5.11: A representation of activity life cycle adapted from [1]

Activity life cycle is an important consideration to build a robust and reliable mobile application. An activity can be in one of the following three states:

- **Created:** the activity is created but not started yet, not visible.
- **Started:** the activity is visible to the user.
- **Resumed:** the activity is visible to the user.
- **Paused:** alive and partially visible but it can be stopped in some low memory situations.
- **Stopped:** alive but not visible to the user and running in the background.
- **Destroyed:** dead and all data associated with it is lost.

To manage the activity life cycle developer can use the callback methods defined by Android. These methods can be overridden so developer can write the code to perform the appropriate actions once triggering a certain activity state.

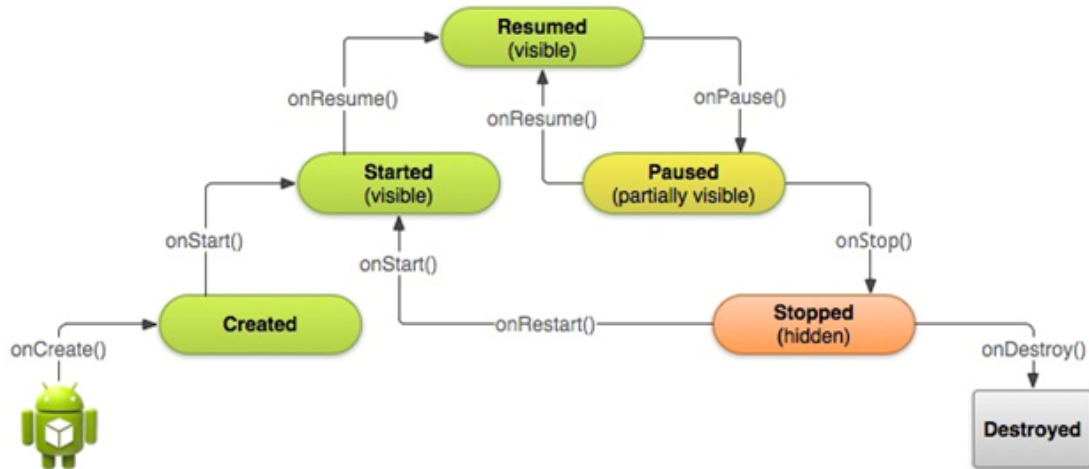


Figure 5.12: Activity states adapted from [1]

Figure shows the activity states and the call back methods associated with these states.

5.6.1 Sign in and Sign up Activities

Sign in activity figure 5.13 is the first activity displayed to the CEET mobile application user when they open the app for the first time. Users must log in to the app to be able to access the system functions. Only registered users can log in to the app. They can log using their email and passwords. Non-registered users must register in the server to have access the system. There is an option for unregistered users to sign up. If new user chooses to register as a new user the sign up activity will show to follow with the sign up steps.

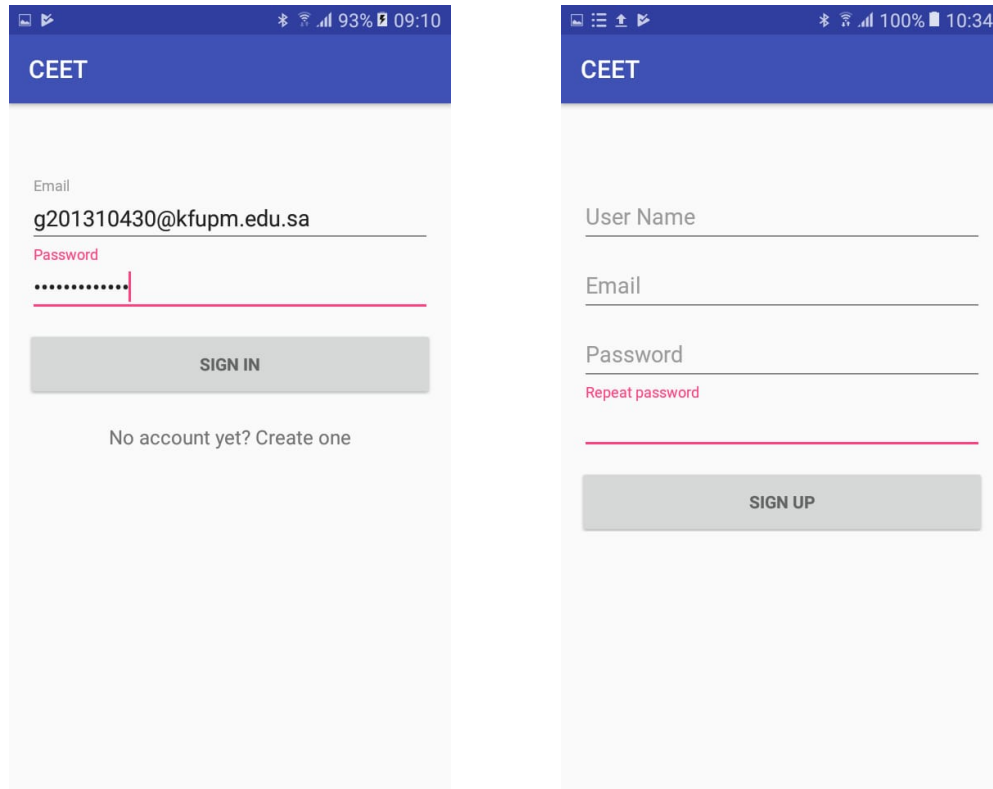


Figure 5.13: Snap shots of the Log in and log up Activities in CEET app

5.6.2 Main Activity

The core functions of the CEET application are hold on the main activity. The clustering, communication and positioning are background activities coordinated by modules defined on the main activity. The figure shows a snap shot of the main activity on a running application. The main activity doesnt require a user interaction, only for navigating for other activities to perform some configuration actions. It shows the current role of the device whether it is a cluster head or a regular node. It also shows the current clustering cost along with some statistical information that are used in the evaluation of the system. A list of the nearby devices are also shown if the current role is trivial cluster head. If the current role of the device is Cluster head, a list of the connected regular nodes are shown.

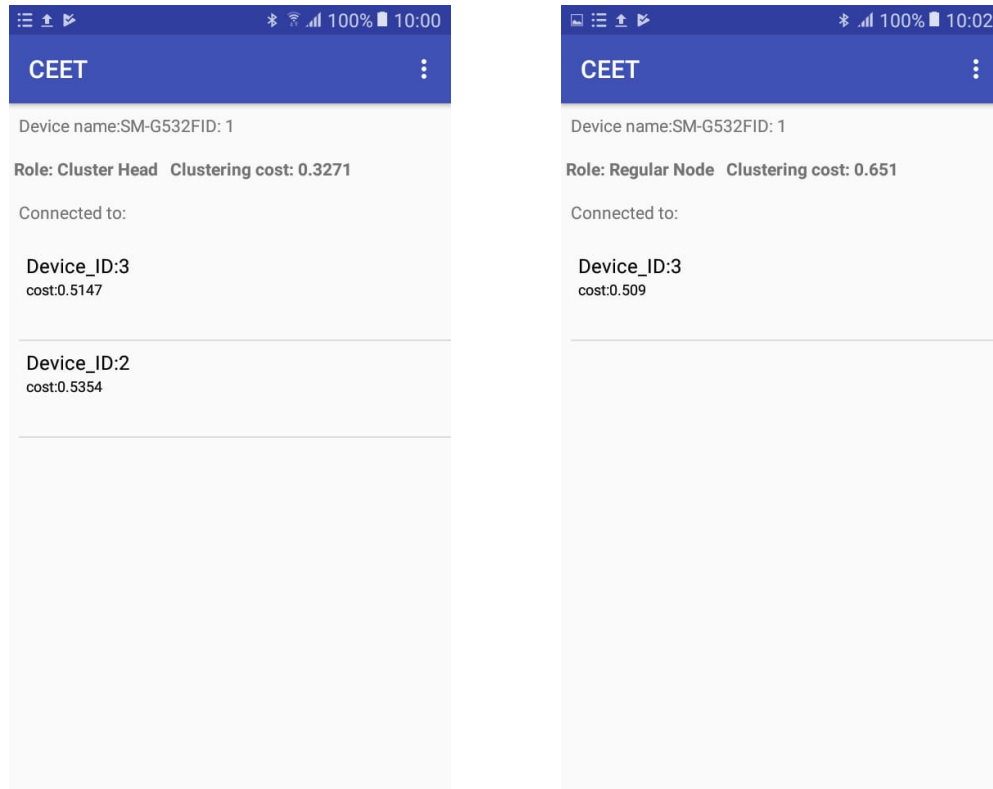


Figure 5.14: Snap shots of the main activity Activity in different roles

5.6.3 Settings Activity

The settings activity in our application allow users to modify the app behaviour and features. Figure 5.16 shows the features that can be modified by users. Some of the options in the settings activity are placed for the application testing purpose.

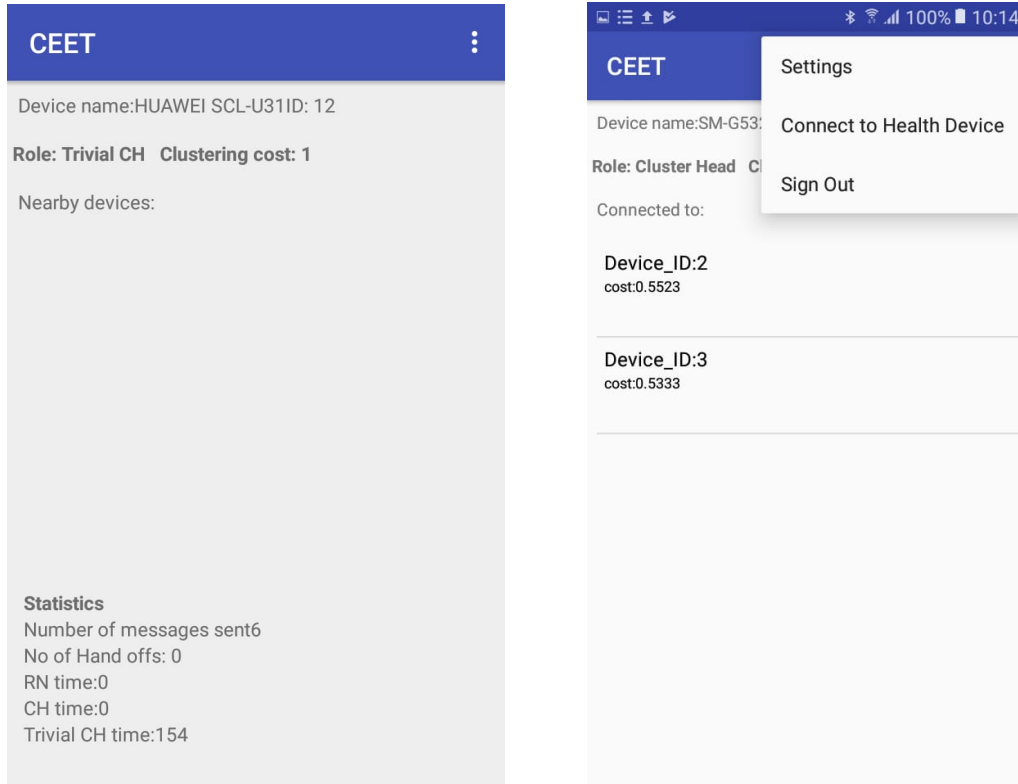


Figure 5.15: Statistics and navigation menu in the main activity

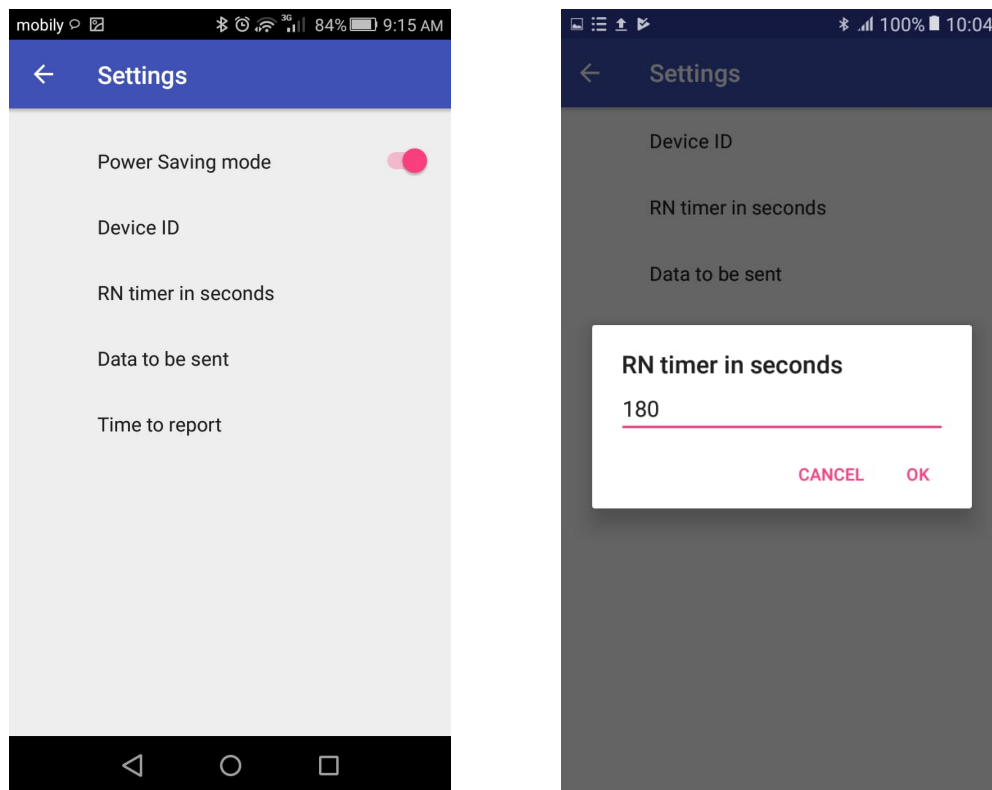


Figure 5.16: Settings activity

CHAPTER 6

PERFORMANCE EVALUATION

In this chapter we evaluate the proposed system using simulation and through real experiments using the developed app. First we present the evaluation through simulation and compare it to the optimal solution obtained from the optimization model. Then we present the performance evaluation of the CEET mobile application.

6.1 Evaluation with simulation

6.1.1 Simulation setup

In this section, we evaluate the proposed approach for tracking through simulation experiments using MATLAB. We assume that all nodes are equipped with WiFi, Bluetooth and GPS modules. All nodes have access to a WiFi access point. We

Table 6.1: Simulation Parameters and Values

Parameter	<i>Abbreviation</i>	<i>Values</i>
Battery level	-	[100:2000] mAh
Data model	-	CBR
Data rate (uniform distribution)	r	[0:1] mbps
Bluetooth on power	P^{B_I}	0.37 mW
Bluetooth Active (Tx/Rx) power	P^{B_A}	37 mW
WiFi on power	P^{W_I}	11.1 mW
WiFi Active power	P^{B_I}	740 mW
GPS power	P^G	185 mW
WiFi TX Rate	R^W	150 Mbps
Bluetooth TX Rate	R^B	2 Mb

assume all nodes are deployed in an outdoor field and all of them have an access to GPS signals. Power consumption values, used in the simulation, are specified in table 1. These values are real-world values obtained from the power profiles in Android developer guide [71].

The nodes mobility follow the random waypoint model. We assume all nodes are uniformly spread into 50*50 meters field. Each node starts at a random location and chooses its next destination randomly. It moves to its destination with a speed selected randomly between 0.5 and 2 m/s with a pause interval between 30 and 60 seconds. The traffic model used in the simulation is constant bit rate (CBR) traffic model. Each node generates random data rate between 0 and 1 mbps. This data rate lasts for a random period between 0 and 120 seconds then it generates another random data rate and it lasts for another random period and so on. The simulation lasts for 30 minutes unless it is explicitly specified.

6.1.2 Evaluation of cluster construction

In this section, we evaluate our proposed approach CEET, and compare it with optimal solution obtained from the optimization model illustrated in section 3.3. The optimal solution is based on finding the optimal construction of clusters in terms of energy consumption. We formulate the problem as a mixed Integer Programming problem then we implement our model using GAMS solver. GAMS is a high-level modeling system for mathematical optimization which is designed for modeling and solving different range of optimization problems. It is worth to note that GAMS has limitations which makes it inconvenient to use GAMS for large networks (nodes > 800 nodes). We consider different network densities 100, 200, 400 and 800 and we compare values of objective function provided by GAMS and the average consumed energy values resulting from our approach simulation.

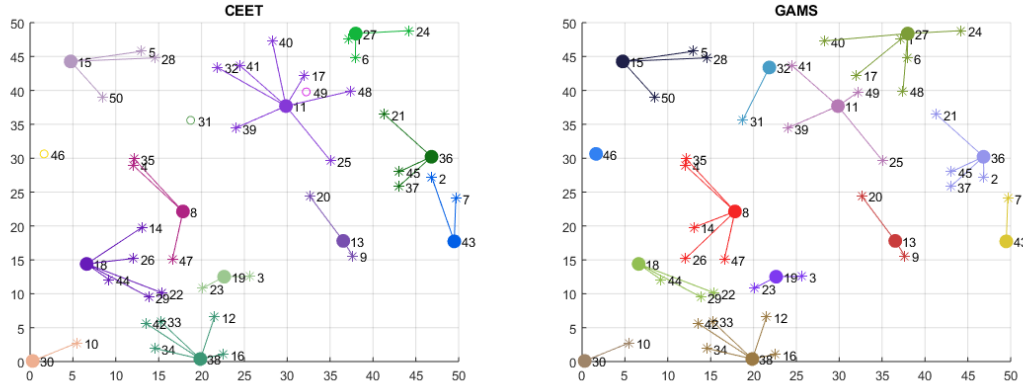


Figure 6.1: Comparison of initial clustering construction between CEET and Optimal construction in term of power consumption over the area of 50x50 m2.

Figure 6.1 shows the difference in the initial clustering construction between CEET and the optimization model solved by GAMS. The optimization model has a global knowledge of the network, unlike our approach where nodes have

local information about surrounding neighbors. Thus, the cluster construction provided by GAMS is more efficient and yields better constellations than the construction done by the simulation. Nevertheless, the power consumption results in our approach are closed to the results of the optimization model solved by GAMS. As illustrated in figure 6.2, power values from CEET simulation and the optimal power values provided by GAMS are very close for different network densities. No need to say, the figure shows huge power reduction (about 70% drop when there are 100 nodes in the field and about 75% drop when more than 200 exist) in both CEET and the optimization model comparing to the traditional approach.

Figure 6.3 shows the cluster size of CEET comparing to CONET and the random Ch selection in different node density. CONET has the smallest cluster size because it has a restricted admittance procedure. CH in CONET approach accepts new nodes only if they have higher cost even if it is already chosen as a CH. In our proposed algorithm CEET, a non-trivial CH accepts new nodes no matter what their cost is, as long as it has enough bandwidth and the number of nodes in a cluster does not exceed the upper bound of the allowed maximum cluster size.

cluster sizes shown in figure 6.3 are with random data rate between 0 and 1 mbps. Nodes are rejected to join clusters if the cluster head can not satisfy their bandwidth requirements. Moreover, nodes disconnect from clusters if their data rate can not be served at any moment. As early mentioned, the data rate in our

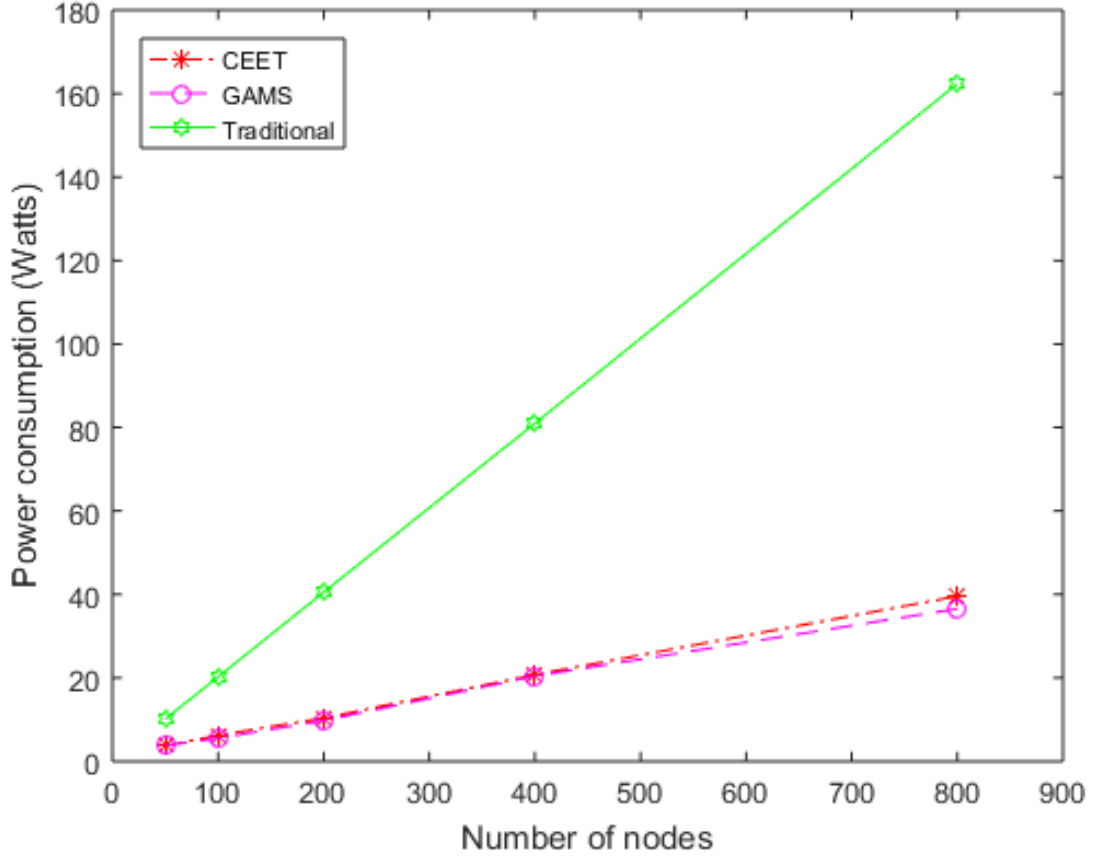


Figure 6.2: Comparison of power consumption for the whole network in respect to the value of the objective function generated by GAMS versus values of simulation results for CEET and traditional approaches

application is so low and can be neglected so the bandwidth don't play a role in admitting or disconnecting from a cluster. Figure 6.4 shows the cluster size with very low data rate (20 bytes every 30 seconds). Cluster size is doubled in CEET when there is dense nodes in the field. Whereas CONET does not get significant improvement due to the cost constraint.

Figure 6.5 shows the effect of node density and the choice of clustering algorithm on the cluster organization. As earlier described, CONET has stricter admission policy than the other two algorithms CEET and random. In the all different densities tested in the experiment, CONET has the less average time as

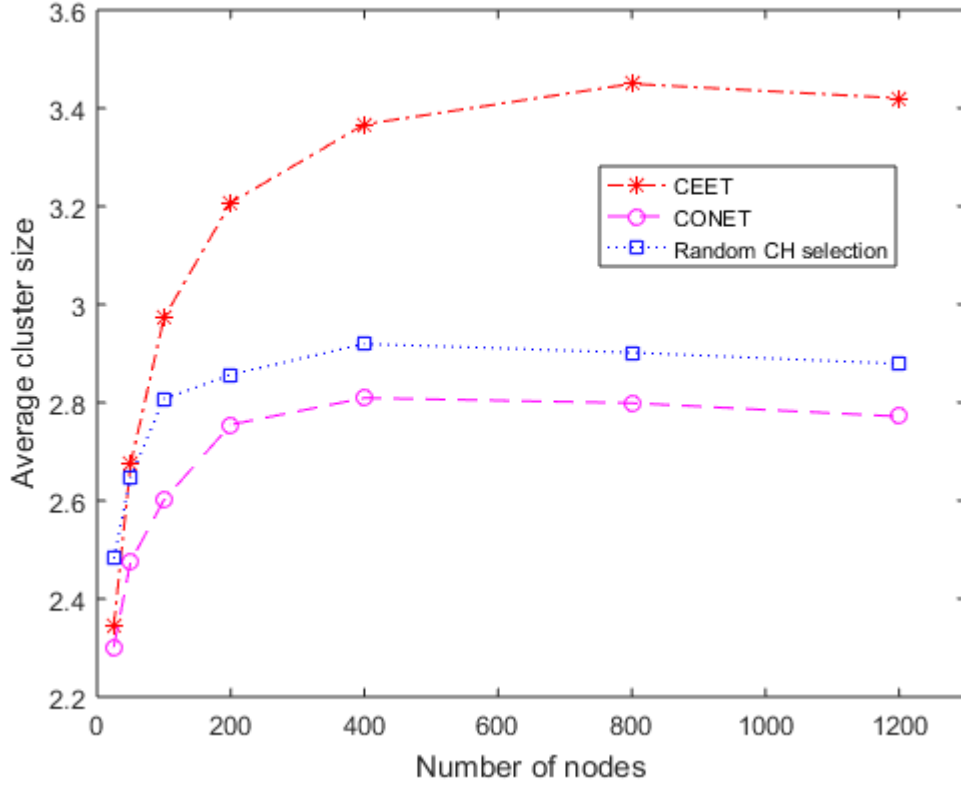


Figure 6.3: Comparison of cluster size in our algorithm to other algorithms with random data rate between 0 and 1 mbps

a regular node. For example, when there are 25 nodes in the field nodes spend less than 45% of its time as a regular node, While it spends more than 55% in both CEET and Random. As the number of the nodes increases, the percentage of the average time of nodes spend as a trivial CH (not cooperating) decreases since it has more neighbouring nodes to cooperate. When there are 800 nodes in the field nodes spend more than 30% in the CH role in the CONET approach due to the small cluster size illustrated in Figure 6.4 while nodes spend in average as CH around 15% in CEET and around 23% in Random.

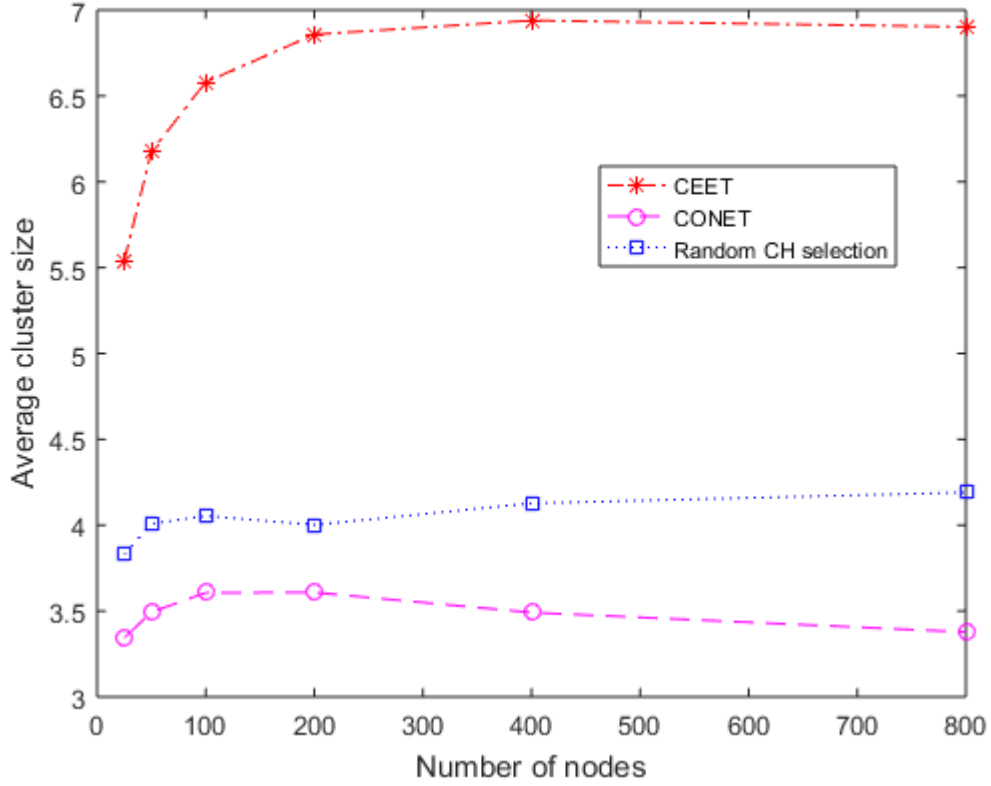


Figure 6.4: Comparison of cluster size in our algorithm to other algorithms under our application requirements (data rate: 20 bytes every 30 seconds)

6.1.3 Evaluation of power consumption

In this section, we present and discuss the performance results of CEET compared to CONET, the traditional approach and the random CH selection approach (Random). In the traditional approach each node is working individually using its own WiFi and GPS for tracking. CEET, CONET and Random are using clustering for sharing the tracking task. However, both CEET and CONET define a cost function that is used as a base for selecting the CH. On the other hand, Random used probability values randomly generated and assigned to nodes to be used for selecting CH without considering any other metric.

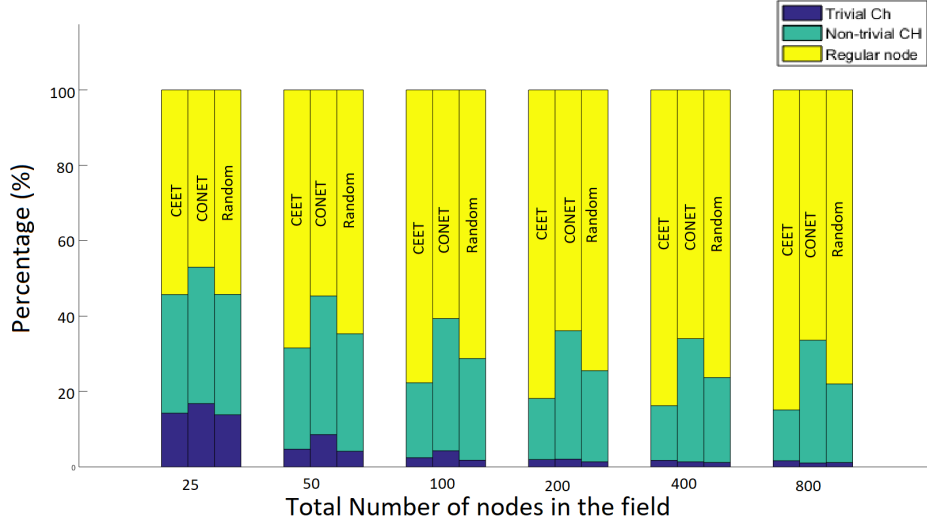


Figure 6.5: Effect of clustering algorithm and node density on the cluster organization

Figure 6.6 shows the effect of node density on the energy consumption per node. On average, each node consumes around 700 Joules for tracking when it uses the traditional approach for the experiment period of one hour. On the other hand, it is obvious that the node tracking energy consumption decreases when applying a clustering algorithm. For example, when applying CEET the average power consumption per node when there are 100 nodes in the field, is 118 Joule which is 17 percent of the power used in the traditional way. The energy saving increases when more nodes exist in the field because nodes can spend more time as regular node, hence, it consumes less power for positioning and communication. From this figure, we can see that the average power consumption decreases as the number of nodes decreases till some point where the power consumption stabilizes and no matter how many nodes added to the field. In this example, there is no substantial difference in the power consumption as the number of nodes increase

above 100 nodes in the field.

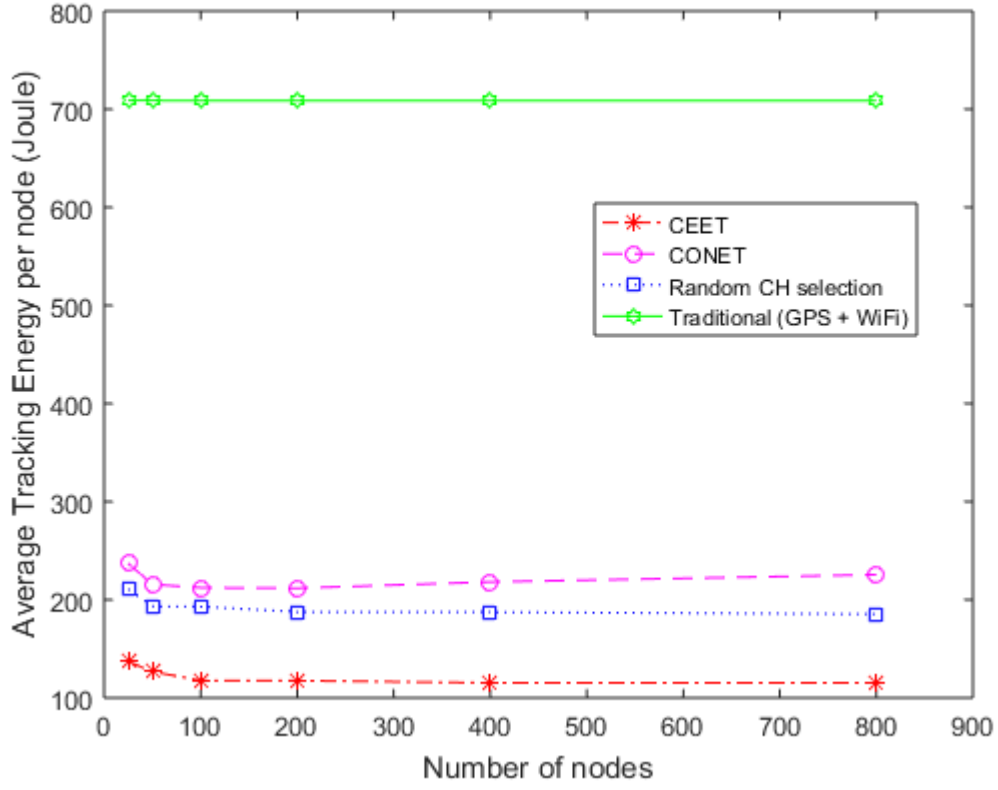


Figure 6.6: Power consumption in CEET and different approaches using WiFi with different node density in field (10x20 m), data rate between (0 and 500 kbps) and experiment time 1 hour.

Figure 6.7 shows the energy consumption when using the cellular mobile data instead of WiFi in all above mentioned approaches (traditional, CEET, CONET and random), The power values of cellular data for the experiment were got from [71] same as other power values used in the experiments.

Figure 6.8 shows the average power consumption per node with low data rate 20 bytes every 30 seconds (to simulate the data rate in our application). The energy saving is higher with low data rate because more regular nodes can be admitted and longer time they can stay as regular nodes.

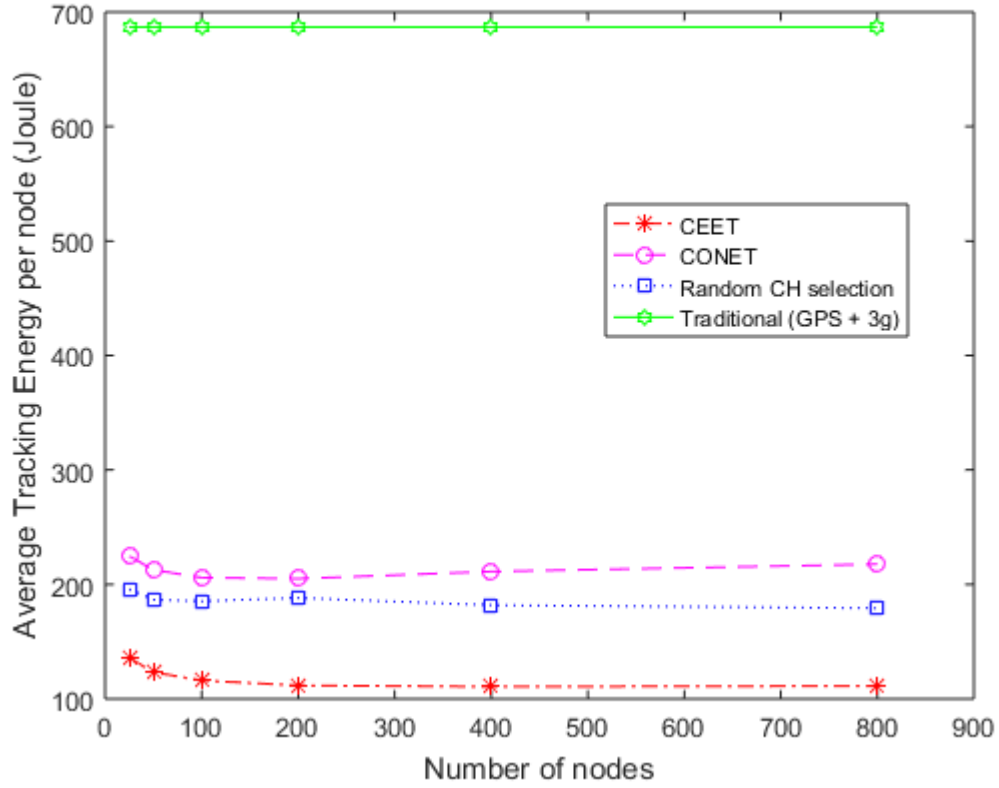


Figure 6.7: Power consumption in CEET and different approaches using 3g mobile data with different node density in field (10x20 m), data rate between (0 and 500 kbps) and experiment time 1 hour.

Figure 6.9 shows the average power consumption per node with low data rate 20 bytes every 30 seconds (to simulate the data rate in our application). In this setup we modified the traditional approach. The WiFi and GPS stay off and only switch on periodically every 30 seconds to obtain the location data and send the tracking data to the server through the WiFi interface. Once the data is sent, both GPS and WiFi are switched off again for 30 seconds till the next scheduled reporting. We also modified the CEET such that the CH only switch on its GPS and WiFi once every 30 seconds. Other regular nodes don't need to switch on their WiFi and GPS since they forward their data to the CH through

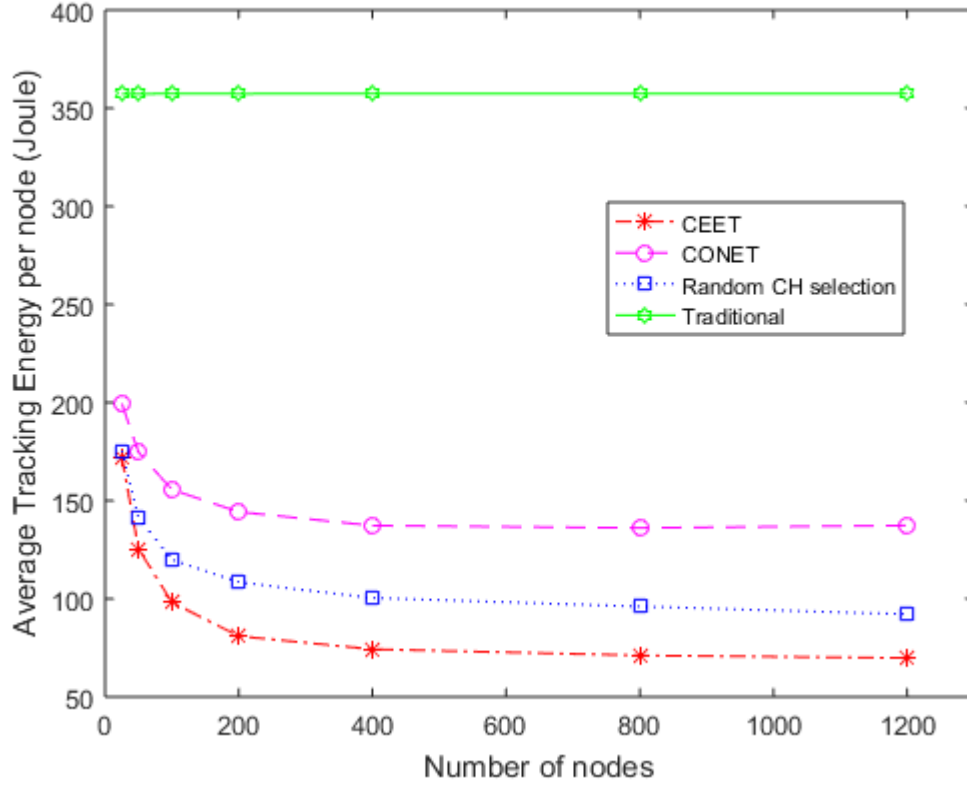


Figure 6.8: Power consumption in CEET and different approaches with different node density with low data rate 20 bytes every 30 second.

the Bluetooth. Although CEET requires additional power for the Bluetooth, but it still outperforms the traditional approach because all regular nodes save the GPS power since GPS is off all the time they are in the regular node rule.

Figure 6.10 shows the cumulative battery capacity for all nodes in the network over time. In this experiment, we have 400 nodes in the field and the battery level of each node is chosen randomly between 100 and 2000 mAh. The same values have been used to test the different schemes in three different experiments run for 4 hours each. Furthermore, figure 6.11 demonstrates the effectiveness of CEET by minimizing the number of dead nodes due to their drained batteries of

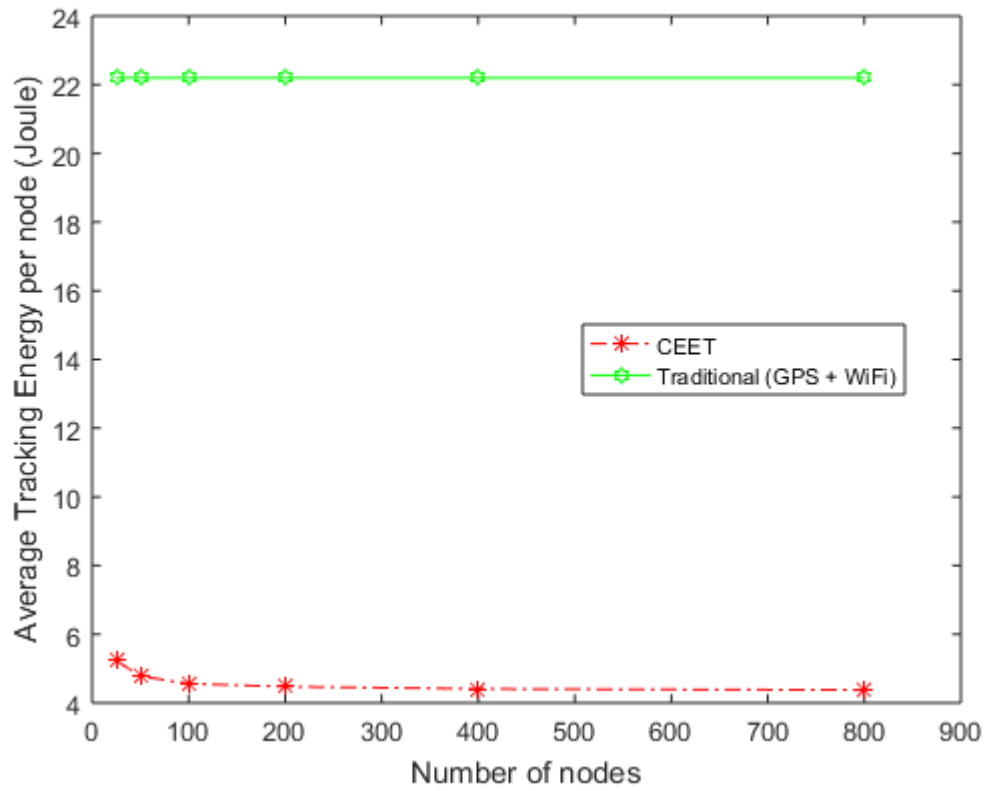


Figure 6.9: Power consumption in a modified approach of both CEET and the traditional approach where GPS and WiFi wake up every 30 seconds to obtain location data and send it along with the tracking data through WiFi interface; experiment time 1 hour

participating nodes.

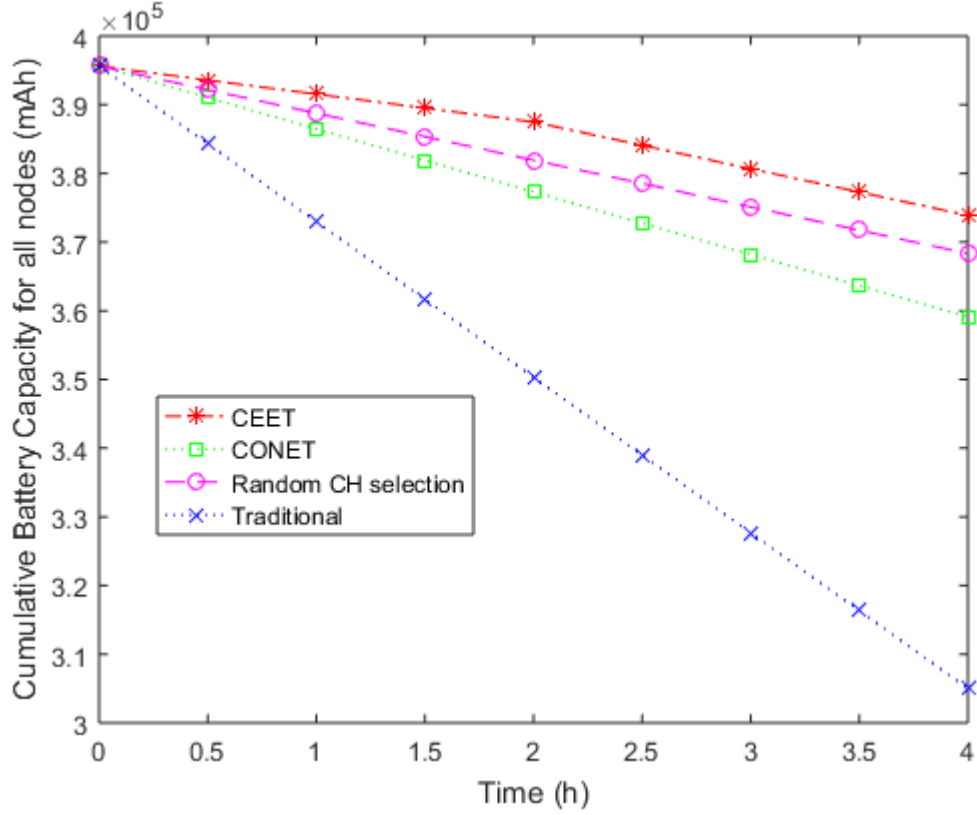


Figure 6.10: Comparison of cumulative battery capacity for the whole network. Number of nodes in the network is 400. The battery capacity is randomly generated between 100 and 2000 mAh for all nodes.

6.1.4 Fairness and load balancing

Fairness is very important performance measure that should be addressed in a cooperative approach. The fairness of battery saving depends on the clustering scheme used and the role switching time. Figure ?? shows the Jain fairness index [?] for CEET compared to CONET and the random approach for different network densities. The Jain fairness index is based on the battery saving ratio (SR) for each node which is computed based on the ratio of saved energy to the energy

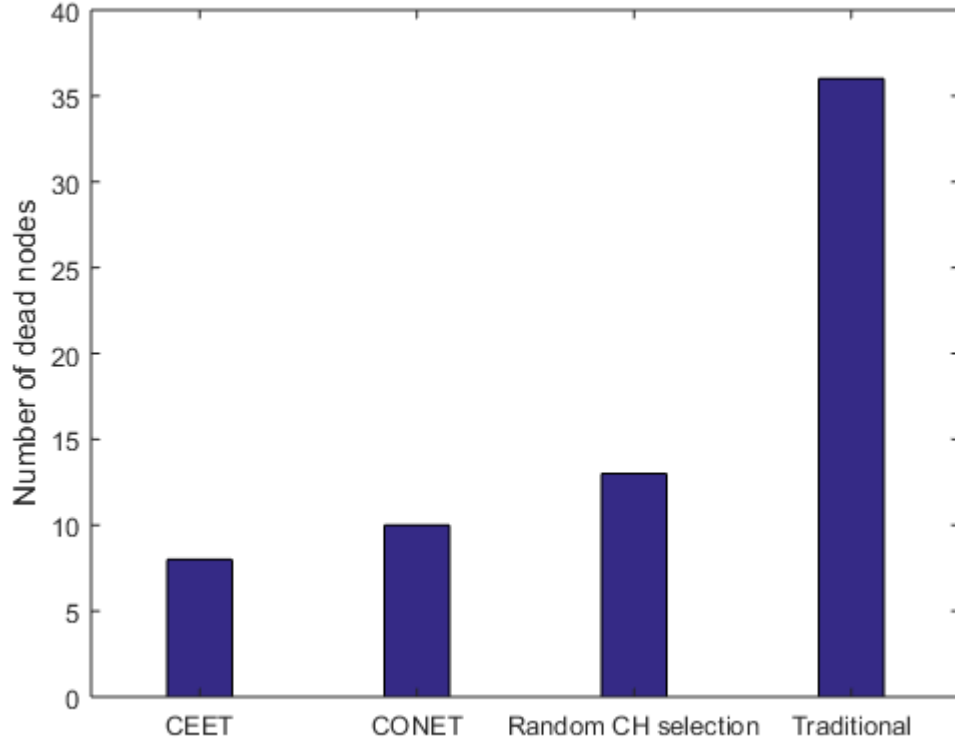


Figure 6.11: Number of dead nodes out of 400 nodes for experiment time 4 hours and same capacity values for all approaches.

used by the traditional approach. SR for node i can be defined as follows.

$$SR_i = \frac{E_i^{Tr} - E_i^{CEET}}{E_i^{Tr}} \quad (6.1)$$

The Jain fairness index is defined as follow:

$$JainFairnessIndex = \frac{\sum_{i=1}^n (SR_i)^2}{n \cdot (\sum_{i=1}^n SR_i)^2} \quad (6.2)$$

A larger value of Jain's index represents a fairer energy saving for all nodes.

Figure 6.12 shows the Jain's fairness index for energy saving. CONET scores

the best in fairness. CEET come next with very close fairness results to CONET. This slightly difference in fairness between CONET and CEET can be tolerated if we see the gain CEET achieves in terms of improving energy efficiency.

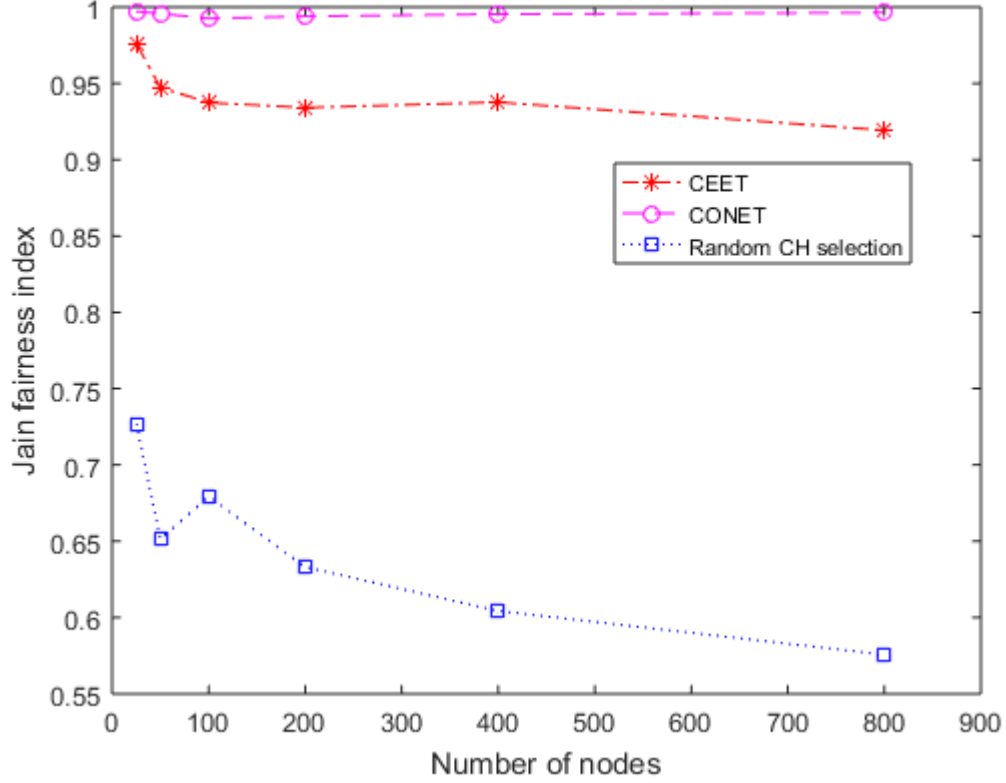


Figure 6.12: Fairness of energy saving in different approaches for experiment time one hour and CH timer 2 minutes

Both CEET and CONET outperform the random CH selection approach in term of fairness for a fixed experiment time of 30 minutes as shown in 6.12. However, Figure 6.13 shows that as the time of the experiment increases the fairness index for the random approach improves and approaches the fairness index of CEET and CONET. This means the random approach is preferable over CONET for situations when the cooperative approach run for long time with enough users nearby along all the time of cooperation because it guarantees high

values of fairness besides the energy savings is better than CONET.

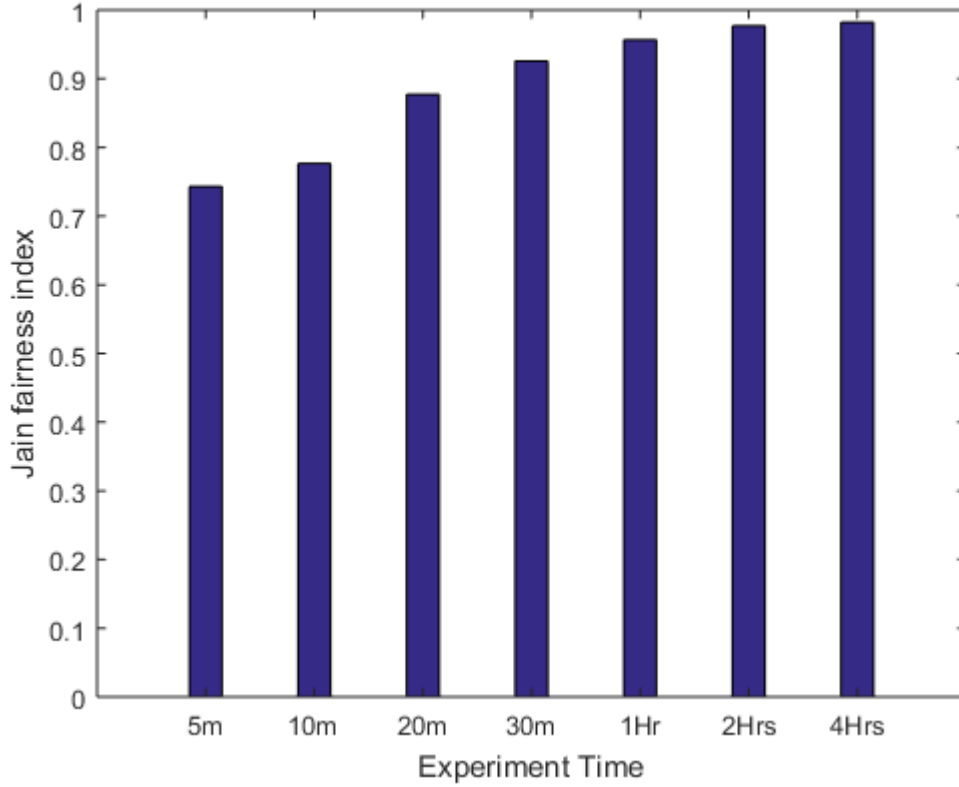


Figure 6.13: Jain fairness Index in the random CH selection approach for energy saving for different experiments times and 100 nodes in the field.

Figure 6.14 illustrates the effect of switching timer on fairness of saving energy. It shows the Jain fairness index for Energy saving ratio with different switching timers. As expected, the figure shows that the smaller switching period, the fairer energy saving for all nodes. However, the figure also shows that the number of hand offs increases as the switching time decreases. Choosing short period for switching will increase fairness among nodes but it may affect the stability of the network due to frequent hand offs. However, choosing the suitable switching time should be determined carefully to assure stability and acceptable level of fairness.

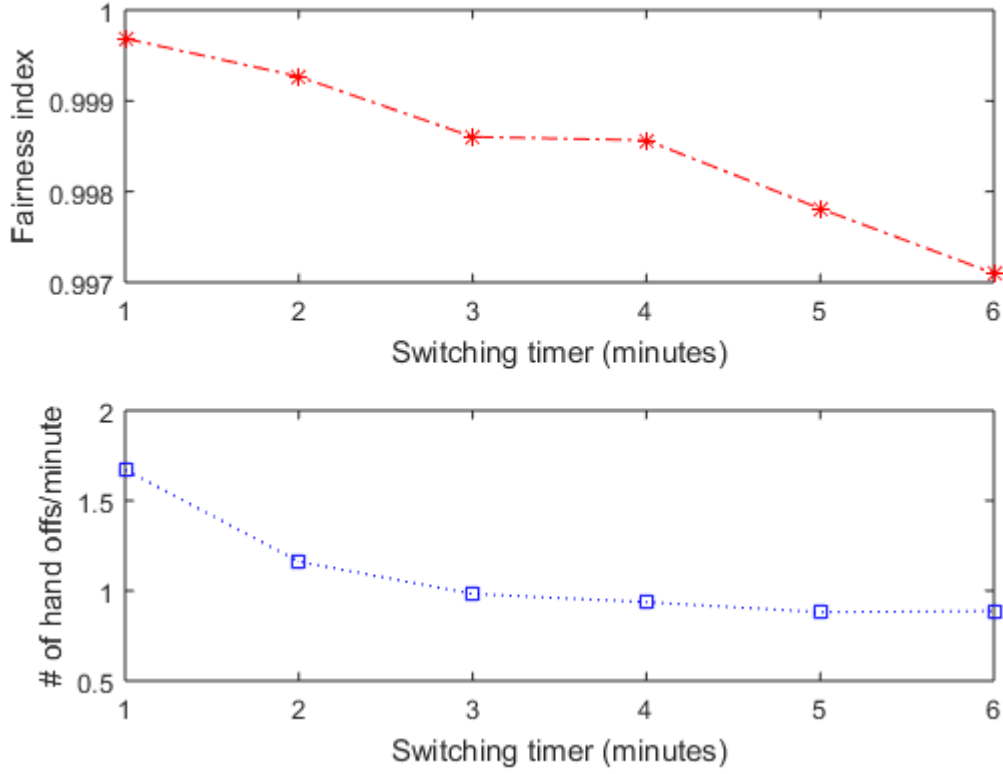


Figure 6.14: Effect of switching period on fairness and stability of the network. Experiment runs for 1 hour for 100 nodes.

6.2 Performance with real experiments

In this section, we evaluate the performance of our system through real experiments using our developed mobile application CEET. The CEET mobile app is installed on 12 smartphones, all have the same specifications. Table shows the main specifications used in the experiments.

6.2.1 Evaluation metrics

To evaluate the performance of the CEET system, we use the following metrics:

- **Power Consumption:** the power consumption is quantified by the battery

Table 6.2: Phones used in our experiments

Specification	Value
Manufacturer	Samsung
Model	Samsung Galaxy Grand Prime Plus
Operating System	Android 6.0.1
Battery	Li-Ion 2600 mAh
Voltage	3.8 V
GPS	A-GPS, GLONASS
Sensors	Accelerometer, proximity
Bluetooth	4.2, A2DP, LE
WLAN	Wi-Fi 802.11 b/g/n
Internal storage	8GB
Release date	2016, November

usage. We fully charged the phones used in the experiments then we start the experiments with fully charged phones. To have fair results, we stop all applications and and smartphone components that has a substantial impact on the battery usage except of those used in our experiments.

- **Delivery rate:** all tracking information messages should be delivered correctly to the server. Message loss will affect the main functionality of the system. To assess the delivery rate, we count number of messages sent from all mobiles during the experiment and compare it with the messages received on the server.

6.2.2 Experiment Setup

We evaluate our proposed system using two different scenarios. The first scenario is conducted without nodes mobility. All phones are booted up and left in the same coordinates for the whole experiment period. The experiment field(the lab)

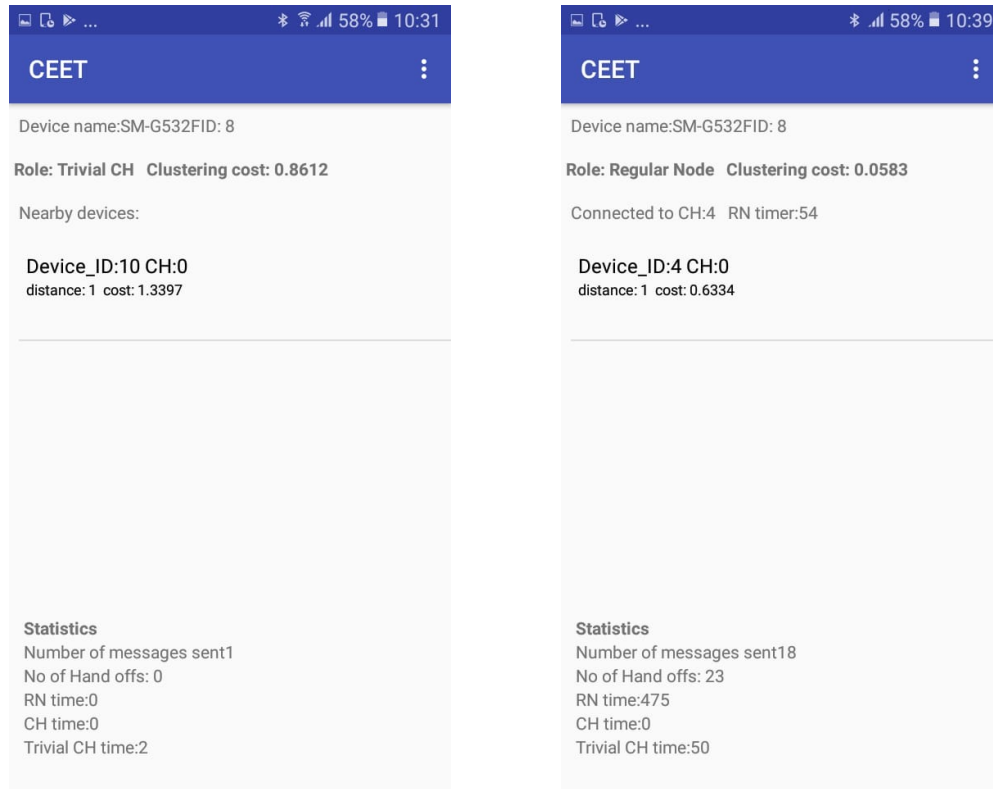


Figure 6.15: Snapshot of main activity in the beginning and end of the experiment is 10x8 m so all nodes are within the Bluetooth range of each other. The second experiment is conducted with user mobility. Twelve smartphones (specifications of smartphones shown in table 6.2), have been assigned to twelve volunteer students. They were asked to move while the application running. The field area where the users move is 100x100 meter. Users were asked to take screen shot for the application at the beginning and the end of the experiment as shown in Figure 6.15. The average running time for the experiments. The switch timer is set to 4 minutes. Cluster head disconnects from all regular nodes when its 4-minute timer expires.

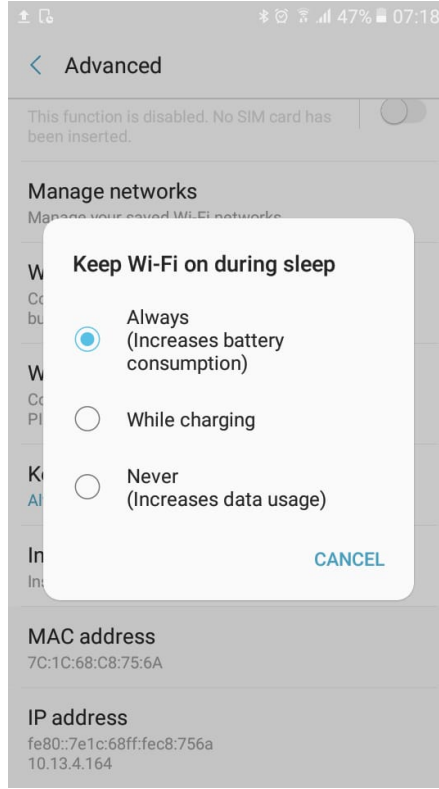


Figure 6.16: WiFi preferences availability of WiFi during sleep mode

6.2.3 Experiments results

In this section we discuss the results of the real experiments conducted using the CEET mobile application. We have conducted two types of experiments, experiment with user mobility to check the cluster construction and hand off in mobile environment. The second type experiments run for long time with fixed location for all nodes to compare the power consumption in the different approaches. In the traditional approach, the WiFi connection should be on during the whole experiment to assure that all messages are sent on the real time to the cloud database server. To assure that it should be set in the WiFi power preferences to keep WiFi on during sleep as shown in Figure 6.16.

Approach	Battery used	In joules	Improvement
CEET	5%	1778.4 Joules	54.5%
CONET	7%	2489.76 Joules	36.4%
Traditional	11%	3912.88 Joules	0

Table 6.3: Battery usage in different approaches

CEET	CEET	CEET
Device name:SM-G532FID: 5 Role: Trivial CH Clustering cost: 0.2805 Nearby devices: Device_ID:3 CH:0 distance: 1 cost: 1.2023 Device_ID:4 CH:0 distance: 0 cost: 0.0608 Device_ID:2 CH:0 distance: 0 cost: 6.4109 Statistics Number of messages sent:19 No of Hand offs: 14 RN time:413 CH time:100 Trivial CH time:29	Device name:SM-G532FID: 6 Role: Regular Node Clustering cost: 0.5497 Connected to CH:4 RN timer:76 Device_ID:10 CH:0 distance: 1 cost: 3.4355 Device_ID:3 CH:0 distance: 1 cost: 1.2162 Statistics Number of messages sent:17 No of Hand offs: 9 RN time:265 CH time:200 Trivial CH time:24	Device name:SM-G532FID: 8 Role: Regular Node Clustering cost: 0.0583 Connected to CH:4 RN timer:54 Device_ID:4 CH:0 distance: 1 cost: 0.6334 Statistics Number of messages sent:18 No of Hand offs: 23 RN time:475 CH time:0 Trivial CH time:50

Figure 6.17: Screen shot from the main activity showing experiment statistics

Power consumption

Smartphones used in the experiments are Samsung Galaxy Grand Prime Plus. They are equipped with batteries with capacity 9.88 Watt-hours (Wh), voltage 3.8 V. The battery capacity in Joules is 35568 Joules. We record the battery level of each phone in the beginning and the end of each experiment to know how much battery has been used during the experiment. Table 6.3 shows the average battery usage of the smartphones during the whole time of the experiment setup which last for 4 hours.

Device ID	Sent messages	Received	RN time	CH time	TCH time	Hand offs
1	16	16	322	100	30	11
2	17	17	456	0	34	8
3	17	17	259	200	32	13
4	19	19	223	299	21	11
5	19	19	413	100	29	14
6	17	17	265	200	24	9
7	19	19	522	0	23	12
8	18	18	475	0	50	23
9	17	17	447	33	10	19
10	17	17	435	49	12	10
11	17	17	261	195	34	13
12	16	16	427	0	27	11

Table 6.4: Experiment result

Results of real experiment with mobility

Table 6.4 shows the results of the real experiment for the 12 phones. The average experiment time 8.4 minutes. The minimum running time is 7.5 minutes and the maximum is 9 minutes. Smartphones spend in average 74.4% of the time as regular nodes and 20.3% as cluster heads and 5.3% as trivial cluster heads. Figure 6.20 shows the average percentage of roles each node spent during the experiment time.

To check the network stability, we have recorded the number of hand offs for every smartphone in the experiment. In average number of hand off per smartphones is 12.8 is equivalent to 1.5 hand off per minute. However there are extreme values such 23 hand offs during the experiment time 8.75 minutes which means 2.6 hand offs per minute. This may affect the performance of the smartphone specially if we know that in half of the hand offs smartphone must turn WiFi and GPS. Figure 6.19 shows a snap shot of the network construction

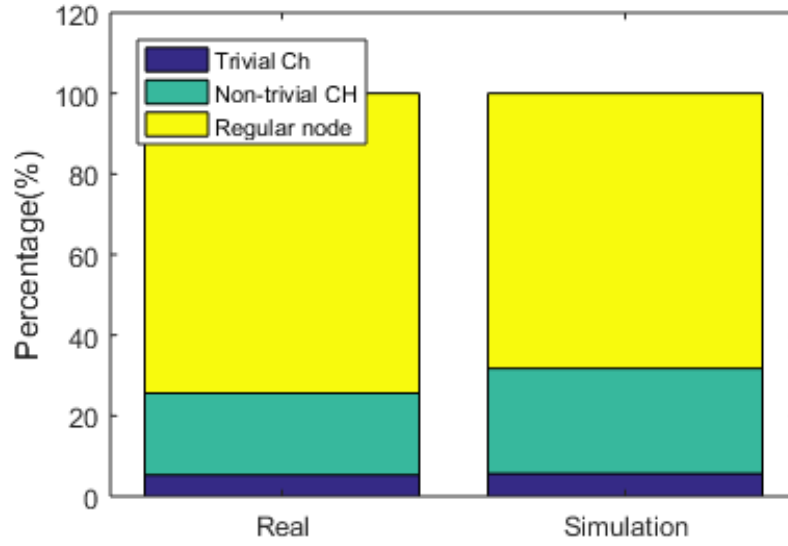


Figure 6.18: Role percentage in CEET real and simulation experiments

in 4 consecutive periods (30 seconds).

The Fairness in this experiment is low. Some nodes did not spend any time in the CH role to serve other nodes like nodes 7,8 and 12. On the other hand, there are some nodes that spend big portion of the experiment time serving as cluster heads. For example, Node number 4 spends around 55% of its time as a CH, nodes 3 and 6 spend around 40%. We have calculated the Jain fairness index for energy saving for nodes and we got the value 0.5023. This relatively low fairness result is due to the short time of the experiment which is roughly twice the CH switch timer.

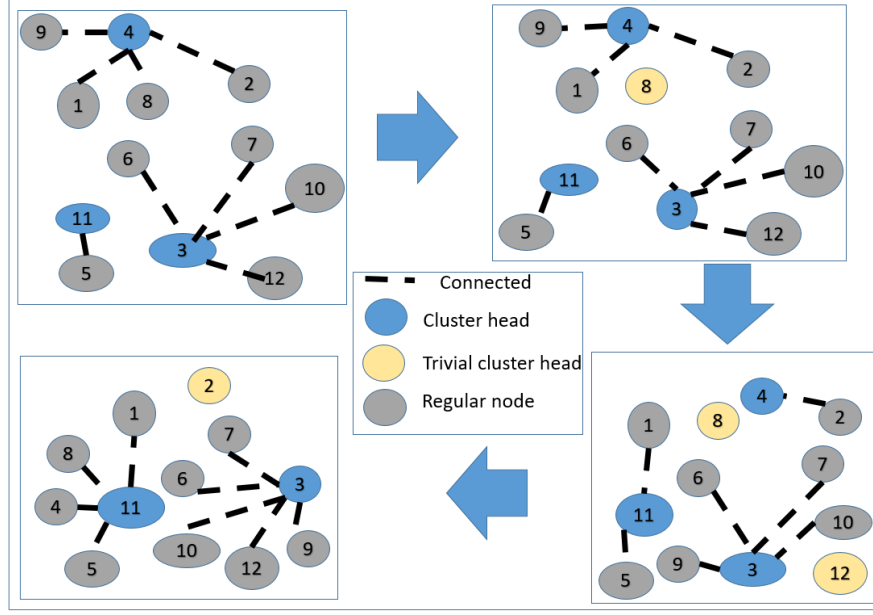


Figure 6.19: Snap shot of the network construction in 4 consecutive periods

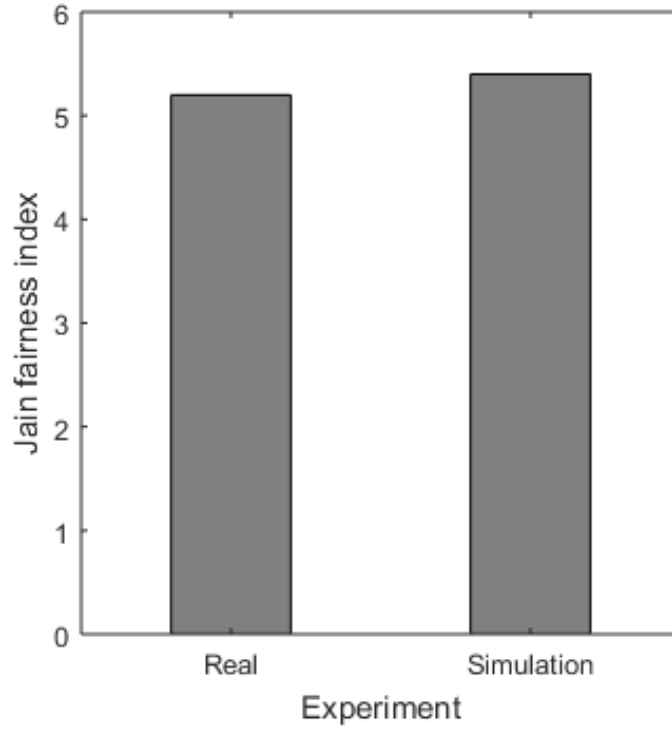


Figure 6.20: Fairness of energy saving in CEET real and simulation experiments

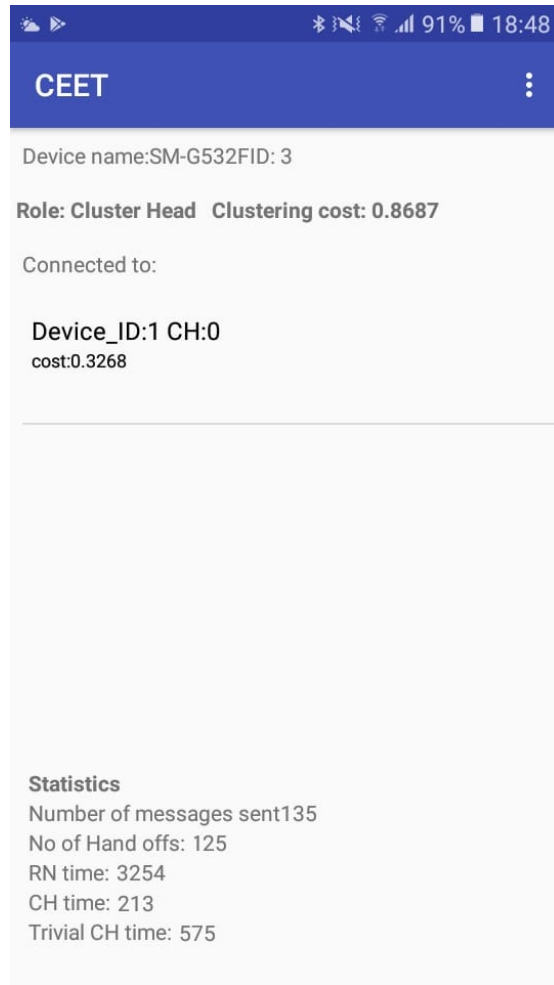


Figure 6.21: Screen shot from the application showing number of messages sent

Delivery rate

For all real experiments conducted using the CEET application, we have achieved 100% delivery rate. All messages sent by the CEET application have been received successfully in the server. We have a counter in the mobile application to count all messages sent by the app Figure 6.21 shows a snapshot of the application's main activity on the running mode. The number of messages that have been sent to the server are shown on the statistics tab . In the server side we can know the number of of all messages received and compare them to the number of all messages sent

by all smartphones during the experiment time. We also can retrieve the messages received of a specific smartphone alone by queering the database by the device ID.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

Real time tracking of elderly and patients using smartphones mobile applications are being increasingly adapted in many systems. Due to the ubiquitous nature of smartphones, using the smartphones in such tracking systems would be time and cost effective. However, the limited battery capacity in smartphones could cause cuts in reporting the tracking information especially in situations when users spend long time without recharging batteries like Hajj for instance. The continuous tracking could be critically important specially for elderly and patients with serious illnesses.

In this Thesis we designed and implemented an energy efficient large-scale tracking system using smartphones. We developed a mobile application that con-

duct all the proposed system functionality. The mobile application was developed for Android smartphones. On the server side, we exploited the Google Firebase real database that receives the tracking information of the users and can notify the data changes within milliseconds.

To save energy we proposed a cooperative energy aware protocol for tracking. The proposed protocol uses clustering to reduce the power used for positioning and communication. Only cluster head uses GPS and WiFi to report tracking information. The remaining members of the cluster use Bluetooth for communication and they obtain their location information from the CH. The clustering algorithm is based on the ratio of saving energy for each node.

We studied the feasibility of implementing the proposed system in real smartphones. We address the technical issues that could raise when implementing such systems in real mobile apps. Smartphones manufacturers enforce strict security measure to protect users that can affect the functionality of the proposed system. which requires auto Bluetooth pairing and auto connection and automatic enabling and disabling location services. We addressed all these technical issues and provide a guide to alleviate these issues in a manner satisfies our system requirements and not compromise on user security and privacy.

We presented a power consumption analysis of the protocol and we formulate the proposed approach into a mixed integer programming optimization model. The model was used to evaluate the cluster construction in the used clustering algorithm in terms of power consumption.

We present a performance evaluation of the system through simulations and through real experiments. The real experiments evaluate the system using limited number of phones (12) and we used simulation to evaluate situations when there are hundreds of nodes on the field. The results show outstanding performance of the proposed system in reducing the tracking energy. The energy saving is around 55% when there are more than 100 nodes in the field. It is important to address that our proposed system does not require any modification to the manufacturing specifications of the smartphones neither to the established wireless environment. Only mobile application is installed to the smartphones using apk file or from the Google play.

7.2 Future work

We plan to propose the following tasks for future work:

- **Extend work to other radio interfaces:** this work can be extended into other communication means like Bluetooth/cellular data as cellular data is integrated to any recent smartphones. Then other metrics will be considered such as price charged.
- **Implement the system on iPhone system:** we consider Android phones as a case study in this thesis as Android system is the most prevalent in the market. We address the technical aspects related to Android phones. Similar feasibility study and implementation on iPhone system should be conducted in the future.

- **Improve the positioning accuracy:** in our system the positioning is performed by the cluster head. All regular nodes in the cluster are assumed to have the same position as the cluster head. This results in a positioning accuracy error up to the Bluetooth range in addition to the GPS error. For future work we can exploit the existence of other cluster heads in the field. A regular node can apply some triangulation techniques to improve its positioning instead of having its position only from its cluster head. More cluster heads in the field means higher positioning accuracy.

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[1] Yousef Ali, Uthman Baroudi."CEET: Cooperative Energy Efficient Tracking System using Smartphones"2019 15th International Wireless Communications Mobile Computing Conference (IWCMC). IEEE, 2019. (Accepted).

[2] Uthman Baroudi and Yousef Ali "Design and Implementation of Cooperative Energy-Efficient Tracking System using Android Smartphones"

